A feasibility study for a low cost mission to the Saturn moon Titan
This report is a feasibility study of a Swedish mission to the moon Titan. The goal is to study the surface, atmosphere and plasma environment of the moon. The study has been performed as a project within the course Space Mission Design at Uppsala University.

The students have been given a scenario. In this scenario, a low-cost Swedish spacecraft will be taken to the Titan/Saturn system by an ESA mother-ship.

Essentially everything in the report is based on real facts, but the authors do not take responsibility for the use of this study in the planning of a real space mission.

Mats André, Johan Köhler
Uppsala, May 2006
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# Mission Overview

1. **Summary of TAGE Mission**  
   1.1 **Scientific Goals and Instrumentation**  
   1.2 **The Platform**  
   1.3 **Orbit Insertion, End of Life and Testing Procedures**  
   1.4 **Conclusions**

2. **Objectives and Requirements for TAGE**

3. **The Balloon, an overview**

4. **Important Budgets**
   4.1 **Mass Budget of Satellite**  
   4.2 **Economic Budget**  
   4.3 **Time Budget of Project**  
   4.4 **Human- and Technology Resource Budget**

5. **Mission Perspectives (Space Program Level)**
   5.1 **ESA Cosmic Vision**  
   5.2 **Cassini/Huygens-Mission**  
   5.3 **TAGE-Mission**

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# Atmospheric Science

6. **Introduction**
   6.1 **Why study Titan?**  
   6.2 **Scientific goals**

7. **The Saturn/Titan system**
   7.1 **Overview of Titan**  
   7.2 **Saturn’s magnetosphere**

8. **Atmosphere & Ionosphere of Titan**
   8.1 Composition and evolution  
   8.2 **A chemical factory**  
   8.3 Atmospheric loss

9. **Measurements**
   9.1 **TAGE measurements**  
   9.2 **HASSE measurements**  
   9.3 **Optional measurements**

# Ground Science

10. **Introduction**  
11. **Missions to Titan**
Power

7.1 Introduction ................................................................................................................. 56
7.2 Requirements for the Power Sub Systems ................................................................. 56
  7.2.1 Power Budget TAGE ............................................................................................. 57
  7.2.2 Power Budget HASSE ......................................................................................... 57
7.3 Power Source Alternatives ......................................................................................... 58
  7.3.1 Solar Arrays ........................................................................................................... 58
  7.3.2 RTGs .................................................................................................................... 59
  7.3.3 Batteries ............................................................................................................... 63
7.4 Recommendation Regarding Power Subsystem ....................................................... 64

Communication

8.1 Introduction .................................................................................................................... 65
8.2 The Choice of Communication Subsystem .................................................................... 65
  8.2.1 TAGEs Antenna System ....................................................................................... 66
  8.2.2 Cassini 2 Antenna System ................................................................................... 68
  8.2.3 Ground Segment .................................................................................................. 69
  8.2.4 Recommended Solution for the Communication Subsystem ................................ 69
8.3 Data Rates .................................................................................................................... 70
8.4 Sizing the Communication Subsystem ........................................................................ 71
  8.4.1 TAGE .................................................................................................................. 71
  8.4.2 HASSE ................................................................................................................ 72
8.5 Total Link Design ........................................................................................................ 72
  8.5.1 TAGE .................................................................................................................. 73
  8.5.2 HASSE ................................................................................................................ 74
8.6 Conclusions .................................................................................................................. 74

Computers

9.1 Introduction .................................................................................................................. 75
  9.1.1 General overview ................................................................................................. 75
  9.1.2 TAGE mission specific overview ......................................................................... 75
9.2 Functions of the Command and Data Handling System ............................................. 76
  9.2.1 Reliability ............................................................................................................. 76
  9.2.2 Complexity .......................................................................................................... 77
  9.2.3 On-Board Computer Pre-processing .................................................................... 77
9.3 Environmental Concerns ............................................................................................ 78
  9.3.1 Temperature .......................................................................................................... 78
  9.3.2 Radiation .............................................................................................................. 78
9.4 Hardware to be used .................................................................................................. 78
  9.4.1 Baseline configuration ......................................................................................... 78
  9.4.2 CPUs ................................................................................................................... 79
  9.4.3 Non-volatile program memory ............................................................................ 79
  9.4.4 Primary computer memory (processing/working memory) .................................. 80
  9.4.5 Secondary memory (storage) ............................................................................. 80
  9.4.6 Antenna control ................................................................................................... 81
9.5 Internal communication ............................................................................................... 81
  9.5.1 Possibilities being used today ............................................................................. 81
  9.5.2 Moving beyond tradition ..................................................................................... 82
  9.5.3 Why wireless? ..................................................................................................... 82
  9.5.4 Why Bluetooth? .................................................................................................. 82
  9.5.5 How Bluetooth works ......................................................................................... 83
  9.5.6 Will Bluetooth work in spacecraft? ...................................................................... 84
9.6 The additional mission – HASSE ................................................................. 84

**Attitude Control & Determination** ................................................................. 85

10.1 Introduction .................................................................................................. 85
10.2 Control modes and requirements ............................................................... 85
  10.2.1 Orbit Insertion .......................................................................................... 85
  10.2.2 Acquisition .................................................................................................. 86
  10.2.3 Normal ......................................................................................................... 86
  10.2.4 End of life ..................................................................................................... 86
  10.2.5 Maneuvers ................................................................................................... 87
10.3 Satellite control ............................................................................................. 87
  10.3.1 Passive control ............................................................................................ 87
  10.3.2 Spin control ................................................................................................ 88
  10.3.3 Three-axis control ....................................................................................... 88
  10.3.4 Effects on requirements ............................................................................. 88
10.4 AC&D system hardware ............................................................................. 89
  10.4.1 Sensors ....................................................................................................... 89
  10.4.2 Actuator ....................................................................................................... 92
10.5 Disturbance Environment .......................................................................... 92
10.6 Orbit maintenance ....................................................................................... 93
10.7 Economics .................................................................................................... 94

**Thermal Control** ............................................................................................ 95

11.1 Introduction .................................................................................................. 95
11.2 Thermal sub-systems overview ................................................................... 95
  11.2.1 TAGE .......................................................................................................... 95
  11.2.2 Heat shield .................................................................................................. 96
  11.2.3 HASSE ........................................................................................................ 96
11.3 Theory ........................................................................................................... 96
  11.3.1 Requirements ............................................................................................. 96
  11.3.2 Thermal environment ............................................................................... 97
  11.3.3 Thermal control methods .......................................................................... 98
11.4 Designing the thermal sub-system .............................................................. 101
  11.4.1 Orbit around Titan ..................................................................................... 101
  11.4.2 Travel phase .............................................................................................. 102
  11.4.3 Aerocapture ............................................................................................. 103
  11.4.4 HASSE ....................................................................................................... 103
11.5 Mass, power and cost estimates ................................................................. 104

**End of Mission** .............................................................................................. 105

12.1 Introduction .................................................................................................. 105
12.2 Conclusion .................................................................................................... 105
12.3 Planetary Protection .................................................................................... 105
  12.3.1 What is planetary protection? .................................................................. 105
  12.3.2 Bodies included ......................................................................................... 106
  12.3.3 How to achieve? ....................................................................................... 107
  12.3.4 Earlier Saturn missions .......................................................................... 107
12.4 Ending of TAGE mission .......................................................................... 108
  12.4.1 Disposal orbit ............................................................................................ 108
  12.4.2 Crash into Saturn ..................................................................................... 109
  12.4.3 Outer space trajectory ............................................................................. 110
  12.4.4 Crash into Titan ....................................................................................... 110
  12.4.5 The ending of HASSE ............................................................................. 111
1.1 Summary of TAGE Mission

Titan Atmosphere and Ground Explorer, or TAGE, is the current working name for a low cost mission initiated by ESA to the Saturn moon Titan. In this pre-phase-A study we show that this mission is indeed possible to carry through and also that the knowledge it will provide us with are of such value that an orbiter such as TAGE actually is desirable. In this introductory chapter I will give an overview of the space-craft that we are sure would be the best solution to put in orbit around Titan.

1.1.1 Scientific Goals and Instrumentation

So, what is so interesting about Titan and why do we want to go there at all? Beginning with the scientific point of view there are two aspects that we are interested in. The first part is the atmosphere and the ionosphere. One focus here would be to reach a better understanding about the composition of the atmosphere, this could for example help us to understand the evolution of life here on earth since the composition of Titans atmosphere is believed to resemble that of earth when life first formed here. We would also learn about the evolution of planets in general by studying Titan. For more details about this, see chapter 2. The second interesting portion is ground studies. Here, ground penetrating radar would provide us with crucial information regarding Titans geology beneath the surface and its behaviour. For more details, see chapter 3. These aspects together are of great importance to human science and the benefits from studying such important behaviours with great accuracy from a low-cost mission could be, and are, very immense.

In addition to this, some of the instruments that would be desirable to bring into an orbit around Titan would be a set of Langmuir-Probes, Spectrometers, a Top-Side Sounder, Wire Boom Antennas, Flux-Gate Magnetometers and the Ground Penetrating Radar. For more details, see chapter 4.

1.1.2 The Platform

The platform, which will bring the payload into orbit, keep it alive and support it with communication, should consist of a semi-cylinder with eight sides and a diameter of about 120cm and a height of about 80cm. It should have a 0.8cm thick layer of Sandwich Panel with Aluminium Honeycomb Structure in order to protect itself from small high-velocity objects. There will be a total of four booms (on the sides of TAGE). They will carry the Langmuir-Probes and they will also make up the radar. For details regarding the structure, see chapter 6. The platform will be spin-stabilized since none of our instruments demand such a high attitude determination that three-axis stabilization would

Figure 1.1 TAGE satellite
be necessary. For attitude control and orbit maintenance TAGE will have eight thrusters and a total fuel-supply of 25.0kg. This will be enough for orbit maintenance during the year-long operational time period as well as supporting the End-Of-Life manoeuvre. For more details regarding attitude control and orbit maintenance, see chapter 10. A Radio Thermal Generator, RTG, from NASA, will power TAGE. The RTG will be mounted “under” the spacecraft and since it is rectangular shaped it will “lie down”, thus helping to keep the spin-vector stable. The neutron radiation from the RTG will not possess a real threat to the spacecraft, as the accumulated calculated dose is 1.9 rad at a distance of one meter during 9 years. At the vast distance from the sun where Saturn is situated solar panels are far too ineffective and mass consuming to use. For details about the power-system and the complete power-budget, see chapter 7. On the “top” of the cylinder TAGE will be equipped with an Electronical Phase-Shifting Array Antenna. This will maximize our capability of keeping in contact with Cassini 2 and Earth if needed while at the same time, minimize mass. For specific details I refer to chapter 8. For the distribution of data from the instruments to the antenna and for internal control TAGE will have an intelligent wireless internal communication-system within its OBDH. TAGE will be able to store large amounts of data safely when waiting for an opportunity to transmit the data to Cassini 2. For details, see chapter 9. To keep TAGE at a reasonable temperature it will be covered by a blanket of multi-layer insulation, or MLI. There will also be some active thermal components operating and the RTG will also give some heat that can be used. This will ensure that the thermal constrains set by the payload and other sub-systems will be followed while TAGE is in operation. The RTG will not be covered by MLI. Further description is found in chapter 11.

1.1.3 Orbit Insertion, End of Life and Testing Procedures
When Cassini 2, which will deliver TAGE to the Saturn system, has separated, TAGE will perform a controlled aero-braking in Titans atmosphere. This manoeuvre will save a lot of fuel and therefore mass. The aero-braking manoeuvre is made possible due to a new aero-braking system in development. TAGE will release a big torus-shaped balloon that will help reduce speed to the desired level. The balloon will then be separated and TAGE will enter a polar orbit around Titan. For details regarding orbit insertion, see chapter 5. After the separation, this balloon will flow freely in the atmosphere and carry a small payload of 5kg and perform measurements in-situ for as long as it stays alive. This actually means that we are delivering two spacecrafts within this one mission. For further information, see section 1.3 in this chapter. After exiting the atmosphere TAGE will release the heat shield that is placed as a bubble over the antenna.

When the mission objectives are fulfilled and it is time to dispose TAGE it will perform an End-of-Life manoeuvre. This manoeuvre is needed in order to guarantee that TAGE will not crash onto the very surface of Titan itself and thereby pose a risk of contamination. The manoeuvre consists of bringing TAGE to an orbit where it will not cross paths with Titan for at least 100 years. For details regarding the End-of-Life procedures, see chapter 12.

When designing a satellite there is of course a rigorous scheme of testing procedures that needs to be fulfilled. Every satellite has its own individual design and each operate in an environment where repairs and maintenance are either impossible or very expensive. That means that the design that is proposed must be tested over and over again in great detail to ensure acceptable functionality. TAGE will go thru such a program and the details for this are found in chapter 13 of this report.
1.1.4 Conclusions

So, is this mission feasible? Will it work? Is it worth it? My answer to these three questions is, “Yes!” This mission has potential to become one of ESA's most successful missions regarding the output of science compared with input of money. The only reservation is that the Cassini 2 mission also has to prove to be feasible.

Within ESA's Cosmic Vision one of the four main pillars state: “How does the solar system work?”[1]. The TAGE-mission is a formidable tool to bring us closer to clarity of just that. The chapters following mine will show in more detail the different subsystems and phases of TAGE. So, enjoy your reading of this report and let yourself be inspired.

1.2 Objectives and Requirements for TAGE

When starting this investigation we were given some initial objectives and requirements from ESA, these are:

• …[that] ”Sweden shall contribute a low-cost spacecraft to study Titan.”
• …“understanding of the evolution of the atmospheres and ionospheres of planets and large moons.”
• …”understanding of the structure and evolution of the surfaces of planets and large moons.”
• …”the Swedish spacecraft will be launched 2016.”
• …”shall be operational in orbit around Titan for at least one year.”
• …”maximum total funding available … is 20 million Euro.”

Starting from this we have identified some scientific objectives that TAGE should and will fulfil. For more details, see chapter 2 and 3. Briefly these are.

• Determination of the composition of Titans atmosphere
• Studying the atmospheric loss-process thus giving us knowledge about atmospheric evolution.
• Exploration and mapping of Titans geology beneath the surface thus gaining knowledge about surface evolution.

From here we have identified some requirements that the spacecraft should and according to our design will follow. These requirements are quite general but show the overall problems with this mission pretty well.

• TAGE shall have a maximum weight of 200kg when mounted on Cassini 2.
• TAGE shall be able to put itself in orbit around Titan after separation with Cassini 2.
• TAGE shall be able to maintain in a polar orbit around Titan for at least one year.
• TAGE shall remain operational during the above mentioned time and cope with the surrounding environment.
• TAGE shall be self-powered.
• TAGE shall be able to communicate with earth via Cassini 2 and send back all scientific data that the instruments collect during the above mentioned period.
• TAGE shall regulate its temperature so that OBDH and instruments will function properly.
• TAGE shall, after mission objectives are completed, put itself in a safe orbit where the risk of a crash with Titan is eliminated for at least 100 years.
1.3 The Balloon, an overview

When the balloon that we are using to aero-break TAGE has fulfilled its primary objective, and TAGE has reached its desired speed to enter an orbit around Titan, it will be released from TAGE. TAGE will at the same time release a total payload of 5kg that is attached to the Balloon. This will take place at an approximate height of 500km. The payload will then follow the balloon down on a journey into the atmosphere of Titan. This is a challenging second objective for the balloon and we believe that it is an economical- as well as mass-effective way of obtaining science from within the very atmosphere itself. The mechanisms used during the critical release from TAGE are described in chapter 5.

The balloon will then flow around freely as long as it is lighter then the surrounding atmosphere. Titan’s gravitational acceleration is 1.35 m/s² and since the balloon has a volume of approximately 285m³ and is filled with helium-gas we believe that it might take days before it lands. However, the payload that it brings is estimated to survive for hours due to the cold temperature that it will endure. Some of the measurements that are of interest to perform are:

- Obtain a better temperature curve of the atmosphere.
- Examination of winds in the atmosphere.
- Humidity examinations.
- Determination of chemical compositions of the atmosphere.
- Pressure measurements.

A far more detailed description of the measurements can be found in chapter 3. Information regarding the instruments can be found in chapter 4. The balloon payload will not only consist of instruments, but also of a power supply made up of batteries, an antenna for transmitting the data to TAGE and/or Cassini 2 as well as a small processing system and thermal protection. Table 1.1 shows the mass budget for the balloon-payload. The link-budget is found in chapter 8 and some thermal calculations in chapter 9 regarding the balloon.

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass [kg]</th>
<th>Comments</th>
<th>Chapter Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload Instruments</td>
<td>1.0</td>
<td></td>
<td>Chapter 3 and 4</td>
</tr>
<tr>
<td>Power</td>
<td>2.5</td>
<td>Batteries</td>
<td>Chapter 7</td>
</tr>
<tr>
<td>Communications</td>
<td>0.3</td>
<td></td>
<td>Chapter 8</td>
</tr>
<tr>
<td>Altimeter</td>
<td>0.5</td>
<td></td>
<td>Chapter 10</td>
</tr>
<tr>
<td>Thermal, Structure and small Computer</td>
<td>0.7</td>
<td></td>
<td>Chapter 11, 6 and 9</td>
</tr>
<tr>
<td>Total</td>
<td><strong>5.0</strong></td>
<td></td>
<td></td>
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</tbody>
</table>

*Table 1.1: Total Mass-Budget of Balloon Payload*

The balloon has been given the working name: High Altitude Sailor for Science Exploration, or HASSE.

1.4 Important Budgets

In a pre-phase-A study different kinds of budgets are of great importance. The reason for this is that they show if the mission is at all possible to carry out and they will reveal any weak points in the design. Therefore, balancing and finding good compromises between the
different budgets are of great importance. As with TAGE all budgets are functional and are within the given limits. I have listed the budgets to take in consideration:

- Economic Budget (sets the economical frames for the whole mission)
- Mass Budget (finds compromises between subsystems)
- Power Budget (finds compromises between power consuming subsystems)
- Link Budget (gets all communication parameters to work)
- Time Budget (keeps deadlines)
- Human Resource- and Technology-Budget (who can build this spacecraft?)

Below, the complete Mass- Economic- and Time-Budgets for the entire TAGE-mission are listed and explained in detail. A brief Human Resource- and Technology-Budget is also described. The complete Power-Budget can be found in chapter 7 and the complete Link-Budget in chapter 8.

1.4.1 Mass Budget of Satellite

The mass budget is one of the most important features of a satellite mission. It sets physical limits to what you can bring onboard and therefore to what extent your satellite can perform. It also reflects your economical budget in the sense that a smaller satellite is more often less expensive than a larger one. However, this connection is not linear or even definite since new micro- and nano-satellites can consist of new, recently developed, components and extremely sophisticated systems that are very expensive. However, a small satellite is of course less complex to handle while on the ground and also a lot cheaper to launch. The new trend within satellite missions is to keep the mass down in order to save cost and time when planning and producing the satellites and at the same time maintain the performance level. Even the grade of redundancy is being brought down and NASA has actually stated a name for this trend; “Faster-Better-Cheaper”.

As for the TAGE-mission we have negotiated an upper limit of 200kg. That is quite small for such a big mission as sending an orbiter around Titan is. As a comparison the ESA-Lander Huygens had a mass of 350kg [2]. However, when we were first given the task to perform this Pre-Phase-A study on a mission for Titan ESA gave us a mass limit of 125kg. Within these parameters we would not have to take into account any kind of orbit insertion since Cassini 2 was to deliver us into an orbit around Titan. We were then given new directions that TAGE itself should be able to perform this manoeuvre. A computation revealed that we needed 75kg of fuel to put a 125kg satellite in orbit around Titan. We therefore needed to increase the mass of TAGE to 200kg in order to be able to perform this breaking with thrusters. For more details regarding this, see chapter 5. Subsequently, ESA agreed to an increase of mass to the desired level.

As a result, our total mass budget has been adjusted to a mass of 200 kg. The overall mass budget for TAGE is listed in table 1.2. The overall fuel mass budget is listed in table 1.3. The local mass-budgets for the individual subsystems are found in respective chapter.

<table>
<thead>
<tr>
<th>Components</th>
<th>Mass [kg]</th>
<th>Percentage of Total Mass [%]</th>
<th>Comments</th>
<th>Chapter Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload</td>
<td>20</td>
<td>10.1</td>
<td>All instruments including wire-booms.</td>
<td>Chapter 4</td>
</tr>
<tr>
<td>Separation and Orbit Injection</td>
<td>53.8</td>
<td>27.1</td>
<td>Includes separation mechanisms from ESA-spacecraft and complete Aero-Capture system.</td>
<td>Chapter 5</td>
</tr>
</tbody>
</table>
Structure | 20.0 | 10.1 | Aluminium Honey-Comb structure 16kg. 4kg reserved for screws etc. | Chapter 6
---|---|---|---|---
Power Subsystem | 34.0 | 17.1 | RTG | Chapter 7
Communication Subsystem | 13.0 | 6.6 | Patch-antenna subsystem including wires. | Chapter 8
Computers and On Board Data Handling, C&OBDH | 3.0 | 1.5 | Complete subsystem. | Chapter 9
Attitude Determination and Control, AD&C | 11.5 | 5.8 | Includes Thrusters 4kg, Sensors 5kg and Fuel-Tanks 2.5kg. | Chapter 10
Thermal Components | 13.0 | 6.6 | 7kg heat-shield and 6kg of MLI. | Chapter 11
Fuel (including 10% margin) | 25.0 | 12.6 | Including all fuel needed. | See Table 1.3
Balloon Payload | 5.0 | 2.5 | Including all subsystems. | Chapter 1.3
**Total** | **198.3** | **100** | | |
Margin | 1.7 | 0.9 | Additional margins exist in individual subsystems. | |

Table 1.2: Total Mass-Budget for TAGE-satellite

<table>
<thead>
<tr>
<th>Fuel Component</th>
<th>Mass [kg]</th>
<th>Comments</th>
<th>Chapter Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Orbit insertion fuel</td>
<td>9.9</td>
<td>Fuel needed during orbit-insertion in cooperation with balloon.</td>
<td>Chapter 5</td>
</tr>
<tr>
<td>Orbit maintenance fuel</td>
<td>7.5</td>
<td>Fuel needed to maintain orbit.</td>
<td>Chapter 10</td>
</tr>
<tr>
<td>End of Life fuel</td>
<td>4.9</td>
<td>Fuel needed for the End-of-Life manoeuvre.</td>
<td>Chapter 12</td>
</tr>
<tr>
<td>Residual fuel</td>
<td>0.4</td>
<td>Fuel left in tank that can never be used.</td>
<td>N/A</td>
</tr>
<tr>
<td>Margin (10%)</td>
<td>2.3</td>
<td>Safety margin.</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>25.0</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1.3: Fuel Mass-Budget for TAGE-satellite

The solution presented above is the most mass effective according to our calculations. One can always add a bigger antenna or more payload but at some point you have to do trade-offs between different systems in order to reach a maximum of overall functionality within given limits. However, some systems are hard to do trade-offs with, one example is the RTG from which the technology of today comes in one piece and can not be scaled. Also, some systems add more mass when increasing their performance compared with other systems. The satellite-system will therefore include what is referred to as “mass-drivers.” As for TAGE the most significant mass-drivers are fuel- and the communication subsystem. That is one of the reasons why we have selected an aero-braking system and patch-antennas.
One question that one might ask is why the payload only receives 10% of the total mass. If we increased that mass we would have to decrease the mass for another subsystem. Furthermore, having more payload would also mean that more data would be collected, which in the end would require a higher bit-rate when transferring the collected data as well as demanding a higher performing OBDH-system. The Antenna- and OBDH-system would then demand more power and mass. This chain of demands and events continues thru all subsystems when changing a parameter. So, as previously stated, it is important to make compromises between subsystems so as to reach the maximum functionality. We do obtain a lot of science from this 10% and the remaining 90% simply makes sure that the results collected accurately reach Earth.

One drawback is the small margin. However, there are margins within the different subsystems included and I refer to a respective chapter for more information. So, the final parameters of the masses of the individual sub-systems will most likely change during more detailed investigations done in preliminary- and detailed definition. The aim with this report is to show that this mission is indeed possible to carry through.

1.4.2 Economic Budget

The economic budget for a mission can sometimes be difficult to predict. The diversity of different missions in general and the increase of commercial missions in particular have created a situation were traditional cost-analysis methods are no longer as accurate as they once were. The ongoing entry of specific low-cost missions onto the market is additionally increasing this uncertainty regarding cost-analysis.

The funding limit for this mission, including all costs, is 20 million Euros. This funding will be available in equal parts starting from September 2006 and ranging up to September 2016. For simplicity all costs in this report will be presented in Fiscal-Year 2006 Euros (FY06€), this is in order to avoid confusion and increase accuracy when dealing with different parameters.

I will perform a work breakdown structure [3] or WBS where I will divide our mission into different phases and parts in order to identify specific costs more easily. Thereafter I will perform a parametric cost estimation [3] or PCE on the different parts identified. There are a number of different ways to estimate costs and calculate budgets but the parametric cost estimation is the method that is increasingly becoming more and more common at the expense of other methods, such as bottom-up estimations or analogy-based estimations [3].

1.4.2.1 Work Breakdown Structure (WBS)

There are three major economical phases for TAGE, these are:

- Research, Development, Testing and Evaluation (RDT&E)
- Production
- Operations and Maintenance (O&M)

Investigating the different parts of our TAGE-mission can be performed as follows:

- Program Level Costs, such as Management, System Engineering and Integration (SE&I)
- The TAGE-Satellite, which includes the parts to the whole platform and the payload.
- Launch Segment, which includes the method of launch and launch operations.
- Ground Segment, includes facilities, equipment, software, logistics, management and SE&I.
- Operations and Maintenance, here we find personnel training, maintenance, spares, mission operations as well as command, communications and control.
1.4.2.2 Parametric Cost Estimation (PCE)

The PCE is based on a typical top-down approach of the complete system. An overall budget estimation for the whole TAGE-mission is shown in table 1.4. In table 1.5 is a more detailed budget for the TAGE-satellite shown. The estimated overall price for this mission at this stage is 19.720.000 FY06€.

<table>
<thead>
<tr>
<th>Cost Parameter</th>
<th>Estimated Cost [FY06€]</th>
<th>Percentage of Total Cost [%]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Management and SE&amp;I.</td>
<td>11.000.000</td>
<td>55.8</td>
<td>Includes salaries during phase A-D for ten persons and costs for testing, approximately 9% of total budget. Facilities and administration costs included.</td>
</tr>
<tr>
<td>TAGE-Satellite</td>
<td>7.100.000</td>
<td>36.0</td>
<td>Cost for parts making up TAGE-satellite, see Table 1.2.</td>
</tr>
<tr>
<td>Launch Segment</td>
<td>N/A</td>
<td>0</td>
<td>Included in Cassini 2 budget.</td>
</tr>
<tr>
<td>Ground Segment</td>
<td>N/A</td>
<td>0</td>
<td>Included in Cassini 2 budget.</td>
</tr>
<tr>
<td>Operations and Maintenance</td>
<td>1.620.000</td>
<td>8.2</td>
<td>Includes salaries for three persons during 9 years.</td>
</tr>
<tr>
<td>Total</td>
<td>19.720.000</td>
<td>100.0</td>
<td></td>
</tr>
<tr>
<td>Margin</td>
<td>280.000</td>
<td>1.4</td>
<td></td>
</tr>
</tbody>
</table>

Table 1.4: Overall cost estimation for TAGE-mission

<table>
<thead>
<tr>
<th>Cost Parameter</th>
<th>Estimated Cost [FY06€]</th>
<th>Percentage of Total Satellite Cost [%]</th>
<th>Comments</th>
<th>Chapter Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload</td>
<td>3.200.000</td>
<td>45.1</td>
<td>Includes GPR 1/3, Langmuir-Probes 1/6, Spectrometers 1/3 and Magnetometer 1/6.</td>
<td>Chapter 4</td>
</tr>
<tr>
<td>Separation and Orbit Injection</td>
<td>800.000</td>
<td>11.3</td>
<td>Including 100% margin due to system not in function yet.</td>
<td>Chapter 5</td>
</tr>
<tr>
<td>Structure</td>
<td>20.000</td>
<td>0.3</td>
<td>Includes Sandwich Panel, RTG-lock and antenna mechanisms.</td>
<td>Chapter 6</td>
</tr>
<tr>
<td>Power Subsystem</td>
<td>N/A (But will be around 12.000.000)</td>
<td>0</td>
<td>This Cost is lifted up to ESA centrally since negotiations with NASA are required.</td>
<td>Chapter 7</td>
</tr>
<tr>
<td>Communication Subsystem</td>
<td>1.500.000</td>
<td>21.1</td>
<td>Approximate price from Saab Ericsson Space for HASSE = 55.000.</td>
<td>Chapter 8</td>
</tr>
<tr>
<td>Computers and On Board Data Handling</td>
<td>30.000</td>
<td>0.4</td>
<td>Includes all OBDH components.</td>
<td>Chapter 9</td>
</tr>
</tbody>
</table>


### 1.4.3 Time Budget of Project

The Time-Budget of a mission is crucial in order to comprise a strict order of occurrences as well as having a clear course of the project. The statement “time is money” has a double meaning since an actual delay off course can cost significant amounts, but it can also be very costly to make changes in the design at a late state of the project. Since it is crucial to avoid such changes it is important to state that “from this point nothing should be changed regarding this parameter in the project”. Formal deadlines for different stages of the process of realizing a satellite are a great tool in achieving this. The suggested deadlines for this mission are listed in table 1.6.

<table>
<thead>
<tr>
<th>Phase A</th>
<th>Mission Analysis, Needs Identified</th>
<th>Deadline June 2006 (this report)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase B</td>
<td>Preliminary Definition</td>
<td>Suggested Deadline June 2007</td>
</tr>
<tr>
<td>Phase C</td>
<td>Detailed Definition</td>
<td>Suggested Deadline June 2008</td>
</tr>
<tr>
<td>Phase D</td>
<td>Production/Ground Qualification and Testing</td>
<td>Suggested Deadline December 2010</td>
</tr>
<tr>
<td>Phase D</td>
<td>Integration and testing with Cassini 2</td>
<td>Suggested Deadline December 2015</td>
</tr>
<tr>
<td>Phase E</td>
<td>Utilization</td>
<td>Launch September 2016, reaching Titan in 2023</td>
</tr>
<tr>
<td>Phase F</td>
<td>Disposal</td>
<td>As late as possible, 2024 or later.</td>
</tr>
</tbody>
</table>

Table 1.6: Suggested deadlines for TAGE-mission.

Table 1.6 follows the directions stated by ESA for different stages of a mission. With this report the Pre-Phase-A stage can be considered fulfilled.

### 1.4.4 Human- and Technology Resource Budget

A requirement given in our specification was that Swedish technology and knowledge should be used whenever possible. Here we actually don’t see any major concern. Even though Sweden is a small country it is well equipped with companies, knowledge and technology for producing such a high-tech spacecraft such as TAGE.

Our suggestion is that ESA let the Swedish Space Corporation situated in Stockholm be in charge of the development and production of TAGE. The reason is that this commercial and government owned organization has produced high performing, low-cost satellite missions before such as Astrid and Odin [4].

Further on, there are a lot of Swedish corporations that could potentially be contracted for different parts and/or subsystems. One example is Saab Ericsson Space, which is proposed to be contracted for the communication system together with Ångström Aerospace Cooperation.
(ÅAC), see chapter 8. Another example of Swedish technology is the Langmuir probes, which are produced by the Swedish Institute of Space Physics (IRF). Additionally, the MLI can for example be produced by SAAB. For details regarding specific parts of TAGE I refer to the respective chapter.

However, there are a few concerns. One is that we need an RTG for this mission. The only organization that possesses these devices today is NASA. But ESA is already aware of the fact and it was noted in our initial specification. Another concern that has occurred is in regards to the proposed aero-braking system. For a discussion on this topic, see chapter 5.

A conclusion regarding the technological aspect of TAGE is that the human knowledge of building it can be found within Sweden. Some technological devices, though, will have to be brought in from abroad but mainly from within Europe. One example here is our star tracker, which is a Dutch construction. But we must keep in mind that hardly any mission that is initiated by ESA is produced completely by one nation. Cooperation and multi-nationalism are key words here.

1.5 Mission Perspectives (Space Program Level)

When one is planning for a space-mission it is important to know in what exact frames you are working regarding overall objectives. That is, what part does our spacecraft play when put into perspective concerning all other missions that have either been accomplished, are undergoing operation or still being planned. Such frames are called a space-program.

1.5.1 ESA Cosmic Vision

ESA's Cosmic Vision is a platform of guidelines for exploration of space that were established at a conference in 2004. It sets out the parameters that ESA will strive to bring clarity to between 2015 and 2025. Those Parameters are [5]:

- What are the conditions for planet formation and the emergence of life?
- How does the Solar System work?
- What are the fundamental physical laws of the Universe?
- How did the Universe originate and what is it made of?

Even though it is most likely impossible to completely solve these mysteries by 2025, such questions mark a clear path for scientists and space-missions to follow in the upcoming decades. The TAGE-mission follows that path.

1.5.2 Cassini/Huygens-Mission

The Cassini Mission was planned and launched before Cosmic Vision existed. However, its objectives serve the Cosmic Vision very well. The only thing one must remember here is that Cassini is a NASA spacecraft. ESA provided the Titan Lander Huygens that successfully entered Titans atmosphere and landed in January 2005. It gave us valuable knowledge of Titan itself and its atmosphere. However, one Lander and a spacecraft simply performing casual flybys cannot give a very detailed view of the world of Titan.

