Delft University of Technology

Laser Swarm

Mid Term Review

Design Synthesis Exercise

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Abstract

In February 2010 the ICESat mission ended after 7 years of measuring ice sheet mass balance, cloud and aerosol heights, as well as land topography and vegetation characteristics using a space based Light Detection And Ranging (LiDAR) system. ICESat used only one of the possible approaches for LiDAR, namely the use of a high energy laser and a large receiver telescope. The other approach is using a high frequency, low energy laser and a single photon detector. The advantage of the latter approach is that it has a much lower mass, but it is uncertain if even a single photon per pulse reaches the receiver. One possible solution could be to use a swarm of satellites around the emitter, each equipped with a single photon detector. However, the technical feasibility of this concept has not yet been proven.

The baseline report provides an overview of the initial look into this concept. This document contains the requirements analysis, functional breakdowns, risk assessments and initial design options. A preliminary business assessment is also conducted at this stage. It provides the basis for the trade-off made later in the project to find the most feasible system, which incorporates this concept.

Contents

List of Acronyms

ADCS Attitude Determination and Control Subsystem

ASTER Advanced Spaceborne Thermal Emission and Reflection Radiometer

BRDF Bidirectional Reflection Density Function

CMG Control Moment Gyro

DEM Digital Elevation Model

ECEF Earth-Centered, Earth-Fixed

EPS Electrical Power System

GDEM Global Digital Elevation Model

GLAS Geoscience Laser Altimeter System

JAT Java Astrodynamics Toolkit

laser Light Amplification by Stimulated Emission of Radiation

LEO Low Earth Orbit

LiDAR Light Detection And Ranging

MPD Micro Photon Device

MTR Mid Term Review

RAMS Reliability, Availability, Maintainability and Safety

TOD True Of Date

WBS Work Breakdown Structure

WFD Work Flow Diagram

WGS84 World Geodetic System 1984

Chapter 1

Introduction

In February 2010 the ICESat mission ended after 7 years of measuring ice sheet mass balance, cloud and aerosol heights, as well as land topography and vegetation characteristics. To do all this, ICESat had only one instrument on board: a space based LiDAR system (Geoscience Laser Altimeter System (GLAS)), allowing for an unprecedented 3D view of the Earth's surface and atmosphere. The laser lifetimes, however, were severely limited because of manufacturing errors in one of the laser components.

ICESat followed only one of the possible approaches for LiDAR, namely the use of a high energy laser and a large receiver telescope. The other approach is using a high frequency low energy laser and a single photon detector. The advantage of the latter approach is that it has a much lower mass, but it is uncertain if even a single photon per pulse reaches the receiver. One possible solution could be the use of a swarm of satellites around the emitter, each equipped with a single photon detector. However the technical feasibility of this concept has not yet been proven.

This is the baseline report on the technical feasibility of this approach to achieve one or more applications of ICESat. It will mainly go into depth on the requirements, technical risks and define the initial design options. It will be the basis for the technical trade off to be made, which specifically requires the in-depth understanding of the subjects treated in this report.

Chapter **??** describes the functions and requirements of the system as a whole, whereas Chapter **??** shows the multiple budget breakdowns and resource allocation. In Chapter **??** the technical risks are investigated. Chapter **??** illustrates the different design options. Since sustainable engineering is an important factor, Chapter **??** is devoted to this subject. In Chapter **??** the return on investment and operational profit are discussed and finally in Chapter **??** the Reliability, Availability, Maintainability and Safety (RAMS) are studied.

Chapter 2

Technical Design Development

In this chapter an update is given on the Technical Design Development as given in the Project Plan. All charts and documents have been updated. First the project approach description is updated in section 2.1. Work Flow Diagrams and Work Breakdown Structures are updated in sections 2.2 and 2.3, whereas the Gantt chart is revisited in section 2.4.

2.1 Project Approach Description

2.1.1 Group Procedures

The DSE project is approached by first establishing specific roles for the group members, so that every group member is assigned a clearly defined managerial and technical function. After this the group operational procedures are defined. They are as follows:

1. The Chairman will lead a 'scrum' meeting every morning upon arrival of all members to establish what everyone has done the day before and what they will be doing the day of the meeting. This is done in order to keep all members up-to-date with all aspects of the project. The meeting concludes with updates on any external communications (with organizations and teaching staff) as well as any other points relevant at that time.
2. When done, groups responsible for certain design tasks will present their results to the rest of the team.
3. The team meets with tutor and coaches at least weekly.
4. Everyone is present at The Fellowship between 09:00 and 17:00 every workday, except for a 45 minute lunch break.
5. Upon completion of a deliverable, a meeting is conducted to establish a plan for the next deliverable.

2.1.2 Reporting

The reporting is done in LaTeX. There is a main report file which contains the layout of the report and the references to other files that contain the chapters, sections, figures, tables and other documents required for the report. When the file is compiled and printed it will show the entire report.

This has the advantage that work can be easily divided among group members, and any change made to a file will not influence the rest of the report. The file sharing is performed using Subversion (SVN). SVN not only allows file sharing, but it automatically assigns versions to a document and keeps track of changes. The repository is hosted with Google™Code.

2.1.3 Project Outline

The official start of the DSE project is the establishment of the Mission Need Statement. At this point all members should be aware of the main goal of the assignment.

The design process is started by defining the tasks in the project plan, then finding the requirements and functions. From the requirements, a set of design options will be created for the Mid Term Review (MTR). In the MTR a trade-off will be made based on an extensive functional and risk assessment. After the MTR, work on the detailed design can begin. At this stage all subsystems will be given a careful consideration in terms of cost, mass and power budgets. Final decisions on detailed parameters and variables will be made. Leading up to the Final Review (FR), the feasibility study can be concluded.

Parallel to the design phase, the simulator software will be developed by a team of 3 to 4 people, depending on workload and time available. This software should be able to perform calculations accurate enough to aid the trade-off scheduled before the MTR.

2.2 Work Flow Diagram

The tasks to be done on the simulator have been updated and presented in more detail. Some tasks have also been changed in the Work Flow Diagrams (WFDs): they now start earlier or later so as to better describe the work flow of the project. The tasks in the green and blue boxes respectively describe the simulator design finalization and tradeoff execution in more detail. Red boxes are tasks which are explicitly needed for the Mid Term Review (MTR). The updated WFD of the MTR is given in figure 2.1, page 7.

The WFDs of the final report have also been updated. In retrospect, a very important part if the final report was not present in the WFDs: perfecting the design and the feasibility determination. Now these tasks have been added to the daigram to make it complete. As with the WFD of the MTR, all boxes in red are explicitly required for the final report. The diagram can be seen in figure 2.4, page 10.

2.3 Work Breakdown Structure

The Work Breakdown Structures (WBSs) have been updated like the work flow diagrams. Some extra and other more detailed tasks defined in the WFDs have also been added to these structures. Also, the layout has been changed somewhat to improve readability and correctness. The updated WBSs can be seen in figures 2.3 and 2.4, starting on page 9.

