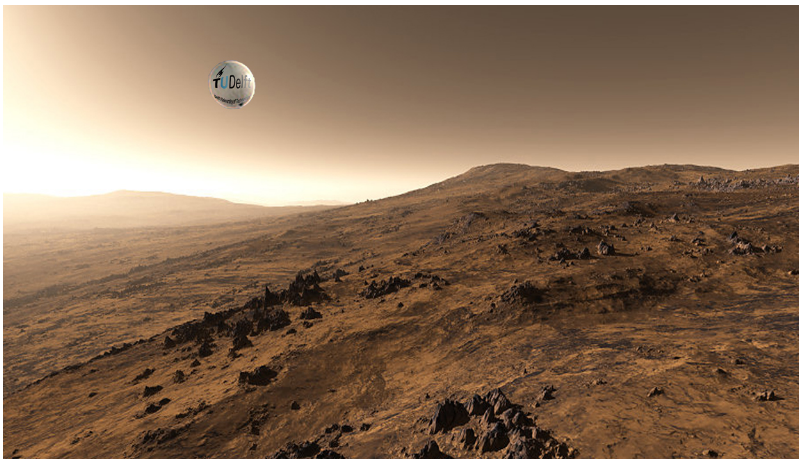
Delft2Mars Balloon

Baseline Report

Design Synthesis Exercise 2010



Author	*Student number*
B. Ashari	1366130
S. Boer	1365207
B. van Bruchem	1365223
N.H. Geschiere	1260871
A.Y.C. Naessens	1390120
E.M. Ras	1216252
J.R. Slob	1216376
F. Sluis	1261673
K. Tai	1357158
J.H.A. Wissink	1307118

Tutors and coaches
M. Menenti
R. Koenders
G.F. Brouwer
H.M. Jara Orue

April 29, 2010

Document management

Issue	Date	Affected pages	Brief description of change
1	29-04-10	all	Baseline report version 1.0

Contents

List of abbreviations

Abbreviation	Description
COSPAR	Committee on Space Research
COTS	Commercial off-the shelf
EDL	Entry descent landing vehicle
EDLS	Entry, descent and landing system
ESTEC	European Space Research and Technology Centre
FBS	Functional breakdown structure
FFD	Functional flow diagram
LLDPE	Linear low density polyethylene
MNS	Mission need statement
PEN	Polyethylene naphthalate
PET	Polyethylene terephthalate
RDT	Requirement discovery tree
RTG	Radioisotope thermoelectric generator
UHF	Ultra high frequency transceiver
UV	Ultraviolet radiation
UV-C	Type of ultraviolet radiation

Introduction

This report presents the results of the second project phase of the Delft2Mars Project: the baseline phase. The resource allocation and design option tree deliverables have not been included. They can not be created before the balloon concepts have been worked out, which has been planned for the next project phase. Instead, to facilitate concept creation, the system and mission analyses have been performed.

In chapter 1 functional analysis and requirement analysis is conducted, ultimately leading to the list of requirements. This list can be used to check the feasibility of the concepts that are created in the next project phase.

To facilitate the concept design during the next project phase, system and mission analyses are performed in chapter 2 and 3 respectively. The system analysis focuses on specific subsystems of the balloon, such as balloon dynamics, positioning, communication, and power. Here, preliminary calculations have been carried out to investigate how a balloon operates and to get a feeling of what a balloon is able to carry. The mission analysis contains information on possible mission concepts for the balloon, as well as a risk assessment for the complete mission, and information on sustainability. In the next project phase, the system and mission analysis will be used to support concept creation and trade-off. Where needed, it will be improved and extended in the following phases.

Chapter 1

Requirement and functional analysis

To get a basic overview of what the balloon system does on Mars, and how the system will function, several diagrams are shown and discussed in this chapter. First the functions of the balloon are visualised in the Functional Flow Diagram (FFD). The diagram will be explained and discussed. From this diagram the functions will be broken down in several parts. These parts are elaborated further, resulting in the Functional Breakdown Structure (FBS). Then the requirements will be visualised in the Requirement Discovery Tree (RDT). These requirements are not only based on the external constraints, given by the mission outline and created by the environment, but are also based on the functions the balloon will perform, which are extracted from the FFD and FBS. The three diagrams will be used as a guide in the design process.