1.5.3 TAGE-Mission

Compared with Cassini/Huygens TAGE will be significantly cheaper and will gather a lot more science from Titan. Measurements previously taken by Cassini/Huygens will be improved and verified since TAGE will stay in an orbit around Titan for a whole year. One example is the complete mapping of Titan, which Cassini has failed to complete.
2.1 Introduction
A space mission to Titan, to study its atmosphere, ionosphere and surface, is of high scientific importance. Even though Cassini/Huygens is currently examining the Saturnian system with its moons, a closer and more continuous study of Titan would provide more detailed knowledge about the interesting moon. Hopefully, it would also unveil secrets about how life began here on Earth since Titan’s atmosphere resembles the atmosphere on Earth before biological organisms started producing oxygen.

2.1.1 Why study Titan?
Titan is an interesting and fascinating world in many aspects; for example, its environment and atmosphere seem to resemble the conditions on Earth before life evolved. By studying the chemical processes taking place in Titan’s atmosphere it might be possible to understand how the first building blocks of the organic molecules on which life is based, were formed [5]. By studying the mechanisms by which Titan is losing its ionosphere and determining the loss rate, knowledge about the evolution of atmospheres of terrestrial planets and large moons would be provided.

2.1.2 Scientific goals
The prime scientific objectives of the TAGE mission, and the additional balloon-mission HASSE, concerning Titan’s atmosphere and ionosphere, are

- Gaining knowledge about under which conditions life evolved on Earth by determining the composition of Titan’s atmosphere and the relative amounts of complex chemical compounds within it.
- Performing investigations of the evolution of the atmospheres and ionospheres of planets and large moons by studying the atmospheric loss processes of Titan.

Supporting measurement objectives to fulfil these goals include

- Determination of the electron and ion distribution functions and densities and the ion and neutral composition of Titan’s atmosphere and ionosphere using different spectrometers and particle detectors and a gas sensors.
- Mapping of the ionospheric profile using a topside sounder.
- Determination of plasma waves, electric and magnetic fields, electron temperature and ion velocity using Langmuir probes, wire boom probe antennas and a magnetometer.
2.2 The Saturn/Titan system

Saturn is the second largest of the planets in the solar system and with its spectacular ring system it might be the most beautiful. Saturn is very remote, it moves at an average distance from the Sun of 9.5 AU and it takes almost 30 years to complete one revolution, but because Saturn is so large and reflective it can be seen with the unaided eye as a bright star.

Saturn has a large number of moons; seven of them have diameters larger than 400 km and they were probably formed at the same time as their mother planet. The rest are tiny satellites which are either captured asteroids or collision fragments of ice and rock. The planet-sized moon Titan is bigger than the planets Mercury and Pluto and is actually a terrestrial world. [6]

2.2.1 Overview of Titan

Titan is the largest moon of Saturn and the second largest satellite in the solar system after Jupiter’s moon Ganymede. Titan was discovered by the Dutch astronomer Christian Huygens in 1655 and has since then been one of the primary targets for the Voyager missions in the 1980s and the Cassini mission that is still taking place. In January 2005 the Huygens probe landed on Titan and sent back the first images of the surface. In the 2020s TAGE is planned to be the first satellite in orbit around Titan.

Titan is the only satellite in our solar system that is known to have a substantial atmosphere; the neutral atmosphere consists mainly of molecular nitrogen and methane but Titan also possesses an ionosphere due to ionization of the neutrals by photons in the solar wind and energetic electrons in Saturn’s magnetosphere. The TAGE mission is a unique opportunity to study the interesting processes that are taking place in the atmosphere and ionosphere as well as examine some of the surface features of the moon.

Titan and Saturn have the same orbital period, which means that the same side of Titan is always facing Saturn. The low density of Titan implies that it consists of a mixture of ice and rock. Titan does not have an internal magnetic field of its own and hence the solar wind and the plasma in Saturn’s magnetosphere can interact directly with the upper atmosphere.

Table 2.1 gives some physical parameters about Titan. [7], [8]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (km)</td>
<td>5150</td>
</tr>
<tr>
<td>Distance from Saturn (RS)</td>
<td>20.3</td>
</tr>
<tr>
<td>Orbital period (days)</td>
<td>16.0</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>1.34×10^{23}</td>
</tr>
<tr>
<td>Average density (kgm^{-3})</td>
<td>1880</td>
</tr>
<tr>
<td>Surface temperature (K)</td>
<td>94</td>
</tr>
<tr>
<td>Surface pressure (kPa)</td>
<td>1.46</td>
</tr>
<tr>
<td>Surface gravity acceleration (ms^{-2})</td>
<td>1.35</td>
</tr>
<tr>
<td>Mean orbital velocity (kms^{-1})</td>
<td>5.57</td>
</tr>
<tr>
<td>Relative velocity of Saturn’s magnetosphere (kms^{-1})</td>
<td>120</td>
</tr>
<tr>
<td>Background magnetic field (nT)</td>
<td>5.0</td>
</tr>
<tr>
<td>Electron number density at 1000 km altitude(cm^{-3})</td>
<td>2000</td>
</tr>
<tr>
<td>Electron temperature at 1000 km altitude (eV)</td>
<td>0.1</td>
</tr>
<tr>
<td>Debye length at 1000 km altitude (mm)</td>
<td>0.5</td>
</tr>
<tr>
<td>Debye length in Saturn’s magnetosphere (m)</td>
<td>7</td>
</tr>
<tr>
<td>Ionospheric escape flux (s^{-1})</td>
<td>10^{25}</td>
</tr>
</tbody>
</table>

Table 2.1: Physical parameters of Titan
2.2.2 Saturn’s magnetosphere

In 1979 Pioneer 11 discovered the magnetosphere of Saturn, see figure 2.1, with its bow shock at ~24 Saturnian radii. The magnetic field was measured to be 600 times stronger than the magnetic field on Earth and aligned with the rotation axis of Saturn. [6]

It is thought that convection in the planets interior is the source of Saturn’s magnetic field but exactly how the field is generated cannot be explained by current theories and is now investigated by Cassini. The magnetic field lines are frozen into the plasma that is confined in the magnetosphere, that is, the magnetic field and the plasma corotate with the planet and thus have approximately the same rotational period as Saturn, ~10.7 hours. The magnetospheric plasma and Titan rotate in the same direction around Saturn but since the plasma rotates much faster it hits Titan with a relative speed of ~120 km/s. Because of this interaction, and the incident solar radiation, Titan’s upper atmosphere gets ionized and parts of it are carried away; see section 2.3.3.

Saturn’s magnetosphere does not have the same concentration of charged particles as for example Jupiter’s, because the icy particles in Saturn’s rings are good absorbers. Therefore, Saturn’s magnetosphere is the only one in which neutral molecules are more abundant than ions. The charged particles that do exist are concentrated in radiation belts similar to the Van Allen belts in the Earth’s magnetosphere. There are enough of these particles to produce auroras around Saturn’s poles. [7]

![Figure 2.1: Saturn’s magnetosphere](image)

2.3 Atmosphere & Ionosphere of Titan

About a hundred years ago, scientists started to suspect that Titan might have an atmosphere, because it is cool and massive enough to keep heavy gases. In 1944 Gerard Kuiper discovered spectral lines of methane in sunlight reflected from Titan, which confirmed the earlier suspicions. Today, Titan is known to be the only satellite in the solar system with a substantial atmosphere.
2.3.1 Composition and evolution

Titan’s atmosphere is very dense and the surface pressure is 50% higher than the surface pressure on Earth. Since the gravity on Titan is much weaker than on Earth, it means that about ten times more gas lies above a square meter of Titan’s surface than above a square meter of Earth’s surface. More than 90% of the atmosphere consists of molecular nitrogen (N₂), which comes from the break up of ammonia (NH₃) by solar radiation. Since Titan’s gravity is too weak to keep the hydrogen, these atoms escape into space while the nitrogen remains in the atmosphere. There is also a few percent of methane (CH₄) in Titan’s atmosphere, which interacts with the ultraviolet light from the Sun to produce so called hydrocarbons and other complex molecules; see section 2.3.2.

The question of where Titan’s atmosphere came from is still to some extent unanswered. Since ammonia is quite common in the outer solar system it is thought that Titan’s atmosphere first consisted of this compound that then broke up into hydrogen and nitrogen as discussed above. That would explain the high content of nitrogen observed in Titan’s atmosphere. The amount of observed methane is harder to explain because in the early solar system the much stronger solar wind would have swept away all the methane from Titan. Therefore a source of some kind has to exist, that constantly supplies new methane. This source could be impacting comets that bring the methane with them to Titan, or volcanoes that supply the methane from the moon’s interior. Another theory is that methane became frozen in with water-ice when Titan was formed, and that this material now slowly leaks methane to the atmosphere; see chapter 3 for a further discussion about volcanic activity and the origin of the methane.

When looking at Titan from outside, opaque layers of particles in the atmosphere prevent any view of the surface. Because of the low temperature, the complex molecules produced in the upper atmosphere condense and form a thick haze at about 100-200 km altitude. The haze prevents sunlight from penetrating down to the surface and it also gives Titan its orange-red colour.

The temperature profile of Titan’s atmosphere resembles that of Earth’s; see figure 2.2. First, the temperature decreases with height in the troposphere after which it rises throughout the stratosphere to peak at around 175°K, which is about 80° warmer than the surface temperature. This warming is due to the ultraviolet radiation from the Sun and its absorption contribute to the photochemical processes in the atmosphere, excites the resulting molecules and warms the material making up the haze. [6]
2.3.2 A chemical factory

Solar radiation and energetic electrons in Saturn’s magnetosphere ionize the upper parts of Titan’s atmosphere, and an ionosphere is created. Complex photochemistry takes place in the ionosphere due to the presence of methane and energy inputs; see figure 2.3. The interaction of the methane with ultraviolet radiation from the Sun produces a large number of hydrocarbons. The most dominant species are ethane ($C_2H_6/C_2H_7^+$), ethylene ($C_2H_4/C_2H_5^+$) and acetylene ($C_2H_2/C_2H_3^+$), which can condense into droplets, fall as precipitation to Titan’s surface and form liquid hydrocarbon lakes and rivers.

Airborne hydrocarbons also combine with nitrogen in Titan’s atmosphere producing other interesting compounds, such as hydrogen cyanide ($HCN/H_2CN^+$). Hydrogen cyanide can join together with other molecules in long, repeating molecular chains to form so called polymers. The heavier polymer particles fall down to Titan’s surface, probably covering it with a thick layer of sticky muck. Proteins are a form of polymers where different amino acids make up the subunits in a biologically active molecular chain, but no such complex molecules are likely to be found in Titan’s ionosphere due to the very cold environment far away from the Sun and the lack of oxygen. Nevertheless, some of the compounds of hydrogen, nitrogen and carbon present in Titan’s atmosphere are the building blocks of the organic molecules on which life is based. A detailed study of the composition and the chemical processes taking place there might give clues about the origin of life on Earth. [7]

![Figure 2.3: A simplified diagram of the photochemical processes taking place in Titan’s ionosphere. Ultraviolet radiation from the Sun breaks methane into various fragments, called radicals (enclosed by the dotted line). Titan’s gravity is too weak to keep the molecular hydrogen, which escapes to space. The radicals recombine into different organic molecules, most abundant is acetylene and ethane. These molecules can then react with other hydrocarbon and nitrogen radicals to form more complex substances.](image-url)
2.3.3 Atmospheric loss

Titan’s atmosphere acts as a source of both neutral gas and plasma for Saturn’s outer magnetosphere. The corotating magnetospheric plasma outruns Titan and sweeps the upper parts of the atmosphere with it, creating an ionospheric tail in Titan’s wake; see figure 2.4. The Saturnian magnetosphere is thus important for the structure and dynamics of Titan’s ionosphere.

When the magnetospheric plasma approaches Titan’s atmosphere it interacts with the ionospheric plasma. The mass of the magnetosphere is increased close to Titan due to this interaction, a process called mass loading, and the magnetospheric plasma is slowed down. Since the magnetic field lines are frozen into the magnetospheric plasma, the parts of the field lines that intersect with the mass-loading region are slowed down as well. The field lines are deformed and draped around Titan. The external plasma flow and the Saturnian magnetic field induce an electric field that acts on the ions in the ionosphere. The ions are picked up by the electric field and accelerated downstream.

![Figure 2.4: A schematic picture of the processes by which Titan is losing its atmosphere.](image)

Two other processes contributing to the mass loss of the atmosphere are sputtering and loss via photochemical interactions. Sputtering takes place when energetic electrons and ions from the solar wind and the magnetosphere hit the particles in the ionosphere and cause ejection of atoms and molecules. The incident solar radiation (EUV) also causes ionization and dissociation of atmospheric material, so called photo absorption.

Usually Titan orbits within Saturn’s magnetosphere but under conditions when the solar wind pressure is higher than usual, for example during increased solar activity, the magnetosphere becomes compressed and Titan sometimes lies outside the magnetopause. Since Titan does not have a large-scale magnetic field of its own, the solar wind can then
interact directly with the ionosphere (called exosphere in figure 2.4), which increases the ionization rate and the atmospheric loss via sputtering, photo absorption and ion pickup further. The total escape flux of Titan’s atmosphere was recently measured by the Cassini spacecraft and amounts to $10^{25}$ ions per second. [9], [10]

### 2.4 Measurements

To fulfill the stipulated scientific objectives, different measurements will be performed at different locations in TAGE’s orbit around Titan as well as in the lower atmosphere during the lifetime of HASSE. These measurements will hopefully make it possible to draw conclusions about the evolution of the atmospheres of planets and large moons in general. Even though Titan is a remote icy moon it has a lot in common with the terrestrial planets when considering their atmospheric loss and evolution. In the early days of the solar system, Venus, Earth and Mars had similar atmospheres that then evolved differently. Mars, which is smaller than Venus and Earth, cooled faster and lost its magnetic field and protecting magnetosphere. The solar wind could then interact freely with the Marsian atmosphere and an atmospheric loss process started similar to the one taking place on Titan today. Studying Titan can therefore give information about how the atmospheres of our own planet and closest neighbors evolve over large time scales and the reason for, and size of, the atmospheric loss.

#### 2.4.1 TAGE measurements

TAGE’s orbit will be polar with an orbital time of about 10 hours at the start of the operational phase. Pericenter will be at a height of 950 km during the whole mission, which is inside the ionosphere; see the left sketch of figure 2.5. In this part of the orbit, the composition of the ionosphere will be determined using the spectrometers and particle detectors of the Aspera-3 package; see chapter 4 for information about the scientific instruments. The electron and ion densities and distributions will be measured as well as the relative amounts of different ions and neutral particles. This will provide an increased knowledge about the photochemical processes taking place in the ionosphere and the complex molecules that are formed.

At first, apocenter will be at a height of 8000 km, but this distance will decrease during the mission because of the frictional drag that the satellite will experience in the ionosphere each orbit. In the part of the orbit that lies outside the ionosphere the outflow from Titan will be investigated, the ionospheric profile will be mapped and electric and magnetic fields will be measured. This will be accomplished using Langmuir probes on wire booms and a Topside Sounder. The Langmuir probes will measure plasma waves, electron temperature, ion speed, and the required fields and the Topside Sounder will provide the ionospheric profile. Together this will give knowledge about how much mass that is being lost from the atmosphere, how much of the mass loss different mechanisms are responsible for and how the atmospheric erosion varies with time and Titan’s location relative Saturn and the Sun. By extrapolating back in time it will be possible to understand how Titan’s atmosphere has evolved on a large time scale. Clues can then hopefully be acquired about how Earth’s atmosphere looked like at the time of the origin of life. [11]

During the mission, the plane of TAGE’s orbit will be placed differently in relation to the outflow from Titan. Apocenter will be at different inclinations from Titan’s equatorial plane, as shown in the middle sketch of figure 2.5, and TAGE’s orbital plane will rotate around its axis, as shown in the right sketch of figure 2.5. All in all this will lead to a large coverage of Titan’s ionosphere and ionospheric tail flow.
2.4.2 HASSE measurements

In order to get into the correct orbit without using large amounts of fuel, which would limit the payload mass and thus, the possible science output, a balloon for aero-capture will be used; see chapter 5. The balloon will be dropped off from TAGE after the entry into Titan’s ionosphere and it will then work as an additional mission, with the working name HASSE; see figure 2.6. HASSE will fly down into the lower atmosphere to perform in-situ measurements. The balloon will be equipped with rather simple instruments, such as thermometer, wind speed meter, pressure meter and a gas sensor, but it will give us important information about the atmospheric composition and behavior at different altitudes. The measurements will be important for both the atmospheric science and the ground science because it will give knowledge about the complex molecules descending from the ionosphere as well as the supposed fluctuations in the concentrations of ammoniac and methane which could be an indication of volcanic activity on the ground below. Our goal is that HASSE will survive considerably longer than Huygens did and give us data from different locations in the lower atmosphere.

Even though HASSE will be an important tool for understanding different processes on Titan, both chemical and geological, its main purpose is the aero-capture maneuver. Using it for scientific studies is a great bonus but the emphasis of the mission is the science TAGE will perform.
2.4.3 Optional measurements

When choosing the scientific payload for the TAGE mission, the weight, cost, power consumption and scientific output of the instruments have been considered. The measurements described in the two previous sections will be able to fulfill the scientific objectives of the mission. However, if the mass of TAGE would be allowed to increase, so that more instruments could be included in the payload, there are some interesting measurements that could be conducted. First of all, an IR-spectrometer would allow measurements of the atmospheric composition to be done even more accurate and the very small densities of some of the complex molecules could be obtained. An IR-spectrometer detects different vibrational frequencies of chemical compounds, for example it can distinguish between the six different vibrational modes of the atoms in a CH$_2$ group, which is found in organic compounds. Thus it can be used to characterize very complex mixtures of molecules in atmospheres and ionospheres. Secondly, an instrument that measures the chirality of molecules would be an option to bring to Titan. A molecule is said to be chiral if it can not be superimposed on its mirror image. A chirality instrument would be able to decide whether the molecules found in Titan’s atmosphere are organic and if so, if they are biologically active, like for example amino acids.
3.1 Introduction
The planet of Saturn’s moon Titan has always been a fascinating object for science. Titan has a very thick and dense atmosphere and it has for a long time been impossible to see what hides beneath the atmosphere. ESA’s Cassini/Huygens mission has given a lot of information, but there are still lots of questions. Here is where the TAGE mission comes in, which will among other things examine the origin of the wet mysterious surface and the meteorological conditions.

3.2 Missions to Titan

3.2.1 First discovery
Titan was discovered by the Dutch astronomer Christian Huygens in March of 1655. Huygens was studying Titan with a long-focus telescope of his own design. He also calculated the orbit, measured the brightness and estimated the size. Titan is the planet Saturn’s biggest moon and the second biggest moon in the solar system. Titan has always been one of the most fascinating objects in the solar system, but it has never been closely studied before the Cassini mission. [14]

3.2.2 Cassini
The NASA owned Cassini spacecraft was launched on 15 October 1997 and orbits Saturn. Cassini released the ESA owned science probe Huygens on 25 December 2004 and it landed on the surface after a parachute descent on 14 January, 2.5 hours after the release. The probe is named after Christian Huygens, who is mentioned above. Before the probe landed, the nature of the surface was unknown. In the early 1980s the Voyager spacecraft confirmed that methane was the second-most abundant constituent in Titans atmosphere after nitrogen. This revealed a rich organic chemistry and gave hints about a liquid surface, but the cameras could not see though the thick and dense atmosphere to photograph the surface. Additional images were also obtained later from the Hubble Space Telescope and ground-based observations, at various resolutions, but the pictures could only reveal bright and dark areas on the surface. Even the images obtained by Cassini were almost as baffling as those taken from the events mentioned above. Therefore no direct evidence of the expected liquid surface was found before the Huygens probe. [12]
3.2.3 The Huygens probe

From the abundance of methane in the atmosphere, there were theories that the dark areas seen from distance could be methane oceans. But recent observations have restricted the fraction of the surface covered with liquid to be just a few per cent. When the probe touched the surface the impact was rather smooth. It seems that the surface has properties like some kind of wet sand.

There are two theories explaining the wet sand, which is similar to a bog. The bog-like area consists of sand and liquid methane. One of the theories is that the methane originates from heavy methane rain long ago. The other theory claims that methane forces its way out from underground reservoirs.

The results from Huygen show that Titan appears to have an extraordinarily Earth-like meteorology, geology and fluvial activity, in which methane would play the role of water on Earth. While many of Earth’s familiar geophysical processes appear to occur on Titan, the chemistry involved is quite different. Instead of liquid water Titan has liquid methane. Instead of silicate rocks Titan has ice. Instead of dirt Titan has hydrocarbon particles settling out of the atmosphere. Titan is a fascinating world having Earth-like geophysical processes operating under alien conditions. [12]

3.3 Interesting phenomena

When choosing the payload for TAGE, the main question is: which phenomena are the most interesting and possible to examine on Titan’s surface?

Regarding this question two sub questions have to be taken into consideration:

- What has never been examined by Cassini/Huygens?
- Which discoveries by Cassini/Huygens can be improved?
The Cassini mission has performed radar mapping of Titan’s surface and taken pictures with a special technique, using a combination of infrared and UV sensing spectrometers to see through the thick atmosphere. Huygens on the other hand has performed in situ measurements including chemical composition, temperature, pressure, wind speed, humidity of the atmosphere and albedo reflection among other things. The most important for the whole project is to prove that TAGE will perform studies to improve the knowledge about Titan. That is why the questions above are very important.

Interesting objectivities for the balloon:

a) Perform a better temperature curve vs. the height.
b) Explore the wind speed at different heights and locations, and examine windy regions.
c) Measure the humidity of the air to locate misty or cloudy regions.
d) Determine the surrounding chemical composition.
e) Measure the pressure at different heights.
f) Give us overall information about the meteorological and geological conditions.

A better temperature profile is always necessary, especially to support objective f. The wind speeds are fascinating because the wind-shear descent from a height of 450-120 km. Between 100-60 km Huygens discovered an unexpected layer of higher wind shear, which could be worth to examine further. The winds are blowing in the direction of Titan’s rotation. Objective d, to determine the chemical composition, might be the most interesting objective in many views. One possibility is to measure complex molecules scattered from the ionosphere, for example ethane and cyanide ions. These studies will lead to conclusion of the interaction between the ground and atmosphere studies. Another interesting measurement is the presence of ammonia, which might indicate volcanism. Moreover measure the percentage of methane and the noble gases. Huygens did an unexpected discovery, they didn’t detected any krypton or xenon, only argon. That was very surprising and it would be good to perform additional measurements to establish the result. Finally after all studies, conclusions of the meteorological and geological conditions can be drawn. These conclusions about Titan can be useful to understand our own processes on Earth and also tell about Earth’s origin. [13]
3.4 Payload

3.4.1 Choosing TAGE’s payload, early ideas

In the very first planning of the payload, it seemed to be a good idea to perform mapping with either spectrometer camera or radar. A spectrometer camera would demand a dual spin attitude control system, with the camera mounted on a platform to always have it pointing on the surface. The advantage comparing with Cassini is that TAGE is able to perform a much more complete and detailed mapping. Cassini’s orbit is around Saturn and has a very high eccentricity and is therefore only available to take pictures when it passes close to Titan. TAGE was first planned to have a circular orbit and the camera always pointing at the surface, which had resulted in perfect mapping of the surface. It can also be mentioned that the power consumption won’t be a problem, because TAGE will be equipped with a RTG-device. For information about the RTG see the power chapter. However, there are drawbacks that are hard to handle. The first drawback is that an infrared spectrometer is very heavy and not available in MEMS technology. Cassini’s infrared spectrometer weighs for example ~37 kg. The other drawback is that a dual spin satellite with a platform is very complicated. Due to these circumstances the camera was dismissed at an early stage.

The radar is a very good instrument for mapping, but like the spectrometer it seemed to be too heavy and consume too much power. Even here the radar was compared with the Cassini radar, a high gain parabolic antenna with a weight of ~41 kg and a peak operating power of ~108 W. Therefore the radar was also dismissed.
3.4.2 Final payload

3.4.2.1 Ground penetrating radar

As mentioned before, there were two theories about the origin of the methane-sand bogs. These would either originate from heavy methane rain or from methane underground reservoirs. The theory about the rain has not been examined further. So it would be very satisfying to examine the geology beneath the surface. That’s why TAGE will be equipped with ground-penetrating radar. As mentioned before the radar was dismissed at an early stage because of the expected high weight. A less heavy radar on a spinning satellite was at first disregarded, but it became an excellent solution in many ways. The first advantage is that a spinning satellite is able to have light wires instead of steady booms, which will reduce the mass considerably. The other advantage is that the radar will be combined with a top-site sounder. The radar consists of four Langmuir probes on long wires mounted on each side of the hexagonal hull, and an antenna pointing on the surface to receive the echo.

The radar has many advantages, it is able to beam short pulses and measure the time of the echo, to obtain a height profile. It will also measure the power reflected by different materials. This will give information of both the depth and the constituency of the geology beneath the surface. Another option is to perform measurement on the surface; a ground penetrating radar is not restricted to scan the sub-terrain regions. The frequency can easily be regulated for surface scanning. For technical information about the radar see the instruments chapter.

Figure 3.3: The picture shows how a satellite with a GPR is working.
3.4.2.2 Scientifically equipped balloon

HASSE is a balloon equipped with gas sensor, thermometer, pressure sensor, wind speed sensor and humidity of the atmosphere sensor. There will be no camera onboard for PR pictures. The main reason is that the radar is fully capable to take nice pictures of the surface; therefore it is no important need for a camera. Another minor reason is that the payload for the balloon is only five kg. Due to the low temperature (95K) the batteries will work badly. At least half the payload has to consist of batteries. A camera won’t be heavy, but the belonging telemetry equipment including memory, data handling and antenna among other things, will constitute too much weight. Therefore the camera is removed in favour to the other instruments. The chosen instruments are very light, simple and reliable, with the exception of the gas sensor. The gas sensor is a little bit more complex than the other instruments and might need extra shielding from the RTG-device to avoid distortion. The remaining instruments are very simple and not affected by distortion from the RTG.

The balloon is an excellent solution for the mission in two different points of view. In the first stage it will help TAGE during the aero brake, and then it will carry a package of instruments, which will perform scientific studies. The highlight is that this solution will save weight. Instead of heavy rocket-systems an aero-braking balloon is much lighter and very reliable. A kind of simulations, named Monte Carlo simulations have shown 100% success-rate. This is explained in more details in the orbit chapter. Therefore the instruments carried by the balloon after releasing from TAGE are a great bonus. The instruments will be placed in a circle around the torus-shaped balloon. A special height of flight won’t be chosen, because it is hard to know how the balloon will act beforehand and it will be satisfying to obtain information from different heights. To adjust the height the balloon will be equipped by a height sensor and a small helium tube, which by a simple command can inhale or exhale the gas. The problem is not the flying capability but the batteries, which will be damaged because of the cold.

![Figure 3.4: The picture shows HASSE, a torus-shaped balloon carrying a small packet of instruments.](image-url)
3.5 Summary
TAGE’s main objectives regarding ground studies on Titan are to examine the surface consistence and perform meteorological measurements in the lower atmosphere. For the surface consistent TAGE will be equipped with a ground penetrating radar that will discover suspected underground reservoirs. If such reservoirs will be found it helps to explain the bog-like consistence of the surface. The balloon HASSE will examine the meteorological conditions including examinations of mist, clouds and windy regions. A gas sensor will measure the chemical composition that among other things will lead to conclusions of the interaction between the ground and atmosphere studies. Volcanism will also be studied. The combination of studies from beneath the surface up till the atmosphere will result in a very good overall understanding of Titan, and it will also give information about Earth’s development and processes. TAGE will gather extremely much information comparing to the low budget and mass.
4.1 Introduction

When the scientific goals for a mission is set, it’s time to find the right instruments to suit the mission and its objectives. There are many different aspects to consider when doing so. You of course have to have an instrument that can handle the accuracy of the measurements that you want to make. The instrument shouldn’t cost or weigh too much and it shouldn’t use too much power. The easiest way to find what you need is to look for instruments with a heritage, meaning instruments that fulfil your needs and that has been flying on other missions before. That will save a lot of time and money from development and testing. If you can’t find what you want in that area, you look for something that exists but hasn’t been in space before. And if those two options fail, you develop something new. Another smart thing to do is to try to combine two or more instruments, so that they can use parts from each other as a weight saving manoeuvre. All of the above methods have been used in this feasibility study.

4.1.1 Atmospheric science

Following in the footsteps of Cassini and Huygens, [15], there are already many things we know about the Titan atmosphere. The difference, compared to Cassini, is that we will be placing TAGE in an orbit around Titan and that will enable us to make measurements with much higher accuracy and also open up for measurements never made there before. The spectrometers belonging to the instrument ASPERA will help us decide the composition of the Titan atmosphere, things like the ion and neutral composition and the electron and ion distribution functions and densities. That could, for example, help us to understand the evolution of life here on earth, resembling the Titan atmosphere to early earth atmosphere. The wire boom antennas and Langmuir probes will help us to study and understand the mechanism behind the atmospheric erosion.

4.1.2 Ground science and science of the lower atmosphere

With the pictures and measurement of the Huygens probe [16], we’ve learned a lot about Titans surface and its chemical composition. With the ground penetrating radar (GPR) on TAGE we’ll be able to look underneath the surface, to see what the Titan “upper” inside is made of, if there are any subsurface lakes or other interesting phenomena? The GPR will also enable us to make a thorough surface characterization. To put TAGE into orbit the balloon HASSE is used for aero breaking in the Titan atmosphere. This brought an opportunity to use the balloon for scientific purposes too. With some simple instruments such as a thermometer, a wind speed meter, a gas sensor etc we’ll be able to determine the composition and behaviour of the atmosphere at different altitudes.
4.2 Limitations

All space missions have limitations, which are mostly due to cost, and a low-cost spacecraft like TAGE is of course not excluded. For example the weight budget put limitations on what instrument you can use and how many. Time limit, power and data budgets are other issues to take into consideration. In the TAGE case we where also asked to, as far as possible, use and involve Swedish space technology industry and developers, which of course added to the limits. There’s also a struggle between how much of the resources that should be spent on the ground science and how much that should be spent on the atmosphere science.

The balance between the number of kilos of payload for ground science and atmospheric science turned into a natural choice after a while. To maximize the amount of collected science on TAGE the set of instruments chosen was the best, and in the end almost the only alternative. The limitations eventually forced us to prioritize and eventually give up on a couple of instruments that we first thought would be a good idea to have on the mission.

4.3 Atmospheric instruments

4.3.1 ASPERA

The IRF developed instrument, Analyzer of Space Plasmas and Energetic Atoms (ASPERA) will be used to analyse the ions, neutrals and electrons of the Titan atmosphere. The two-parted instrument can be divided into four basic subunits and has been used in both the MARS EXPRESS and the VENUS EXPRESS mission, by the names ASPERA-3 and ASPERA-4 respectively. [17], [18]. The Main unit is containing three sensors; NPD (Neutral Particle Detector), NPI (Neutral Particle Imager) and ELS (Electron Spectrometer), plus the DPU (Digital Processing Unit). The sensors and DPU is mounted on the mechanical scanner that is used to sweep the detectors to enable measurements at different angles. The unit that is separated from the main one is the Ion Mass Analyser (IMA). Containing its own computer it can actually be considered as a complete instrument by itself. See figure 4.3.1 a) and b). [19] TAGE will be exposed to a lot of high-energy particles on its way to Titan. This fact included the neutron radiation from the RTG made us believe that ASPERA would have to be assembled with the sensitive electronics and data units apart from the sensors, to be placed more sheltered inside the S/C. But after some consulting with the ASPERA experts it was realised that it wasn’t possible to divide the instrument in that way, but that the sensitive parts are protected up to more than 100 kRad. From the reliability-team the information is that TAGE only on its way to Titan will be exposed to up to 100 kRad of radiation. The solution is then to mount the instrument on that side of TAGE that will be facing Cassini 2 during the journey to the moon, and in that way be shielded from the worst radiation. The accuracy of the onboard attitude knowledge is ±1°.
4.3.1.1 Neutral Particle Imager (NPI)

To measure the flux of energetic neutral atoms (ENA) the first thing the NPI need to do is to distinguish the charged particles from the neutrals. This is done by an electrostatic deflection system that consists of two discs separated by a 3 mm gap. By putting a 5 kV potential between the discs a strong electric field is created and this field sweeps away the charged particles with energies up to 60 keV, while the neutral particles can pass through. This gives a satisfactory performance since the ENA flux greatly exceeds the charged particle flux for energies greater than 60 keV. The deflection systems can be operated in four different modes. Apart from being ON or OFF it can also be operated in the alternative or the sweeping mode. The alternative mode is used for a more accurate separation between charged and neutral particles by turning the deflection system on and off for one period. And the sweeping mode is used by gradually sweeping the deflection high voltage from a maximum value to zero, giving a more approximate measurement of the plasma energy. When the neutrals are passing through the deflection system they’re hitting a 32-sided cone target. The interaction with the target results in a secondary particle production of ions and electrons and/or reflection of the primary neutrals. The particles leaving the target are then detected by a micro channel plate (MCP) stack, which gives the direction of the primary incoming neutral. The NPI produces an image of the ENA distribution in the form of an azimuth x elevation matrix. To suppress the ever-present flux of UV photons that produces an UV background in the measurements a coating for the target is used. [19]
4.3.1.2 Neutral Particle Detector (NPD)

While the NPI is measuring the ENA flux, the NPD sensor performs the velocity and mass measurements. The NPD is composed of two identical pinhole cameras that serve as detectors, shown in figure 4.3.1.2. In the same way as the NPI (see the NPI description above), the NPD sweeps away all charged particles up to 70 keV. The ENA beam hits the START surface and causes a secondary electron (SE) emission. The SE is then transported to one of the two MCP assemblies giving the start signal for the time-of-flight electronics. The reflected atomic ions leaving the START surface will then impact the second surface, the stop surface, and again produce SE that are detected by one of the three MCP assemblies giving the stop signal. The time of flight over the fixed distance of 8 cm then defines the velocity of the particle. A closer analysis of the SE and the start and stop signals can then give an estimation of the ENA mass. [19]

4.3.1.3 Electron Spectrometer (ELS)

The Electron Spectrometer is formed by one spherical electrostatic analyzers top-hat and one collimator system. The particles can enter the aperture at any angle in the plane of incidence. By applying a positive voltage to the inner spherical electron deflection plate the electrons are then deflected into the spectrometer. After being filtered in energy by the analyzer plates the electrons hit the MCP. The hits are then detected and the number of hits per sample interval is then registered and further processed in the DPU. Electrons with energies up to 20 keV/q will be measured, with a maximum time resolution of one energy sweeps per four seconds. [19]

4.3.1.4 Ion Mass Analyser (IMA)

The particles enter the analyzer through an outer, grounded grid. A deflection system is situated behind the grid, with the purpose to deflect particles coming from angles between 45 to 135 degrees, with respect to the symmetry axis, into the electrostatic analyzer (ESA). Ions within a swept energy pass band will pass the ESA. A cylindrical magnetic field set up by permanent magnets will then make the ions deflect, deflecting lighter ions more than heavy ions into the centre of the analyzer. And finally they will hit a MCP and be detected by an anode system. Both direction and mass per charge of the ions are analysed simultaneously. To post accelerate the ions the magnet assembly can be biased with respect to the ESA and this enables a selection of both mass range and mass resolution. [19]

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Mass (kg)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Unit</td>
<td>6.0</td>
<td>10</td>
</tr>
<tr>
<td>IMA</td>
<td>2.2</td>
<td>3.5</td>
</tr>
<tr>
<td>Total:</td>
<td>8.2</td>
<td>13.5</td>
</tr>
</tbody>
</table>

Table 4.3.2 – ASPERA Mass/Power budgets
4.3.2 Wire boom antennas and Langmuir probes (LP)

Langmuir Probe pairs on wire booms that will be deployed when TAGE goes into orbit. The wire booms are then held straight with help from the centrifugal force due to the spin of the S/C. The length of the booms should optimally be longer than the local Debye length and preferably twice as long. The reason for this is that when the plasma is thin, there’s a chance of ending up only measuring the S/C own emitted photoelectrons. [20] In the case of Titan, the longest Debye length in the atmosphere is 7 m, which indicates use of approximately 15 m long wire booms. The booms are also going to serve as antennas for the instrument GPR/Topside Sounder and this instrument will set the length of the booms to 20 m which is well enough for the electric field measurements. The Swedish Institute of Space Physics (IRF) and the Alvén Laboratory will manufacture the booms. And the LP will be manufactured by IRF in Uppsala and Kiruna, Sweden.