2.4 Gantt chart

As the WFDs and the WBSs have been updated, so the Gantt chart has also been updated. Now that we are further along in the project, it is easier to estimate which tasks need to be done for the mid-term and final reports. The estimated duration of these tasks also was much easier to estimate. The Gantt chart has been updated to contain all tasks set in the WFDs. Special care was taken to make sure the Gantt chart is

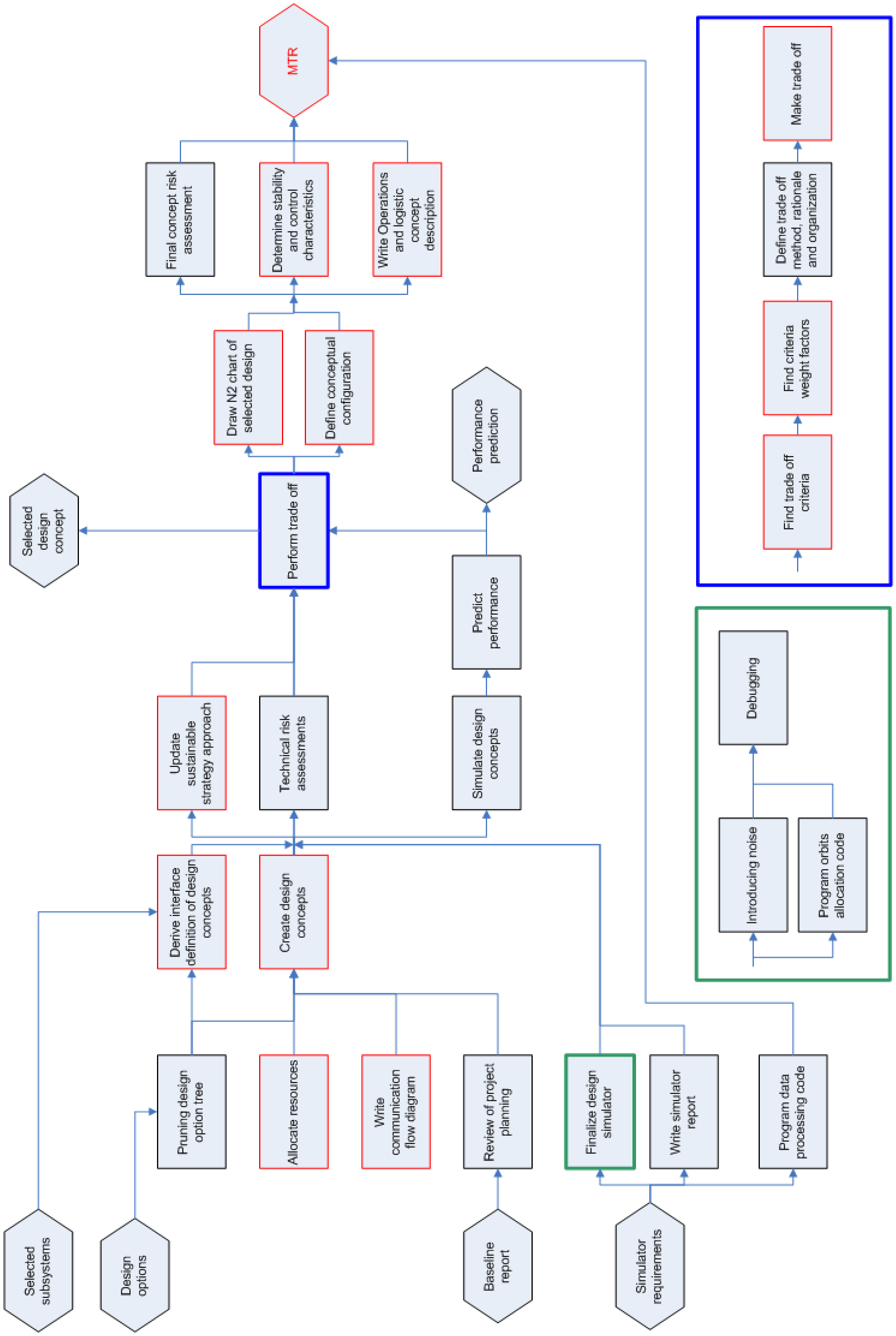

Figure 2.1: Updated work flow diagram for the mid-term report

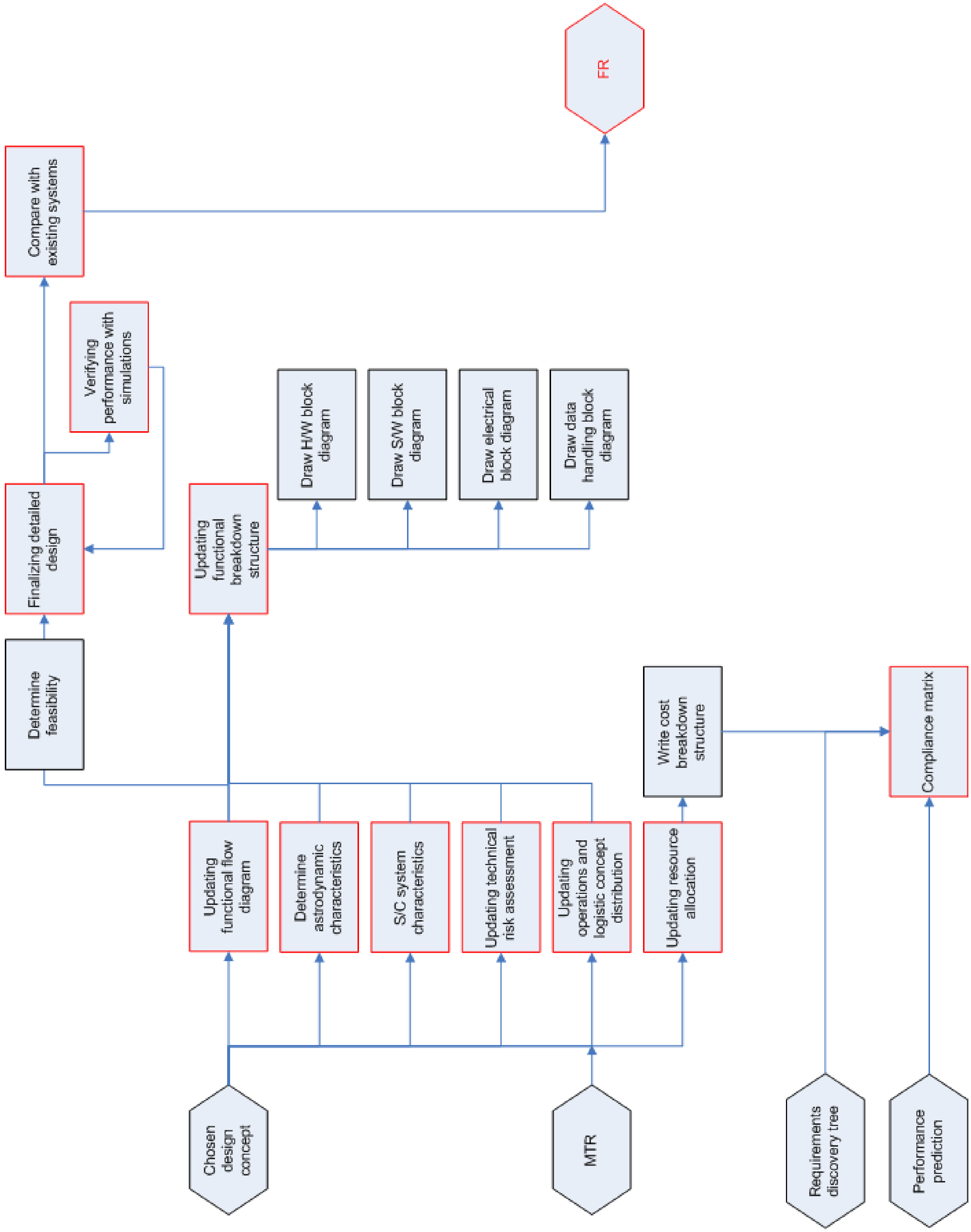

Figure 2.2: Updated work flow diagram for the final report

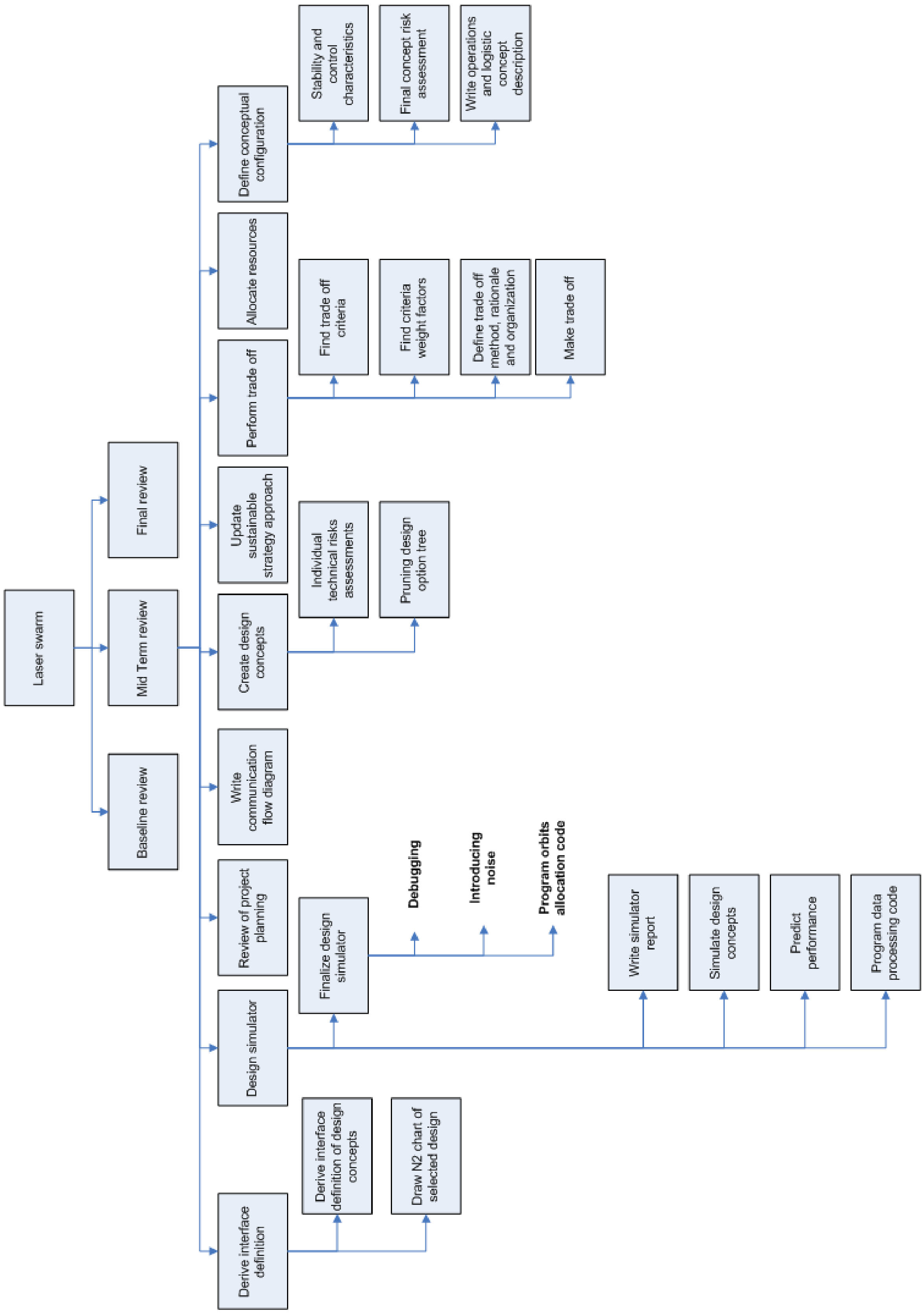

Figure 2.3: Updated work break-down structure for the mid-term report

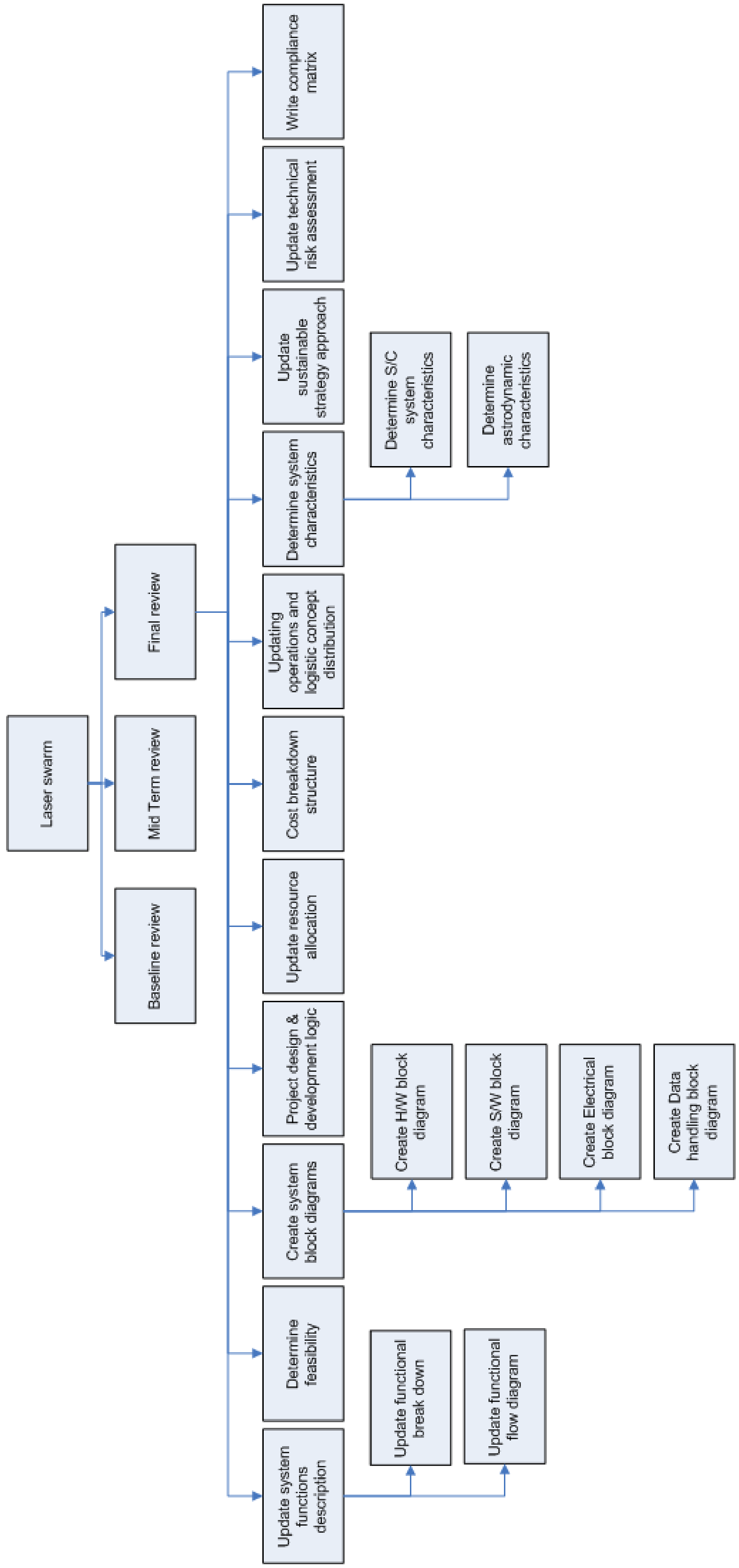

Figure 2.4: Updated work break-down structure for the final report

consistent with the WFDs and the WBSs. This time the simulator tasks were not separated from the rest of the project because the simulator is more involved with the rest of the project for the mid-term and final reports. The updated Gantt chart can be found in appendix A, page 27.

Chapter 3

Simulation

In this chapter the simulation of the satellites, moving through space and sending and receiving laser pulses, is discussed. In section 3.1 the emitter and receiver satellite orbits are considered. In section 3.2 the way the Earth's surface was modeled is explained. In section 3.3 the path of the signal is examined, whereas in section 3.4 the introduction of noise into the signal is disclosed.

3.1 Orbit

The orbit of each satellite in the constellation is defined by means of six Keplerian elements. These define the shape of the orbit, the orientation of the orbit with respect to the center of the Earth and the position of the satellite on the orbit.

As there are a number of rotating bodies, three reference frames are used in order to facilitate the process of locating the satellites in space. The three reference frames used in the simulation are described below.

The first is True Of Date (TOD). Its X-axis points towards the direction of the vernal equinox and its Z-axis coincides with the axis of rotation of the earth. TOD takes into account nutation and precession of the earth. For practical reasons, it does not rotate with respect to the Sun.