1.1 Requirement discovery

To help discover all requirements, a Requirement Discovery Tree (RDT) was created (figure 1.1) by brainstorming about all possible problems the balloon could encounter. The tree is divided in two parts: namely the constraints and the functional requirements. The constraints represent requirements which are dictated by external factors such as the Mission Need Statement (MNS), the Martian climate, and the launch vehicle. The functional part represents the requirements which are a result of performing the mission.

1.1.1 Constraints

Constraints represent the external requirements to the mission. These requirements cannot be changed by changing the mission concept, and are therefore fixed. For the constraints, the following subdivision has been made:

- **Mission requirements**
  The MNS qualifies what the mission should do. If the mission does not perform according to the MNS it could be viewed as a failure. Therefore compliance with these constraints should be monitored carefully during the mission design phase. All items in this branch are directly derived from the MNS definition, sustainability requirements and cost requirements.

- **Launch vehicle compatibility**
  Before the balloon system is deployed on Mars it travels on a launcher. The balloon system should therefore be able to comply with all launcher requirements and loads. The balloon should not only have the right dimensions to fit in the launcher, but should also survive the loads present on the launcher. Furthermore, the balloon should be low-risk, meaning it should not pose any other threat to the launcher.

- **Martian environment**
  The last external constraint is the Martian environment. After deployment, the balloon should be able to withstand the harsh environment for the full mission duration. The balloon has to cope with thermal, radiative, and pressure loads. Also the composition of the atmosphere and wind profile should be treated as constraints.

1.1.2 Functional requirements

The functional requirements are dictated by the mission concept and the design of the balloon system. To prevent the RDT from becoming too limiting during the initial design phase, the tree is kept as generic as possible (i.e., neglecting additional constraints of the different mission concepts). The functional requirements can be divided into an operational and structural side:

- **Operations**
  The operation requirements are largely determined by the balloon abilities and instrument requirements. The balloon should be able to (re-)deploy, and rise to a specific altitude to allow for spatial and temporal change in measurements. All on-board systems should be able to function properly, so each of them has specific requirements. Power has to be supplied, the position of the balloon must be determined, and measurements have to be performed. Performing measurements also means sending data back to Earth, so the downlink is also a constraint. One should also consider the stability of the balloon, which could influence the measurements. Other operations of the balloon are hovering and of course the deployment.

- **Structural**
  Structural requirements are the requirements which are related to the construction of the balloon system, and which will be largely dictated by the design concept (tethered versus untethered). Important for the structural requirements, is that all loads can be handled without failure, and that the materials are able to withstand any additional constraints as a result of the design concept (on top of the Martian environment).