In total there will be 5 wire booms with LPs on, two pairs and one LP contra balancing the magnetometer boom. The probe pairs will be placed symmetrically perpendicular to the spin-axis of the satellite. This set up of 5 LPs gives good flexibility and also redundancy to the instrument. A wire boom/LP-pair can’t simultaneously make typical LP measurements together with E-field measurements, which means that either a timeshare between the two measurements has to be done, or one pair is set to do the LP measurements and the other pair will take care of the E-field. The fifth probe will bring even more flexibility to the system and do pure LP measurements, for example at the same time as the radar is running, when the wire boom pairs are being used as antennas. If needed, it also brings a possibility of doing interferometry measurements.

![Diagram](image)

Figure 4.3.2 – Basic operation modes for the LP. (a) and (b) shows the principle of voltage sweep, the voltage is varied and the current measured. In (c) a constant bias voltage is applied and the current is measured. In (d) an estimate of the E-field is made by applying a constant current and then measuring the probe voltage. [21]

Typical LP measurements are to measure the ion and electron density and temperature, and to measure the plasma flow velocity and plasma density fluctuations $\delta n/n$. The temperature and density of the plasma is measured by setting the probes in a voltage sweep mode, the voltage is then swept from negative to positive bias and the current is measured. A negative potential on the probes will attract positive ions and a positive potential will attract electrons. See figure 4.3.2 (a) and (b). Then by plotting the voltage and current the densities, $n_e$ and $n_i$, and temperatures, $T_e$ and $T_i$, can be obtained. By instead biasing the probes with a constant positive voltage relative to the S/C it’s possible to estimate the relative plasma density fluctuations $\delta n/n$, figure 4.3.2 (c). If this is made simultaneously at two spatially separated points, the signal will show a substantial degree of correlation, but with a time shift corresponding to a propagation velocity. A similar method can be used to monitor the atmospheric outflow.
To measure the E-field the probes are biased with a constant current, figure 4.3.2 (d), and then the potential difference between the probes is measured. This will then give the corresponding E-field by taking the potential difference of the two probes and divide it by the probes separation distance. Here the advantage of having the probes in pairs is being showed. If only one probe is used, the setup will be more sensitive to changes in the S/C potential. But with two probes the S/C potential can easily be cancelled out. By using the two orthogonal boom pairs at the same time the 2D E-field components in the spin plane can be measured instantaneously. [20], [22]

<table>
<thead>
<tr>
<th>Instrument Mode</th>
<th>Measured Quantity</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential sweep</td>
<td>( n_e )</td>
<td>( 0.1 \times 10^5 \text{ cm}^{-3} )</td>
</tr>
<tr>
<td></td>
<td>( T_e, V_{Te, -7 (T_e m_1)} )</td>
<td>( 0.01 \text{ - } 200 \text{eV} )</td>
</tr>
<tr>
<td></td>
<td>( \Phi_{2D} )</td>
<td>( =50 \text{V} )</td>
</tr>
<tr>
<td>UV intensity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smn, interferometer</td>
<td>( N_e, \text{Smn} )</td>
<td>( 0.1 \times 10^6 \text{ cm}^{-3} )</td>
</tr>
<tr>
<td></td>
<td>( V_{Smn} )</td>
<td>( &lt;10 \text{kHz} )</td>
</tr>
<tr>
<td>Electric field</td>
<td>( E )</td>
<td>( \text{Max} 1 \text{ V/m} )</td>
</tr>
<tr>
<td>(long wire booms assumed)</td>
<td></td>
<td>( \text{Res} -0.02 \text{m V/m} )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \text{DC} -3 \text{MHz} )</td>
</tr>
</tbody>
</table>

Table 4.3.2 – Properties of the LPs [22]

*) Depending on plasma density. Lower if density falls below 1,000 \( \text{cm}^{-3} \)

**) Depending on sampling frequency and probe separation

4.3.3 FluxGate Magnetometer (FGM) with boom

A digital detection and feedback generation FMG will be used for the mission. The design originates from the fluxgate magnetometer onboard the Swedish Astrid-2 satellite, and further developed to suit the requirements of the NanoSpace 1 satellite. It operates with the physical principles of the classical compensated fluxgate. The Alfvén Laboratory at the Royal Institute of Technology (KTH) in Stockholm, Sweden will manufacture the sensor assembly. The magnetometer will be used as a reference for other measurements, like electric field and LP measurements, but the high accuracy of the instrument will also enable more scientific type of measurements if needed. The FGM has a miniaturized fluxgate sensor for measuring the B-field vector from DC to 100 Hz. To avoid magnetic disturbance from the S/C the tri-axial sensor will be mounted on a deployable rigid boom that will be at least 2 m long.

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Mass (kg)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 Langmuir probes + 40 m tip-to-tip Wire booms</td>
<td>4.0</td>
<td>3.0</td>
</tr>
<tr>
<td>(LP- and 2D E-field measurements)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 Langmuir probe + 10 m Wire boom</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>(Correct balance the magnetometer boom)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Margin</td>
<td>1.0</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>5.5</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Table 4.3.2.1 – LPs and wire booms mass and power budgets
The core of amorphous magnetic materials is, by a current in an excitation coil, periodically driven into saturation. The signal from the core is generated by the external magnetic field and then detected by a pickup coil. Operating in the compensation mode, the instrument is generating a feedback current to compensation coils that cancels the external field. Each pickup coil is sensitive to one component of the external magnetic field, so that three magnetic cores are used in a rigid mechanical assembly, and the three compensation loops operate simultaneously. An early digitalisation of the pickup signal enables the field detection and feedback generation to be carried out digitally. An important difference from the Astrid-2 magnetometer is that the digital signal processing previously done in three processors (one for each axis) has been replaced with a single FPGA (field programmable gate array) to achieve a smaller circuit board area. The FGM will measure the fields with a resolution of ~0.1 nT and with a range of ~±100 µT. [23]

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Mass (kg)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor + instrument</td>
<td>0.01 - 0.19</td>
<td>1</td>
</tr>
<tr>
<td>Rigid boom &gt; 2 m - release mechanism</td>
<td>0.8</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

*Table 4.3.5 - Fluxgate magnetometer Mass Power budget*

4.3.4 TopSide Sounder (TSS)

To get the electron density profile of the Titan ionosphere, mapping will be done by a Topside Sounder. This is an instrument that is integrated with the Ground Penetrating Radar described further on in the rapport. For technical details see section 4.4.1. The ionospheric sounding measurements will be performed to give the ionospheric reflection point at a wide range of frequencies, swept from the lowest to the highest. The delay time measurements will be inverted to give electron density profiles with an accuracy of a few percent. A horizontal resolution of about 20 km and a vertical resolution of about 7.5 km will be reached. [24]

4.4 Instruments for ground and lower atmosphere

4.4.1 Ground Penetrating Radar (GPR)

This is an instrument that is based on the instrument MARSIS, which is the subsurface radar on the satellite, MARS EXPRESS. The instrument is a multi-frequency nadir looking pulse limited, radar sounder and altimeter. It consists of two antenna assemblies and an electronic assembly and will be most effective when the S/C is as close to the moon as possible. Therefore the radar will only be used during the pericenter passages, when the altitude of the S/C is the lowest. Maximum penetration depths are achieved at the lowest frequencies of the instrument, and the transmitter frequency is set by the Electron Plasma Frequency (EPF), which is depending on the electron density in the ionosphere. To penetrate the Titan atmosphere a frequency above the EPF is needed. Because of the far distance to the sun the density of the Titan ionosphere is not very high and this is important due to the fact that TAGE won’t be able to go closer to the Titan surface than 950 km.

The radar will operate on different frequencies depending on if it’s going to map the subsurface, the surface or the ionosphere. The signal will have a bandwidth of 1 MHz and will be generated and transmitted at each operating frequency for a period of about 500 microseconds. Then the radar switches to a receiving mood and records the echoes from the subsurface and surface for the expected duration. Simplified, the radar generates a pulse of
high power energy, which is radiated towards the Titan surface. The surface will reflect some of the energy from the first surface towards the sounder. Some of the energy falling in on the first surface will be transmitted to the subsurface and will then travel towards the next reflecting surface and undergo attenuation by the material. Some of the RF energy will then be reflected from this second layer and returned towards the sounder and some will be transmitted to the next layer and so on. The strength of the subsurface returns is decreasing with the depth until the predominant signal is limited by either surface clutter or cosmic noise. As seen from figure 4.4.1 the detection of a subsurface feature is depending on the strength of the subsurface return rising above both the noise level of the system and the level of the other surface returns arriving at the same time as the echoes from the subsurface. [25], [26], [27]

The GPR can functionally be split into three subsystems:
- Antenna Subsystem (ANT)
- Radio Frequency Subsystem (RFS)
- Digital Electronics Subsystem (DES)

4.4.1.1 Antenna Subsystem (ANT)
To save weight, the antenna subsystem will be using the wire booms as antennas. It won’t be possible to run the GPR simultaneously with the Langmuir probes, but it will be easy to switch between the different measurements. For this, so called “nano switches” will be used and they will be developed by the Chalmers and Linköping universities. The wire boom pairs will be used as the main dipole antennas and is dedicated to both the transmission of the signals and to their reception. The antenna must be designed to have its maximum efficiency at the frequency bands of interest. At a frequency of 3.8 MHz a half-wavelength dipole has a tip-to-tip length of about 40 m. This will be the selected length for the primary antennas of the GPR. A simple dipole has a characteristic resistive impedance of approximately 73 ohms at the half wavelength resonance and can therefore easily be matched to a very high efficiency. To make the primary sounder antenna radiate efficiently over a broad range of frequencies, some suitable technique must be used to broaden the bandwidth of the antenna and still get a suitable impedance match to the transmitter. This is achieved by having a resistive load near the tip of the antenna and a lumped element-matching network at the base of the antenna. Without the matching network we would need very long antennas when operating the radar at lower frequencies. For example, a frequency of 1 MHz would generate an antenna tip-to-tip
length of 300 m. A spool at the base of the antenna, to reach the optimum performance, will then compensate for this mismatch. A transformer is used to couple the ~200-300 ohms to the 50 ohm output impedance of the transmitter. These changes result in an antenna with an acceptable impedance match over a frequency range from about 1-6 MHz. A plot of the radiation efficiency as a function of frequency is shown in figure 4.4.2.

There will also be a secondary antenna, a monopole that will be used only for reception. This antenna will be deployed at the same time as the wire booms and point in the nadir direction of the S/C. The target of this antenna is to distinguish surface clutter from the subsurface echo. It’s easier to compensate for short length with an antenna that is only used for reception so the antenna is chosen to be 2 m long, which is a suitable length for a S/C of this size. The antenna is under development by IRF, Uppsala and will work like a steel tape measure. The antenna element is cylindrical and made out of copper-beryllium foil. The weight of the whole unit will be about 150 g of which the antenna weighs about 50 g.

The nadir-aligned orientation of the antenna can be accomplished by having the monopole pointed either in the nadir direction or opposite to it and the knowledge of the orientation of the electrical axel is required to be 1 degree. The monopole, whose radiation pattern has a null in the nadir direction, is used to receive only off-nadir surface returns. The return echoes from both the primary antenna and the nadir-pointing one are collected and then by subtracting the unwanted surface echo from the main antenna echo, which contains both surface and subsurface returns, the result is a big improvement in the subsurface to surface clutter ratio and thus enhance the ability to detect subsurface features. [25], [26], [27]

4.4.1.2 Radio Frequency Subsystem (RFS)

The RFS contains all the radio frequency parts of the instrument and consists of a power amplifier, a transmission/reception switch and two receivers to collect echoes from each of the antennas. The RF signal is sent to the surface and the echo reception is amplified and down-converted by the receiver. The receiver output is then converted to digital form by a digital-to-analogue converter for processing by the DES. A power converter in the RFS provides the regulated voltages for the electronics. Up to four channels of data can be processed and recorded simultaneously. These channels will under normal operation standards consist of main antenna and secondary antenna (nadir pointing antenna) receive stream, each at two frequencies. The return echoes are directed to one of four filters in the channels to eliminate any out of bounds interference and noise. Then the signals are routed through a band-select switch to a class A amplifier before down conversion. To save weight on the mission, a dialogue with SAAB communications is kept, about developing a new lighter type of transmitter suitable for this type of radar. At the moment no specification on such a device has shown up from SAAB, which means that the same type of transmitter that was used in the MARSIS radar also will be used for the GPR of TAGE. The advantages with a lighter transmitter would of course be the saving of weight, but it could also mean some improvement on the radar. It could allow two transmitters, one for each of the two LP-pairs. This would improve the measurements and give higher accuracy and resolution to the results.

10 g Multi Chip Modules (MCM), developed by the IRFU, will be used as receivers. They are in the size of a matchbox including three completely digital channels. [25], [27]

4.4.1.3 Digital Electronics Subsystem (DES)

All the logic for the instrument and interfaces with the spacecraft is contained in the DES. The DES consists of 1) a timer and controller for generating all instrument timing, 2) a sounder frequency generator which generates the signals for transmission as well as providing the RFS with all the necessary local oscillator frequencies and 3) an onboard digital processor to process the echoes received from both the antennas into fully digital sounder data streams.
The received signals are passed to a digital-to-analogue converter and compressed in range and azimuth. The integration of the azimuth accumulates about one second of pulses and this is resulting in an along-track footprint of 5 km and a cross-track footprint size of 10 km. Digital on-board processing greatly reduces the output data rate to approximately 10.4 kbps. The echo-profiles show the received power as a function of time delay, resulting in a depth resolution of 50-100 m, depending on the propagation speed of the waves in the Titan crust. [25], [27]

### 4.4.2 Data

To get a rough estimate on the amount of data that the instruments would collect, two different modes have been looked at. One called the maximum and the other called intermediate mode. The estimate is done considering only the instruments ASPERA and GPR because they will be the most data consuming instruments on TAGE. The instrument ASPERA can collect data from measurements in four different modes, the burst 18.2 kbit/s, high 6.2 kbit/s, normal 2.2 kbit/s and low mode 0.6 kbit/s. The GPR has only got one mode with the data rate 10.4 kbit/s. All these numbers are compressed data. The estimate is then made assuming 10 minutes of measuring for each of the 1300 revolutions that TAGE will make in one year time, five minutes for the GPR and five for ASPERA. In the maximum mode ASPERA will use its burst mode for the full five minutes, while in the intermediate mode it will run: 1 min burst, 2 min high, 1 min normal and 1 min in the low mode. And the GPR will then measure every second orbit. The amount of data collected in the two different modes can be seen in table 4.4.2. It has to be remembered that this is a rough estimation and that more data will be added from the other instruments, but at least it will be in this order. Maybe some onboard analysing of the collected data could also be made to be able to transfer more data to Earth.

<table>
<thead>
<tr>
<th>Assembly</th>
<th>Mass (kg)</th>
<th>Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF + Digital Electronics</td>
<td>3.5</td>
<td>19-27</td>
</tr>
<tr>
<td>Dipole Antenna</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Monopole Antenna</td>
<td>0.05</td>
<td>0</td>
</tr>
<tr>
<td>Cabling</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>Margin</td>
<td>0.55</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>4.3</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 4.4.1 – GPR/TopSide Sounder Mass/Power budget

### 4.4.3 Instruments on HASSE

The instruments on HASSE will pretty much be chosen as the best available when closing in on the launch of TAGE. They can be seen as a pure bonus and will be added on in order of priority until the power, mass and data rate budgets are filled. The payload weight on HASSE is estimated to 1 kg, where the instrument for meeting chemical compositions is expected to weigh at least 0.5 kg and the other instruments will add the rest of the weight. The effect budget is set to 5 W. Possible instruments on HASSE are a thermometer, pressure meter, wind speed meter, hygrometer and a meter for chemical composition.
Chapter 5

Separation & Orbit Insertion

Anders Persson

5.1 Introduction

Orbit insertion has in the past been the most mass consuming subsystem of interplanetary missions. The problem is the large velocity changes needed. Thus systems with high specific impulse are preferable. Here three different orbit insertion systems will be presented. Two follow the traditional way of insertion. They are using a solid rocket motor and a liquid rocket engine, respectively. The third one is an aerocapture system, utilizing the thick atmosphere of Titan. This is a new type of propulsion often referred to as the future of orbit insertion.

The conclusion was that an aerocapture system using a trailing ballute design was preferable while it enables the HASSE balloon in addition to TAGE. Thus two missions for the price of one were achieved. The total mass of the systems will be 53.8 kg. Given that the ballute system makes up the supporting structure of HASSE the dry mass fraction will be 0.88, which is incredibly high, compared to analogues missions.

All the calculations in this chapter were done in MatLab. Only the results are presented in the text. The code can be provided upon request.

5.2 Separation

A separation mechanism consists of two principal parts: a structure holding the probe to the carrier and a mechanism separating the crafts when the joint is broken. They are often called attachment and deployment mechanisms [28].

There are two main types of attachment mechanisms, marmon clamps and separation bolts. The marmon clamp or clamp band system has a ring shaped joint. It is held together by a clamp with an automatic release mechanism. The actuator is often one or two pyrotechnical bolts, although new applications using pin pullers or electromagnetic actuators have been developed [29].

Separation bolts are often pyrotechnically operated. The actuator either severs the bolt or releases a nut. They offer a more arbitrary joint between the probe and the carrier then the clamp band. Usually four or more bolts are needed for a rigid connection.

The deployment mechanism is in most cases either spring or motor operated. Its primary task is to ensure that the separation is conducted in such a way that no risk of collision between the crafts exists. A second task can be to initiate a spin for stabilization. Springs are very reliable but a bit blunter in performance compared to motor driven mechanisms. Such mechanisms are on the other hand both heavier and more complex.

The separation system of TAGE is mounted on the same side as the antenna cupola. Given the mission requirement to use Swedish components if possible the 1194 mm clamp band system from SAAB Ericsson Space is chosen. It is made up of a clamp band with two pyrotechnic bolt cutters. In addition to this four separation springs conducts the deployment.
The springs are chosen in such a way that the probe is deployed into the orbit insertion mode defined in the attitude control chapter.

### 5.3 Traditional Orbit Insertion

The initial Titan rendezvous orbit of Cassini 2 is very elliptical with an eccentricity of about 0.92. In the closest point of approach, which is set to 1200 km above Titan’s north pole, the relative velocity between the probe and Titan is 6.1 km/s. To be inserted into orbit the relative velocity has to be less than the Titan escape velocity. The velocity change required for orbit insertion is 3.9 km/s. The fuel needed for this burn will make up about 71% of the spacecraft’s wet mass, given a $I_{sp}$ of 320 s. Due to the strict limitations that this would put on the payload and thus the possibility of producing good science this orbit is rejected.

![Figure 5.3.1 Rendezvous orbits.](image)

The problem with the initial rendezvous orbit is the high relative velocity. The most efficient way of decreasing it is to utilize Titan’s own orbital velocity. This is done by approaching Titan in an orbit where the velocity vectors of the probe and the moon are parallel. The easiest way of attaining such an orbit is making a ‘half” Hohmann Transfer as presented in figure (5.3.1). The velocity change needed is 1.5 km/s. The maneuver also requires that the epoch of the initial orbit is changed making it possible to rendezvous with Titan. Fortunately such epoch change is possible according to ESA.

The semi major axis of the new rendezvous orbit is 800 Mm and the eccentricity is 0.53. The velocity in the point intersecting Titans orbit is 3.8 km/s and the orbital velocity of Titan itself is 5.6 km/s. Therefore the probe will approach Titan with a relative velocity of 1.8 km/s. The closest point in the approaching orbit is very hard to calculate. In the initial mission requirements this point was set at 1200 km above Titans north pole. With the new rendezvous orbit this point is no longer valid. The orbit will be perturbed when passing from Saturn’s to Titan’s sphere of influence. The effect of these perturbations can probably only be calculated numerically. Lacking both the time and the tools for such a calculation an approximation of the process will be sufficient. For simplicity the closest point is chosen equal to the one in the initial conditions. While the spacecraft will tend to fall towards Titan it becomes obvious that an inclination change has to be made. The $\Delta V$ needed for the maneuver will be set by the numerical simulation but an approximation of about 5% velocity change required for the rendezvous orbit change will be sufficient. This corresponds to about 5 kg of fuel and will give a margin of about ± 7500 km. Also a small velocity change of 0.5%, to trim the approaching trajectory, is included.
The escape velocity is 2.2 km/s in the closest point. Therefore the probe will be caught in orbit around Titan. Again the exact elements of this orbit will be very hard to calculate without numerical aid but the orbit will definitely be polar and elliptic. An estimate of the orbit from insertion orbits of analogous missions is presented in figure (5.3.2). Due to the uncertainty in the orbital elements it is hard to say if any science can be conducted in this phase. Most likely the probe will not pass through the atmosphere of Titan. Therefore the orbit will have to be adjusted before the mission science phase can start. To approximate an initial orbit we assume the velocity and radius vector in the point to be perpendicular. This results in an orbit with a semimajor axis of 5300 km, an eccentricity of 0.30 and an apocenter of 4300 km above Titan’s surface. This approximation will in many ways serve as a worst case scenario while the argument of pericenter is 90°.

**Figure (5.3.2) Insertion orbit.**

### 5.4 Aerocapture

Aerobraking by flying through the upper part of an atmosphere is commonly used to circularize orbits after insertion. It is a very useful method while ideally no fuel is needed. The Mars Global Surveyor among others has used Aerobraking. It is also used for end of life maneuvers in low earth orbits. Using the same principle but for orbit insertion is called aerocapture. The idea is to decelerate the spacecraft enough to insert it into orbit during only one atmospheric pass. Aerocapture has to this date newer been utilized but is very interesting while it may dramatically increase the inserted payload mass. It has been stated that the increase of inserted mass may be as large as factor three and that some systems may have an equivalent $I_{sp}$ of up to 1200 s.

The reason why aerocapture has never been used is mainly because of the difficulty in calculating the exact effects that it will have on the orbit. It is dependent on error in the approach trajectory, navigation system, ballistic coefficient, atmospheric density and the density scale height among other things. All these errors may be fairly large, in particular the last two while they are heavily dependent on the knowledge of the atmosphere in question. The atmospheres of Venus and Mars have been studied by many missions and their dynamics are fairly good known. Still the effects of the atmospheric drag are uncertain. Titan’s atmosphere has not been subject to much exploration so the error will therefore be substantial. There are different ways of overcoming these obstacles. NASA’s In-Space Propulsion Technology Office at the Marshall Space Flight Center in Huntsville has considered four different aerocapture concepts for development [30], [31], [32], [33].

#### 5.4.1 System Designs

The **blunt body, rigid aeroshell design** has a strong heritage from previous NASA atmospheric reentry missions. The concept is based on a protective aeroshell shielding the spacecraft from the external heating during the aerocapture. After the maneuver the shell is jettisoned. The advantage of this design is that it is space qualified both on the component and the system level. The main disadvantage is that the blunt body has very limited maneuvering
capability during the aerocapture. This makes it vulnerable to the uncertainties mentioned above.

The *slender body, rigid aeroshell design* is based on the same principles as the blunt body one although instead of minimizing the volume of the aeroshell it is elongated into a slender shape. This may complicate stowing during launch but increases the maneuverability noticeably. The slender body, rigid aeroshell design has only been tested on a component level.

The trailing ballute (balloon parachute) design is another approach to the problem. To increase the atmospheric drag a toroidal ballute is deployed behind the spacecraft as shown in figure (5.4.1). The ballute stays attached until the required $\Delta V$ is accomplished. Then the ballute is released and the spacecraft continues into orbit. This design is very flexible and can handle large errors. It also reduces the need for thermal protection of the payload while most of the drag force will be incurred by the ballute. The disadvantage is that few of the components are space validated and some additional research has to be made.

The *attached ballute design* is similar to the blunt body design but with an inflatable ballute attached to the aeroshell increasing the surface area. Thereby the atmospheric drag increases and using the same deployment mechanism as for the trailing ballute the error dependents decreases. The design has the same disadvantages as the trailing ballot design.

In the summer of 2003 aerocapture was selected to be a part of NASA’s New Millennium Program ST-9 mission. It is also rated as a high priority technology in the In-Space Propulsion Technology Program and efforts are currently being made to raise the technology readiness level of all the designs to TRL-6 [34].

### 5.4.2 TAGE Design

In the case of TAGE one of the ballute designs will be the most practical. The rigid body aeroshell will not work while the atmospheric uncertainties are too great. A slender body design would work but the maximum volume attached while to the Cassini 2 is restricted. Taking into account that a ballute enables the HASSE balloon makes such design favorable. The trailing ballute design will work better as a balloon than the attached ballute and it is therefore the best choice. The function of the ballute after separation will be discussed further in other chapters. Here follows a presentation of the trailing ballute as an aerocapture system.

It is based on the report *Trailing Ballute Aerocapture: Concept and Feasibility Assessment* written by Kevin L. Miller from the Ball Aerospace and Technologies Corporation among others. This is a case study ordered by NASA investigating the possibility of sending a probe to Titan. It is therefore very applicable on our report. The Ball case study used Monte Carlo simulations for their calculations and lacking such software only scaling will be used when transferring data over to the TAGE mission.

The main concern in aerocapture technology is overcoming the navigation and atmospheric uncertainties and their effects on the robustness of the maneuver. In the case of the trailing ballute this is done in a very straightforward way. The aerocapture maneuver is presented in figure (5.4.2). Initially the ballute is stowed on top of the probe (1). A few hours before entering the atmosphere the ballute is inflated (2). This is done to give the deployment
mechanism sufficient time for inflation. A trajectory correction maneuver may also be conducted trimming the atmospheric entry flight path angle, $\varphi$, to minimize uncertainties mentioned above. When entering the atmosphere (3) a rapid deceleration is begun. The ballot is intentionally oversized so that if it were to be attached during the whole aerocapture the spacecraft would undoubtedly crash. This ensures that the spacecraft will under no conditions continue in a hyperbolic orbit. Using accelerometers and a central force of gravity model the on-board computer can calculate when the required velocity change is obtained. This is done with high precision. When the $\Delta V$ is obtained a pyrotechnic separation mechanism releases the ballute (4). While the projected area of the spacecraft itself is only a fraction of the ballutes it continues almost unperturbed out of the atmosphere although an orbit correction may be necessary to correct the apocenter altitude (5). Finally the science orbit can be obtained through orbital maneuvers described in the next chapter (6). After separation the ballute will continue the rapid deceleration until it starts acting as an ordinary balloon (7).

![Figure 5.4.2 Orbit insertion via aerocapture using a trailing ballute.](image)

The calculations in the Ball case study were made for a spacecraft with an entry mass of 500 kg, an entry speed of 6.5 km/s and a ballute area of 751 m$^2$. The velocity change was 4.6 km/s, the deceleration was at most 4.1 g and the lowest altitude was 405 km. The TAGE mission has an entry mass of 200 kg (40% of 500 kg) and an entry speed of 6.1 km/s. Assuming the drag coefficient and the approach trajectory to be the same the ballute area can be approximated from the atmospheric drag deceleration

$$a_D = \frac{1}{2} \rho \frac{C_D A}{m} V^2 \Rightarrow \frac{1}{2} \rho \frac{C_D A_{\text{Ball}} V_{\text{Ball}}^2}{m_{\text{Ball}}} = 1 \iff A_{\text{TAGE}} = A_{\text{Ball}} \frac{m_{\text{TAGE}} V_{\text{TAGE}}^2}{m_{\text{Ball}} V_{\text{Ball}}^2} = 0.45 A_{\text{Ball}} \quad (5.4.1)$$

The ballute area of the TAGE probe is therefore approximately 340 m$^2$. The thickness of the ballute fabric is dependent on the maximum heating, which is approximately the same in both cases. Therefore also the ballute mass should be about 45% of Ball’s. Assuming that the rest of the ballute system (inflation and separation mechanisms, gas tank, accelerometers and so on) scales in the same way or slower than the entry mass it becomes evident that the mass of
the whole aerocapture system scales slower than the entry mass. The Ball case study argues that the mass fraction of the trailing ballot design is about 40% of that of a hard aeroshell, which results in about 18% of the entry mass. Many other approximations also end up in the region between 10-20%. Using the argument above some margin should be added to this in our case. While the argument is fairly blunt a margin of 25% is applicable. This results in an aerocapture system mass of 45 kg wherein 19 kg is the ballute itself. If we instead use the equivalent specific impulse of the trailing ballute design, namely 1200 s, we end up with approximately the same numbers.

One of the greatest advantages of the trailing ballute design is that the insertion orbit is independent of mass. This is enabled by the fairly exact $\Delta V$ delivered by the system. The choice of $\Delta V$, and thereby insertion orbit, is set by the science orbit. It has an apocenter altitude of 8000 km. The pericenter will be decided by when the ballute is detached. This is an autonomous decision by the computer based on in-situ measurements of the deceleration. Therefore it is hard to calculate the exact pericenter. It will certainly be higher than the one in the Ball case study while both the entry velocity and the velocity change is less. Using 500 km as a guideline is a reasonable approximation. To accommodate for the introduced uncertainty an extra margin should also be added to the $\Delta V$ budget.

The maximum deceleration will also be less for the same reason as the higher pericenter. Nevertheless the balloon payload might be exposed to a higher g-force after detachment. Also the heating rate will decrease but this will be further discussed in chapter 11. To sum up the discussions the essence is that no new hazards have been introduced. It is therefore possible to assume that the high success rate of the Monte Carlo simulations is also applicable to the TAGE system although there are some general remarks to be made.

5.4.3 Critical Issues

The trailing ballute design is still under development and there are some critical issues to be solved. Almost all of the individual components such as the ballute fabric and pyrotechnic separation mechanism have been validated in a laboratory environment, although some component testing still remains. For example doubts have been raised if the current seaming technology for thin-film inflatables can handle the extensive heating during aerocapture. Studies in ultra-sonic welding and stitching with cover tape have been conducted. Another approach is to try to separate the seams from the high heating areas. There is also some testing to be done concerning the effect of the long storage time. The candidate material has thus far at least shown good persistence against aging.

On a system level there is more to be done. The attachment between the tethers and the ballute has been a problem. The tethers must be able to withstand up to 5 g but the stitching techniques mentioned above will probably ease this problem too. Also the deployment of the ballute may cause a problem. This is done in empty space which might cause a risk of tethers getting entangled or even collisions between the ballute and the prob. This can be solved by letting some of the tethers be inflatable columns providing stability also in a vacuum. When entering the atmosphere the problem vanishes but if the ballute is to be used for scientific purposes after detachment column tethers may again be useful for increased stability.

There are also some concerns about the interaction between the hypersonic rarefied flow and the ballute. Also the interaction between the ballute and the probe bow shocks is an issue. Studies of these phenomena are currently being conducted both in wind tunnels and computer simulations. The use of the ballute as the basis for the HASSE balloon will probably demand some extra modifications to be made to the system.