In the second place there is Earth-Centered, Earth-Fixed (ECEF). Its X-axis points towards 0° latitude and 0° longitude. The XY plane lies in the plane of the equator. Its origin is in the center of mass of the Earth.

Thirdly there is the PQW. The P-axis points towards the perigee of the orbit, the PQ plane lies in the plane of the orbit and the W-axis is perpendicular to the plain of the orbit. The origin of the frame is at the focal point.

The program converts between the before-mentioned reference frames for the user's convenience.

The position of the satellite is defined with respect to the TOD reference frame. Kepler's equations are solved for a certain time to determine the position. The orbit is determined for every satellite in the constellation. The orbit is assumed to be perfect, meaning that its orientation and shape do not change: perturbations are not considered.

The Earth's rotation about its own axis and around the Sun is simulated in order to provide a more realistic simulation environment. From the rotation of the Earth around the Sun, the sun vector is deduced; this is used in noise calculations.

Most of the functions are adapted to the simulator from the Java Astrodynamics Toolkit (JAT) library.

3.2 Earth Model

The Earth model is the digital representation of the Earth surface. It stores a Digital Elevation Model (DEM), and the scattering characteristics of the local terrain. In section 3.2.1, the DEM implementation will be elaborated and section 3.2.2 describes the way incoming radiation is scattered.

3.2.1 Digital Elevation Model

A Digital Elevation Model is a digital representation of a topographic surface. For the ground representation in the simulator a few tiles of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) were used. This DEM was created using the complete history of the ASTER instrument launched on the Terra satellite. This DEM has a spatial resolution of one arc-second and a vertical accuracy of $7 - 14$ meters. The elevations of the intermediate points were obtained using nearest-neighbor interpolation.

The ASTER GDEM elevations are expressed with respect to the World Geodetic System 1984 (WGS84) ellipsoid. To simplify the internal simulator, the DEM tiles were projected to the EPSG:3857 spheroid. The projection is done using the GeoTools Java toolkit [**?**].