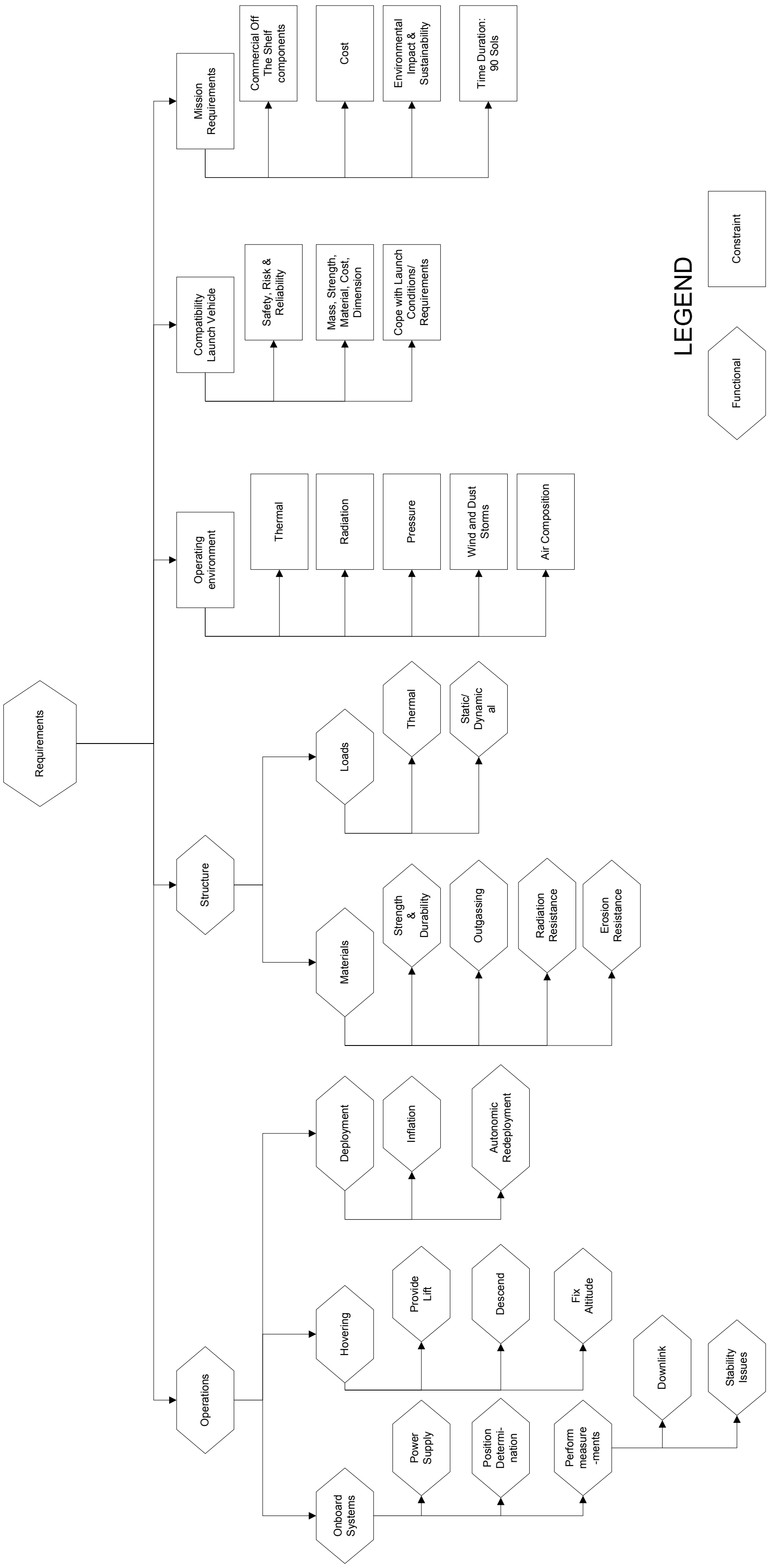


Figure 1.1: Requirements Discovery Tree

1.2 Functional flow diagram and description

The Functional Flow Diagram (FFD) is used to define the operational and support sequences for systems [47]. Here it has been used to map the flow of functions that the balloon system will perform during its active life on Mars.

As can be seen in figure 1.2 the functional flow diagram first lists the three top level functions of the balloon system. In order to keep the diagram readable the subdivision of the top level functions will be depicted in three separate diagrams, each diagram representing the subdivision of a top level function.

The top level function flow starts with the pre-measurement actions of the system that will be performed before the system becomes operational. Because deployment is not part of the operating phase (during which the measurements will be performed) this function has been classified as a pre measurement operation. Before the balloon system is deployed one will have to make sure that all systems are functioning as they are supposed to in order to prevent loss of sensors and damage being done to the system during critical phases like deployment and start-up of the system. The instruments and systems on-board the balloon system will be checked one by one and then contact will be established between the balloon system and the relay satellite or Entry, Descent and Landing System (EDLS). If not all systems and instruments react as required the system will be started again in order to try and get everything working, this has not been incorporated in the flow diagram to maintain oversight and clarity. Should restarting the system fail to fix all problems the mission may have to be cancelled or be continued in a limited form, depending on the importance of the broken subsystem or instrument.