The ballute will be mounted on the same side of the probe as the RTG. The ballute itself will be packed in a half torus with an inner diameter of 1 m and on outer diameter of 1.2 m. The height will be 0.2 m. The top of the torus will be covered with a protective membrane and gas
tanks, electronics and the balloon payload will be mounted on the inner wall. Given the argument above at least four of the tethers should be inflatable. Four different gas tanks are therefore preferable giving some redundancy. Helium is a good choice of balloon gas since it will not need any heating before inflation. The separation system between the balloon and the probe may be a problem. Given the extremely high relative deceleration of the balloon compared to the probe after detachment a very clean separation is required. If the separation inflicts any sideways force on the probe and/or the balloon the consequences may be devastating. The probe may end up in an uncontrollable spin or worse the RTG may be damaged and the whole mission lost. The safest separation system would be a single separation bolt but this is not possible since the RTG is situated in the center of the surface. After consulting SAAB Ericsson Space the same separation system as used for the Cassini 2 joint was considered safe enough and therefore chosen.

### 5.5 Transfer to the Science Orbit

The science orbit will initially have a pericenter of 950 km and an apocenter of 8000 km above Titan’s surface. The reason for this choice is discussed in chapter 2-4. The transfer to the science orbit will be made in similar ways for the different orbit insertion techniques. These are presented in figure 5.5.1. For the traditional technique the pericenter must first be lowered into the atmosphere. Then the apocenter can be elevated and the science orbit obtained. The calculations are very straightforward and only small additional margins have to be included.

In the case of aerocapture ideally only one maneuver is necessary while the apocenter of the insertion orbit is optional. Nevertheless Monte Carlo simulations have shown that the uncertainty in the apocenter altitude is substantial. Therefore a margin covering a 50% error in this parameter is included. After securing the apocenter a pericenter elevation has to be made to accomplish the science orbit.

After insertion the science orbit will be subjected to perturbations. This will demand some orbit maintenance to be carried out. These operations are further discussed in chapter 10.

### 5.7 ΔV Budget

The velocity change needed for an orbital manoeuvre is simply the difference in velocity between the initial and the sought orbit in the point of the burn. This assumes that the velocity change is instant. In reality no propulsion system can deliver such impulse and a small thrust will result in a large error in the calculation. Therefore several trajectory trims may be necessary. The velocity in an elliptical orbit is given by

---

**Figure (5.5.1) Transfer maneuvers to science orbit.**
\[ V = \sqrt{\frac{MG}{r} \left( \frac{2}{a} - 1 \right)} \]  

(5.7.1)

where \( M \) is the mass of the orbited body, \( G \) is the gravitational constant, \( r \) is the radius vector and \( a \) is the semimajor axis.

The \( \Delta V \) budgets for the different orbit insertion methods are presented in table (5.7.1) and (5.7.2). The stated times are counted from separation.

<table>
<thead>
<tr>
<th>Time [d h m]</th>
<th>Event</th>
<th>Velocity change [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0 0 10]</td>
<td>Apocenter lowering manoeuvre</td>
<td>1497</td>
</tr>
<tr>
<td>[0 14 44]</td>
<td>Inclination change manoeuvre</td>
<td>75</td>
</tr>
<tr>
<td>[4 6 26]</td>
<td>Trajectory change manoeuvre</td>
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</tr>
<tr>
<td>[4 17 2]</td>
<td>Pericenter lowering manoeuvre</td>
<td>21</td>
</tr>
<tr>
<td>[4 18 30]</td>
<td>Apocenter elevation manoeuvre</td>
<td>118</td>
</tr>
<tr>
<td>[4 20 26]</td>
<td>Apocenter trim</td>
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</tr>
<tr>
<td></td>
<td>Orbit maintenance</td>
<td>224</td>
</tr>
<tr>
<td></td>
<td>End of life manoeuvre</td>
<td>94</td>
</tr>
<tr>
<td></td>
<td>Total ( \Delta V ):</td>
<td>2038.5</td>
</tr>
</tbody>
</table>

Table (5.7.1) \( \Delta V \) budget for a traditional orbit insertion.

<table>
<thead>
<tr>
<th>Time [d h m]</th>
<th>Event</th>
<th>Velocity change [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>[2 1 33]</td>
<td>Trajectory change manoeuvre</td>
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</tr>
<tr>
<td>[2 7 30]</td>
<td>Aerocapture</td>
<td>( \sim 4000 )</td>
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<tr>
<td>[2 8 14]</td>
<td>Apocenter trim</td>
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</tr>
<tr>
<td>[2 11 36]</td>
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<td></td>
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<tr>
<td></td>
<td>Total ( \Delta V ):</td>
<td>4404</td>
</tr>
</tbody>
</table>

Table (5.7.2) \( \Delta V \) budget for an aerocapture insertion.

5.8 Mass Budget

There are a large variety of different propulsion systems on the market. They can be divided into three groups namely cold gas, electrical and chemical propulsion systems. The first two are not feasible for a Titan mission. This is because cold gas operates with a very low specific impulse and it is therefore very fuel consuming. Electric propulsion on the other hand has a very high \( I_{sp} \) but instead it is very power consuming, often several kW. Given the limited power delivered by the RTG chemical propulsion is the only option. While one of the mission requirements was to build the probe with Swedish components if possible, it was decided to use the ECAPS fuel together with thrusters from the Swedish Space Corporation for attitude control. ECAPS is a liquid monopropellant, which unlike many other fuels is environmentally friendly. In addition to monopropellants there are bipropellant and solid fuel chemical systems. Bipropellant systems have the highest \( I_{sp} \) of all chemical propulsion systems but they are quite complicated. Solid fuel systems are on the contrary fairly simple and very reliable. Their greatest disadvantage is that they are not restartable in contrast to mono- and bipropellant systems. Solid fuel systems are often called motors while liquid fuel systems are called engines. The equation to use when calculating fuel mass is
$$m_{\text{fuel}} = m_{S/C} \left( 1 - e^{-\Delta V / I_{sp}} \right) \quad (5.8.1)$$

where $m_{\text{fuel}}$ is the fuel required for the velocity change $\Delta V$, $m_{S/C}$ is the total spacecraft mass before the manoeuvre, $I_{sp}$ is the specific impulse and $g$ is the gravitational acceleration on earth. It is a rewrite of the rocket equation.

In case of a traditional orbit insertion two systems will be presented. One uses a solid fuel motor for the large insertion burn and then the attitude control thrusters for the rest of the manoeuvres. The other one is using a bipropellant liquid engine for all manoeuvres except for trajectory trimming. In the case of aerocapture only the attitude control thrusters will be used. The reason why the fuel required for orbit maintenance and end of life manoeuvres are included is to observe possible advantages from co-use of different systems.

In the first case the STAR 13B motor was chosen. It has a thrust of 7 kN, an $I_{sp}$ of 285.7 s and a propellant mass fraction of 0.88. The total fuel mass of the motor is 41 kg. Two such motors will therefore exactly fulfill our total fuel requirement. The use of off-the-shelf components reduces the system cost significantly. The STAR 13B motor has an extensive flight heritage and the STAR 13A motor, which is of the same family, was used on the Swedish Freja satellite. The mass budget of this configuration is presented in table (5.8.1). The power needed for the motor is limited to ignition and while only a few other systems are active at that point it should not lead to any problems.

In the second case the Astrium S400-20 bipropellant rocket engine was chosen. It has a thrust of 400 N and an $I_{sp}$ of 318 s. The rocket engine will consume some power while used and may also need some additional heating of the tanks. A continuous 5 W is therefore accommodated. The S400-series has an extensive flight heritage on several ESA missions. Thanks to the high $I_{sp}$ the system reduces the total mass compared to the first case as presented in table (5.8.2). The cost of the loaded system is approximately 0.4 M€.

In the third case only the ECAPS thrusters will

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two STAR 13B rocket motor</td>
<td>12.0</td>
</tr>
<tr>
<td>Solid fuel</td>
<td>82.0</td>
</tr>
<tr>
<td>Orbit insertion liquid fuel</td>
<td>11.0</td>
</tr>
<tr>
<td>Orbit maintenance fuel</td>
<td>14.0</td>
</tr>
<tr>
<td>End of life fuel</td>
<td>3.1</td>
</tr>
<tr>
<td>Residual fuel</td>
<td>0.6</td>
</tr>
<tr>
<td>Margin (10%)</td>
<td>2.9</td>
</tr>
<tr>
<td>Tank</td>
<td>3.2</td>
</tr>
<tr>
<td>System mass</td>
<td>128.7</td>
</tr>
</tbody>
</table>

Table (5.8.1) Mass budget for the solid fuel motor.

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Astrium rocket engine</td>
<td>3.4</td>
</tr>
<tr>
<td>Insertion burn fuel</td>
<td>74.0</td>
</tr>
<tr>
<td>Orbit insertion trim fuel</td>
<td>4.1</td>
</tr>
<tr>
<td>Science orbit transfer fuel</td>
<td>5.3</td>
</tr>
<tr>
<td>Orbit maintenance fuel</td>
<td>10.9</td>
</tr>
<tr>
<td>End of life fuel</td>
<td>3.1</td>
</tr>
<tr>
<td>Residual fuel</td>
<td>1.9</td>
</tr>
<tr>
<td>Margin (10%)</td>
<td>9.9</td>
</tr>
<tr>
<td>Tank</td>
<td>10.9</td>
</tr>
<tr>
<td>System mass</td>
<td>123.6</td>
</tr>
</tbody>
</table>

Table (5.8.2) Mass budget for the liquid fuel engine.

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ballute mass</td>
<td>19.0</td>
</tr>
<tr>
<td>Inflation gas mass</td>
<td>6.0</td>
</tr>
<tr>
<td>Gas tanks</td>
<td>1.0</td>
</tr>
<tr>
<td>Electronics</td>
<td>0.5</td>
</tr>
<tr>
<td>Clamp band</td>
<td>7.3</td>
</tr>
<tr>
<td>Bolt cutters</td>
<td>0.6</td>
</tr>
<tr>
<td>Structure</td>
<td>11.0</td>
</tr>
<tr>
<td>Orbit insertion trim fuel</td>
<td>9.4</td>
</tr>
<tr>
<td>Science orbit transfer fuel</td>
<td>0.5</td>
</tr>
<tr>
<td>Orbit maintenance fuel</td>
<td>7.5</td>
</tr>
<tr>
<td>End of life fuel</td>
<td>4.9</td>
</tr>
<tr>
<td>Residual fuel</td>
<td>0.4</td>
</tr>
<tr>
<td>Margin (10%)</td>
<td>2.3</td>
</tr>
<tr>
<td>Tank</td>
<td>2.5</td>
</tr>
<tr>
<td>System mass</td>
<td>72.9</td>
</tr>
</tbody>
</table>

Table (5.8.3) Mass budget for the separation system.
be used. The mass of the ECAPS thrusters will not be included in any of the budgets while they are already accounted for in the attitude control mass budget. The total mass of the trailing ballute system is presented in table (5.8.4). In all of the cases the mass of the separation system must be added. This is shown in table (5.8.3). One should also note that the mass of an independent HASSE system must be added in the first two cases.

An estimate of the total cost of the ballute system is very hard to compute while no analogues system exists. Adding up the cost of the individual components and then adding some margin for construction costs would be a way of estimating this. Another would be to use inflatable atmospheric re-entry systems as an analogy. For simplicity only adding a margin of 100% to the price of traditional propulsion system is applicable. This yields a cost of 0.8 M€.

5.9 Conclusion
The advantage of chemical propulsion systems are their reliability and extensive flight heritage. The main disadvantage is their substantial mass fraction. For the liquid rocket engine the dry mass fraction is only 0.45 and in the solid rocket motor case this number is 0.43. The aerocapture system manages to raise the dry mass fraction to 0.61. This is if the ballute is regarded as fuel. If it is regarded as dry mass, given that it also has a scientific purpose, the fraction is 0.88. Such mass fractions are unheard of in traditional spaceflight.

The main disadvantage of the ballute design is that it is not flight tested. It is for the moment in the so called TRL death valley and assuming that the development will be completed in 2016 might be risky. Taking into account that aerocapture is a part of the ST-9 program and that NASA is planning to use it in their new Mars program it is at least fair to assume that the development will receive all necessary funding. The chances of making it out of the death valley are therefore good. Assuming that NASA will have a flight tested aerocapture system 2016 is consequently feasible.

Even though a flight tested aerocapture system will probably exist by the time of launch, being dependent on NASA is a great disadvantage. Nevertheless it is my opinion that every space agency that wants to be a serious player in future interplanetary spaceflight must develop its own aerocapture technology. It is fully feasible that ESA, or even the Swedish space industry, can have a flight tested ballute system on the market in ten years, but development should be started soon and additional funding is required. The possibilities of high payload missions to Venus, Mars, Titan and the outer gas giants make the effort well worth while.

My conclusion is therefore that the trailing ballute system for orbit insertion is preferable. In addition to this the use of Swedish components such as the SAAB Ericsson Space separation system and the SSC thrusters and fuel is a great way of displaying Sweden’s capability in space.
6.1 Introduction

In my work with the structure and mechanisms I have looked for simple ways to fulfil the requirements of the environment and scientific goals. By using simple reliable materials and mechanisms I have ensured that the structure is producible and that the TAGE (Titan Atmosphere and Ground Explorer) mission will be a success.

When making the choices around the structure of the probe TAGE some tough parts have been to make all criteria fulfilled for the different subsystems. Every subsystem is in some way dependent of the choices made around other subsystems. For example the communication and scientific instruments is dependent of the attitude that is dependent of the choice of stabilization.

After a few project meetings and lots of careful thinking all of the conflicts have been solved with quite simple techniques and not so many moving parts. It has been difficult but by setting up good models in Matlab I have been able to quickly insert corrections from subsystems and see if the numbers are reasonable. I am very satisfied with the result and I think that the mission is feasible.

In this chapter you can read about the motivations for the different structures and mechanisms and what solutions that are best suited for this mission.

6.2 Basic structure of TAGE

TAGE is spin stabilized which means that the probe spins around a fixed axis and uses its moment of inertia to keep the same attitude. There are a few disadvantages with this stabilization in comparison with three-axis stabilization.

The first is that when the probe is spinning it cannot be facing with the same side towards the planet all the time. If that would be a prioritised criterion for any instrument it would not be wise to use spin stabilisation since it would take lot of fuel to turn it.

Another disadvantage with a spinning probe is that the communicating parabola would also spin which makes it hard to retain the link between the probe and receiver. It is possible to have a spinning probe with a counter spinning plate but this is quite complicated and involves many moving parts that could struggle.

It is also important to make sure that the spin axis is stable. Which means that one has to make sure that the centre of mass is on the desired spin axis and that the moment of inertia is the largest around that axis.

The advantages with spin stabilization is that it does not use any fuel once it has been put into spin and the spin makes it possible to use very long wire antennas.

All of the disadvantages were at first causing trouble with instrumental requirements but it has all been solved using wire antennas for science and a phase shifting array antenna for communication.
As seen on figure 6.1 I chose a cylinder shaped body since it is has a relatively stable spin axis and the nut shape makes it is easy to attach inner electronics and instruments on the flat sides. The symmetrical shape makes it also easy to centralize the mass and calculate the moment of inertia.

To protect the electronics inside the body from radiation during the seven-year voyage to Titan and protect from impacts with space debris the entire body is covered in sandwich panels with aluminium honeycomb structured core. These plates have the good properties that they are stiff and have a low weight, which makes them perfect for space missions. They are attached to each other in corners with special made splints and then welded together.

On top of the probe is the phase shifting array antenna which instead of rotating, the antenna rotate its power lobes. When the probe is linked to Cassini 2 it first steer the lobe towards Cassini 2 and then rotate the lobes in the counter direction of the spin. This is our solution to the spin problem number two as I described earlier.

Since Titan is so far from the Sun it is irrational to use solar panels since they would have to be large as football fields. If the probe should get power from batteries it would require about seven tons, which makes it absolutely necessary to use a radioactive power source. In our case a Stirling motor driven by radiation is chosen which gives much power and has a long lifetime.

The SRG is visible in figure 6.1 sitting under the probe and consists of two integrated Stirling motors with a total weight of 34 kg. This was very troublesome since the SRG have to be outside the probe to get rid of heat and radiation. Since it weighs quite much it contributes to a moment around the centre of mass around both the desired spin axis and the undesired spin axis.

If the SRG would be placed on the side of the probe it would move the centre of mass from the desired spin axis, which is unacceptable. It might also disturb the measurements with its radiation so it had to be placed underneath the probe. Which instead made the desired spin axis less dominant. With careful calculations I have calculated that it would be adequate to
place the SRG at a distance of 11 centimetres to get the SRG heat panels free and still have a stable spin.

To get even more stable spin I have placed the fuel in four spherical tanks symmetrically around the centre of mass along the walls of the probe. This means that the stability in the spin will be largest in the early stages of the mission and decrease until all of the fuel has been used. The tanks are visible as dotted circles in figure 6.3.

The thrusters are visible to the right in figure 6.1 and there are four more thrusters placed on the opposite side of the probe. They are placed 13 centimetres from the bottom, which is the height for the centre of mass. It is very important to place them around the centre of mass to make sure that they work in the right direction. If one of the thrusters would not work then it would still be possible to steer the probe with only one thruster.

The science radar requires 25 metres long antennas, which is hard to achieve with stiff antennas. Therefore we chose wire antennas that are deployed and held straight using the spin. To reduce noise there is one 2 metre long stiff antenna under the probe, called the nadir pointing antenna.

When all of the subsystems mass, size and requirements where clear. I placed them accordingly with respect to stability and requirements. The result is shown in figure 6.1 and with dimensions in figure 6.3. This took some work calculating to prove that the design is good enough. But after some writing and calculating a solution was declared.

### 6.3 Calculations and results

Most of my calculations are about the moment of inertia and centre of mass. Since the probe is so small and stable the vibrations during launch will not be a problem.

The formulas I have used are centre of mass for a particle system, Steiner’s theorem and different kinds of moments of inertia for simple bodies.

<table>
<thead>
<tr>
<th>Formula</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ \vec{R} = \frac{\sum m_i r_i}{\sum m_i} ]</td>
<td>Centre of mass for system of particles [38]</td>
</tr>
<tr>
<td>[ I = I^* + ma^2 ]</td>
<td>Steiner’s theorem [39]</td>
</tr>
<tr>
<td>[ I_{z,cyl} = \frac{1}{2} mr^2 ]</td>
<td>Solid cylinder [40]</td>
</tr>
<tr>
<td>[ I_{x,cyl} = \frac{1}{12} m(h^2 + r^2) ]</td>
<td></td>
</tr>
<tr>
<td>[ I_{z,cyl.shell} = \frac{1}{2} m(r_1^2 + r_2^2) ]</td>
<td>Cylinder shell of radii r&lt;sub&gt;1&lt;/sub&gt; and r&lt;sub&gt;2&lt;/sub&gt; [40]</td>
</tr>
<tr>
<td>[ I_{x,cyl.shell} = \frac{1}{12} m(h^2 + r_1^2 + r_2^2) ]</td>
<td></td>
</tr>
<tr>
<td>[ I_{z,block} = \frac{1}{12} m(a^2 + b^2) ]</td>
<td>Rectangular block [40]</td>
</tr>
<tr>
<td>[ I_{z,sphere} = \frac{2}{5} mr^2 ]</td>
<td>Solid sphere [40]</td>
</tr>
<tr>
<td>[ I_{z,block} = \frac{1}{5} m(a^2 + b^2) ]</td>
<td>Ellipsoid [40]</td>
</tr>
</tbody>
</table>

*Figure 6.2 Formulas for calculating moment of inertia*
Most of my calculating is done in Matlab where I set up a model for of the probe. Then I wrote the dimensions and masses in the program and the results came out.

One important result is the stability quote, which is the quote of moment of inertia around the desired spin axis divided by the moment of inertia around an orthogonal principal axis. This quote have to be larger than one to ensure a stable spin which is very important for this mission since the antenna functionality is depending on the spin.

Since the fuel is contributing to the spin stability the stability quote drop during the mission. Actually I have chosen the quote so that it drops below one just after TAGE enters end of mission (EOM). Because then it will not need the spin stability and the last fuel will be burned all at once to put the probe in circular orbit. There it will not need to have any contact with Cassin 2 and it will not do any measurements. If it would be contactable and be able to do measurements of interest it would be considered as a bonus.

In figure 6.4 I have plotted the spin quote versus the fuel mass and it is possible that this not absolutely accurate. But I think that the curve gives a fair appreciation of the real probe and shows that it is possible to keep a stable spin with this construction.
6.4 Structure materials

6.4.1 Sandwich panel with aluminium honeycomb structure

For all space mission design it is very important to save as much mass as possible since the launch cost is intimately connected to the satellite mass. If mass can be spared you can either save money or upgrade the payload. One way to reduce the mass of the satellite and at the same time keep up with the required properties is to use I-beam technology applied in two dimensions. This is often used in solar panels and the basic structure of these plates consists of two sheets of metal separated with honeycomb wall structure. In this way the mass is reduced while the stiffness remains.

For example if we have a panel of aluminium sheet that is one centimetre thick. We split it in half and separate these two sheets by three centimetres of honeycomb structured aluminium walls. This will give the new panels an increase of area moment of inertia 37 times larger than the original panel. The increase of moment of inertia indicates on a drastic change in stiffness while the mass remains the same. In comparison it would take a solid aluminium sheet of 3.3 centimetres to achieve the same stiffness but then it would have three times more mass. [35]

Since TAGE do not need and cannot afford plates of such thickness. The sandwich plates on TAGE will have a thickness of 0.5 mm and the honeycomb structure walls will be 7 mm, which gives a total shell thickness of 8 mm and weight of 16.0 kg. Which leaves 4 kg for booms, nuts and additional structure.
6.4.2 Silicon plates in aluminium frames
TAGE’s structure will not only be supported by the covering outer shell, but also by the inner structure. This is because some of the subsystems have their electronics in silicon plates that are screwed and glued on aluminium frames. Where the glue also has a vibration damping effect on the silicon disks.

The compact and homogeneous shape of these subsystems makes them self-supporting and there for contributing to the total stability of the entire probe.

6.4.3 Carbon fibre booms
There are three stiff booms on TAGE, one holding out the magnetometer and two holding on to the SRG. The carbon fiber is a good structure since it is very stiff, strong, has low density and a low thermal expansion coefficient. [37]
6.5 Mechanisms

6.5.1 Deploying and releasing mechanism of the balloon

The balloon in figure 6.7, also known as HASSE, that we are going to use as an aero breaking device to save fuel. The payload attached around the SRG on the bottom of TAGE and the balloon packed on top of that. The entire balloon system including payload, separation mechanism, balloon and blow up mechanism weighs 54 kg. It may sound much but it actually would take much more fuel to achieve the same breaking force as with the balloon.

When TAGE is going through Titans atmosphere it absorbs a lot of energy that heats up the probe. Therefore we have attached a heat shield of 7 kg around TAGE over the phase shift array antenna. It is this side with the heat shield and antenna that is facing Cassini 2 during the voyage to Titan. This is so the heat generated by the SRG can dissipate to free space.

After the probe has been released from Cassini 2 the balloon is inflated with gas. Then the probe enters the atmosphere and the aero breaking starts.

When an algorithm has calculated that the probe has the right speed the second separation of the balloon starts. Then the separation bolts fires HASSE from TAGE so the balloon and its payload can sail into Titans atmosphere.

After the releasing of the balloon the heat shield is released by fire bolts and TAGE makes its final adjustments to enter the desired orbit. Then the thrusters set the probe into spin. [41]

![Figure 6.7 Illustrating HASSE](image)

6.5.2 Separation of heat shield

The separation mechanism of the heat shield consists of fire bolts with a total mass of 3 kg. These separation bolts is fired when the balloon is released. Just before the TAGE is put into orbit.
6.5.3 Deploying mechanism of magnetometer

The mechanism for this boom is inspired from the FAST satellite launched 1996. This stiff boom will be attached along TAGE during the aero breaking and deployed when TAGE starts spinning. The boom is released by cable cutting pyrotechnics and then spring force motivates the boom to the desired position. See figure 6.8 for illustration of approximate folded position before deployment.

In the FAST mission it was the spin that motivated the boom into position. But the disadvantage of this is that when the probe is spinning the magnetometer might rub the spin slightly. Therefore I think that the boom should be deployed before the probe is in spinning to prevent this disturbance. Though I know that the temperature is very low in Titans atmosphere, which reduce the flexibility of any metal, including springs. But with the right dimensions and material I believe that a spring solution is possible.

If the spring solution would turn out impossible, it would be possible to minimize the impulse momentum of the magnetometer to reduce momentum. By folding the boom with a few more joints the momentum might be negligible so that we can use the spin for deployment instead. [37]

6.5.4 Wire antenna deployment mechanism

In figure 6.8 on the illustration in the middle, two of the boxes containing the wires are visible. There are totally five wire antennas that are rolled up during launch and the voyage to Titan. When TAGE is in orbit and is spinning, the wire antennas are deployed by pure motivation from the spin force. To assure that stability is preserved during deployment, each wire is controlled by an electric motor. Which makes sure that all of the antennas are deployed at the same time and with controlled speed. The deployment mechanism can be compared to that used for the wire antennas on the FAST mission. [37]

6.5.5 Nadir pointing antenna deployment mechanism

Visible as folded in red and deployed on the left illustration in figure 6.8 is the nadir antenna. The single stiff antenna is 2 metres long and is on the same side of the probe as the SRG. The mechanism for deployment is tested on the MARSIS experiment and is a good solution for TAGE as well. The mechanism consists of cable cutters and pyrotechnics that fire the antenna to straight position from folded position. [36]
6.6 Conclusions

There are some parts of the structure of TAGE that I would personally like to improve the margins for, to increase the success rate. I would like to increase the covering aluminium shell thickness to improve durability against radiation and impact with debris in orbit. I would also like to make the spin quote larger. A better value would be about 1.2–1.3 to assure that the spin is stable and self-stabilizing.

Otherwise I think that the result is better than expected. That the structure and mechanisms follow most of the ten steps to a reliable mechanism, or can be followed during later stages of the mission. The steps are [42]:

1. Keep the design simple
2. Design with high margins to the torque that is variable or uncertain
3. Take advantage of all available tools and people
4. Design with production in mind
5. Design to minimize contamination and its effects
6. Carefully select, work with, and monitor suppliers
7. Participate in reliability and failure mode analyses
8. Include redundant components selectively and intelligently
9. Develop a sound test program
10. Follow the mechanism through production and test.

From a structural point of view, I think this mission is feasible.
Chapter 7

Power

Erik Winkler

7.1 Introduction

Almost all the satellites subsystems need power to function. It is therefore important to find a reliable power source that will function in the environmental specifications given. In this case, when the spacecraft is far out in the solar system, orbiting the moon Titan, the specifications are more onerous.

Another important aspect is the contamination risks. Titan is at this time not considered as an object where the possibility of life is high. But still a policy is to leave as little traces of Earth’s life in space. Usually it is not acceptable for any destruction, i.e. the spacecraft itself changes the composition of chemicals, of the environment on or around the object of the mission. This is a trade-off, when it is always a risk of contamination, where an acceptable level of the risk must be reached. These contamination risks primary deals with earth life brought to the object. If we find life it must be certain it is not an Earth emigrant. For more information about this read chapter 12.

7.2 Requirements for the Power Sub Systems

The environment around Titan is quite cold. The Sun has little if any influence on the temperature of the surroundings. This leads to the requirement that the power subsystem has to either deliver enough power to drive heaters to keep itself in operating temperature or to be able to function in the temperatures around Titan. For HASSE, the balloon, that is little above 95 Kelvin. The time of survival for HASSE is not near as long as for TAGE, as it is not essential for the overall mission.

The power system has to be reliable. It has to withstand eventual stresses caused by the journey and environment. In short it needs to sturdy.

A power subsystem will eventually have effects on the other subsystem on the spacecraft. If the power is generated by a radioactive source the radiation can cause problems on instruments and data handling, and the other systems as well. The effect of this has to be within an acceptable level i.e. the other systems have to be able to function regardless of the radiation flux emitted from the power system.

The power TAGE is going to need is set to 100W. This is during the entire mission i.e. one year after arrival to Titan. For HASSE the power required is 17W. The duration of HASSE’s mission on Titan is specified to no more than it is wanted to last as long as possible.

The mass of the power subsystem is limited to 34kg for TAGE. For HASSE the limit is 2.5kg.
7.2.1 Power Budget TAGE

If everything that is onboard TAGE demand power at a given time, the power subsystem would not manage to provide it for all the systems. In order to manage, simply, all systems cannot have power at the same time. To solve this problem different modes have been set up. When the vital systems for the spacecrafts survival need more power all other systems will be put on hold.

<table>
<thead>
<tr>
<th>POWER [W]</th>
<th>Mode 1</th>
<th>Mode 2</th>
<th>Mode 3</th>
<th>Mode 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>60</td>
</tr>
<tr>
<td>GPR</td>
<td>-</td>
<td>3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>LP</td>
<td>-</td>
<td>15</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Aspera</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Magnetometers</td>
<td>-</td>
<td>-</td>
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<td>-</td>
</tr>
<tr>
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<td>20</td>
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<td>70</td>
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<td>Attitude Control</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Thermal</td>
<td>25</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Power system</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Data handling &amp; Command</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>∑</td>
<td>70</td>
<td>70</td>
<td>100</td>
<td>92</td>
</tr>
</tbody>
</table>

Table 7.1. Power budget TAGE

The survival systems have a priority. When attitude or thermal need power the instruments and communications have to be silent for a while. This is mode 1. When they are done with whatever that needs to be done, the mission may continue i.e. instruments and communication systems powers up and runs.

Mode 2 is when most of the instruments are doing their measurement and the communication system is sending its housekeeping data.

When the instruments data need to send to the mother ship all other activity has to cease. Otherwise the power supplied will not suffice. This is mode 3.

In mode 4 the ground penetrating radar, GPR, is doing its measurements. Due to the power it needs, most of the other activities are put on hold.

7.2.2 Power Budget HASSE

On HASSE the mass sets the limits of what can be applied. Here there are no alternatives other than batteries. Sufficiently small RTGs, both in size and mass, do not exist to current date.

<table>
<thead>
<tr>
<th>POWER [W]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Instruments</td>
<td>5</td>
</tr>
<tr>
<td>Height sensor</td>
<td>0.05</td>
</tr>
<tr>
<td>Communication</td>
<td>10</td>
</tr>
<tr>
<td>Heaters</td>
<td>1</td>
</tr>
<tr>
<td>∑</td>
<td>16.05</td>
</tr>
</tbody>
</table>

Table 7.2. Power budget HASSE
7.3 Power Source Alternatives

The power system that will be chosen has to fulfil all the requirements stated in 7.2. Here three options will be evaluated: Solar arrays, RTGs and batteries. Fuel cells are not an option when they need a lot of fuel and produce a lot of its by-product water. The spacecraft is not manned, by either man or animal, so there is no need for all this water. Thus this option will not be any further evaluated.

7.3.1 Solar Arrays

In Saturn’s orbit around the Sun the solar flux is 100 times less than at the Earth’s orbit. This implies that Titan has very cold surroundings. Most solar cells cannot handle the temperatures this far out in our solar system. ESA is developing a solar cell for the cold surroundings around Jupiter, LILT, but specification about these has not been found. So how they manage around Saturn, which is twice the distance from the Sun than that of Jupiter, is not known.

The solar cells are here assumed to tolerate the temperature of Titan. A comparison will be made with GaAs solar cells. They have an effectiveness of 20% in laboratory tests. The solar flux is $13.67 \text{Wm}^{-2}$ at Saturn, 10AU from the Sun.

With the power needed, effectiveness of the cells and solar flux, the area of the solar panels can be obtained by:

$$ A = \frac{P}{\text{effectivity} \cdot \text{solarflux}} $$

(7.1)

![Inherent limitation of solar power](http://centauri.larc.nasa.gov/newfrontiers/09_NF_PPC_Schmidt.pdf)

Where P is the effect required for the spacecraft. The solar flux at Saturn is about, some changes do occur, 13.67. This gives a solar panel area of $37 \text{m}^2$. The solar panels have an
average weight of 1.9kg/m² [49]. The panels will then have a mass of 70kg. To this comes the mass for the batteries that have to supply the vessel with power during the eclipses. These batteries are going to need power to recharge and thus take power from the other subsystems. Either the other subsystems have to concede to less or the spacecraft power requirement has to be modified. These solar cells have this effectiveness in 28° C, thus even more power is required to warm these up.

Another problem concerning this choice of power system is that the solar cells have to be on panels outside the spacecraft i.e. not on the spacecraft’s body. This implies that the panels have to unfold from TAGE. These kinds of mechanical problems should be avoided if at all possible.

7.3.2 RTGs

Radioisotope power system, RPS, produces power from a radioactive source; most common these days are Pu-238. The radioactivity produces heat that is converted into electrical power. The effectiveness of RTGs are generally low, about 5-8%, the rest dissipates as heat. They give a lot of power even though. The heat is due to α-radiation. An alpha particle is easily stopped, so these particles will cause no problem whatsoever. Unfortunately this α-activity gives rise to neutrons that are not as trivial to stop. RTGs are therefore usually placed as far from sensitive equipment as possible.

The US, whose government is leading in the development of these systems, has a standard module where the Pu-238 is contained. These modules are called GPHS, general-purpose heat source, and were used in the Cassini mission RTGs and are used in the new types of RTGs that the US is developing.