The digital elevation is used to compute the total distance (and thus the time) that the laser pulse travels. Because scattering is dependent on the terrain normal, this normal is derived form the DEM, using the two perpendicular surface gradients that can be extracted from the DEM.

3.2.2 Scattering Model

Scatter is the physical process where incident radiation is absorbed and reflected back towards the atmosphere. To this end a scattering model is used. This scattering model is a way to construct a Bidirectional Reflection Density Function (BRDF). A BRDF is a distribution of the incident light over the hemisphere [**?**, pages 47-49]. An example is shown in figure 3.2.2, page 14.

The most basic example of a BRDF is the Lambertian model [**?**, pages 49-50]. This model assumes a homogeneous perfectly rough surface, causing a homogeneous scattering distribution. Apart from the index of refraction of the air, the incident radiation vector and the exittant radiation vector (which are all known), use of Snell's law is needed to find Fresnel's coefficients, thereby requiring the index of refraction of the ground.

A modification that can be made to take into account the tendency of surfaces to scatter more in the direction of the surface normal, is called the Minnaert model [**?**, page 50]. It causes a more elliptical BRDF. It depends on the Minnaert parameter κ.

Another important modification is the Henyey-Greenstein term. It accounts for the tendency of surfaces to back- or forwardscatter [**?**, page 51]. This rotates and deforms the elliptical BRDF obtained from the Minnaert model. The Henyey-Greenstein term is parameterized by Θ. The final result is shown in figure 3.2.2, page 14.

This is the scattering model used in the program. Because there is no data from which all three parameters can be accurately determined, a coefficient map was made up. It does not matter much what the precise form of the BRDF used in the simulation is, so long as it can be retrieved.

With the help of the formulae from [**?**, pages 43-51], the incidence vector can be taken and the number of photons radiated in a specific direction can be calculated. Note that the program does not integrate over part of the sphere: because the angle of the cone is very small, the BRDF is assumed to be constant over the cone. The error induced here is worth avoiding the computationally expensive integration.