After all system are up and running, the deployment of the balloon system follows. This is depicted in the second function level in figure 1.2. First the EDLS will be opened, then the balloon will be inflated after which the ground calibration will be performed. Because the ground calibration has to be done in the Martian atmosphere the EDLS will be opened so that the sensors will gather data of the outside atmosphere and not of the atmosphere as influenced by the EDLS. However the balloon will be inflated first before the calibration will be performed, this is done to ensure the calibration circumstances closely resemble those of the actual mission (to include for example the influence of the temperature of the gasses). Note that every step in the second level of the functional flow diagram incorporates checks to ensure that all functions have been performed satisfactorily. This is not shown in the diagram to maintain oversight.

When the calibration has been performed the balloon and payload will be released so that the sensor package will be lifted into the Martian atmosphere. The calibration consists of the first measurement (calibration measurement), sending these values and then storing this reference data. The first measurement will serve as the reference for the other measurements hence it is sent to the relay station and then set as reference value in the system. Calibration data is sent to Earth from the relay satellite, so one can check whether the sensors are functioning as required or not.

After deployment the operation of the balloon system starts, this is shown in figure 1.3. The operational mode comprises most of the system's life cycle. In order to know at what position, altitude and attitude the measurements have been done the attitude and altitude of the balloon will have to be determined, so this is done first and then stored. Then the measurements will be performed and the resulting data is labelled with the measurement position and altitude. Depending on whether the relay station, EDLS or an orbiting relay

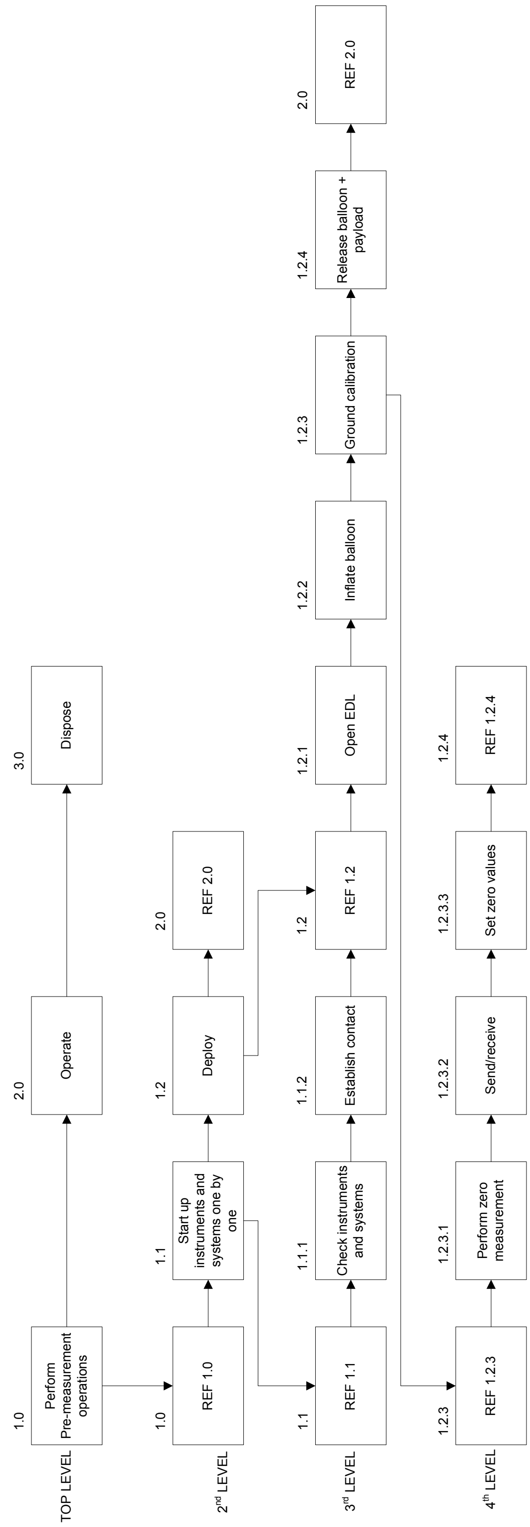


Figure 1.2: Functional Flow Diagram part 1. The rectangular blocks represent functions, each level gives a different example of functional flow paths. The numbers above the rectangles indicate (sub)function numbers.