Fig 7.2. Here are a few GPHS modules in a stack. From “New Frontiers AO Radioisotope Power System (RPS) Information Summary”, October 2003.
The three RTGs on Cassini, named GPHS-RTG, have 16 of these modules each. This accumulates to total 11kg of Pu-238 on each RTG. Every one of these RTGs gives an electrical power of 300W, a heat power of 4400W and weighs 55.5kg. This model of RTG is too heavy for the TAGE-mission. It has a high electrical output but with it comes a high radiation and heat due to the great amount of Pu-238. This unit was solely designed for operation in space but NASA’s requirements for RPS on future mission have expanded to operations on planetary bodies. The US has one of these left in its inventory. That unit is going on New Horizon Pluto mission, planned launch somewhere in 2006-2007. This implies that there are no GPHS-RTGs to acquire for the TAGE-mission to Titan.

![GPHS-RTG Diagram](image)

**Fig 7.3. GPHS-RTG, from “New Frontiers AO Radioisotope Power System (RPS) Information Summary”, October 2003.**

There are two promising projects concerning RPS technology. Both these units use GPHS modules and operate at a power level greater than 110We, watts electrical, at BOL, beginning of life.

The **MMRTG**, Multi Mission RTG, has 8 GPHS modules, an output of 100We, watts electrical, and produces 2000W in heat with a weight of 40kg. It is fulfilling the required power output for TAGE. The heat produced will not be a problem when it can be used, in the cold environment around Titan, to keep the spacecraft at its operating temperature. The amount of Pu-238 can still be an issue due to radiation. The weight is an issue when the mass budget is very limited. The extra 6kg may be unrealistic.

Much of the MMRTG power converter design is based on the SNAP-19 RTG, which flew on Viking 1 and 2 Mars landers and the Pioneer 10 and 11 spacecraft. The technique has in all these missions been well tested and proved reliable.
The second of the two promising RPS projects is the SRG, sterling radio thermal generator. It has a nominal output 100W, with a weight of 34kg. This is good regarding the mass budget and the power budget. The SRG has only two GPHS modules, one at each end. This fact decreases the neutron flux quite much and this is possible due to its two sterling motors. The neutron flux from the SRG at one meter is $200\text{cm}^2\text{s}^{-1}$. During the entire mission, i.e. the journey and the one-year at Titan, the total radiation dose from neutron at one meter will be 1,6Rad and a gamma ray dose under 9 years of 315Rad [47]. These values are scaled from the GPHS-RTG and are thus an assumption of the actual values. If this system is chosen a complete simulation, of these radiation levels, is required. The sterling motors increase the effect of the unit to over 20% but they introduce moving parts on the spacecraft. It will fly into space first in the year 2008 under NASA’s “The New Frontier” program. In the beginning of the SRG’s space service there is a requirement from NASA that there has to be two SRGs on every mission these units participates in. This redundancy will hopefully not be a requirement from ESA in 2016 when its reliability has been well observed.
Fig 7.5. The SRG Design Concept, from “New Frontiers AO Radioisotope Power System (RPS) Information Summary”, October 2003.

It will take TAGE seven years to reach Titan. The designed power output during its one-year mission at Titan is 100W. As is shown in fig 7.6 both these new units are capable of delivering the required power during the entire mission.

<table>
<thead>
<tr>
<th>Power Source</th>
<th>MMRTG</th>
<th>SRG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (We)</td>
<td>&gt; 110 BOM (nominal 123)</td>
<td>&gt; 110 BOM (nominal 112)</td>
</tr>
<tr>
<td></td>
<td>~100 @ 14 yrs</td>
<td>~94 @ 14 yrs</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>40</td>
<td>34</td>
</tr>
<tr>
<td>Envelope (length x fin-fin width)</td>
<td>65.0 cm x 63.0 cm</td>
<td>88.9 cm x 26.7 cm</td>
</tr>
<tr>
<td>Fuel Load</td>
<td>8 GPHS modules (~4 kg Pu-238)</td>
<td>2 GPHS modules (~1 kg Pu-238)</td>
</tr>
<tr>
<td>Voltage (Vdc)</td>
<td>28 +/- 0.2</td>
<td></td>
</tr>
<tr>
<td>Operational Environments</td>
<td>Space &amp; Atmosphere</td>
<td></td>
</tr>
<tr>
<td>Design Lifetime (yrs)</td>
<td></td>
<td>~14</td>
</tr>
<tr>
<td>Design Vibration Load (g/Hz)</td>
<td>0.2 (example for new ELV)</td>
<td></td>
</tr>
<tr>
<td>Design Acceleration Load (g)</td>
<td>40 (example for new ELV)</td>
<td></td>
</tr>
<tr>
<td>EMI/EMC (nT @ 1 meter)</td>
<td>25 (mission-specific)</td>
<td></td>
</tr>
<tr>
<td>Sterilization (Mars only)</td>
<td>NASA 4A or 4B</td>
<td></td>
</tr>
<tr>
<td>Availability</td>
<td>July 2009</td>
<td>See Section 3.2</td>
</tr>
<tr>
<td>Delivered Hardware Cost per Unit ($M)*</td>
<td>20</td>
<td>5.15**</td>
</tr>
</tbody>
</table>

* Does not include additional costs for NEPA/EIS, Launch Approval, Emergency Preparedness and Planning, Integration, etc. See Section 5.0 for information on these elements.

** $5M per unit for first three units (fabricated under current SRG development program). $15M per unit for fourth and additional units.

Table 7.3 Data Concerning MMRTG and SRG from “New Frontiers AO Radioisotope Power System (RPS) Information Summary”, October 2003.
If ESA aspires to become one of the agents that explore the outer parts of the Solar system they have to develop this technology themselves when solar panels are not an option in these regions.

### 7.3.3 Batteries

The major problem of batteries for sole power source on TAGE is the weight and the fact that they cannot be recharged, when this is the primary power system. The requirement of 100W for one year has to be fulfilled. Calculated for a battery with the energy density 350Whkg$^{-1}$, for one year:

$$\frac{(365 \times 24 \times 100)}{350} = 2607\text{kg}$$  \hfill (7.2)

This does not meet with the mass requirement. This is under the assumptions that they can stand the cold, they do not degenerate at all under the journey to Titan and that there mass can be linearly scaled to the energy density. It is the best possible scenario and it is unacceptable.

For HASSE on the other hand this is the only option available at current date Lithium-ion batteries are here an interesting option. Here much research is under way. They are preferable stored 40% discharged and in freezing temperature i.e. -40°C.
7.4 Recommendation Regarding Power Subsystem
The solar cells weights too much and introduce problems, both mechanical problems when they have to be deployed, and storage problems during the journey to Titan. They are also sensitive to the cold; their usually operating temperature being +20°C.

The mass of batteries needed to comply with the power output requirement makes it impossible to launch with Cassini-2 and TAGE.

Recommended is the SRG mentioned in section 7.3.2, due to its low radiation of neutrons and that it meets all the requirements. The MMRTG is not recommended due to its slightly larger mass and radiation risks. Mass is a critical issue in the TAGE design. The GPHS-RTG is not an option since it is too heavy and is not accessible when the last unit is scheduled for a trip to Pluto. It gives three times the power of the other two systems but then the mass would limit the rest of the subsystems and the mass of the payload so the power it produces would not be required.

HASSE has to have batteries, lithium-ion batteries. Since the requirement of survival is not that long, hours, it should be loaded with as much as possible and than hope for the best e.g. maximum 2.5kg of batteries. Since the launch date still is far off it is recommended that the batteries chosen should be the best at that time. Development is still going on. The lithium-ion batteries should be kept at a low temperature and 40% discharged during most of the journey. When the spacecraft is closing in on Titan the batteries should be warmed up and charged with the SRG.

A SRG for TAGE and lithium-ion batteries for HASSE is the recommended choices for the power subsystems in this chapter. Further investigations are needed if indeed this mission will take place.
Chapter 8

Communication

Elin Andersson

8.1 Introduction

A vital part of any space mission is the communication subsystem. The subsystem is important in two aspects; obtaining information from the scientific measurements and to be able to monitor and control the satellites health. If communication fails during a mission, no information can be transmitted to Earth and the satellite could in worst case be lost forever. The major problems in this mission are the limitations of TAGEs mass as well as in the financial aspect; these can be solved in various ways, which have their advantages and disadvantages. The focus will be on two solutions, a parabolic antenna and an electronically phase shifting array antenna. Other important aspects of the mission are the need of redundancy and the long communicational distances during the mission, the distance between Titan and Earth can be up to 10.5 AU. Two options are therefore considered in this chapter, TAGE can either communicate directly with ground stations on Earth, e.g. Deep Space Network, or the satellite could communicate to Earth via the ESA spacecraft, which is called Cassini 2. At this stage it is important to clarify how this would affect the larger spacecraft. The problems addressed in this chapter are thus:

- The mass and size of TAGE.
- The communication distance.
- The need of redundancy for the communications subsystem.

The solution that will be recommended, and will therefore be analysed further, is the electronically phase shifting array antenna that transmits via Cassini 2 down to Earth.

8.2 The Choice of Communication Subsystem

The complete communication subsystem is made up of TAGE, Cassini 2 and ground stations on Earth. These segments can be used in various ways; as mentioned earlier two alternative antenna solutions will be considered as well as two alternative paths for the link, these are summarized in figure 8.1. The figure shows three different alternatives in both antenna and path choices. In figure 8.1a TAGE is equipped with a parabolic antenna that transmits information down to Earth via the larger ESA spacecraft. Figure 8.1b-c show TAGE equipped with a electronically phase shifting array antenna. In the first scenario, 8.1b, TAGE is communicating directly to Earth. The second scenario, which is shown in figures 8.1c and d, illustrates how TAGE communicates with Earth via Cassini 2 with different modes. These solutions will be further explained below.
8.2.1 TAGEs Antenna System

8.2.1.1 Parabolic Antenna

A parabolic antenna subsystem is often used in space missions. It is reliable, accurate and can transmit with a high gain thus offering high data rates. However a parabolic antenna has some disadvantages, for a satellite so far from Earth as TAGE will be, the parabola must be very large if the spacecraft is to transmit directly to Earth. For example, Cassini has a four diameter large antenna for transmitting data with sufficiently high data rate. An antenna with this aperture is not an option for a satellite of TAGEs size. Therefore, if TAGE has a parabolic antenna it must communicate with Earth via a relay satellite, see figure 8.1a. This solution would set a number of requirements on the all of the subsystems, for example pointing accuracy. The larger spacecrafts antenna is similar to Cassini, in which the high-gain antenna has a very good pointing accuracy. This is calculated accordingly to equation 8.1, which is derived in SMAD, and with a frequency of 2 GHz it would be $\approx 3^\circ$, this frequency lies in the S-band [50].

$$\theta \approx \frac{21}{fD}$$ (8.1)

where $f$ is the frequency in GHz and $D$ is the diameter of the antenna. Thus, TAGE will need to be re-positioned towards the Cassini 2 precisely, which will require a high accuracy in the attitude subsystem. The fact that TAGE is spin-stabilized will create further problem. Another aspect when using a parabolic antenna is the risk of losing TAGE if the ESA spacecraft is lost or if the parabola itself is malfunctioning. This scenario is mentioned below in section 8.2.2.1.
8.2.1.2 Electronically Phase Shifting Array Antenna

An alternative to the parabolic antenna mentioned above is an electronically phase shifting array antenna, also called a scanning array antenna. Using this antenna makes it possible to shape the beam of the antenna by changing the excitation phase of the elements of which the antenna is composed of. Thus, no physical movement is required to alter the antenna beam shape [51]. The elements of TAGEs antenna are MEMS based patch antennas and they are also constructed so that they have circular polarization to minimize polarization losses. The elements are placed on a dome on TAGE. The phase scanning array antenna offers several advantages, which creates unique solutions. As can be seen in figures 8.1b-d, the satellite can either transmit directly to Earth or via a relay satellite. In an earlier space mission where the Vega balloons transmitted with 5W from Venus, the signal was received by the Earth based system that existed before the Deep Space Network. This proves that it is possible to send small amounts of information across large distances. Another option, that offers a higher data rates, is to use Cassini 2 as a relay satellite. In this solution TAGE would send both housekeeping and scientific data to the ESA spacecraft. When transmitting housekeeping data, TAGE first locate Cassini 2 by using an omni-directional beam, after the large spacecraft is located, a narrow low-powered beam transmits the data, which is then forwarded to Earth by Cassini 2. This solution requires some modifications of the ESA spacecraft, more on this in section 8.2.2.2. The scientific data is transmitted through a high-powered narrow beam that is received by Cassini 2. One advantage with this solution is that if something would happen to the larger spacecraft, the beam could be formed so that it transmits directly towards Earth, and therefore TAGE would not be lost. With this solution, commands could also be sent to TAGE via Cassini 2 without having to wait for a transmission option, as would be necessary if using a parabolic antenna.

Other benefits when using this antenna are the size and mass of the antenna, which are important factors due to the restrictions made on TAGE. The size of the individual antenna elements becomes smaller when higher frequencies are used, thus offering several implementation options. One option that is currently being developed is a patch antenna that is based on MEMS-technology and operates in the S-band. The element is placed on a 68x68mm large module, see figure 8.2 for a picture of a similar antenna element. The modules are planned to be used in space before 2010. [52]

![Figure 8.2 showing the first results on a micro machined GPS module, see references for further information.][53]

There are some issues with the scanning array antenna that needs to be considered, it is a new technique, which has not been so far out in space as TAGE will be. However there are some indications that this solution to the communication subsystem is being considered in modern missions. Another problem with this antenna choice is the thermal control and how the array is calibrated, testing on this has been done and it has been shown that the antenna can compensate for these disturbances. [54], [55]
It should also be mentioned that Cassini 2 have to re-position itself towards TAGE during transmission of scientific data, due to the fact that during these higher data rate transfers the large antenna must be used. However, the only requirement of TAGEs attitude is that the dome, on which the antenna elements are placed, is roughly in the direction of the ESA spacecraft and that the computers onboard can calculate the beam direction precisely enough. New technology that deals with the steering of the individual elements are on their way, this allows the beam to sweep over an area and thus enabling continuous contact over a longer period. The need for redundancy in TAGEs antenna system is not so large when using a scanning array antenna compared to using a parabolic antenna, due to the fact that there are numerous elements in the array which are not dependent of each other to function. So, if one element would fail, there would be a decrease of gain, but the antenna would still be able to function. However, a vital part of the communication subsystem is the cables, switches and it is recommended to have redundancy on these components.

8.2.2 Cassini 2 Antenna System

The larger spacecraft is stationed in an elliptical orbit around Saturn while TAGE is placed in an orbit around the moon Titan, see figure 8.2 below. Thus the distance between the spacecrafts varies over time. The line-of-sight changes as well, sometimes Saturn lies in between the transmitter and receiver, and sometimes it does not. This makes it very difficult to calculate exactly the time of contact; therefore, only certain distances are used when designing the communication links. See the chapter concerning the link budget. Cassini 2 is equipped with a 4 m in diameter antenna and it is possible at this stage to make small additions on the spacecraft at this stage of the mission.

8.2.2.1 Parabolic Antenna

If a parabolic antenna is used, both TAGE and Cassini 2 must change their position so that they are pointing at each other. Since the larger spacecraft has its own scientific mission, the number of time it can re-position itself is limited. The number of contacts depends on the larger spacecraft, the distance between it and TAGE and how long they can see each other, thus making them very limited. Engineers, who are concerned with the health of TAGE, are therefore restricted to information that could be obtained during these opportunities of contact.

Another aspect, previously mentioned, with using a parabolic antenna is if the ESA spacecraft is lost for some reason or if TAGEs antenna has a problem. It will then be hard to communicate with TAGE. If this would happen, TAGE must either be re-orienting its parabola towards Earth to be able to send data, or have a redundant omni-directional antenna. This solution would need a larger amount of power and the use of Deep Space Network, which is very expensive.
8.2.2.2 Electronically Phase Shifting Array Antenna

The solution using an electronically phase shifting array antenna uses either Cassini 2 as a relay satellite or transmits directly to Earth. If TAGE sends directly to Earth, as shown in figure 8.1b, only a ground station is needed which will be further discussed in the section below. If instead the other option is used and TAGE transmits towards Cassini 2, the ESA spacecraft will have to be equipped with small, omni-directional antennas to be able to receive housekeeping data continuously. The antennas can either be mounted on a bar that points out from the spacecraft, or mounted directly on the side of the spacecraft. These different solutions affect Cassini 2 in certain ways, see table 8.1 for further information. The recommended antenna for the larger spacecraft is the Saab Ericsson Space S-band antenna, which weighs less than 240 grams and uses an effect of 10W. The recommended solution is to place the antennas on Cassini 2's body, the total weight of the extra antennas therefore becomes 0.75-0.96 kg and the total power will be 30-40W, depending on the number of antennas [56]. These antennas are only used to ensure a continuous flow of housekeeping data from TAGE. It is also possible to use this channel to send command from Earth to TAGE.

When transmitting larger amounts of data, Cassini 2 will still have to re-orient its large antenna towards TAGE as mentioned in the previous section.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>The spacecrafts body does not obstruct the view.</td>
<td>No increased risk and an easy solution to implement.</td>
<td></td>
</tr>
<tr>
<td>Disadvantages:</td>
<td>Extra weight and risk with a bar, which requires extra mechanism.</td>
<td>Must have 3-4 antennas to be able to be seen from every angle.</td>
<td></td>
</tr>
</tbody>
</table>

Table 8.1 shows the advantages and disadvantages of the two solutions for the extra antennas on Cassini 2.

8.2.3 Ground Segment

It is assumed that Cassini 2 has continuously contact with the ground station, which consist of either one or several stations; e.g. the Deep Space Network. Which one TAGE is to communicate with depends on the communication subsystems implementation. If the subsystem is constructed so that TAGE uses Cassini 2 as a relay satellite the ground segment will be under ESAs control and management. If instead TAGE would communicate with its scanning array antenna directly to Earth, the signal would have to be received by the Deep Space Network. This is, as mentioned above, very expensive and should be avoided if possible.

8.2.4 Recommended Solution for the Communication Subsystem

Table 8.2 and 8.3 shows the advantages and disadvantages of the different solutions for TAGEs communication subsystem. The first table summarizes the solutions physical characteristics, e.g. gain, size and mass, the second table covers the cost and reliability.

<table>
<thead>
<tr>
<th>Parabolic via Cassini 2.</th>
<th>Gain</th>
<th>Flexibility</th>
<th>Distance</th>
<th>Size &amp; Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>High gain requires a large antenna.</td>
<td>Low, unless an extra antenna is used.</td>
<td>Smaller due to the usage of Cassini 2</td>
<td>High, see gain.</td>
<td></td>
</tr>
<tr>
<td>Antenna array directly to Earth.</td>
<td>Low, due to the distance.</td>
<td>Low, cannot change the usage of it</td>
<td>Large, direct to Earth.</td>
<td>Low, using MEMS-technique.</td>
</tr>
</tbody>
</table>

Table 8.2 summarizes gain, flexibilities, communication distances, size and weight for the different solutions.
Table 8.3 summarizes reliability and cost for the different solutions.

<table>
<thead>
<tr>
<th>Solution</th>
<th>Reliability</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parabolic via ESA spacecraft.</td>
<td>High, a technique that have been used many times.</td>
<td>Traditional technique, reasonable prize.</td>
</tr>
<tr>
<td>Antenna array directly to Earth.</td>
<td>New technique has however been tested in space.</td>
<td>Higher than traditional technique, but will probably go down.</td>
</tr>
<tr>
<td>Antenna array via ESA spacecraft.</td>
<td>New technique has however been tested in space.</td>
<td>Higher than traditional technique, but will probably go down.</td>
</tr>
</tbody>
</table>

From these tables it is clear that the best solution for this mission is a scanning array antenna with patch antenna elements, which uses the ESA spacecraft as a relay satellite. During housekeeping and command transmission an omni-directional beam is first sent from TAGE to locate Cassini 2. Then a narrow low-powered beam transmits the data, this beam is received by small antennas mounted on Cassini 2. During scientific data transmission, the larger satellite will have to point towards TAGE to receive a narrow high-powered beam thus allowing a higher data rate. TAGEs patch antenna elements are further discussed in the section concerning sizing the communication subsystem. Figure 8.6 in the section concerning link design shows how the spacecraft communicate.

### 8.3 Data Rates

Data rates during the different transmitting modes differ significantly due to the different requirements in instruments and sensors. Another requirement that differ for the two modes is the bit error rate, BER, which is how many bits that is allowed to be faulty during a transmission. For housekeeping and command data, a probability of bit error of $10^{-5}$ can be allowed, but for scientific data it is more suitable with $10^{-7}$. This is lower than the bit error probability for the housekeeping because the science information is more important than controlling the satellites health. The BER will affect the bit energy to incremental noise, $E_b/N_0$; the lower BER the higher $E_b/N_0$. To further increase the correctness of the data, forward correcting coding is used. However, this reduces the $E_b/N_0$. There are several ways to increase the data rate by modulation, for TAGE, the binary and quadriphased phase shift keying, BPSK respectively QPSK, will be used. For example, the QPSK takes two bits and sends them as a symbol, which is defined by the phase, thus doubling the data rate, see figure 8.5. During this mission, Reed-Solomon and Viterbi coding will be used. The Reed-Solomon coding takes a block of data and adds extra bits, these are then used for correction when errors occurs during transmission [57]. This type of coding is common in space applications, another often used method is the Viterbi coding, which is a convolution coding that predicts what is being sent by using different algorithms [58]. There are several implementations of the Reed-Solomon and Viterbi methods, for example Viterbi soft DEC.

For the house-keeping transmission BPSK with Reed-Solomon plus R-½ Viterbi coding will be used, the scientific data will be sent using QPSK modulation with R-½ coding and Viterbi soft DEC, thus enabling a higher data rate. For the house-keeping data, the BER chosen would lead to a required $E_b/N_0$ of 2.5 dB, for scientific transmissions a the required $E_b/N_0$ will be 5.8 dB.
Figure 8.4 a) the BPSK takes one bit and sends it with a corresponding phase; 0 equals to a 0° phase shift while 1 equals to a 180° phase shift. The QPSK takes two bits instead and sends them as a symbol, where 00 is sent with a 0° phase shift, 01 with a 90° phase shift, and so fourth. Therefore, the data rates increases when using QPSK.

8.4 Sizing the Communication Subsystem

8.4.1 TAGE

As the solution for the communication subsystem is chosen to be a scanning array antenna with patch antenna elements based on MEMS technology, the subsystems size and weight can be determined. This depends of course on the dimensions of the dome on which the elements are placed on, see figure 8.5, but it also depends on the implementation and the used materials. As the main materials in the modules are aluminium and silicon, they will determine the weight. A simple calculation leads to an approximate weight of 30 gram per element; this based on the materials densities, which are 2.33 g/cm³ for silicon and 2.70 g/cm³ for aluminium. Thus, if the dome surface is 0.47 m², which corresponds to a dome height of 15 cm, and the individual element have a calculated area of 0.0046 m², the number of elements on the dome becomes 102. However, this is if the modules fit perfectly on the dome, therefore in practise the real number of elements will be smaller. Another, unrealistic, assumption is that the cables, nano-switches etc. is not included in the weight. If these components are included, the total weight of the combined elements is assumed to be 130 gram; this is probably a relatively high estimation. Table 8.3 summarizes the weight of the communication subsystem when different dome heights are used. The table also includes the weight if only the patch elements, without the weights of the cables and nano-switches. Finally a height of 15 cm is chosen thus minimizing the weight of TAGEs communication subsystem.

<table>
<thead>
<tr>
<th>Dome height [cm]</th>
<th>15</th>
<th>25</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td># of elements</td>
<td>102</td>
<td>170</td>
<td>273</td>
</tr>
<tr>
<td>Total weight of elements [kg]</td>
<td>3,06</td>
<td>5,1</td>
<td>8,19</td>
</tr>
<tr>
<td>Total weight of system [kg]</td>
<td>13,26</td>
<td>22,1</td>
<td>35,49</td>
</tr>
</tbody>
</table>

Table 8.4 summarizes the weights when only the elements are taken into account as well as the whole system.
8.4.2 HASSE

The ballute which purpose is to slow TAGE down into its orbit has also a scientific goal and there is several ways to transmit the data from HASSE down to Earth. In order to have redundancy for the data from it, it is recommended that both TAGE and Cassini 2 are used during the ballutes active time. This means that TAGE has to have its antenna dome pointing towards Titan and that Cassini 2s large antenna is pointing correctly, these solutions will be further discussed in the link design.

The antennas on HASSE require a lightweight solution due to the restricted mass of the ballute. A Swedish option would be the Saab Ericsson Space S-band helix that weighs less than 240 grams. This antenna has been discussed previously in section 8.2.2.2. With this solution, the antenna on TAGE does not have to pinpoint the ballute due to the omnidirectional like beams of the antennas. This solution requires 10W of the batteries on the ballute; however the gain of the antenna is quite low. The cost for the Saab Ericsson S-band antenna lies between $50,000 and $70,000. Another option would be to integrate the antenna with the ballutes structure. However, this solution would require further development and would therefore probably result in a more expensive solution than that mentioned above.

8.5 Total Link Design

The total link design for the TAGE mission includes the communication between the ballute, TAGE, Cassini 2 and Earth, see figure 8.6. However, in this section the communication between the ESA spacecraft and Earth will not be discussed. In all of the links the S-band is used and the link budgets in the report TAGEs Link Budget are based on the directions from SMAD. To be able to determine the data rate and margin for the communication link, it is essential to calculate the $E_b/N_0$; this is done with equation 8.2 that is derived in SMAD.

$$E_b / N_0 = P + L_t + G_r + L_{pr} + L_s + L_a + G_t - 10\log(k) - 10\log T_s - 10\log R$$  \hspace{1cm} (8.2)

where $P$ is the power with which the antenna is transmitting, $G_r$ respectively $G_t$ is the gain of the transmitting and receiving antennas. The $L_t$, $L_{pr}$, $L_s$ and $L_a$ are the losses; which are the line losses of the antennas, pointing error losses, space loss and atmospheric loss. The space loss is in TAGEs case very large and is the reason why the data rates are limited; see SMAD for derivation of it. The $T_s$ and $R$ are the system temperature and the chosen data rate and $k$ is the Boltzmann’s constant. The phase scanning antenna gain in the link budgets are calculated with a parabolic antenna with an equivalent aperture to the beam angle. The data rate is an important parameter when designing the link, this parameter allows the designer to be able to
change the $E_b/N_0$ be high enough so the margin is acceptable. The margin is determined with equation 8.3 below.

$$M = E_b/N_0 - (E_b/N_0)_{\text{required}} + L_i$$  \hspace{1cm} (8.3)$$

where the required $E_b/N_0$ is determined by the BER and $L_i$ is the implementation loss, which is assumed to be -1 dB. Both $E_b/N_0$ and the margin are calculated in dB. [59], [60]

### 8.5.1 TAGE

The link between TAGE and Cassini 2 consists of two modes, one that transmits with a low data rate and one with a higher rate. The low data rate transmitting mode, used during housekeeping, can be further developed by first using the omni-like beam for locating Cassini 2 and then re-shape the beam so it follows the larger spacecraft when in contact. To locate the ESA spacecraft, TAGE uses a 5W RF signal, that is an approximately 20W DC signal assuming the system has an efficiency of approximately 30%, transmitted with a 45° broad beam. After locating Cassini 2 the beam narrows to 3°. Both housekeeping modes function with BPSK, R-$\frac{1}{2}$ Viterbi coding and require BER of $10^{-5}$. The data rate of the broad beam signal, when assuming that the spacecrafts are furthest apart, e.g. a distance of $10^7$ km, is in the order of 0.30 bps with a margin of -2.81 dB. However, if the spacecrafts are at a minimum distance the margin would increase to 18 dB, thus allowing an increase in the data rate without risking a dangerously small marginal. When transmitting with the narrow low-powered signal, a data rate of 30 bps could be attained with a margin of 0.66 dB for the largest distance. If instead the nearest distance was used, that is $9 \times 10^5$ km; the data rate goes up to 3.5 kbps with a margin of 1.08 dB.

During the transmission of the science data, the transmitting beam is 3° and Cassini 2s large parabola assumed accurately pointed towards TAGE. During this transmission a RF signal of 20W is used, thus requiring 70W DC from the power subsystem. During transmission of science data QPSK modulation will be used with R-$\frac{1}{2}$ convolution coding and Viterbi Soft decoding and a BER of $10^{-7}$. If transmission occurs at minimal distance between the spacecrafts a data rate of 550 kbps with a margin of 6.54 dB could be obtained. If a mean

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**Figure 8.6 shows the overall link design, where mode I and II sends from HASSE and mode III and IV transmits from TAGE to Cassini 2. Mode V is from Cassini 2 to Earth.**
distance of 7·10^6 km is used in the calculation a data rate of 10 kbps with a margin of 6.18 dB is possible. The margin is an important parameter, especially when using new techniques, and therefore the data rates have been adjusted so that a reasonable marginal is attained. TAGEs link budgets marginal for scientifically transmissions, which are approximately 6 dB, can be compared to the telecom satellite INTELSAT that has a margin of 4-5 dB [61].

An important question is if the data rates of the scientific transmissions are high enough for sending sufficient amount of data to Earth. This is a question for the scientist that depends on the measurements. But the largest amount of collected data that could be transferred with the established link can be calculated from the data rate. If TAGE transmits with the mentioned mean distance every second month, the instruments can measure up to 12 Mb a day, if transmission occurs every month they can collect 24 Mb a day. These calculations assumes that every connection with Cassini 2's large antenna last up to 20 hours. The scientific instruments collect between 30.6 Mb and 12.7 Mb a day, depending on how the measurements are estimated. A comparison between the amount of data that can be transferred and the amount that the instruments collect shows that it is not reasonable to only transmit scientific data every second month. It is therefore recommended that TAGE and Cassini should be able to connect with each other every month and thus be able to provide the essential data from measurements.

8.5.2 HASSE

Information from HASSE can be collected from both TAGE and Cassini 2, as mentioned earlier, this solution offers redundancy if TAGE would be in radio shadow when HASSE is active. The link between HASSE and TAGE consist of two broad beam antennas that are located relatively close, in calculation a distance of 700 km is assumed. The link between HASSE and Cassini 2 consist of the ballutes 90° beam and Cassini 2s 4 m diameter large antenna placed 60,000 km apart. This distance is similar to the one between Cassini and Huygens. The links offers data rates of 150 kbps for the HASSE – TAGE link and for HASSE – Cassini2 link 50 kpbs could be obtained. However, a margin of 4.31 dB is similar for the two systems. The link between HASSE and TAGE is assumed to last 1 hour and during that time 0.54 Gb can be transferred, HASSEs contact with Cassini 2 is assumed to be up to 6 hours thus allowing 1.08 Gb to be sent. Due to atmosphere of Titan BPSK modulation with R-½ Viterbi coding and require BER of 10^-5 is used. This does not allow as high data rate than if QPSK was used, but it demands less than QPSK in terms of complicity and does not suffer from as much distortions from the atmosphere as the QPSK does.

8.6 Conclusions

In this chapter, several solutions of the communication subsystem have been discussed. The recommended system was based on an antenna that consisted of several antenna elements that where based on MEMS technology, thus offering a multifunctional, lightweight solution for TAGE. This solution, however, requires some modification of Cassini 2, which where discussed in the chapter; however, these modifications are very small and could be implemented without any risk to the overall mission. ESA has also permitted small changes to the larger spacecraft. The cost of the communication subsystem, for both TAGE and HASSE have been estimated to 1.5 M€, of which 55,000 € is allocated for HASSEs system. See chapter 1 for further information of economical budget. Link budgets were calculated and it could be shown that transmissions every month could provide the necessary data rate to ensure that enough data could be retrieved from the measurements.
Chapter 9

Computers

Mikael Lundberg

9.1 Introduction

9.1.1 General overview

The computer subsystem onboard a spacecraft is different from all other subsystems. To try and define it is to go looking for trouble, because it is not separate; it has integrated parts into virtually every other subsystem, parts that must also be factored into the computer subsystem. To use an analogy: while most computer systems can be thought of as the brain of the larger system of which it is a part, on a spacecraft the computer subsystem must be seen as the nervous system as well as the brain!

In general, the functions of the computer subsystem (hereafter called CSS) on a spacecraft are, somewhat simplified: to collect, process and package telemetry, housekeeping and scientific data and send this to a receiving control station (e.g. Earth), and to receive, accept and act upon command data issued from the control station. To do this, the CSS consists of one or more CPUs, various types of memory for the storage of programs, collected scientific data and so on, and some form of communication method between all the parts in the system. It may also contain additional circuitry for signal processing, coding, cryptology and a wide range of other additional devices.

9.1.2 TAGE mission specific overview

A schematic overview of the CSS onboard TAGE can be seen in fig. 9.1. It will consist of four (4) computers connected in parallel to a distributed bus [62], to which are also connected the front- and/or back-ends to all the other subsystems onboard TAGE. It is within these interfaces that the computer parts, which directly control the subsystems (instruments, thrusters, sensors etc.), are located. Each computer will consist of a CPU, volatile memory for execution/computation and will have access to a pool of non-volatile memory for firmware. For data storage, a flash memory will be used. The distributed bus will be implemented using the wireless Bluetooth 2.0 protocol [63]. Also, a DSP for controlling the antenna will be included. All parts will be explained in detail in the following sections of this chapter.

TAGE will have a high level of autonomy and an advanced artificial intelligence (AI) to be fully self-controlled, with the ability to handle, on its own, any problem that may arise.

The total power consumption for the whole computer subsystem onboard TAGE will be not more than 5 W at maximum processor load. The total mass of all parts of the subsystem will be less than 3 kg. With margin, the cost for the whole CSS will be €30.000.