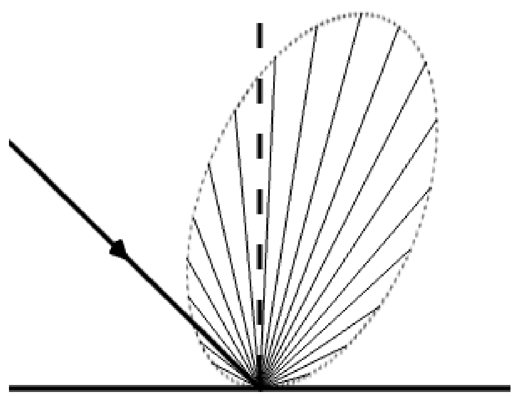

Figure 3.1: Example of a BRDF

3.3 Signal Path

The simulated path that the Light Amplification by Stimulated Emission of Radiation (laser) signal follows is visualized in figure 3.3 on page 14. There are three distinct phases. The first one is the travel of the signal down through the atmosphere. This is followed by the scattering on the Earth's surface. Finally the pulse has to travel back up through the atmosphere. This sequence is elaborated on in more detail below.

The signal originates from the emitter. For each pulse, the emitter position is determined from a set of Kepler elements. The energy in the pulse is found by distributing the emitter power over a constant number of pulses of a given duration.

The signal then starts to propagate through the atmosphere. The atmosphere affects the signal in several manners, but the most important one is the attenuation of the signal. Attenuation is the only disturbance by the atmosphere taken into account. The pulse energy exponentially decays with travel distance through the atmosphere. Furthermore also the optical thickness of the atmosphere is taken into account.

Then the intersection of the pulse with the DEM is computed. As a simplification in this process, the intersection of the pulse (i.e., the ray) with a sphere is computed. The sphere has a radius of the average terrain height of the DEM tile plus the Earth radius. Then the ray-sphere intersection point coordinates are converted into latitude and longitude. These are then used to find the actual terrain elevation from the DEM and the three-dimensional position.

Then the scattering characteristics are constructed. For this, the terrain normal and the inbound laser pulse vector are used. The power of the emitted pulse is now distributed over the entire footprint area of the emitter and then scattered back using the scattering technique described in section 3.2.2. The backscattered energy is computed separately for every receiver satellite.

The reflected pulse now travels back through the atmosphere. More attenuation takes place along this path. The energy received by the receivers now depends on the receiver aperture. The received energy can then be converted into photons by dividing the energy received by the energy per photon.

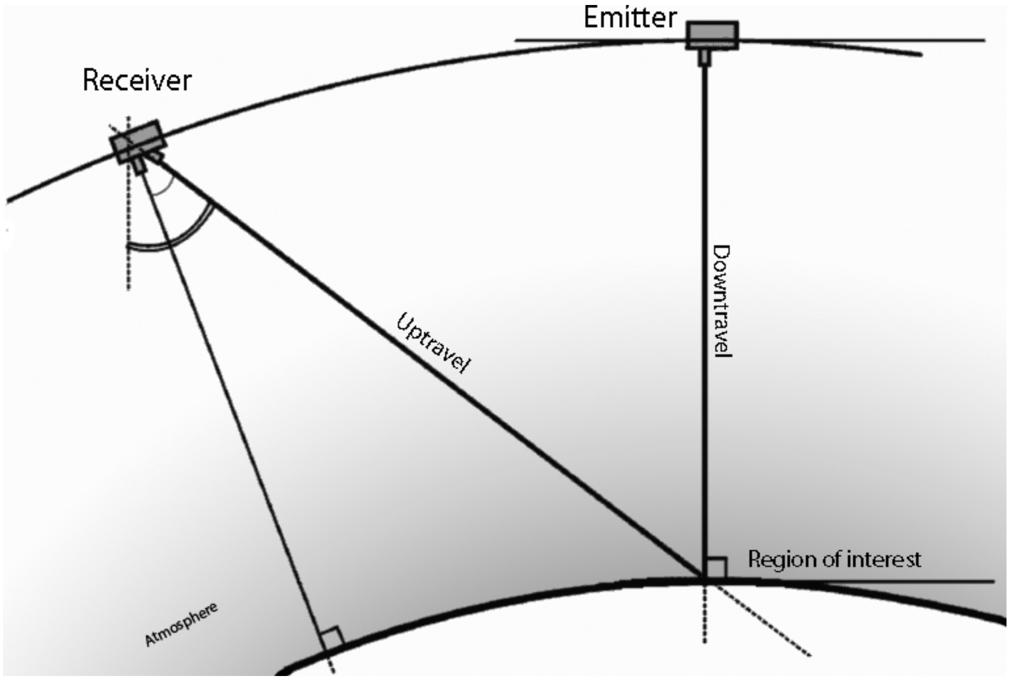

Figure 3.2: Signal path representation

3.4 Noise Introduction

The main source of noise in the system comes from the Earth's surface. This includes sources on the Earth such as lights along highways and reflected radiation, i.e. the Earth's albedo. The amount of radiation that is received by the receivers depends on the footprint of the receivers. This is an ellipse created by the intersection of the cone originating from the receiver with the terrain. A simplification is made in that the DEM is assumed to be a flat area with the elevation of the center point.

The amount of power emitted per square meter is dependent on the illumination of the Earth by the Sun. If the Sun illuminates the footprint, the emitted power is the scattered power of the Sun in the receiver detection wavelength bandwidth. This power can be found by integrating Planck's law over the detection spectrum and the solid angle the Sun subtends to the receiver footprint on Earth. If the Sun does not illuminate the receiver footprint, the only contribution to noise is the Earth's greybody radiation, which is also taken into account.

While noise propagates through the atmosphere it is also attenuated. This attenuation is computed in the same way the signal attenuation is; see section 3.3.

Chapter 4

Data Analysis

In this chapter the analysis of the received photon data taken care of in the software tool is elaborated on. The analysis consists of two parts: the terrain altitude determination and the BRDF determination. The first is expounded in section 4.1, the second in 4.2.

4.1 Altitude Determination

In order to tackle the problem of decrypting the raw data and converting it into a coherent terrain model, various statistical techniques need to be employed. The basic principle behind the altitude determination of the terrain is as following. First the time difference between generation and reception of the pulse is registered. As the position of the emitter at the time when the pulse was sent is known, just like the position of the receiver at the time the pulse was received is, the distance to ground can be determined. In theory only one emitter and one receiver are necessary to determine the altitude, but due to various uncertainties in position and noise characteristics of the received data, more receiving satellites are necessary to obtain a reliable and complete terrain representation.

In the simulator the emitter is modeled such that it records the time when the pulse was sent. The receivers are modeled such that they register the time and intensity (in photons) of the received pulse. The problem is that not all emitted pulses are registered, and sometimes noise, which does not correspond to any emitted pulse, is registered.

One of the ways to solve this problem is to use multiple receivers. The noise could be identified and removed by means of looking for a spike in the received photons for the whole swarm within a certain time range (usually twice the time it takes for a light beam to travel the orbit altitude). This data could be filtered by means of correlating the distance of the receiver to the Earth center and the time of the received pulse. Usually, the larger the distance, the larger the time difference. This method helps to eliminate outliers. Since the footprints overlap, the measured altitudes could be further smoothed out by means of a running average.

4.2 Bidirectional Reflection Density Function Determination

The BRDF returns the ratio of the radiance to irradiance for a given angle perpendicular to the surface. In theory, it is possible to measure it by means of the received photons of all of the receivers for a given pulse, where each received photon indicates the relative intensity. From the position of the receivers the direction of the irradiance vector can be calculated. Having the direction and intensity of the reflected radiation a segment of the BRDF for a specific incident angle could be reconstructed. By making a multiple passes over the same region, a partial BRDF for different incidence angles can be recorded. If the data is interpolated, a complete BRDF can be determined.