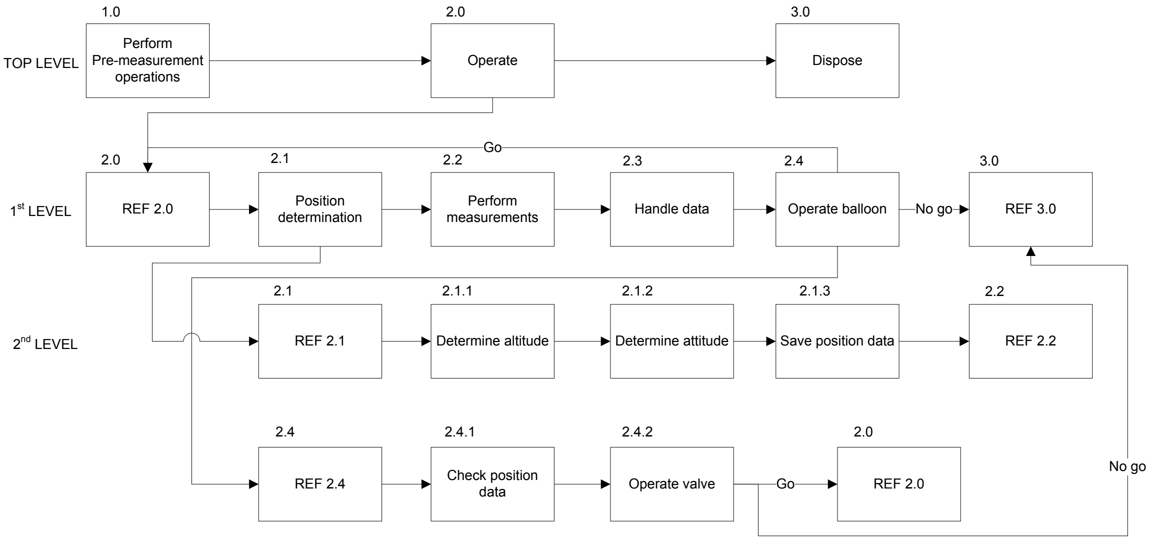


Figure 1.3: Functional Flow Diagram part 2. The rectangular blocks represent functions, each level gives a different example of functional flow paths. The numbers above the rectangles indicate (sub)function numbers.

satellite can be contacted the data will be stored on-board or transmitted, this is summarized in the "handle data" function. The following function concerns the operation of the balloon, because now the position of the balloon is known and a measurement has been performed at this location. Should the position, altitude and attitude of the balloon have to be adjusted this is done here. After the balloon has been operated the system may go on gathering data or the measurements stop and the disposal of the system is initiated.

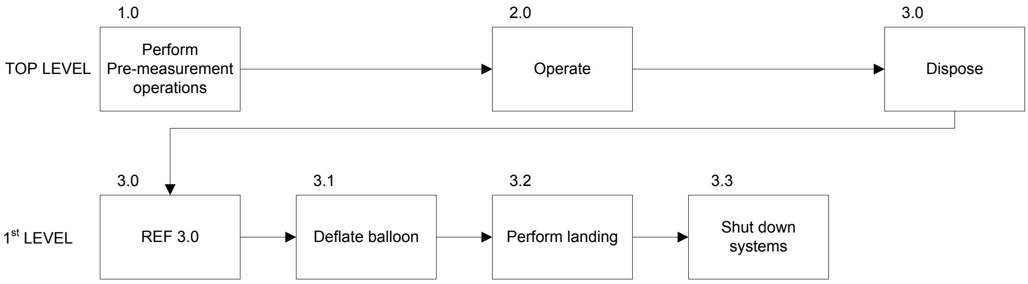


Figure 1.4: Functional Flow Diagram part 3. The rectangular blocks represent functions, each level gives a different example of functional flow paths. The numbers above the rectangles indicate (sub)function numbers.