TAGE will have dedicated access to the main antenna on Cassini2 for 24 hours once every month (see chapter 8), during which the transfer of the collected science data will take place.
9.2 Functions of the Command and Data Handling System

### 9.2.1 Reliability

The CSS is one of the most important subsystems – the so-called ‘mission critical’ subsystems. They are so named because if one of these – for any reason – stops working, it does not matter if the other subsystems are working or not; the mission is a failure. The reliability of such a system is of vital importance in any space mission and TAGE is no exception. The ability to repair a failed system in space is often non-existent, and even in the best case scenario very costly and highly difficult. Thus, a ‘mission critical’ subsystem must never fail.

To ensure the reliability of the CSS, redundancy is most often the primary solution. Redundancy is added in (at the very least) those areas, which are deemed to be critical areas; processors, operating system/firmware for them and memory (non-volatile and more volatile) should be duplicated by a factor of 2-4. This is the minimum requirement in order to ensure the reliability of a working CSS.

On TAGE, the use of a distributed architecture with multiple computers connected in parallel and executing all software on an as-needed basis – with the primary reason being sharing of the computational load – redundancy is built into the solution and comes along at no added cost. This is true of the processors as well as the memories within the computers, and scales linearly with the number of computers connected.

In the final design of the CSS for TAGE a pool solution was chosen for the program/firmware memory in order to handle an issue pertaining to radiation (see section 9.4.3). The solution presented there still provides reliability through redundancy, but it does not scale linearly with the number of computers – in fact, it does not scale at all.

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**Figure 9.1 Schematic overview of the wireless CSS onboard TAGE, using Bluetooth.**

<table>
<thead>
<tr>
<th>Subsystem #1</th>
<th>Subsystem #2</th>
<th>Subsystem #3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component #1</td>
<td>Component #2</td>
<td>Component #3</td>
</tr>
<tr>
<td>Component #4</td>
<td>Component #4</td>
<td>Component #4</td>
</tr>
</tbody>
</table>

- = Bluetooth transceiver
- = Wireless (Bluetooth) bus link
- = Silicon embedded signal path

**Diagram:**

- Computer subsystem
- Patch Antenna
- Matrix Dome
- FlashROM
- SDRAM
- CPU
- EEPROM-pool
- EEPROM

**Legend:**

- DSP (D/A calc. transfer)
- = Bluetooth transceiver
- = Wireless (Bluetooth) bus link
- = Silicon embedded signal path

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76
9.2.2 Complexity

The system complexity for TAGE will be very high. Orbiting Titan in the Saturn system means that the distance between TAGE and Earth is vast; it would take a signal well over an hour to cover that distance. Because of this huge delay TAGE will have to control itself as much as possible rather than being controlled from Earth. TAGE should be able to handle any and all problems and correct any faults/errors that may occur, without the need for any human interaction whatsoever, and the demand for this high level of autonomy introduces the need for a quite advanced artificial intelligence (AI) software onboard TAGE in order to cope with the decision making for any situation that may occur. While this high complexity certainly puts additional demands on the system programmers, and because of that the reliability is further complicated by the human factor and additional testing is required to compensate for it, as of today’s (and future) level of technology this feat is far from impossible to accomplish.

Another aspect increasing complexity is also in a way linked to the distance, and that is communication. Since TAGE will be sending all data not directly to Earth, but via Cassini2, and the contact between them (for scientific data over primary link) is limited to one 24 hour period every month, this leads to the need for storing fairly huge quantities of collected data before being able to send it. This has consequences not only for what type of memory is used for storage, but also how much data each instrument is allowed to gather and how often, leading to complex control of each instrument separately. It also means shutting down most or all of the measurements during the 24 hours while in sending mode.

9.2.3 On-Board Computer Pre-processing

Although TAGE is not sending its data directly to Earth but through Cassini2, the communication distance is still quite large leading to a fairly low data rate on the link (see chapter 8). The scientific instruments onboard (see chapters 2-4) are capable of collecting a lot more data than can be sent directly over the link, and this poses a problem. Since the data rate on the communications link sets an upper limit on the amount of data being possible to transfer and cannot be easily increased, what is left to do is to adjust the amount of data collected somehow.

The most obvious solution is to not having all instruments taking measurements all the time but limit their operation to areas and/or time frames where the scientific data they collect would be the most useful. While this may drastically reduce the amount of data to be sent, it may still not be enough; here comes the need for manipulating the data. The manipulation of the collected data is done by the use of various compression algorithms, which often vastly reduces the size of the data and may or may not be ‘lossless’ – this means whether or not the data can be uncompressed/reconstructed without any loss of information. The degree to which data can be compressed varies with the type of data, and the degree is generally higher for ‘lossy’ compared to ‘lossless’ compression.

An alternative approach to the above would be sort of the inverse; measure often (or all of the time), let the system choose the most interesting parts using data mining, send only those back to Earth and discard the rest. However, this is most likely not a good alternative. Not only because it vastly increases the load on all parts of the CSS, but there is also the fact that scientists might be more interested in all raw data from a certain area rather than just a small part of it. The philosophy here being: better to get all data back to Earth and data mine it there.
9.3 Environmental Concerns

9.3.1 Temperature
Titan, being in the Saturn system and quite far away from the Sun, is a very cold working environment for TAGE. This is a problem in general for most circuitry, and is especially true for computer components, which need room temperature (or thereabout, preferably) in order to perform to optimum efficiency. In an environment that is too cold (or too hot for that matter), the components might not be true to their specifications any longer, and their lifespan might also be severely shortened. This fairly strict temperature requirement puts demands on the thermal subsystem to ensure proper insulation for the components including adaptive mechanisms for dealing with the possibly varying dissipation of heat from components (e.g. processors) depending on their degree of use. Components conforming to MIL-STD-883B are not as stringent when it comes to temperature, and operate efficiently between -55°C and +125°C.

9.3.2 Radiation
The radiation around Titan has been classified as ‘low radiation class’, which means a total ionizing dose below 10 krad(Si). In reality, the radiation is below 5 krad(Si). There is also the matter of the piggyback voyage to Titan. During that 7-year period, Cassini2 is assumed to make the same fly-by’s as Cassini did, which means an additional 40 krad(Si) or thereabout. Normal components can in most cases take up to 70 krad(Si) without any problem, so this means that it is possible to use normal components for TAGE as opposed to being forced to use military class components or even radiation tolerant (RT) components. This is a good thing because it will mean a significant reduction in component cost.

However, the issue here is risk versus cost; whether it can be satisfactorily shown that normal components can survive or not. For this reason, each component will have to be tested in a radiation chamber to make sure they all survive up to about 50 krad (Si). For further information, see chapter 13.

Other side effects from radiation – like single-event upsets (SEUs) – although not breaking components, must still be taken into consideration and dealt with, more on this in section 9.4.

9.4 Hardware to be used

9.4.1 Baseline configuration
This baseline system has been developed under the working theory that normal components could be used without breaking, and that any single event upsets (SEUs) or single event latchups (SEIs) would be handled by using the characteristics of the design below. This means that by careful designing and understanding of what is and is not possible in computer hardware, one might further avoid having to go for RT components. RT components are of course immune to these effects in most cases, in addition to being able to absorb a much higher dose without breaking down, but all this comes at a significantly higher cost.

A schematic of the whole design can be seen in fig. 9.1, with every part of it described in detail below. As mentioned in section 9.1.2 TAGE will have a system consisting of four computers connected in a distributed bus architecture. The four computers will be sharing the load on the bus on an ‘as needed’ basis; each computer either turned on/off depending on load.
Each computer will consist of a CPU and a volatile primary memory, with the non-volatile memory containing all the firmware residing outside the computers and shared by them all.

### 9.4.2 CPUs

The CPU to be used for the four computers onboard TAGE is the LEON3FT. It is a fault-tolerant version of the LEON3 SPARC V8 processor [64]. The LEON3 is a VHDL model of a 32-bit processor which is implemented into a FPGA where it can reach speeds up to 125 MHz, depending on the choice of the FPGA [65].

The reason for the choice of LEON CPUs for this mission is that one of the goals for this satellite project has been to use Swedish technology to the fullest extent possible. The LEON-series is developed by Gaisler Research in Gothenburg and a few years ago they developed the LEON2 under an ESA directive. Their latest creation – LEON3 – however, has been developed without ESA and is completely their own work. Also, LEON is available under GNU GPL, so the only real CPU cost is the price of the FPGAs used.

It should also be mentioned that LEON3FT is available as a system-on-chip (SOC), pre-programmed and tested, where it is implemented in the Actel RTAX2000S FPGA and is tolerant up to at least 300 krad(Si). This added protection does cover all on-chip RAMs as well, but these are so small and are more or less like L1-cache memories for the CPU, so they are not of interest to this mission. So, basically the RTAX only offers protection against breaking for high doses, which are, not present in this mission, and was therefore discarded for this project.

The fact that the CPU speed varies greatly with the choice of FPGA, say between 33-125 MHz, is of little importance to this project. Since the computers share all the workload and can be turned on or off as needed, all speeds in the range work just fine and any FPGA can be chosen.

The CPU itself is per definition immune to SEUs. The way this works is that by using a VHDL model you ‘burn’ the LEON3FT implementation onto the FPGA chip and once completed that’s the way it is. A SEU is a bit change in a component due to incoming radiation but, since the FPGA cannot be altered when it has been burned, the CPU implementation on it is thus immune to SEUs (as well as SELs, for the same reason). The on-chip (L1-cache) memory is still susceptible because it should be possible to write to it, otherwise it would be useless, and its contents can therefore be altered by an SEU.

The CPU’s will also contain a Watchdog-timer to reset the CPU in case it hangs/crashes.

### 9.4.3 Non-volatile program memory

The memory containing all the firmware, operating system and programs, will be of electrically-erasable PROM (EEPROM) type. They are to be EEPROM because of the possibility of uploading software upgrades from Earth to TAGE and reprogram the PROMs.

The sizing of these EEPROMs is very difficult to do at this stage. The software for the advanced AI, decision making and autonomy might be complex and large in both source code and compiled form depending on the programmer(s) and the compiler used. To put a figure on this therefore requires a lot of experience in the field, and is in any case a step for a later phase in the project. This author provides the figure of 4 MB for each EEPROM as a first estimate. It should be noted that increasing (or decreasing) this number at a later stage of development will make no difference on the rest of the system other than a negligible increase (or decrease) in cost (in the order of €50) which is factored into the margin of the budget anyway.
Since the programs in them are to be electrically controlled (apply a voltage for WRITE-access), this opens up the possibility (however remote) of SEU susceptibility. Because of this, the EEPROMs are to be moved outside the computers and put in a ‘pool’ of 3 EEPROMs, accessible by all four computers (see fig. 9.1). The reason for doing this is because now any one of the CPU’s can run a comparison between the code in all the EEPROMs; if one EEPROM has had a SEU in it there will be a discrepancy in that byte of code compared to the other two EEPROMs, and by using a simple arbitration voting scheme (which, naturally, requires at least three identical units) the error is detected by being in minority, and corrected (overwritten) by a copy from the majority. By scheduling this comparison on average say once a week or something, any bit errors can be detected and corrected easily, as opposed to having to use RT EEPROMs which would be immune to SEUs but cost a lot more. This way, one will be trading added cost for a very slight increase in processing load, which seems to be a more than fair deal.

The above reasoning is all based upon the fact that bit errors caused by incoming radiation is, relatively speaking, a very rare occurrence. For this solution to fail, there would have to be the same bit error in two of the EEPROMs to fail the vote, causing the CPUs to repeatedly try and load a faulty program code and crash. Statistically, the probability of getting radiation to cause two bit errors in the exact same place in the program code in two of the EEPROMs, between two scheduled EEPROM checks, is so inconceivably low that it can be taken to be totally impossible within the lifetime of TAGE’s RTG power source (14 years)!

9.4.4 Primary computer memory (processing/working memory)

Each computer will have a primary memory of SDRAM type (MEMS-based, if possible [66]) and about ≥64 MB in size. This size is not really important; it only needs to be large enough not to cause a write-out to secondary memory too often (see why in section 9.4.5), and small enough not to waste money. Money governs this choice; the cheapest size possible that is large enough. Note that smaller does not always mean cheaper, there is a turn-off point where the price increases again the farther down in memory size you go.

All software will be read from EEPROM into SDRAM ‘triple redundant’, i.e. read into identical copies on three separate locations in SDRAM, and executed from there. The primary memories will include EDAC and periodic ‘scrubbing’ of the memory to correct for any bit errors caused by incident radiation. This will happen more often than was the case for EEPROM; say once per day or, possibly, even once per hour.

Collected data is stored in primary memory until it reaches a certain size; it is then compressed, timestamped and packaged including error correcting codes (ECC), and written into secondary memory awaiting transfer. ECC is discussed in chapter 8.

9.4.5 Secondary memory (storage)

The secondary memory is to be non-volatile memory of FlashROM type and 32 Gb (4 GB) in size (see fig. 9.1). This is the ‘hard drive’ of the system, and is where all collected data is stored. All data stored here is stored compressed complete with ECC, ready to be sent over the link to Cassini2. The choice of a 32 Gb module as the size of the flash memory comes from the restrictions imposed by the link budget between TAGE and Cassini2. At minimal distance, using 550 kbps data rate during a 20h transfer window once a month, the data that can be transferred is 39,6 Gb. At mean distance, with 10 kbps and the same transfer window, 720 Mb can be transferred. The instruments onboard however are capable of producing a lot more data than can be sent over the link – even in ideal circumstances – so by choosing a 32 Gb module we have enough space to store data for near max transfer. Another reason is that we have the option of forsaking a transfer window when they are farthest apart (worst case for
link) and store the data for another month (thus transferring 2 months worth the following time), when the link speed is better – assuming it is high enough to allow all data to be sent.

As mentioned above, data is kept in primary memory until it becomes near full and then the entire chunk is written to flash all at once, instead of writing one byte at a time. The reason for doing it this way is because of the power profile of a FlashROM; when it is in standby it consumes no power at all, it only uses power when writing to it and the biggest power drain is when powering up the whole FlashROM. By writing a bigger chunk at once it becomes a more efficient use of power. Doing it a byte at a time is a waste and has no benefits. Also, while not a huge concern during TAGE’s scheduled 1-year mission, a FlashROM only has a limited number of writes to it, albeit that number is nowadays quite large (10^5 or 10^6, at least).

The secondary memory will, just like the primary, be using EDAC and scrubbing, but not nearly as often; with all the error correcting stuff already present on the data there, once every few weeks should be more than sufficient.

SDRAM was considered as a possible alternative to FlashROM for secondary memory as well because of TAGE’s continuous and reliable RTG power source. The decision to go with FlashROM instead of SDRAM here was because of the much higher power consumption of SDRAM (being on all the time, and constantly refreshing its memory cells because it is volatile) and the possible concern of storing mission data in a volatile memory for up to two months before sending it.

9.4.6 Antenna control
Integrated into the communication subsystem is a FPGA-implementation of a dedicated digital signal processor (DSP), whose function it is to do all of the complex and demanding calculations of lobes/phases for the phase matrix dome antenna (see chapter 8). The focused lobe is expected to be continuously sweeping, which puts high processing demands on the DSP. The DSP also has the task of controlling the actual sending and receiving of data through the antenna.

9.5 Internal communication

9.5.1 Possibilities being used today
To communicate internally in a spacecraft – that is between subsystems – there are several different solutions being used today. The oldest of them is certainly Controller Area Network (CAN); a multicast serial bus standard from the 80’s originally created for automotive use and designed to be robust in an electromagnetically noisy environment [67], CAN is still used in a wide variety of areas. Being relatively simple and easy to use, CAN is to this day still widely used in spacecraft systems, despite it being somewhat of age.

Moving along a bit in history we find the next popular choice being used today, namely 10BASE-T Ethernet. Being point-to-point, Ethernet requires switches and/or routers to be used in a bus fashion, and is more suited for other architectures, e.g. star or ring [62].

In recent years, with the development of SpaceWire [68] by ESA, Ethernet has been losing ground in aerospace. Coming strongly, SpaceWire is superior to Ethernet in every way and has also been paving the way in the area of MEMS; this probably due in large part to the fact that the development of MEMS and SpaceWire happened to coincide at the same time.

All of the above solutions are wire-based, meaning that they communicate over some form of physical link (cable). Historically, each of the steps above represent an increase in the data
rate by one order of magnitude – CAN 1 Mbps, Ethernet 10 Mbps, SpaceWire 200 Mbps – which alone makes it interesting to see what the next level will be; CDMA fiberoptics, perhaps?

9.5.2 Moving beyond tradition

The time has come to take the next step in internal spacecraft communication, a step that has already been taken here on Earth many years ago and is on its way to being the dominant form of data communication for most applications – namely wireless communication. Mobile phones and wireless LANs can be seen everywhere on Earth and are steadily phasing out older, more traditional, solutions. So why not learn from the development on Earth and apply it to space as well? Well, the time to do just that has arrived!

As previously stated, TAGE will make use of the Bluetooth 2.0 wireless communication protocol for all communication between subsystems (dotted in fig. 9.1). This, in essence, creates a wireless bus inside the spacecraft.

9.5.3 Why wireless?

The choice to go with wireless communication onboard was not only to move forward to the next level in the development of spacecraft technology, there was also another reason for doing so. By choosing a wireless solution instead of a wired you – as can be inferred from their names – eliminate the wires. Radiowaves cannot be damaged by radiation, burn up, melt, get shaken loose during launch or otherwise lose their connection, like cables can. Eliminating all communication wires also means that mass is reduced, and so is cost. True, a wire does not weigh much, but in most satellites there are a LOT of them so their mass become significant when you take all of them into account. Not only that, but when MEMS technology is used, the very notion of wires becomes a real problem. A MEMS chip may be very small and weigh almost nothing, but in order to use it in the system it must be connected to it by wires and a connector or other interface which may both be larger than the MEMS chip and also (most likely) weigh much more than the chip itself. The point being, that there are physical limitations to how small you can make wires and connectors, whilst if you use wireless transceivers, MEMS technology can be applied to them, and build them directly into the chip.

While the reduction in mass and cost offered by a wireless solution may not be worth the effort for many normal space missions, TAGE is a low-cost mission (€20M) with severely low mass constraints (200 kg) in which these reductions start to really matter.

9.5.4 Why Bluetooth?

Once the decision has been made to go with a wireless solution, the next question is which one to choose? In essence, there are really only two standards to choose from; the 802.11 Wireless LAN, and Bluetooth. They both operate at around the same frequencies and have similar support for error correction of data and packet resending. The difference between them is basically in their range and their data rate; while WLAN has a high data rate (7 - 75 Mbps) and can reach up to kilometer distance, Bluetooth (v 2.0) has a lower data rate (2.1 Mbps) and a much lower operating distance (~10 m). Bluetooth also has a much lower power consumption than WLAN. When it comes to the TAGE mission – or pretty much any satellite mission really – the low operating distance of 10 meters for Bluetooth is often enough. The lower range of Bluetooth is of course strongly connected to its low power output, which is an asset; why use more power than you actually need?

One might think that the 2.1 Mbps actual throughput of the Bluetooth link is too low and might opt to go for WLAN for that reason. But consider then that CAN only has <1 Mbps and
is the most commonly used interface today. The fact is, Bluetooth 2.0 is more than sufficient for most spacecraft applications, and for TAGE as well.

When it has been established that we do not need the larger range or higher throughput of WLAN, there really is no need to choose its higher power consumption for no reason when Bluetooth can do the same job just as well for a fraction of the power; hence Bluetooth 2.0 was chosen over WLAN.

### 9.5.5 How Bluetooth works

Bluetooth is, quite simply, a ‘wireless cable’ solution. One of its primary uses is to be a short-range cable replacement, e.g. eliminating all cables between a PC and peripheral devices such as a printer or mouse. It was developed by Ericsson with the main goal of being a low-cost, low-power, short-range and easy-to-use wireless solution. The protocol is general; it is not locked to a specific network type, like Ethernet, but can be used for pretty much any type of link.

<table>
<thead>
<tr>
<th>Class</th>
<th>Power [mW]</th>
<th>Power [dBm]</th>
<th>Range [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100</td>
<td>20</td>
<td>~100</td>
</tr>
<tr>
<td>2</td>
<td>2.5</td>
<td>4</td>
<td>~10</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0</td>
<td>~1</td>
</tr>
</tbody>
</table>

*Table 9.1 Bluetooth power classes and range*

As can be seen in table 9.1, Bluetooth can be set to operate in any one of three power classes depending on what range is required or desired. Most Bluetooth devices operate in class 2 or sometimes even class 3, while class 1 is mostly represented by wireless LAN applications such as Bluetooth access points or routers.

Communication between Bluetooth devices works thus: When two (or more) devices connect to each other one of them takes on the role of the ‘master’ and the others become ‘slaves’. The master works like any of the slaves, but has the added role of arbitrating data transfers and relaying data. Data is sent only between the master and one slave and not between two slaves directly. Thus, since data can be transferred at any given time to or from any slave, the master has to rapidly switch between them in a round-robin fashion [70]. The master can communicate with up to 7 slaves, and this group of 8 devices is known as a piconet (see fig. 9.4). Two or more piconets can be connected together to form what is known as a scatternet. Connecting piconets together is done by some devices simultaneously playing the role of a master in one piconet and a slave in another piconet, thus acting as a bridge between the two piconets.

It was the purpose of Bluetooth from the very beginning to be low-cost, and to accomplish that it had to operate in the license-free ISM radio band at 2.45 GHz. Also, Bluetooth was developed to be used in an electromagnetically very ‘noisy’ environment – think for example of several piconets close to each other having to operate without disturbing one another – and therefore the protocol had to be very robust. To avoid interfering with each other and ensure that the communication isn’t disrupted by other outside interference, the Bluetooth protocol divides the frequency band into 79 channels – each with a bandwidth of 1 MHz – and then jumps between the channels up to 1600 times per second [71].
9.5.6 Will Bluetooth work in spacecraft?

The interior of a spacecraft is often very complex; the structure is most of the time made up of some metal or other, and all the instruments, housings and whatnot filling up that volume with their different surfaces – both in texture and geometry – makes it a very difficult environment to model from the standpoint of radio wave propagation. In fact, many times it may just be near impossible to predict how the Bluetooth waves will propagate and what the RF environment will look like in the end. The effects of multipath, constructive and destructive interference, reflection, refraction and scattering give rise to a myriad of waves from just one wave being sent out, and the attempt to model several Bluetooth devices talking to each other at the same time quickly becomes mind-boggling. The quickest and easiest way to find out what the wave environment actually looks like is to construct the spacecraft – or a 1:1 scale model of it – mount the Bluetooth transceivers into it and actually measure the wave propagations directly. But what about interference then, will it work?

Actually, the scheme with channel hopping mentioned above not only allows a multitude of devices close to each other to talk to whomever they want without interference from the others, but in fact makes the protocol so stable from outside interference that as long as two devices are within range of each other (according to power class, see table 9.1) and there is a way for the signal to propagate between the two – meaning not stopped by a wall or similar, the signal can bounce off surfaces many times before reaching the destination – you will have a communication between the two. Think of it in terms of ray tracing; if you can shoot a ray from the sender so that it reflects, refracts and scatters off surfaces and one of the resulting rays reaches the receiver, then you will have a stable link! You could easily do a simple test of this with e.g. a 10 m string of yarn, or something. That takes care of Bluetooth devices interfering with each other, but what about them causing interference to other equipment e.g. the scientific instruments? For this there exists a technology called ‘microwave absorbers’ [72]; a sort of thin foam, customized to a specified frequency, that is glued onto a surface where you want the signal to be absorbed. These absorbers eliminate more than 20 dB consistently within a 10% bandwidth of the specified operating frequency. With these, one can protect equipment sensitive in the 2.4 – 2.5 GHz range by putting them directly onto the equipment, or one could even create use the absorbers to create – in essence – a Faraday cage with all Bluetooth devices (and their waves) safely contained inside!

9.6 The additional mission – HASSE

The CSS onboard HASSE will consist of a computer made up of a LEON3 CPU, one SDRAM module and one EEPROM (no pool) as one unit. Here the SDRAM will be larger than on TAGE though, since it will be used not only as a scratch pad for computations, but will serve the double purpose of being the storage medium as well, for data collected by HASSE before it is sent up to TAGE. The SDRAM size is expected to be 2 Gb for the reasons below. The life expectancy of HASSE is about 8 hours. Should it survive longer it would be no problem for the CSS, because the SDRAM will have margin for that and the transfer link to TAGE can transfer 540 Mbit during 1h, which is more than sufficient. Chapter 8 also discusses using transfer between HASSE and Cassini2 which allows more data to be sent over a longer time span (1,08 Gb over 6 hours). This means that a 2 Gb SDRAM module should be able to store all data that can be collected (and sent back) by HASSE even if it survives longer than 8 hours.
10.1 Introduction
Every mission needs some type of attitude control and determination system. However, it can be very different from mission to mission depending on the requirements. The different requirements are often set by the instruments onboard and these requirements can be i.e. accuracy in pointing, ability to slew fast and need to stabilize quickly. Another thing that should be considered is the antenna used for communication, which often has similar requirements as the instruments. Besides all the pointing and slewing requirements we also have requirements for the stabilization. The most common ways of stabilizing a satellite is spinning or 3-axis stabilization.

When the requirements are set we need to pick sensors that satisfies them. On these interplanetary missions the most common sensors are some type of star sensor along with gyros, sun sensors and horizon sensors. The most accurate sensor is the star sensor and is also often used to navigate and determine position.

The sensor will only tell what is wrong with the attitude but don’t correct it. That is why we also need actuators. The actuators can be thrusters, magnetorquers, reaction wheels or momentum wheels. In this chapter we will go through the requirements and choices we have made.

For the last part of the chapter we will have a brief look at the perturbation forces acting on the satellite and how that will affect the orbit and the attitude of the satellite. Since Titan’s environment is not very well known we will make assumptions to get a approximation of the fuel needed to keep the spin, the attitude and the required orbit.

10.2 Control modes and requirements
To get a better overview of the requirements we divide them into different parts or modes. For each mode of the mission we will have different requirements to fill. The first mode will of course be the orbit insertion where we will be released from the mother satellite, go through the atmosphere where we will release the ballute and then enter our orbit. When we get there we will go in to the next mode, acquisition, where TAGE is going to get the correct attitude and start the spin. This brings us to the next mode, which is the normal mode that we are staying in during the main part of the mission. The last mode we will come to is the end of life mode where TAGE will stay during the rest of its life.

10.2.1 Orbit Insertion
To get to Titan as stable as possible it is best to spin. TAGE will get about 5-10 rpm from the separation process so we do not need to use the thrusters to achieve the spin. Since no instruments will be used in this mode it is not important how fast the spin is. When we get there we will have to stop the spin to avoid complications with the release of the ballute. We
also have to make sure the ballute is pointing in the right direction so that it doesn’t take the RTG with it in the release. The manoeuvres are no problem for the sensors and can be made with low accuracy. We might need to adjust the velocity after the aero capture. This can be made with the thrusters used by attitude system.

10.2.2 Acquisition
After releasing the ballute we get to our science orbit. To start the measurements we need to build up a spin so we can release the wire booms. Since we have similar instrumentation as CLUSTER we will have about the same spin rate, which is 15 rpm. This can seem a bit high but we want to spin as fast as possible both because of the stability and the particle detector. Because of the ground penetrating radar we want to have the RTG side of the satellite pointing towards Titan when we are at the lowest altitude. Depending on how we get out from the orbit insertion this will be a slew of maximum 180 degrees for worst case. [73]

10.2.3 Normal
When we get into the right orbit with the right attitude and the desired spin our main objective is to keep it like that. We will have our spin axis pointed towards the ground when we are in apocenter and pericenter, altitude as we can see in figure 10.1, this is because we will use the nadir pointing antenna when we are at the lowest. Since the communication antenna is a patch antenna it will be able to point by itself without any manoeuvre from TAGE there is no need to change the attitude during the mission. Since we will go as low as 950 km in altitude we will have disturbance forces that have to be taken into calculations. These forces will cause TAGE to slew and this slewing will have to be compensated for. No instrument on TAGE requires any pointing accuracy or speed of slewing so the only accuracy we need now is in TAGE’s position.

![Figure 10.1: TAGE’s attitude during the normal mode](image)

10.2.4 End of life
When the mission is over we will not be able to leave TAGE since it then will crash into Titan. We have to put it into a cemetery orbit, which is a high orbit that can guarantee that TAGE will not crash into Titan in considerable future. To do this we need some extra fuel and then use the attitude system to increase the altitude to the desired height. However we will not have to do anything with the spin. The spin we have in the end of the mission will be enough to hold us stable during the end of life manoeuvre.
10.2.5 Manoeuvres

In total there will not be many manoeuvres. This is because of smart solutions by the other subsystems; the telemetry will not need to change the attitude at all because of the patch antenna, which will redirect the beam instead of the whole antenna, and the payload is not dependent of the attitude except for the ground penetrating radar. We will have to spin down from 5 rpm to 0 rpm, then adjust the satellites attitude once in orbit and spin up to 15 rpm. To calculate the fuel needed for these we use equation 10.1 for the change of spin and 10.2 for the attitude correction. [74]

\[ \Delta m = \frac{I_s \omega}{grI_{sp}} \]  
\[ \Delta m = \frac{I_s \theta}{grI_{sp}} \]  

By using the information about the fuel and thrusters given in section 10.4.2 we will need fuel according to table 10.1.

<table>
<thead>
<tr>
<th>Manoeuvre</th>
<th>Mass [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Despin from 5 rpm</td>
<td>0.0092</td>
</tr>
<tr>
<td>Attitude change max. 180 deg.</td>
<td>0.00002</td>
</tr>
<tr>
<td>Spin up to 15 rpm</td>
<td>0.0276</td>
</tr>
<tr>
<td>Margin (20%)</td>
<td>0.007364</td>
</tr>
<tr>
<td>Total mass</td>
<td>0.044184</td>
</tr>
</tbody>
</table>

Table 10.1: Fuel use during manoeuvres

10.3 Satellite control

TAGE will be stabilized using spin. Spinning gives us the opportunity to use wire booms and that will improve the science since we get away further from the spacecraft. I will go through the different alternatives and explain why spin stabilization suits us so well.

10.3.1 Passive control

There are two ways to stabilize a satellite passively. It’s either to use the gravity gradient to make the satellite point towards the center of the central body or having a permanent magnet to align the satellite along the magnetic field. Both these options are bad for our mission. Since Titan is a small body it has too weak gravitation for the gravity gradient to work. The satellite would have to be very long and still it would be unstable. Because of the elliptic orbit we need for the science, this option is even worse. The magnetic stabilization is not to think of since the magnetic field is too weak and sometimes we are even outside Saturn’s magnetosphere. The conclusion we can get from this is that passive control is out of the picture. [75]
10.3.2 Spin control

As for passive control we can divide spin control into two types. There are just simple spin stabilization and there is dual-spin stabilization. With single spin it simply means that the whole satellite is spinning around a stable axis. The spin creates a gyroscopic stability that resists the disturbance forces in two axes as long as it spins around the axis with the greatest moment of inertia. Good things with spin stabilization are that they are often very simple and live longer then more complicated satellites. It also supplies ideal conditions for instruments and sensors that need scanning motion. Since we will be interested in field and particle measurements we can use the spin both to get relative measurements and to get the instrument far away from the satellite with wire booms. Disadvantages with spin stabilization are almost the same as it advantages, it is more stable and hence it takes a larger force to change the attitude. To achieve the stability the satellite has to be symmetrical both when you start and after different manoeuvres so the fuel has to be placed symmetrical around the spin axis. Since we won’t change the attitude at all this is a good alternative. [76]

In the early stage of the mission we had thought about using a dual-spin satellite, which means that it has two sections spinning with different rates. Often one part spins fast to get of the system gets much higher since you need bearings and slip rings between the two sections.

10.3.3 Three-axis control

For three-axis stabilization there are roughly two main groups. It’s either a momentum biasing with a momentum wheel along the pitch axis or a system using zero momentum with a reaction wheel on each axis. Both systems will probably need some type of thrusters along with the wheels for momentum dumping.

For the zero-momentum system there are 3 reaction wheels responding to disturbances. When an error occurs the wheels change their spin to create a force eliminating the error. During time the wheels will start to spin faster and faster and therefore needs to dump some momentum. This is usually done with thrusters or magnetorquers that keeps the attitude meanwhile the reaction wheels are slowing down. These systems can be very accurate and works well when the satellite needs to do many manoeuvres and fast slews. [77]

The momentum bias system only has one wheel instead which spins with a nearly constant rate to give the satellite stiffness round the spin axis just like the spin stabilized ones. Small changes however can be used to change the satellites attitude. During time the wheel need to dump momentum just like the reaction wheels in the zero-momentum case.

10.3.4 Effects on requirements

Since no pointing accuracy and no slewing is needed we don’t need the advantages of three-axis stabilization. The science we want to do is measuring particles and fields in the atmosphere so we need as long booms as possible. A disadvantage of all three-axis stabilized systems is that wire booms can’t be used. Long booms needs to be stiff and in some way attached to the satellite during the flight to Titan. I.e. the Langmuir probes needs to be at least one Debye length from the satellite. This means that the boom has to be at least 15 meters long. As for the dual-spin this can be good for satellites with cameras or with antennas that needs to be pointed in certain directions. In our case with antenna that points itself and no need to point to the ground with any instrument except for the ground penetrating radar, which only will be able to run 10 minutes per revolution, this option will only bring in extra complications with bearings between the sections and slip rings. Since the environment is
very cold we might have extra complications for the bearings and slip rings. With all the requirements in place there are really no good enough option to the simple spin stabilization.