Chapter 5

Preliminary Pruning of the Design Option Tree

In this chapter the Design Option Tree is pruned. This means that all options that can be dismissed off-hand are removed so as to end up with a table of only serious design options. In section 5.1 the Attitude Determination and Control Subsystem (ADCS) is pruned, whereas orbit options are scrapped in section 5.2.

5.1 Attitude Determination and Control Subsystem

The gravity-gradient stabilisation and passive magnetic options are eliminated because they provide insufficient accuracy and do not allow pointing to a any target other than the mass or magnetic centre of the Earth. The spin stabilisation option is pruned because the satellite needs to be able to make measurements continuously. Double gimbal Control Moment Gyros (CMGs) are also not a viable option, because they are too complex and heavy compared to the other systems. For the attitude determination the initial measurements and magnetometers options are eliminated because of their low accuracy over time. The pruned design option tree can be found in figure 5.1 on page 19.

5.2 Orbit Characteristics

The orbits are determined depending on the characteristics of the payload. Because the payload uses a low power laser this means that the orbits will have to be Low Earth Orbit (LEO) in order for the laser to get any photons to the receivers. The resulting design option tree can be found in figure 5.2, page 20. Further pruning is not possible without a detailed analysis of the remaining options — which will take place in the tradeoff.

5.3 Electrical Power System

In the next section the design option tree for the Electrical Power System (EPS) will be pruned. The design option trees for the power source, storage, distribution and regulation and control will be dealt with individually in sections 5.3.1, 5.3.2 and 5.3.3 respectively.

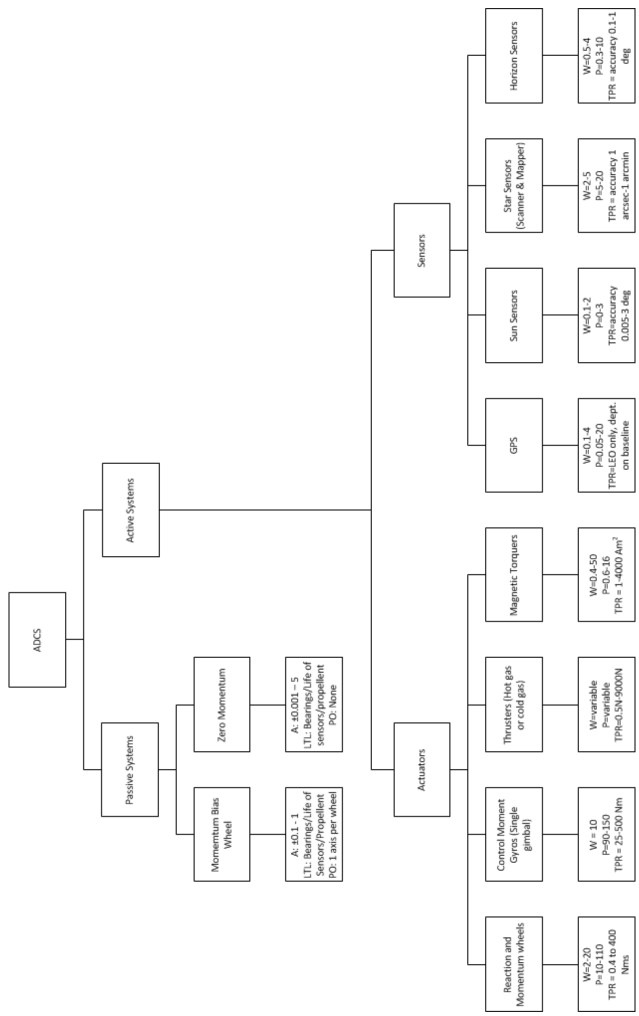

Figure 5.1: Pruned design option tree for the ADCS

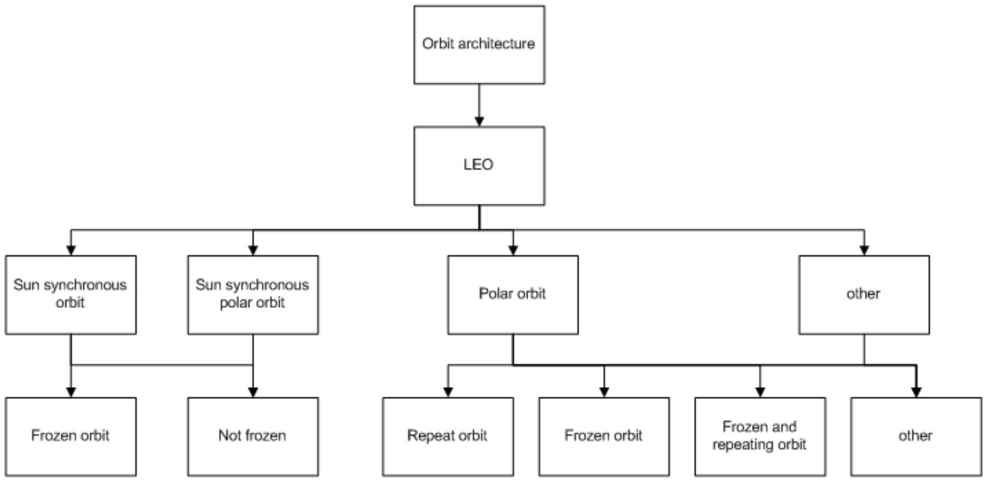

Figure 5.2: Pruned design option tree for the orbit characteristics

5.3.1 Power Source

Fuel cells have a high specific energy density but were not taken into account as a feasible power source because the amount of reactant they would have to bring for long term mission is too large for microsatellites. Primary batteries were equally unfeasible because of their limited lifetime, which is in the order of minutes to months. Radio isotopes and nuclear fission reactors were discarded because of their high cost and low specific power, as were thermionic and thermoelectric conversion for static power sources. This leaves photovoltaics and concentrated solar radiation together with an engine in a thermodynamic power cycle.

The pruned design option tree for the powersource can be seen in figure 5.3

5.3.2 Power Storage

The only obvious candidate for power storage was secondary batteries because, as mentioned before, the lifetime of primary batteries is too short. Of the most common secondary batteries, sodium-sulfur batteries are not an option for us because their operating temperature at 350 degrees Celsius is too high.

The pruned design option tree for the powersource can be seen in figure 5.4

5.3.3 Power Distribution, Regulation and Control

For the power distribution, regulation and control there were no obvious non-candidates. Because the power distribution, regulation and control depend on the type of power source, which depends on the payload power requirements, pruning will be done later on after these subsystems have been chosen — this is done in the tradeoff.

The design option tree for the powersource can be seen in figure 5.5

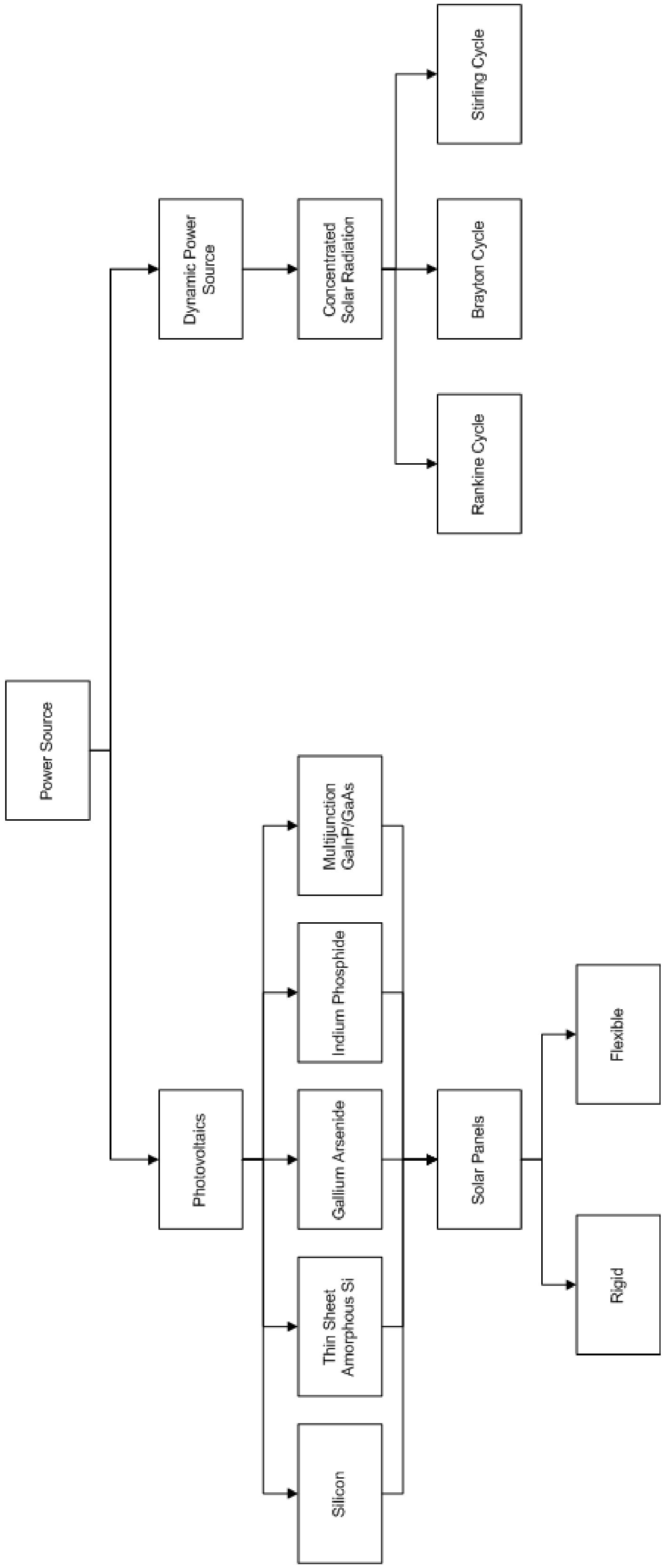

Figure 5.3: The pruned design option tree for the power source

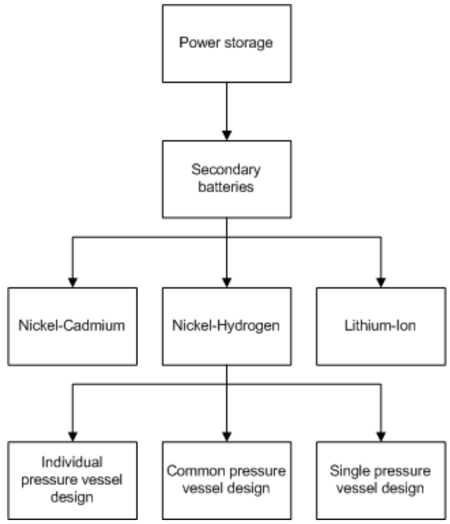

Figure 5.4: The pruned design option tree for the power storage

5.4 Receiver Eliminate

In the design option tree, the GLAS branch is obviously dropped out, since we are trying to improve the whole concept. Meanwhile, the Micro Photon Device (MPD)'s single-photon detection modules branch has different quantum efficiency for different wavelength. Which means MPD can be used as green laser detector with 49% efficiency but it is eliminated for infrared laser with approximate 1% efficiency. The "32x32-Pixel Array with In-Pixel Photon Counting" could be a new approch since............

The pruned design option tree for the laser detector can be seen in figure 5.6.