10.4 AC&D system hardware

Now when the requirements are set and the stabilization of the satellite decided we need to decide how to get our spin, how to detect position, how to detect attitude errors and how to correct for these. For this we need a number of sensors and some type of actuators. Since we have a low cost mission with a small mass budget and the restriction of using Swedish technology as much as possible we couldn’t always chose the newest most advanced technique. However there was impossible to find all components in Sweden so we had to look outside the borders but still stick to European companies.

10.4.1 Sensors

When we begun looking for sensors we needed a star sensor to be able to get our position as accurate as possible. Since the star sensors only decide two degrees of freedom we need a sun sensor to decide all degrees of freedom. The spin rate will be decided with a 3-axis gyro and will also work as a backup if the star or sun sensor breaks. The gyro can also cover for the sun sensor while we are in eclipse and then give it approximate position to find the sun again. The last sensor we need is an accelerometer that measures the velocity change in all directions.

This will have two different objectives. The first is that it will measure the ΔV changes that we need for the correction in the orbit insertion and when we will correct the orbit. With some help from the computer we will also be able to calculate all disturbance forces in the orbit, which is the second objective.

For our scientific ballute, HASSE, we will also need to know its altitude to get as much information as possible from the scientific data we collect during our flight in the atmosphere. The altitude will be measured with a pulsed microwave radar and a clock.

10.4.1.1 Star sensor

The star sensor is called Starmapper and is made by the Dutch company TNO. It is a reliable star sensor that has flown several times with i.e. GIOTTO mission, which did fly-by on comet Haley and on the ESA mission CLUSTER. The Starmapper is also electronically redundant which means that there are two sets of electronics using the same optical unit. [78]

<table>
<thead>
<tr>
<th>Sensor: Starmapper</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical unit weight</td>
<td>3.1 kg</td>
</tr>
<tr>
<td>Electrics unit weight</td>
<td>1.0 kg</td>
</tr>
<tr>
<td>Power consumption</td>
<td>1 W</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-20 to +40 C</td>
</tr>
<tr>
<td>Non-operating Temperature</td>
<td>-30 to +50 C</td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.02 degrees</td>
</tr>
</tbody>
</table>

Table 10.2: Starmapper facts
10.4.1.2 Sun sensor

The sun sensor we intend to use is made by Optical Energy Technologies. Since it is so small and cheap we will be able to have two sun sensors on each side of the spacecraft for redundancy. The sensor is due to be tested in space during 2006 and has a very high reliability with only one breakdown on a thousand in a 15 year long mission. [79]

<table>
<thead>
<tr>
<th>Sensor: Sun sensor</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>0.04 kg</td>
</tr>
<tr>
<td>Power consumption</td>
<td>0.05 W</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>-30 to +80 C</td>
</tr>
<tr>
<td>Accuracy</td>
<td>0.5 degrees</td>
</tr>
</tbody>
</table>

*Table 10.3: Sun sensor facts*
10.4.1.3 Microwave radar for HASSE

On the ballute we will attach a small microwave transmitter which will send down a pulse, a clock will measure the time it takes for the pulse to get back to HASSE and then calculate the distance. Since we have chosen to use microwave frequencies the atmospheric disturbances will be minimal. It is important to know the time exact, the clock will have to be calibrated just before the release from TAGE. Estimations on the facts can be seen in table 10.4.

<table>
<thead>
<tr>
<th>Sensor: Microwave Radar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>Power</td>
</tr>
</tbody>
</table>

*Table 10.4: Estimations on the Microwave Radar*

10.4.1.4 Accelerometers and Gyroscopes

There are many different manufacturers of accelerometers and gyroscopes and the new techniques are able to reduce the mass and power consumption considerably. With MEMS, Micro Electronic Mechanical Systems, it is possible to get really small units. We have chosen the company Omni Instruments from UK who have made a combined triaxial gyroscope and accelerometer called AccelRate3D that only weights 5 g and has very low power consumption. The units are available as military units but still have to be tested for space. To get better reliability we can add extra units since they are cheap as well. [80]
10.4.2 Actuator

The actuator type wasn’t hard to decide. Since we want to use the same system for Orbit insertion, attitude control, orbit maintenance and end of life manoeuvres we needed some kind of thrusters. Inside Sweden we could only find two different kinds of thrusters, one micro thruster being developed by Nanospace and a thruster developed by Swedish Space Corporation using a new green fuel. The micro thruster gives far too small force to be able to use for the orbit manoeuvres but the green fuel is perfect for our low cost mission. The side effect of making an environment friendly fuel is that it is also friendly for humans. A big cost with the common hydrazine fuel is the safety cost for transporting and handling with it. The thruster being developed is called 1N-HPGP and stands for a one Newton thruster using the fuel HPGP, High Performance Green Propulsion. [81], [82]

To be able to get a force in any desired direction the thrusters will be mounted in two clusters with four thrusters in every direction. The thruster cluster will form a cross and sit symmetrical on the satellite.

<table>
<thead>
<tr>
<th>Fuel: HPGP</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Impulse</td>
<td>250 s</td>
</tr>
<tr>
<td>Density</td>
<td>1.3 g/cm$^3$</td>
</tr>
</tbody>
</table>

*Table 10.5: Information about HPGP*

<table>
<thead>
<tr>
<th>Actuator: 1N-HPGP</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight / thruster</td>
<td>&lt; 0.4 kg</td>
</tr>
<tr>
<td>Power / thruster</td>
<td>10 W</td>
</tr>
<tr>
<td>Number of thrusters</td>
<td>8</td>
</tr>
</tbody>
</table>

*Table 10.6: Information about 1N-HPGP*

10.5 Disturbance Environment

There are many torques acting on TAGE that will give error in the attitude. They are the same as for a satellite that are orbiting the Earth but since we are in a different environment all are not as important as they are near Earth. When planning an Earth orbiting mission you have to take four major torques into account. There is the gravitational pull from the central body, in our case Titan, and since we have a high orbit and Titan is a small object this torque will be so small that we can easily neglect it. The second torque is the solar radiation pressure that is dependent of the solar constant. At Titan’s distance the solar pressure is about one hundred of the solar pressure at Earth so this torque will also be small. Magnetic field is the third disturbance we need to look at but as already mentioned; Titan does not have any magnetic field on its own. Saturn’s magnetic field is the only field present and it will be very weak at
this distance. After neglecting three of the disturbance torques there is actually one that matters. It is the torque coming from the aerodynamics in Titan’s atmosphere. The torque can be calculated by using equation 10.3. [83]

\[ T_a = \frac{1}{2} \rho C_d A V^2 (c_{pa} - cg) \]  

In equation 10.3 \( \rho \) stands for the atmospheric density and if we use the lowest orbit it will be about \( 10^{-11} \) g/cm\(^3\), \( C_d \) is the drag coefficient which we use the same as for the Cassini mission at its Titan flybys. \( A \) is the surface area and it is 1.1 m\(^2\), \( V \) is the velocity and since it will be between 1.7 and 2.0 km/s we chose 1.9 km/s. \( c_{pa} \) is the centre of aerodynamic pressure and the last thing, \( cg \) is the centre of gravity. For a worst case approximation lets set \( c_{pa}-cg \) to 0.1 m. This gives us a torque, \( T_a \), of \( 4.2*10^{-6} \) Nm. This will be the largest torque acting on TAGE. But even if this is the largest torque acting on TAGE it is still small and will barely have any effect on the attitude at all. The stiffness of the spinning satellite will hold against the weak force trying to turn it. [84]

10.6 Orbit maintenance

The Keplerian orbit is a convenient way of describing the motion of a satellite in space but it is important to remember that it in the general case only is an approximation. Apart from the gravitation of the orbited body a variety of other forces will influence the satellite. An analytical solution to the problem is therefore often impossible and numerical models must be used, though in a pre-study it is sufficient to only take the strongest perturbing forces into account.

Perturbations can be divided into two groups namely, periodic and secular. Periodic perturbations often have a period equal or less then the orbital period. In opposite to secular perturbations they have no effect on the orbit under a long time span. Secular perturbations will cause a lasting variation in the orbital elements. This chapter is mostly interested in the orbit stability and will therefore only take secular perturbation into account. The tree main sources of perturbation in an orbit around Titan will be the atmospheric drag, the gravitation of Saturn and the oblateness of the moon itself.

When studying perturbations from the gravity field of a third body such as Saturn it is common to establish so called spheres of influence. Doing this it turns out that the effects of Saturn’s gravitational pull is of no significance until 10000 km above Titans surface. It can therefore be excluded from these calculations. The atmospheric drag and the effects of the unspherical Titan will on the other hand have substantial effects on the orbit. Theses are presented in figure 10.6.

![Figure 10.6: Orbit perturbations.](image)
One of the scientific purposes of the mission is to make measurements in the so-called wake. It is located in front of Titan in its orbit. Due to the argument of pericenter the initial science orbit makes such measurements almost impossible. To spend maximum time in the wake and at the same time conserve fuel, it was proposed to use the drift of the argument of pericenter, due to the J2 term, which is a measure of how much it differs from a spherical body, to turn the apocenter into the wake and then stay there. The fuel consumption of keeping the apocenter in the wake turned out to be too large and the argument of pericenter was therefore left drifting free. If Titan has the same J2 term as Earth, \( \omega \) will drift 500°. If the J2 term is half and double earths the drift will be 250° and 1000° respectively. In this way the wake will be passed at least two times during the mission. Also the right ascension of the ascending node will be drifting due to the unspherical Titan. With the same J2 terms as above the drift will be 250°, 125° and 500° respectively. [85]

The other source of perturbation that will have a significant effect on the satellite is the atmospheric drag. It will have a circularizing effect on the orbit. To be able to conduct measurements in the wake the apocenter altitude has to exceed a certain value. This means that the drag effect at some point has to be countered. This altitude was set to 2000 km above the surface. It was reached after 254 days, which corresponds to 885 revolutions. A total \( \Delta V \) of 140 m/s was then budgeted for conserving the apocenter for another 111 days and 563 revolutions. It should also be mentioned that it probably will be possible to keep the science orbit a little longer then calculated using the fuel margin.

### 10.7 Economics

It has been hard to get exact numbers on the price of the different sensors and the thrusters. Therefore the numbers given in table 10.7 is estimates based on earlier projects. For the untested sensors the approximations have taken testing and development into account. The whole attitude system will cost about €1M.

<table>
<thead>
<tr>
<th></th>
<th>Cost [€ 1000000]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thrusters incl. tank and fuel</td>
<td>0.7</td>
</tr>
<tr>
<td>Starmapper</td>
<td>0.25</td>
</tr>
<tr>
<td>Sun sensor</td>
<td>0.05</td>
</tr>
<tr>
<td>AccelRate3D</td>
<td>0.05</td>
</tr>
<tr>
<td>Microwave Radar</td>
<td>0.05</td>
</tr>
<tr>
<td>Total cost</td>
<td>1.05</td>
</tr>
</tbody>
</table>

*Table 10.7: Cost estimation*
11.1 Introduction

The components of a satellite are often sensitive to temperature and each component has temperature ranges, which need to be held to keep the components alive and operational. During the mission TAGE will be exposed to different thermal environments, which will have to be considered when designing the thermal sub-system. There are different ways of controlling the temperature on board a satellite and in this chapter the design of the thermal control sub-system will be presented. The goal in the design is not only to keep the desired temperatures but also to do this without limiting other systems. This have resulted in a few challenging problems of which the heat shield has been the biggest. Reliability is of course very important for the thermal system but keeping mass, cost and power consumption low has also been priorities.

11.2 Thermal sub-systems overview

The total thermal sub-system can be divided into three parts namely TAGE, the heat shield and HASSE. The chosen design will shortly be presented here. More about the components used, theory and calculations will be presented later.

11.2.1 TAGE

Inside TAGE the temperature will be around 15°C. To keep the heat inside the satellite it will have to be insulated. This will be done with 25-layered MLI. In order to keep heat radiation low it will be plated with gold to achieve a low emissivity. This will result in an outside temperature between about -100°C and -30°C. MLI will also be used to insulate fuel tanks, fuel pipes, wiring and instruments on the outside such as the magnetometer.

When the inside temperature drops electrical heaters controlled by thermostats will be used to rise the temperature. Both the internal power dumpers and specific heaters can be used for this. The temperature must not drop bellow 0°C, which is the minimum allowed temperature for the propellant.

When the inside temperature rises, heat will have to be radiated out in space. This will be done by a radiator, which basically is a part of the structure, which is not covered by MLI. Instead it will be covered by a high emissivity coating such as silvered Teflon. A radiator area of 0.13 m² is needed on TAGE.

Because most of the heat coming from outside is from the SRG at the bottom of the satellite heat pipes will be used to spread this heat around in the satellite to make good use of the heat and so the temperature gradient in the structure is not to large. Heat pipes may also have to be used to conduct heat away from components, which produces a lot of heat for a
long time such as the computer and antenna systems. The antenna will also be kept cool by treating in it a suitable surface finish, probably Aluminum.

11.2.2 Heat shield

The aerocapture with a ballute is designed so that the need of extra thermal protection is low. The maximum heating is 3W/cm², which is much lower than during a normal atmospheric braking. However TAGE will have to have some sort of shield. The shield design is based on a lightweight Earth reentry shield concept. It is made of a carbon structure covered by an insulating material and a heat resistant blanket. The shield diameter is a bit larger than the satellite diameter to create a shock region around TAGE to reduce free molecular heating on the satellite body. After aerocapture the shield will be jettisoned.

The heat shield is at this point only a concept and will have to be examined further.

11.2.3 HASSE

The ballute itself is covered in kapton and will reach a temperature of about 500°C during the braking. The atmosphere of Titan is very cold, between about -170°C and -100°C and keeping the heat inside to prevent the batteries from freezing is a major problem. MLI is not a good insulator during atmospheric conditions and instead several layers of Aerogel will be used as insulator. However, HASSE will still be cooled quickly and smart placing of components is necessary. A 1W heater is also used to provide some heat. Our goal is that HASSE will be alive and working for at least more than eight hours.

11.3 Theory

When designing the thermal sub-system the first thing that will have to be considered is which temperatures will have to be kept. The second thing to consider is the thermal environment TAGE will find itself in. With these in mind different alternatives of design can be compared in order to find the best way of keeping the temperature limits.

11.3.1 Requirements

Each component of TAGE will have temperature limits to survive and to operate. The temperature requirements are presented in table 11.1. The survival temperature is the range wherein the component can survive during the non-operating mode and later be turned on. The operational temperature is the range, which has to be kept when the component is operating. Before switching a component on, it is preferred to pre-heat it so that it has operational temperature when being switched on. [86], [87] [88], [89], [90]
Table 11.1. Temperature requirements for TAGE.

<table>
<thead>
<tr>
<th>Component</th>
<th>Operational temperature range [°C]</th>
<th>Survival temperature range [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>-</td>
<td>-200 to 200</td>
</tr>
<tr>
<td>Antennas</td>
<td>-100 to 100</td>
<td>-120 to 120</td>
</tr>
<tr>
<td>Propellant</td>
<td>0 to 50</td>
<td>0 to 50</td>
</tr>
<tr>
<td>Computer box</td>
<td>-20 to 60</td>
<td>-40 to 65</td>
</tr>
<tr>
<td>Power box</td>
<td>-10 to 50</td>
<td>-20 to 60</td>
</tr>
<tr>
<td>Star tracker</td>
<td>-20 to 40</td>
<td>-30 to 50</td>
</tr>
<tr>
<td>Sun sensor</td>
<td>-30 to 80</td>
<td>-40 to 90</td>
</tr>
<tr>
<td>Probes</td>
<td>-200 to 200</td>
<td>-200 to 200</td>
</tr>
<tr>
<td>Magnetometer</td>
<td>-40 to 40</td>
<td>-50 to 50</td>
</tr>
<tr>
<td>ASPERA</td>
<td>-40 to 40</td>
<td>-50 to 50</td>
</tr>
</tbody>
</table>

As seen, the temperature inside TAGE will have to be between 0°C and 40°C when the attitude control is operating. The computer and parts of instruments inside the spacecraft work best at rooms’ temperature. In the design we will try to keep the temperature inside at 15°C. It’s also important that temperature gradient in the structure are not greater than a few tens of degrees. Although the MLI can survive in colder and hotter temperatures we will try to keep it between -100°C and 100°C. This makes it easier to keep instruments and sensors at desired temperatures.

11.3.2 Thermal environment

Heat can transfer in three different ways; radiation, conduction and convection. When designing TAGE, radiation and conduction will be the ones considered. Inside the spacecraft heat will mainly be transferred through the components and structure by conduction but we will also have some radiation between inner surfaces. Outside of TAGE, heat will transfer mostly by radiation. The heat sources are direct sunlight, albedo, IR-radiation from thermal bodies and heat dissipated from TAGE. During the aerocapture we will also have friction heating from the outside.

Figure 11.1 Internal heat transfer through conduction and radiation.

Figure 11.2 External heating through sunlight, albedo and IR-heating and IR- heat loss through radiation.
The mission will be divided into three different thermal environments:

- **Travel phase to Titan.** During a period of the travel phase TAGE will be as close to the sun as Venus before going out to Titan. However the big antenna dish on Cassini 2 will most certainly be used as a sun shield and our spacecraft will not be in direct sunlight. We will also need to consider albedo and IR flux from Venus during the flyby. During the travel phase power consumption will be low which means that we may have to use heaters if the spacecraft interior gets to cold.

- **Aerocapture phase.** When we use Titans atmosphere as braking assistance we will have frictional heating as high as 3 W/cm². This means that we will have to use a form of heat shield. [91]

- **Orbit phase.** Here, the power consumption will be higher and therefore the power dissipation inside the spacecraft will be higher. This will be handled by our radiators and the thermal systems inside TAGE.

This will give the cases when we will have the hottest and coldest cases respectively which will be crucial in the design. When calculating the hottest and coldest temperatures we have to consider when external and internal heating as at its lowest and highest, and which materials and control systems are being used. Degradation of MLI and radiating surfaces will also have to be taken into account.

### 11.3.3 Thermal control methods

Thermal control is often divided into two different categories; passive and active thermal control. Passive control uses material properties, coverings and surface finishes when regulating temperature. Active control on the other hand uses active devices, which are often controlled by electricity or mechanical switches to regulate the temperature. Passive control is often cheaper, simpler and lighter than active and is therefore preferred. However active devices are often needed when passive control is not enough to guarantee that temperature limits are being held. Below, possible passive and active devices are presented and discussed.

#### 11.3.3.1 Passive Thermal Control Hardware

In order to keep the heat inside TAGE must be insulated. In space this is done with *Multi Layer Insulation* (MLI). MLI is made by putting together several layers of thin kapton or Mylar film with spacing in-between. The layers are made to have low emittance (typically with gold or alumina coating) to reduce radiation and since they have little contact the heat conduction is very low. How well the MLI is insulating depends on material, mounting and how many layers are being used. Typically 20-30 layers are used. The performance of the MLI can be seen as its effective emittance, $\varepsilon^*$. A reasonable value of $\varepsilon^*$ for a mounted MLI in space is 0.01 to 0.03. The heat passing through the MLI per unit area is calculated using the equation

$$ q = \sigma \varepsilon^* (T_h^4 - T_c^4) $$  \hspace{1cm} (11.1)

where $\sigma$ is the Stefan-Boltzman constant ($5.67 \times 10^{-8}$ W/m²K⁴) and $T_h$ and $T_c$ are the temperatures on the hot and cold side respectively. [92]
Figure 11.3 MLI mounted on the Huygens probe.

Another way of insulating is to use Aerogel. Aerogel is a silica material, which mostly consists of small air bubbles. This means that it is a good thermal insulator with a thermal conductivity of 3 mW/mK. It is also very light weight, as low as 3 milligrams per cubic centimetre. It has not yet been used as insulator on satellites but it was used as insulator on the Mars Pathfinder rover. Because of these properties and the fact that MLI performance during atmospheric conditions is not as good as in vacuum Aerogel is a good choice for insulation on HASSE. [93], [94]

To dispose of waste heat, radiators will be used. To save weight it’s best to use the existing structure and paint it with a suitable colour or surface finish to achieve desired emissivity, \( \varepsilon \). The heat leaving a radiator of area \( A \) is given by the equation

\[
Q = \varepsilon \sigma AT^4
\]  

(11.2)

where \( T \) is the radiators temperature. [95]

**11.3.3.2 Active Thermal Control Hardware**

The simplest active device is the heat pipe. In fact it is often seen as a semi-passive device since it does not consume any power and it does not need any control. The principle behind the heat pipe is that a fluid vaporizes when heated in one end (the evaporator). When vaporized the pressure increases in the hot end and the vapour moves towards the cooler end (the condenser) where it is cooled and condensed. The capillary effect then makes the liquid go back to the evaporator where it once again is vaporized. Depending on which temperature interval it will be used in different fluids are used.

Figure 11.4 A good example of Aerogel performance is protecting matches from a hot source.
To prevent components from getting too cold, heaters are used. They are needed when a component's temperature drops below its minimum value or to preheat components before turning them on so they will not break. A heater is an electrical resistance, which generates heat when a current flows through it. We will use heaters on the fuel tank, thrusters, some instruments, and sensors. Apart from the normal heaters, we will also have power dumpers on the satellite. Power dumpers are needed to dispose of the power not consumed by the satellites since the SRG produces a nearly constant power all the time. A power dumper is essentially, just like a heater, a resistance and can be placed both outside and inside the satellite. By selecting different sizes and placing them at different places, they are a good extra source of heat and by being able to dump almost all the produced power inside the satellite, we will be given a redundancy system if, for example, heat losses would be larger than calculated due to damage in the MLI. [96]

To control heaters, thermostats are used. They can be either mechanical or electrically controlled. Mechanical thermostats are simpler and cheaper but not as responsive and exact as electrical devices. Therefore, electrical thermostats are needed when very sensitive equipment is being used and the temperature must be almost constant.

To vary how much heat a radiator radiates, a louver may be used. The idea behind a louver is to change the effective emissivity of a radiator by being able to open and close a blind which is mounted on the radiator. The simplest design requires no power to operate and looks just like the Venetian blinds we use in windows to shield sunlight. Louvers are often used when power dissipation inside a satellite varies over a large interval. [97]
11.4 Designing the thermal sub-system

When the required temperatures, environment and possible alternatives are known the design of the thermal sub-system can be done. It is, as said earlier, important to know when the satellite will be at its coldest and hottest, the so called hot- and cold cases.

11.4.1 Orbit around Titan

Because of the cold conditions at Titan TAGE will be insulated with gold plated MLI which has a low emmissivity. 25 layered, gold plated MLI has an emmissivity, $\varepsilon = 0.03$, and absorbance, $\alpha = 0.25$. The emmissivity and absorbance will change with time, which also will have to be considered. The effective emittance can be approximated with $\varepsilon^* = 0.01$ to 0.03 depending on hot and cold cases. Given the environmental heating sources we can now calculate the satellites hot and cold case temperatures. This will show if materials used are suitable and provide information when calculating the size of radiators and power of heaters needed. [98]

The cold case is when we are in orbit around Titan but far away and in eclipse. The hot case is when the satellite is near Titan with maximum power consumption inside. Also note that I have not taken internally dissipated maximum as 100 W as it would be when all the internal power dumpers are on. This will as said provide some redundancy if, for example, the MLI will be damaged and not provide the insulation intended. The hot and cold cases are presented in table 11.2. Note that these are the hot and cold cases during the entire mission and not only in orbit except the short flybys.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hot case</th>
<th>Cold case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar constant, $P_s$</td>
<td>15 W/m²</td>
<td>0 W/m²</td>
</tr>
<tr>
<td>Albedo, $P_a$</td>
<td>3.3 W/m²</td>
<td>0 W/m²</td>
</tr>
<tr>
<td>IR from Titan, $P_{IR}$</td>
<td>1.6 W/m²</td>
<td>0.3 W/m²</td>
</tr>
<tr>
<td>IR from SRG, $P_{SRG}$</td>
<td>188 W/m²</td>
<td>183 W/m²</td>
</tr>
<tr>
<td>Internally dissipated</td>
<td>55 W</td>
<td>15 W</td>
</tr>
<tr>
<td>Absobance</td>
<td>0.25</td>
<td>0.20</td>
</tr>
<tr>
<td>Emittance</td>
<td>0.03</td>
<td>0.10</td>
</tr>
<tr>
<td>Effective emittance</td>
<td>0.03</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Table 11.2 Hot and cold cases fot TAGE.

I have here assumed that the attitude control and computer is on during the cold case. Using the equations

$$T_{\text{hot,cold}} = \left( \frac{P_s A_s \alpha + P_a A_a f (A_s + A_t + A_b) + P_{SRG} A_s \varepsilon + P_{IR} A_b f (A_s + A_t + A_b) + Q_w}{\varepsilon \alpha A_{\text{tot}}} \right)^{1/4} \quad (11.3)$$

where $A_s$ is the projected area as seen from the side, $A_b$ the bottom area, $A_t$ the top area and $A_{\text{tot}}$ the total area. $f$ is the so called view factor which is a geometrical factor and describes how much the surface of Titan and the satellite sees of each other. In the calculations it is assumed to be 0.5.

In the equation for $T_{\text{hot}}$ the values from the hot case are used and in the $T_{\text{cold}}$ equation the cold case values are used. We obtain the values $T_{\text{hot}} = -86^\circ\text{C}$ and $T_{\text{cold}} = -113^\circ\text{C}$. We have to
use equation 11.2 to find how much heat \( Q_w \) is going through the MLI, which is dependent of the temperature outside. This means that’s an iterative process, which will give the temperatures. We will probably have temperatures around \( T_{\text{hot}} = -30^\circ \text{C} \) and \( T_{\text{cold}} = -100^\circ \text{C} \) with margins. It’s also good no notice that even if we had a perfect insulation we would have -113°C on the outside which would not be dangerous. The maximum time in eclipse is about 4 hours.

Now we can calculate the size of the radiators. In the hot case we will have to radiate all the dissipated heat (except what passes through the MLI) which is about \( Q_{\text{rad}} = 50 \text{ W} \). We will also assume that the temperature inside, and also the radiator temperature, is higher than 15°C but not higher than allowed. We assume it to be \( T_{\text{rad, hot}} = 35^\circ \text{C} \). Using equation 11.2 and an emissivity of 0.78 (silvered Teflon). We get a radiator area \( A_r = 0.13 \text{m}^2 \). What temperature will this give in the cold case? Again, using equation 11.2 we will have a cold case temperature of \( T_{\text{rad, cold}} = -46^\circ \text{C} \). We see that the cold case temperature is much colder than we can handle, we need the temperature to be at least 0°C. With a 20 W heater we will reach 6°C. In this case we can use powers dumper as a heater since we do not consume much power otherwise. With this design louvers are not needed which is good because they may fail. [99]

The fluid in the heat pipes will be acetone, which is recommended in the interval between 0°C and 120°C and vaporizes at 57°C. [100]

The interior of TAGE will be painted black so that heat radiation is maximized between the components.

The antenna will be heated by the Sun, Titan, the satellite and the power dissipated in the antenna. When it is not used it will be about the same temperature as the satellite but when it radiates maximum energy it can reach 70°C if it is covered with Aluminium. To keep the antenna cool, around -70°C, which is good when transmitting, heat pipes could be used to conduct heat to radiators sitting around the antenna.

The magnetometer, which is placed on a boom, will have to be insulated with MLI and to make sure it will keep its temperature it will also have a heater. The instruments sitting on the satellite body will also be insulated with MLI and the ASPERA instrument may also need a heater.

11.4.2 Travel phase

During the seven year travel phase TAGE will mostly be in cold space and go further and further away from the sun. However, to pick up speed there will be flybys and TAGE will be as close to the sun as Venus where the solar radiation is high, about 2615 W/m² but the satellite will be shielded by the antenna on Cassini 2. Albedo and IR-radiation from Venus could also be major heating influences. However by having the Cassini 2 body as a shield, also these can minimized. Off course we will also have heat from the SRG. Using equation 11.3 and assuming 0.20 m² is exposed to the sun and the SRG heat power hitting the satellite is 200 W the surface of TAGE would have an equivalent temperature of 115°C. When adding heat from Cassini 2 which could get a bit hotter and some heat from Venus the temperature would be a bit higher but during the rather short flyby the risk that the inside temperature reaches above 50°C is not big. During the rest of the traveling the satellite may get cold but this will be taken care of by power dumpers and heaters. This means that the most important thing to consider during the travel phase is the mounting of TAGE on Cassini 2. [101]
11.4.3 Aerocapture

Going into the atmosphere TAGE will experience free molecular heating. At its peak the heating will be almost 3 W/cm². The ballute is covered in a Kapton blanket and will reach a temperature of 500°C as most. To protect the satellite it will have a heat shield. However the heat flux experienced is not at all as big as during a normal atmospheric braking which means that a simpler type of shield can be used. The construction chosen is a cone with bottom diameter of 1.5 meter and a nose angle of 140°. The reason it’s bigger than the satellite body is so that the satellite body will be inside a shock region and hot gas won’t flow directly on the satellite. The shield is based on a light weight composite Earth re-entry shield where the structure is made of a carbon material covered with an insulating material and a heat resistant ceramic blanket. After the capture phase the shield is jettisoned using three separation bolts. [102], [103]

11.4.4 HASSE

After the ballute is released it will continue to brake in the atmosphere. The payload ring is, as the ballute itself, covered in Kapton to resist the heating during the braking after release. Inside the Kapton layer HASSE will be insulated with a layer of Aerogel. The battery is the most sensitive component, so we will insulate it with an extra layer of Aerogel. Depending on what altitude HASSE will fly it will be in different temperatures. At its lowest HASSE will find itself in about -173 °C (at about 600 km). Today, Aerogel with thermal conductivity of 3 mW/mK is possible. To keep the batteries in operational temperature we need them to be at least 0 °C. Using the equation

\[ Q = \frac{\lambda A \Delta T}{d} \]  

(11.5)

where Q is the heat flux in W through a material with area A, thickness d and thermal conductivity \( \lambda \) (W/mK) and \( \Delta T \) is the difference in temperature between the inner and outer surfaces. In the cold case we would loose 61 W through one layer 2 cm thick Aerogel. Since the internal dissipation is about 15 W HASSE would quickly cool down. Using double layers and a heater will keep us alive a bit longer but flying in these cold regions is not recommended. Down on 200 to 400 km the atmosphere is warmer, about -100 °C, but HASSE would still loose 35 W through one layer. Because of the limited power of the battery we can just afford a 1 W heater which is not enough. Instead several layers of Aerogel and smart placing of components are needed. The design will have to be decided through simulations and testing. Another possibility which can be examined further is to use radioactive sources as heaters which was done on the Huygens probe. The problem is that they might be too heavy and, just as using a RTG, political questions would arise. Radioactive heaters would probably be needed to be bought from Nasa. [104]
11.5 Mass, power and cost estimates

In table 11.3 estimates of mass, power and cost are presented. Note that the power dumpers are not taken into account in the power budget.

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass [kg]</th>
<th>Power [W]</th>
<th>Cost [k€]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLI</td>
<td>3.75</td>
<td>-</td>
<td>150</td>
</tr>
<tr>
<td>Heat pipes</td>
<td>0.3</td>
<td>-</td>
<td>5</td>
</tr>
<tr>
<td>Heaters, thermostats, surface treatments and system</td>
<td>&lt; 2</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>Heat shield</td>
<td>7</td>
<td>-</td>
<td>300</td>
</tr>
<tr>
<td>HASSE</td>
<td>0.5</td>
<td>1</td>
<td>125</td>
</tr>
</tbody>
</table>

*Table 11.3 Estimates of mass, power and cost of the thermal subsystem.*

A possible supplier of MLI and building of heat shield is Austrian Aerospace owned by SAAB Ericsson Space. Heaters and other electrical equipment for European spacecrafts are mainly supplied by the Italian company RICA. There is a Swedish company called Airglass AB who is working with Aerogel and may be involved in the production of our insulating material. [105], [106]
12.1 Introduction
When a space mission has fulfilled its purpose, there must be a disposal plan for the spacecraft. Depending on mission objective there are some rules and policies to follow. There is a policy called planetary protection, created in the beginning when man started with space travel, which should prevent spacecraft from spreading particles and microbes across our solar system. Every time a spacecraft is sent up in space, precautions have to be made to make sure that some places won’t be contaminated. Depending on destination and type of mission, different precautions have to be made.

12.2 Conclusion
Through this chapter the disposal plan for TAGE, the Swedish low cost mission to Titan, will be described. First a discussion will be held in how to apply planetary protection on TAGE, along with some background on the subject. Four different end of mission scenarios will be discussed and their advantages and disadvantages.

The conclusion for TAGEs end of mission is; TAGE will be placed in a circular orbit around Titan, outside the atmosphere. When no atmospheric drag exists TAGE will be stable in the disposal orbit for over 100 years or more. In the future, with advancing technology maybe there will be other solutions to TAGE, but at this point the disposal orbit is the only reasonable end. A disposal orbit will save large amount of fuel and will make the mission feasible, since the saved mass can be used on instruments onboard.

The end for HASSE, the balloon that TAGE will use for aero capture, will be as simple as a crash. HASSE will glide through the atmosphere towards the surface and finally crash on the cold surface.

According to current rules for planetary protection no decontamination will be required, only documentation. These rules concerns both TAGE and HASSE. No special precaution for the SRG onboard is required. The TAGE mission will not be a problem for further missions to Titan even if something unpredictable happens, like TAGE crashing into Titan.