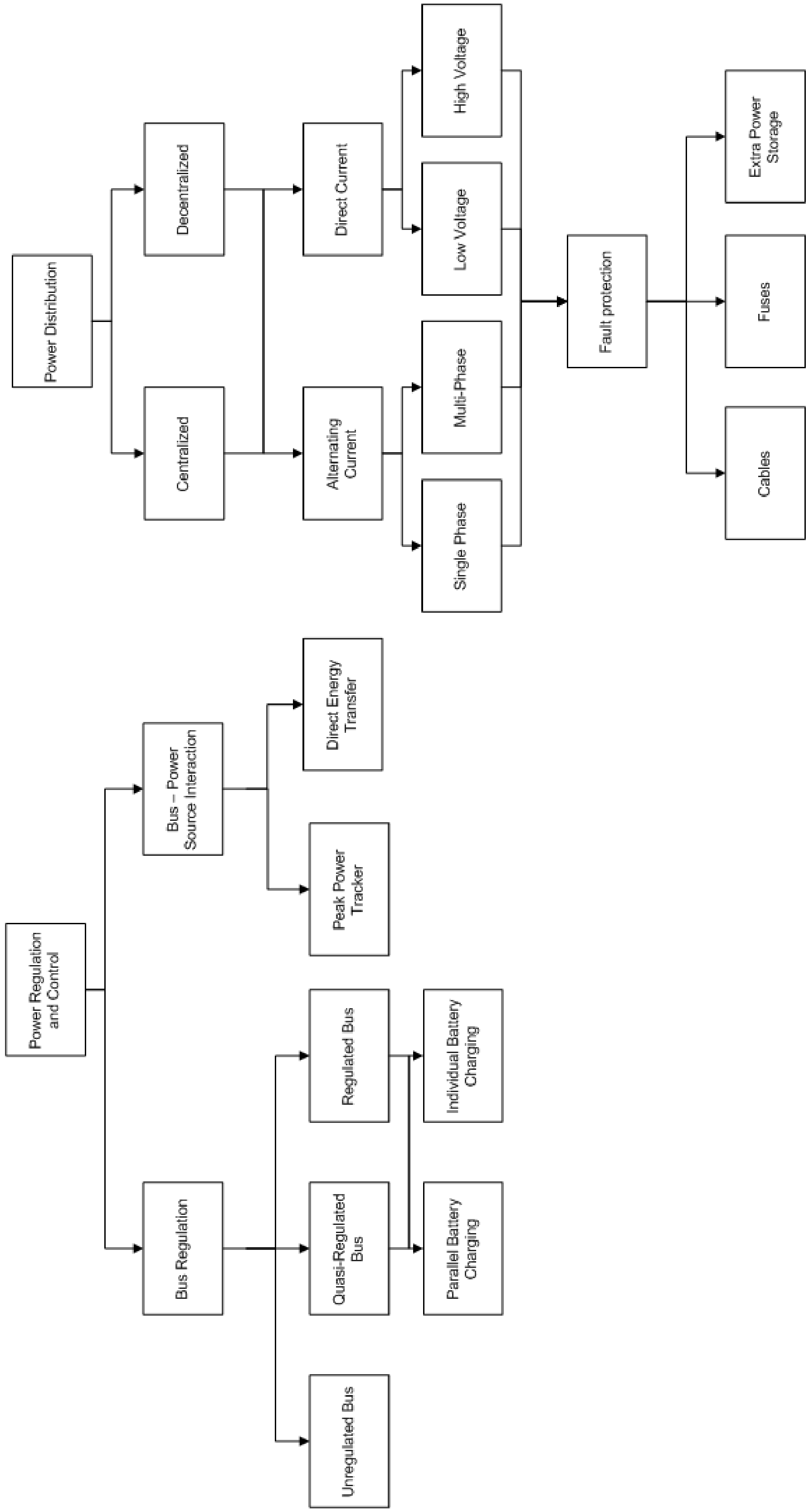

Figure 5.5: The design option tree for the power distribution and regulation and control

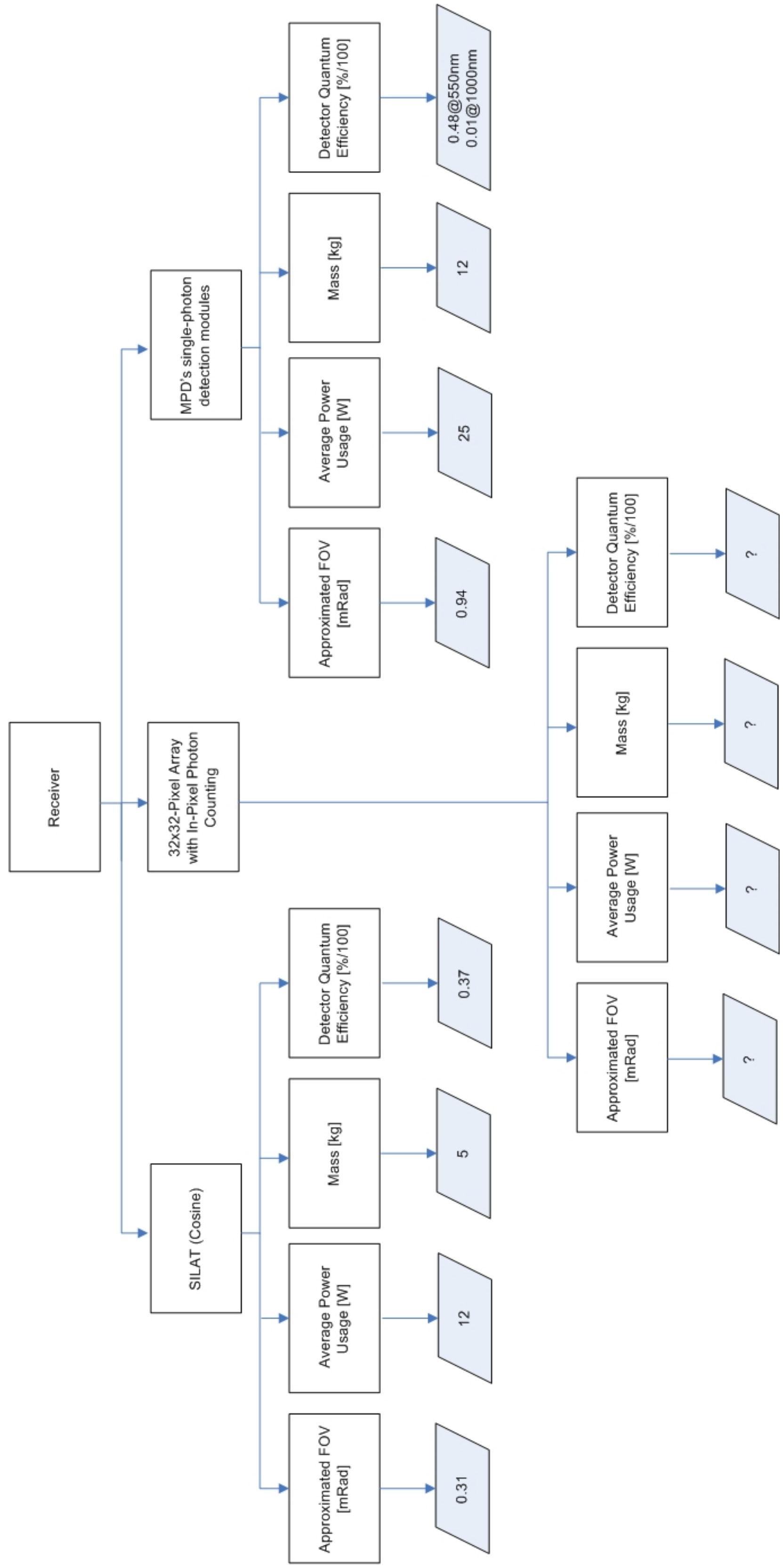

Figure 5.6: The pruned design option tree for the Laser receivers

Chapter 6

Sustainable Development Strategy

In this chapter a Sustainable Development Strategy is discussed in the order of production (section 6.1, page 25), operations (section 6.2, page 25) and end of life (section 6.3, page 26).

6.1 Production and Logistics

The design is aimed at a swarm of mostly identical satellites. This may allow for series production which is more efficient in terms of resources than a one-of large satellite with a lot of unique components. This also implies that the number of different spare parts could be reduced. Smaller satellites could also use smaller facilities for production and testing.

Transportation can be split up into two parts: transportation to the launch site and the launch from the surface to the final orbit in space. On both occasions the system can again profit from its small size. If the satellites are not launched all together, they can piggyback on another satellite's launcher.

Spreading the swarm, i.e. piggybacking using different launchers, has several advantages. First of all the emissions are lower than in case of a dedicated launcher. Also, if the first satellite fails before the launch of the rest of the swarm, the others can be repaired and thus less resources are wasted.

6.2 Operations

Once in orbit, the satellite's influence on the Earth is very limited. The only real concern is the debris it leaves behind during launch and deployment, which can be dangerous to other satellites orbiting the Earth. The deployment mechanism however, which is responsible for most of the debris, is not included in this technical feasibility study. Later studies developing the ideas from this feasibility study should keep an eye on it, since more satellites could mean more deployment mechanisms and hence more waste. One aspect that can be dealt with is the efficient use of resources. The swarm can be designed in such a way that if one of the satellites fails a replacement satellite can be sent, whilst any remaining satellites can be reused.

6.3 End of Life

Each satellite will be at the end of its life if it cannot perform its function anymore. It is important that after the mission is over all satellites are removed from their orbit and burn up in the atmosphere so that they do not pose any danger to other satellites. Final decommissioning of the swarm will be more complex than for a regular satellite, since every individual satellite has to be decommissioned separately.

Appendix A

Gantt Chart