12.3 Planetary Protection

12.3.1 What is planetary protection?
Planetary protection is a term used for different kinds of space missions concerning bodies in our solar system with a possibility to contain any form of life or some information that can help us figure out how life appeared on Earth.
According to UN Space Treaty established in 1967 every country “shall pursue studies of outer space, including the moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination” [107]. COSPAR, Committee on Space Research established by the International Council for Science in 1958, is now the committee that maintains and makes sure that all space nations follow the Space Treaty to avoid contamination. Depending on mission objectives the spacecraft and its components must be cleaned and sometimes sterilized, also heavy documentation is required. All this is to prevent contamination with Earth microbes on solar system bodies that are subjected to contain possible life forms. The treaty was also issued to prevent Earth from being contaminated with extraterrestrial life that could exist on returning spacecrafts. Protection requirements for a specific mission are determined by policy guidelines, and every mission is categorized by its encounter (flyby, orbiter or lander) and its final destination. Missions designed for looking after chemical compounds usually have a lower protection category, because future missions will not be jeopardized by a possible contamination, than missions that are looking for bodies with a potential to support life. Every mission has to be carefully designed and planed to make sure it complies with the protection policy.

12.3.2 Bodies included

One of the primary objectives with space missions is to explore our universe and search for life. While doing this we do not want to spread microbes to unknown planets and we do not want any extraterrestrial life to return to earth uncontrolled. Different bodies in our solar system have different kinds of protection category. The first category does not require any protection control at all. Bodies included under first category are Mercury, our moon and the Sun. These three bodies go under the classification: “not of direct interest for understanding the process of chemical evolution” [108].

Other bodies that are considered to be good sites to investigate are some moons of Jupiter and Saturn, but the actual planets themselves are not suited to contain any life. This also complies with the outer planets like Uranus, Neptune and Pluto and their moons.

Considered good means that scientists hope to find chemical compounds that can explain the process of evolution, also called Category 2 missions. This mean the chances to jeopardize future missions are so small, the mission only needs documentation while sterilization is not required [109]. The only body in the outer solar system that is considered to be extra interesting for scientists around the world is Europa, one of Jupiter’s moons, along with Mars. Indications now show that Europa could have liquid water underneath its ice crust and this could imply some kind of organic life. According to COSPAR policy every mission to possible life containing body must be able to guarantee that no microbes of our own will contaminate and destroy our research. At this point Mars and Europa are classed as Category 3 missions, heavy documentation is required but also the whole spacecraft must be assembled and tested inside approved clean rooms.

Impact is not intended for Category 3 missions, for landing vehicles and probes we require the classification Category 4 mission instead [109]. Category 4 missions also just include Mars and Europa, and maybe in the future some other planets. Here the precautions have to be extended even more, all according to planetary protection policy. As an example there is the Viking mission launched in 1976 with two orbiters placed around Mars and two landers placed on the surface; the project was classed as a Category 4 mission and the whole spacecraft had to go through even more documentation than you need in Category 3 missions and besides the clean-rooms, the whole spacecraft needed to be sterilized. All this to make sure those future missions to Mars wouldn’t be put at risk. The price tag for the Viking mission ended up on almost one billion dollars and one-fourth was spent on the sterilization [110].
12.3.3 How to achieve?
Several methods are used to reduce spacecraft contamination, all according to specified demands depending on destination. All parts of spacecrafts are carefully assembled and often done in clean rooms to make sure that the contamination is minimized. Another step, if the mission is classified with a high protection category, is that every part of the spacecraft is sterilized. Techniques, as dry heat reduction of microbes, used on the old Viking spacecraft are still used today.

12.3.3.1 Clean Rooms
Regular rooms contain around thirty thousand particles per cubic decimetre. While assembling spacecrafts in clean rooms the air inside must meet the required specification of less than four particles per cubic decimetre. To achieve, the clean rooms use a special airflow, like a light breeze, that start from one end of the room and flows parallel through the room and exits through fine filters. All personal working inside must meet special requirements and always wear protective suits. Microbial barriers may also be used to prevent the spacecraft to be recontaminated after the cleaning process. There are two different kinds, one is using high pressure and the other one is operating at normal pressure but uses fine filters that filter out around 99.97% of all particles/organisms.

12.3.3.2 Sterilization
The sterilization method used on the Viking mission is still used today and is the only approved method by NASA. The sterilization process is done by reducing particles and organisms through dry heating. All spacecraft parts are put in oven at 111.7 degrees for thirty hours.

Some parts can be sensitive and be damaged in high temperatures; therefore new methods are under investigation. So far the only method that would be effective enough to replace dry heating is hydrogen peroxide sterilization.

12.3.4 Earlier Saturn missions
In 1997 Cassini-Huygens was launched into the space with a mission to explore Saturn and its environment. So far the largest mission ever made in planetary exploration and was a joint NASA/ESA/ASI mission. Onboard the Cassini spacecraft was the Huygens probe, which mission was to explore Saturn’s largest and also the most interesting moon Titan. Huygens was a landing probe sent down to explore the surface of Titan, and on the way down also investigating the atmosphere. According to current COSPAR policy about bodies similar to Titan, no direct protection against contamination of an unknown planet was taken. Even though Huygens was sent down to the surface no sterilization was required. The only planetary protection cost in Cassini-Huygens mission was spent on the documentation, which had to contain detailed information of every single part onboard the mission [112]. According to applicable rules today and that the Huygens probe never required anything else than documentation the TAGE mission could be launched without any special precautions.
12.4 Ending of TAGE mission

12.4.1 Disposal orbit

After a year in orbit TAGE will have fulfilled its mission and should then have a disposal plan. To place TAGE in a disposal orbit after completed mission is simple and fuel-efficient. No extra attitude control is needed after the launch so for this purpose all the fuel left in the tanks can be used to put TAGE in an outer orbit. This scenario will be a good solution to TAGE mission since the project is a low cost mission and the mass budget is very tight. Calculations are made and the final orbit around Titan before initiating “End of mission” is elliptic orbit with pericentre at 950 km and apocentre at 2000 km above Titans surface. The easiest and most fuel efficient solution is to launch TAGE into a circular orbit at 2000 km when TAGE is in the apocentre of the elliptic orbit.

When placing TAGE in the circular orbit and it is done in apocentre, we only need one \( \Delta V \) change. If a higher altitude is preferred a second \( \Delta V \) change is required, but there’s no point in placing TAGE in a higher orbit and due to this, fuel will be saved. A simple calculation will show that only 5 kg of fuel is required for this final manoeuvre, see equations 12.1-12.5 (solved with Hohmann transfer equations [111]).

\[ a_{tr} = \frac{R_{First} + 2R_{Titan} + R_{Circular}}{2} = 4050\text{km} \] (12.1)

\[ R_{First} = 950\text{km} \]
\[ R_{Titan} = 2575\text{km} \]
\[ R_{Circular} = 2000\text{km} \]

\[ V_{fb} : \text{the velocity needed to stay in circular orbit at } 2000\text{km above the surface} \]
\[ V_{fb} = \sqrt{\frac{\mu}{r_B}} = 1,403\text{ km/s} \] (12.2)

\( \mu = GM \)
\( G = \text{gravitational constant} = 6,67259 \times 10^{-11}\text{ m}^3/\text{(kgs}^2) \)
\( M = \text{Mass of Titan} = 1,35 \times 10^{23}\text{ kg} \)
\( r_B = \text{Distance from Titans centre of mass to TAGE orbit in apocentre} = 4575\text{km} \)
\( r_B = \text{Distance from Titans centre of mass to TAGE orbit in apocentre} = 4575\text{km} \)
\( V_{txB} \), the current velocity in the elliptic orbit at apocentre

\[
V_{txB} = \sqrt{\mu \left( \frac{2}{r_B} - \frac{1}{a_{tx}} \right)} = 1,309 \text{ km/s} 
\]

(12.3)

\[
\Rightarrow \Delta V_B = |V_B - V_{txB}| = 94 \text{ m/s} 
\]

(12.4)

\[
\Rightarrow m_p = m_0(1 - e^{-\frac{\Delta V}{gI_{sp}}}) = 4.90 \text{ kg} 
\]

(12.5)

\( m_0=130,4 \text{ kg} \)
\( g=9,81 \text{ m/s}^2 \)
\( I_{sp}=250 \text{ s} \)

In the above equations \( \Delta V \) denotes the extra velocity TAGE needs to transfer from the elliptical orbit into the circular. \( m_0 \) is the remaining mass after one year. \( I_{sp} \) is the specific impulse of the thrusters. Finally \( m_p \) is the fuel mass required to transfer TAGE into circular orbit.

Leaving TAGE in a circular orbit on 2000 km will be safe since the drag from Titans atmosphere at this far distance from the surface is insignificant. The disposal orbit at this distance will be stable for a very long time and the chances for TAGE to crash are eliminated. According to this, there is no reason to send TAGE in an orbit that’s even further out. Then TAGE would need even more fuel onboard and the mass will increase. On the final design there is no room for any more fuel. The chosen disposal orbit should be stable enough to keep TAGE in orbit for at least 100 years or more. Later on in further missions to Titan, TAGE can be picked up and thrown out in the outer solar system or maybe in the far future even taken back to earth for disposal.

A disposal orbit is the cheapest one and will be the end for TAGE after one year. If TAGE is left in orbit for more than a year, there will not be enough fuel left to achieve the desired disposal orbit. This is due to the required attitude control, which will consume some of the fuel otherwise. Control over the fuel must be done to make sure it is not used for other purposes since the same tanks are used for both attitude control and “End of Mission”. When TAGE finally will reach the disposal orbit the spin of TAGE can’t be reserved for sure. As a result of drained fuel tanks the mass will decrease and the moment of inertia will be harder to keep and because of the empty tanks, there will be no fuel left to maintain the spin. At this point no spin is required, since there is no need for “aiming” anymore. No direct problems appear with a disposal orbit as end of mission for TAGE.

### 12.4.2 Crash into Saturn

A Saturn crash will definitely make sure a crash into Titan after mission shutdown is impossible. During the deorbiting manoeuvre there will be enough energy from the SRG onboard to control the whole end and make sure that TAGE doesn’t end up on an unwanted place. The downside with the scenario is the amount of fuel needed. The distance to Saturn is over one million kilometres and to place TAGE in a trajectory towards Saturn will cost at least 27kg, which will take up around 14% of the mission start weight onboard. Not just to make the final velocity change, but also extra fuel is required if something happens on the way towards Saturn.

Maybe the trajectory will be disturbed on the way and lose or gain energy so TAGE will miss Saturn. A solution could be to use an ion engine, but the approach of Saturn will then
take some time. For both types of engines a very good accuracy is required since Saturn is so small in comparison to the far distance between Titan and Saturn. On the other hand the SRG will produce enough power for a very long time and as long as TAGE is under control, the time needed for the approach is not an issue. An ion engine only needs a small fraction of fuel in comparison to bipropellant engines because of the system’s large specific impulse. Because of the slow acceleration you gain from ion engines, the trajectory must look more like a spiral rather than an ellipse. This will make the final trip more complicated, since the attitude control system have to be used during the whole way to make sure that the ion engine fires in the desired direction. Using the attitude system during the trajectory will demand a lot from other systems, especially communication. Without the possibility to communicate no one can be sure where the satellite is travelling. With bipropellant engine the acceleration is much higher and an elliptic orbit can be achieved towards Saturn. Soon after launch into the trajectory there is no need for any special attitude control, if nothing unexpected appears, and therefore less fuel is required. If the scenario would have been TAGEs end of mission, TAGE could have been used to explore some of Saturn on the way towards the end. Some of the measurements done by Cassini, during its orbit around Saturn, could be extended in such case. The conclusion though is that the fuel mass required is too big and therefore there is no possibility for the TAGE mission to end in Saturn.

12.4.3 Outer space trajectory

Probably easier to achieve than a Saturn crash, but the same problem exists with the amount of fuel required. There is almost no difference between the amounts of fuel needed for an outer trajectory compared to a crash into Saturn, just a few tens of grams. Because of the distance it is easier to miss Saturn than to crash into it, and therefore some extra fuel could be saved on attitude control instead. Even here an ion engine could be a good solution. The advantage is that no direct aiming is necessary; just make sure that TAGE travels away from Titan. As long as TAGE is put in a trajectory going towards the outer space there will be no chance of destroying anything vital. Outside Saturn there is nothing special of interest that can be destroyed by a TAGE crash. Even here the same problem with the attitude control would appear, as in the scenario with a Saturn crash, if an ion engine is used. The advantage with using an ion engine is still the mass saved on fuel. Also here TAGE could be used to explore more, than just Titan, on the way “out”. If mission objectives extends the requirements of end of mission will increase since the collected data must be transferred in some way. In the same way as with the Saturn crash scenario, too much fuel mass is required and therefore this scenario will also be excluded.

12.4.4 Crash into Titan

The most controversial ending of them all, but could still be an option since current COSPAR rule for Titan does not exclude a crash and does not say anything about SRGs [112]. A crash into Titan will be even more fuel efficient, no fuel should be required for orbit change since the atmospheric drag will handle that, and more mass onboard TAGE will be saved. Every time TAGE goes through pericentre it will loose speed because of atmospheric drag, and if no
orbit control is made TAGE will eventually crash. A simple, but time consuming method that could work since we have all the time in the world and on the way down TAGE can be used to collect data. The downside with this alternative ending is the SRG onboard and the economic budget. The SRG onboard will probably survive during an entry into Titan and land intact on the surface. The SRG emits 500 W and will heat up the surface, which in turn could start chemical reactions and create other compounds that never existed before. This is highly unlikely since the surface is -178 degrees and the chance for some life forming is practically impossible. Even if some life could appear from the heat it would die immediately from the neutron radiation, radiated from the SRG. Things that are of more significance to the mission are the economic budget and if the COSPAR rule is changed before the launch in 2016, so it will include rules for SRGs.

The project is supposed to be a low-cost mission and since it is a Swedish project we do not have to have the heavy documentation NASA and ESA use on their missions to category 2 bodies. This only applies as long as we plan not to crash on Titan. If we plan to crash we also have to document every single part down to milligram level in the same way as NASA and ESA. Here is the reason why a crash on Titan is not a possible “End of Mission” scenario because our budget is not big enough to document whole TAGE. If the unpredictable occurs though and TAGE falls down on Titan, further missions would not be jeopardized.

12.4.5 The ending of HASSE

When TAGE is dropped of in Titans atmosphere some kind of brake is required to fall into orbit. Traditionally, propulsion systems are used. To save mass, since TAGE is a low cost mission, the plan is to use a large balloon, called HASSE, as an aero brake and when the right velocity is reached HASSE is released. When HASSE is released it will bring a payload with scientific instrument to investigate the atmosphere of Titan. On the approach towards the surface, HASSE is expected to deliver rewarding data. The data is then sent to TAGE for further transmission, as long as the batteries onboard will supply power. Since HASSE is practically just a big balloon, there will be no chance to retrieve it back from the surface. The end for HASSE will be a simple crash on the surface of Titan, very similar to Huygens. The descent will probably not be as rapid as it was for Huygens, in view of the fact that Huygens had a parachute and HASSE will have a large balloon. The impact will also be less energetic and maybe HASSE will glide down very nicely. The batteries on HASSE will probably not survive the cold for so long and there will be no chance to monitor the last part of the descent.

As described in the planetary protection part, the Huygens probe never needed to be disinfected and at this point HASSE won’t have to either. This will save a lot of money and time, but still to remember is the documentation. The possibility for HASSE is that more documentation can be needed than for TAGE because HASSE is supposed to land. This could raise the price tag a bit, but since the payload onboard is only 5kg there won’t be many parts to document and therefore the price shouldn’t be too high. The mission will still be in the budget for this new Swedish low cost mission to Titan.

Figure 12.4: The release of HASSE and its way towards the surface.
13.1 Introduction
On a space mission to Titan you must take into account many things, which are both time consuming and expensive. The s/c will be exposed by a numerous of different sources, starting with the construction and not ending until the mission is over. The mission timeline, starting with the launch in 2016, are not ending before 2024. The long time spam adds higher reliability on the individual parts and on the integrated vessel, as well as higher accuracy on the testing of each system.

The s/c and the individual subsystems must be tested for three major things and that is radiation, temperature and also you must make sure that each system can perform the task it’s suppose to do. The vessel must also be hardened for the particle flux it will encounter as well as the bombardment of micrometeorites and space dust.

In this chapter I will present the different tests that must be performed on TAGE. I will also do some calculations showing the reliability for the s/c.

13.2 Environmental Impacts on TAGE
The impacts the environment will have on TAGE will change during the mission. You can divide it into three different parts namely the launch, the journey to Titan and finally when TAGE reach Titan and is injected into an orbit. The environment will be completely different in each of the three parts and will therefore be discussed in separately chapters.

13.2.1 Launch
The launch is set to 2016 and the rocket to be used is an Ariane 5, which basically will launch the mother ship, Cassini 2, with TAGE attached to it.

The launch is one of the most critical moments for the entire mission. All the different subsystems will be affected by very strong vibrations, which easily can destroy important system. This will add high requirements on the engineers constructing the s/c as well as on the testing of each system and the integration of them.

Mainly five different tests will be performed on TAGE, which will provide us with the data telling if it can endure the launch. The five tests are as follow:

- Steady state acceleration test
- Sinusoidal vibration test
- Acoustic vibration test
- Random vibration test
- Electromagnetic environment test
One thing that should not cause any problem is the thermal environment, but it should be stated. The temperature level can differ between 11°C, the coldest outdoor temperature at the lunch pad, and up to (24 ± 3)°C in the payload container.

In the following subchapters (5.3.1.1 – 5.3.1.5) the different requirements for each test will be presented.

13.2.1.1 Steady state acceleration
Using an Ariane 5 rocket the accelerations will not exceed a longitudinal acceleration of 4.55g, a lateral acceleration of 0.25g and in order to reduce the heat flux from solar radiation an angular motion up to 2deg/s can be necessary. By doing this, the radiation is spread out over the entire rocket.

13.2.1.2 Sinusoidal vibration
In the following table the maximum sinusoidal vibrations that will affect TAGE are presented.

<table>
<thead>
<tr>
<th>Direction</th>
<th>Frequency band (Hz)</th>
<th>Sine amplitude (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td>5-100</td>
<td>1.0</td>
</tr>
<tr>
<td>Lateral</td>
<td>2-25</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>25-100</td>
<td>0.6</td>
</tr>
</tbody>
</table>

*Table 13.1: Sinusoidal vibrations at launch [117]*

13.2.1.3 Acoustic vibration
On the ground the venting system will not exceed a noise level higher then 94 dB. During the flight acoustic pressure vibrations will be caused by engine operations as well as atmospheric phenomena. Different pressure levels for different frequencies are presented in the table below.

<table>
<thead>
<tr>
<th>Octave centre frequency (Hz)</th>
<th>Flight limit level (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reference: 0 dB = 2 x 10^{-5} Pa</td>
</tr>
<tr>
<td>31.5</td>
<td>128</td>
</tr>
<tr>
<td>63</td>
<td>131</td>
</tr>
<tr>
<td>125</td>
<td>136</td>
</tr>
<tr>
<td>250</td>
<td>135</td>
</tr>
<tr>
<td>500</td>
<td>132</td>
</tr>
<tr>
<td>1000</td>
<td>126</td>
</tr>
<tr>
<td>2000</td>
<td>120</td>
</tr>
<tr>
<td>OASPL (20 – 2828 Hz)</td>
<td>140.5</td>
</tr>
</tbody>
</table>

*Table 13.2: Acoustic vibrations at launch [117]*

OASPL = Overall Acoustic Sound Pressure Level

13.2.1.4 Random vibration
The random vibrations less than 100 Hz are covered by the sinusoidal vibration defined in 13.2.1.2 and the frequencies above 100 Hz are covered by the acoustic vibration defined in 13.2.1.3.
13.2.1.5 Electromagnetic environment

The launch vehicle has electronic equipment generating electromagnetic fields that can interfere with TAGE’s equipment. The different systems are as follow, a telemetry system operating in the 2200-2290 MHz band with a transmitter power of 8 W, a telecommand system operating in 440-460 MHz band and a radar with a reception frequency of 5690 MHz and transmission frequencies in the 5400-5900 MHz band with a peak power of 400 W.

13.2.2 The voyage to Titan

During the voyage to Titan the main things that can cause problems are radiation, impacts of particles and micrometeorites.

The bigger ESA mother ship Cassini 2 will carry TAGE on its way through the solar system and release the vessel close to Titan. To gain necessary energy to reach Saturn Cassini 2 will do several swingbys similar to the ones that Cassini did, which is Venus-Venus-Earth-Jupiter. The encounters near Venus will be close to the sun, which will increase the intensity of the solar radiation, and here the vessel is most vulnerable. Also the Earth-swingby sets higher requirements because of the probability of an impact, in the case that ESA will lose control over Cassini 2. TAGE uses a RTG for power supply, which must be kept intact if an Earth-impact should occur.

The radiation will mainly affect the electronics onboard. Those will degenerate over time and eventually they will be destroyed. To prevent this to take place radiation hard components can be used. In the case we use none radiation hard components they must be rigorous tested before they can be implemented. To reduce the amount of radiation accumulated by the components it will be required to use aluminium, which will stop a part of it, dependent of the thickness of the aluminium. The lifetime of the different components should be designed to last at least equal to double the lifetime of the mission.

The s/c must also be shielded to withstand micrometeorites that constantly bombard the satellite. The below table show the number of meteorite impacts. The data comes for the ROSETTA mission, which does similar swingbys.

<table>
<thead>
<tr>
<th>Minimum Mass (g)</th>
<th>Diameter (mm)</th>
<th>( N_{\text{met}}(\text{m}^2/\text{10.5 years}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 E-13</td>
<td>4.57 E-4</td>
<td>2.77 E+4</td>
</tr>
<tr>
<td>1.0 E-12</td>
<td>9.85 E-4</td>
<td>1.15 E+4</td>
</tr>
<tr>
<td>1.0 E-11</td>
<td>2.12 E-3</td>
<td>4.96 E+3</td>
</tr>
<tr>
<td>1.0 E-10</td>
<td>4.57 E-3</td>
<td>2.13 E+3</td>
</tr>
<tr>
<td>1.0 E-9</td>
<td>9.85 E-3</td>
<td>1.00 E+3</td>
</tr>
<tr>
<td>1.0 E-8</td>
<td>2.12 E-2</td>
<td>393</td>
</tr>
<tr>
<td>1.0 E-7</td>
<td>4.57 E-2</td>
<td>101</td>
</tr>
<tr>
<td>1.0 E-6</td>
<td>9.85 E-2</td>
<td>15.7</td>
</tr>
<tr>
<td>1.0 E-5</td>
<td>0.212</td>
<td>1.47</td>
</tr>
<tr>
<td>1.0 E-4</td>
<td>0.457</td>
<td>0.109</td>
</tr>
<tr>
<td>1.0 E-3</td>
<td>0.985</td>
<td>6.29 E-3</td>
</tr>
<tr>
<td>1.0 E-2</td>
<td>2.12</td>
<td>3.24 E-4</td>
</tr>
<tr>
<td>0.1</td>
<td>4.57</td>
<td>1.57 E-5</td>
</tr>
<tr>
<td>1</td>
<td>9.85</td>
<td>7.4 E-7</td>
</tr>
</tbody>
</table>

Table 13.3: Flux of meteorite impacts
To make sure that TAGE will survive the space environment during the seven year long voyage to Titan a numerous of different test will be performed on TAGE or its individual subsystems or components. The tests are as following:

- Thermal vacuum test
- Solar simulation test
- Leak test
- Radiation exposure test

13.2.2.1 Thermal vacuum test
The thermal vacuum test will make sure that the thermal control system can maintain the temperatures required for the system onboard TAGE. The space environment is reconstructed to give a good simulation. During a two-week period the s/c will be put in a chamber where the temperature is varied between warm and cold, usually 10°C above the maximum allowed temperature and 10°C below the coldest required temperature.

13.2.2.2 Solar simulation test
During the swingbys TAGE will change the distance to the sun and consequently change the incoming the solar radiation flux that will affect the thermal control onboard. To be sure that the system can handle solar radiation a test similar to the thermal vacuum test will be done. Here the temperature will be changed like it will do in space to make sure the control system can keep the required temperature.

13.2.2.3 Leak test
Several systems onboard must be controlled for leakage. On TAGE the thrusters must be tested as well as the tanks containing the helium gas for the balloon used in the orbit injection. The vibrations at launch and the vacuum will affect those systems, especially the seven-year long journey to Titan before TAGE reach Titan.

13.2.2.4 Radiation exposure test
TAGE will be exposed by high-energy radiation throughout the mission. The exposure will affect the choice of components used especially the electronic components. The use of radiation hard parts will increase the costs and mass of each component but will reduce the weight of the shield. This mission is similar to other deep space mission and therefore a comparison to them will provide us with enough data. In the figure below the radiation level compared to the thickness of the shield is presented for the ROSETTA, CASSINI/SOLAR PROBE and GALILEO PROBE.
Radiation hard components tolerate at least 100 krad and non-radiation hard components 10 krad up to 70 krad. In the table below the different thicknesses required for the shielding is stated.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Radiation hard components</th>
<th>Non radiation hard components</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROSETTA</td>
<td>0.4 mm</td>
<td>2.5 mm</td>
</tr>
<tr>
<td>CASSINI/SOLAR PROBE</td>
<td>1 mm</td>
<td>6 mm</td>
</tr>
<tr>
<td>GALILEO PROBE</td>
<td>2.7 mm</td>
<td>37 mm</td>
</tr>
</tbody>
</table>

Our mission does the same swingbys as Cassini 2 and therefore TAGE will required the same shielding. The structure we use is called honeycomb, which is 9 mm thick while 8 mm of it is the honey structure leaving us with an effective thickness of 1 mm. This means that the use of the expensive radiation hard components can be avoided. Instead the use of radiant tolerant components or military/avionics components should be sufficient and also ordinary components if they can tolerate radiation around 50 krad. This will drastically reduce the costs and the mass.
13.2.3 Orbiting Titan
At Titan we will have a more dynamical environment. Titans orbit will sometimes be inside Saturn’s magnetosphere and sometimes it will move outside. This will affect the incident of solar particles, and if TAGE’s trajectory will pass by Saturn’s radiation belts the shield protecting the s/c must be sufficient.

When TAGE reaches Titan it will be, for the first time, on its own. Throughout the voyage to Titan it has been attached to Cassini 2. To ensure that TAGE will be able to function during the one year mission sever test must be done. The following tests are important to perform on TAGE:

- Mass properties measurement and balance test
- Appendage test
- Antenna pattern test
- Electrical performance test
- Magnetic moment measurement test

13.2.3.1 Mass properties measurement and balance test
To make sure that the s/c can be manoeuvred correctly the weight, centre of gravity and moment of inertia must be determined and see if they agree with the calculated values. For a spin-stabilized satellite it’s also important to assure the balance to avoid nutation and coning movements.

13.2.3.2 Appendage test
On TAGE we have several booms that must correctly be deployed after the orbit injection. An appendage test will test if those things work properly. We don’t use solar panels for power supply, which make those tests much easier. But we have long booms, which should be deployed automatically while in spin.

13.2.3.3 Antenna pattern test
The antenna pattern must be measured correctly to makes sure that no problems occur when the satellite communicates with Cassini 2 or the Earth.

13.2.3.4 Electrical performance test
In the electrical performance test all connections are tested so they work properly and that all equipment works on the predicted currents and voltages.

13.3 Costs
The testing of an s/c is a time consuming and expensive part of a space mission. It is hard to state how much it will cost in the end. If the testing phase progress without major problems the costs will be reduced, but in many cases discrepancies arise which has not been forth seen. Those discrepancies, or anomalies, are very expensive to correct and can significantly increase the cost. Therefore it is important to do as accurate investigation as possible to avoid those discrepancies. A rigorous testing phase is also needed to be sure all possible discrepancies are found before the launch because they can jeopardize the whole mission if they happen in space.
At this level the best estimate of the costs is to look at previous space mission and form them calculate an approximate value. A typical cost for the testing is between 8-9% and will be used to calculate the testing phase for TAGE. [113]

The most expensive tests are those involving vibration and thermal vacuum. They need large facilities and take long to perform.

At this stage the facilities used in the testing phase are not yet determined. But to reduce the costs Swedish test facilities will be used as far as possible and radiation test for the electronic components can be performed in The Svedberg laboratory in Uppsala. In Kiruna at IRF different kind of vacuum simulations can be performed and at Packforsk in Kista TAGE can be vibration tested.

13.4 Reliability
Reliability is the probability that no failures occur in a given time interval. For TAGE reliability will be defined as the probability that it will operate for nine years. This includes the voyage to Titan and that it will operate at least one year at Titan.

13.4.1 Definitions
The calculations this early in the project must be kept simple and should work as a guide for further investigations. As the project moves forward the requirements can change which will affect the reliability.

The model used in this chapter relies on the combining of probabilities. If A and B are two independent events with probabilities \( P(A) \) and \( P(B) \), the combining probability that both events occur is:

\[
R_{AB} = R_A \times R_B
\]  

(13.1)

To get a good estimate of the reliability the above equation is the only equation you need. Combining every system will in the end result in the reliability for the integrated s/c.

The mathematical model for TAGE is shown in Figure 5.4.1, the satellite is divided into seven subsystems.

![Figure 13.2: Model for the calculations of the reliability](image)

The combined reliability is

\[
R_{sys} = R_{comm} \times R_{comp} \times R_{power} \times R_{thermal} \times R_{Adc} \times R_{orbit} \times R_{scien}
\]

(13.2)

13.4.2 Calculations of the reliability
The communication systems antenna is a patch antenna and has therefore a built in redundancy. If one patch is destroyed the antenna will still work. The reliability \( R_{comm} = 1 \).
For the orbit injection a balloon is used. The balloon system we use has not been in space yet and has not been fully developed. In this case it’s hard to get an accurate reliability, but in Monte Carlo simulation it has a 100% success rate. The separation system is manufactured by Saab Ericsson Space and has been used in 275 successful satellite separations and has a 100% success rate. At this point in the development of this system it’s no point to set the reliability anything other than $R_{\text{orbit}} = 1$.

For the attitude control a starmapper and a sun sensor are used. Both of them have very high reliability.

**Starmapper:** Probability for a complete failure = $1.2 \times 10^{-4}$/ year, hence it has a reliability of 0.9989 to survive 9 years.

**Sun sensor:** > 0.999 for a 15-year mission

The combined reliability for the attitude system is:

$$R_{\text{att}} = 0.9989 \times 0.999 = 0.998$$ (13.3)

The scientific instrument are very reliable and don’t need redundancy, their reliability $R_{\text{scien}}$ is set to 1. Also if one instrument should be destroyed it is not the end of the mission. The scientific instruments are not dependent of the others.

We can now multiply each subsystem to get the combined reliability for TAGE:

$$R_{\text{sys}} = 1 \times R_{\text{comp}} \times R_{\text{power}} \times R_{\text{thermal}} \times 0.998 \times 1 \times 1 = 0.998 R_{\text{comp}} R_{\text{power}} R_{\text{thermal}}$$ (13.4)

We now have three subsystems left and those are computers, power and thermal. The thermal subsystem is not a high-risk system. Known designs will be used and are therefore reliable. For that reason I set its reliability to 1. The computer and power subsystem are the most complicated and hardest to get accurate reliabilities at this early stage.

The power system consists of a RTG, which not yet have been tested in space. Before TAGE is scheduled to launch many missions are planned with the specific RTG, which means that more data regarding the RTG will be available. NASA recommends redundancy, which in our case is not an option because of the weight it will add.

The computers are the most complicated subsystem. The electronics consist of many different electronic components that are degenerating in space due to mostly radiation. Redundancy is important and TAGE have therefore four processors which means it will still work even if one processor dies. The storage is also a problem when the memories also degenerate in space. Redundancy is also here important. The computer subsystem on TAGE uses redundancy, which improves the reliability, but in this stage it’s impossible to calculate an accurate reliability because all the components are not yet selected.

The final expression for the reliability will be:

$$R_{\text{sys}} = 0.998 R_{\text{comp}} R_{\text{power}}$$ (13.5)

The computer subsystem and the power subsystem are the critical systems. New technology is used which not yet have been tested in space. Therefore it’s important to do further investigations on those systems as well as testing to make sure they will survive the space environment.
References


[14] Page 1ff, J. Kelly Beatty, 1999


[19] Barabash and Gimholt, ASPERA-3 design description IRF, Kiruna, 1999

[20] Lecture notes from the course Space Physics 2 at Uppsala University, 2006


[22] Wahlund et al, Science opportunities with a double Langmuir Probe and electric field experiment for JIMO


[31] Page 1ff, Aerocapture Technology, National Aeronautics and Space Administration, Marshall Space Flight Centre, Huntsville, 2005


[34] Page 1f, Larson, Wiley, Wertz, James, 2003


[38] Page 163, Nordling, Österman, Physics Handbook, Studentlitteratur, 2004


[40] Page 171ff, Nordling, Österman, 2004


[47] Outer Planets Program, Environmental Requirements, August 1999

[54] Fischman, Mark et al, A Digital Beam forming Processor for the Joint DoD/NANA Space Based Radar Mission, Jet Propulsion Laboratory, California Institute of Technology, 2004
[55] McWatters, Dalia et al, Antenna Auto-Calibration and Metrology Approach for the AFRL/JPL Space Based Radar, Jet Propulsion Laboratory, California Institute of Technology, 2004
[56] Saab Ericsson Space, S-band Conical Helix Antenna, 2005
[60] Page 1ff, TAGE’s Link Budget, Andersson, 2006


[106] Peter Rathsman, Swedish Space Corporation


[112] Jean-Pierre Lebreton, ESA Project Scientist and Mission Manager for the Huygens Mission