The last function to be performed is the disposal of the balloon system, see figure 1.4. At the end of the life cycle, when there is insufficient power generated or the system is critically damaged, the system itself will initiate its disposal. To minimise the impact on the Martian environment, in accordance with the Planetary Protection Policy [33], the balloon will be brought back to the surface of Mars without crashing.

1.3 Functional breakdown structure

The functional breakdown structure shows the functions needed to support the exploration of the Martian atmosphere. In figure 1.5 the functional breakdown structure is shown for the balloon mission. The functional breakdown structure was created by combining the operational aspects of the functional flow diagram (section 1.2) and requirement discovery tree (section 1.1). The breakdown structure is divided into two parts: instrument support and instrument operation.

1.3.1 Instrument support

First the instrument support side on the left side of figure 1.5 is discussed. All third level functions are numbered below as they are in figure 1.5. Lower level functions underneath third level functions are described within the numbered functions in the list below.

1. **Start-up and check systems**
   Before the balloon can be deployed and the measuring can begin, start-up and verification of all systems need to be performed.

2. **Determine position and attitude**
   To be able to link measurements with a position, the position needs to be determined. Depending on the instrument requirements, also the attitude may be of value. Determining the position and attitude consists of reading the relevant instruments, and processing the results. Processing could involve calculating the weighted average position, or correcting measurement errors.

3. **Provide communication**
   The system should provide both communication with the EDL (e.g. for opening the shell), and communication with Earth (e.g. for sending measurement data). Important for communication is that reception is provided during contact moments. Also, the communication subsystem should provide error correction and tele-command verification to ensure error free communication.

4. **Provide electrical power**
   To deliver electrical power to al instruments. The power distribution is present to connect all instruments to the power regulation which receives power from the power generation source.

5. **Provide monitoring**
   To detect problems or errors early, the balloon system needs to be able to monitor system parameters and report possible problems.

6. **Handle data**
   Data which is created by the instrument package needs to be compressed and transmitted to Earth. As there is no continuous connection with Earth, data needs to be saved intermediately. Possibly, data created by the instrument needs to be processed before they can be transmitted.

7. **Lift payload**
   Obviously the instrument package needs to be lifted by the balloon. After the EDL has landed the balloon needs to be inflated and released. After release, the balloon will control ascent, descent, and re-ascend in the case of a grounding of the balloon.

8. **Provide disposal**
   The balloon needs to be disposed properly. This requires the system to deflate the balloon and shutdown all systems.

9. **Provide suitable environment**
   The system needs to withstand mechanical and thermal loads. Also, safety and reliability are an issue.

1.3.2 Instrument operation

The functions in this category are related to the science aspect of the mission and can be found on the right side of figure 1.5. As before levels below third level are described in the third level description numbered as in the figure 1.5.

10. **Calibrate instruments**
    Before instruments are used, they need to be calibrated. This can be performed either on Earth or on Mars. The calibrating is performed by comparing instrument output to a known reference, possibly adjusting the instruments, and then setting the calibration values.

11. **Perform measurements**
    Performing measurements is done by sampling all instruments and tagging the results with position and time values. The sampling interval could be different for each instrument.

1.4 List of Requirements

The list of requirements can be set up easily using the Requirement Discovery Tree (RDT) as a powerful tool. From the RDT, one can divide the requirements in constraints and functional requirements. The difference between the two is that the constraints are formed by external factors, like the operating environment, launch vehicle requirements and of course the mission requirements. These external factors are fixed, no matter how the mission changes. The functional requirements however, are based on design options. The requirements depend, among other factors, on what measurements the balloon will perform and what shape it will have. From both the constraints and functional requirements one can set up a list of requirements:

- The balloonsystem provides sufficient power for the on board systems to function properly
- The balloonsystem is able to determine its position for communication and measurement.
- The balloonsystem has to perform measurements. To perform these measurements two sub requirements are necessary:
  - The balloonsystem has a downlink budget sufficient to support the data transfer produced by the instruments.
  - The balloonsystem has sufficient dynamic and static stability to support correct measurements.

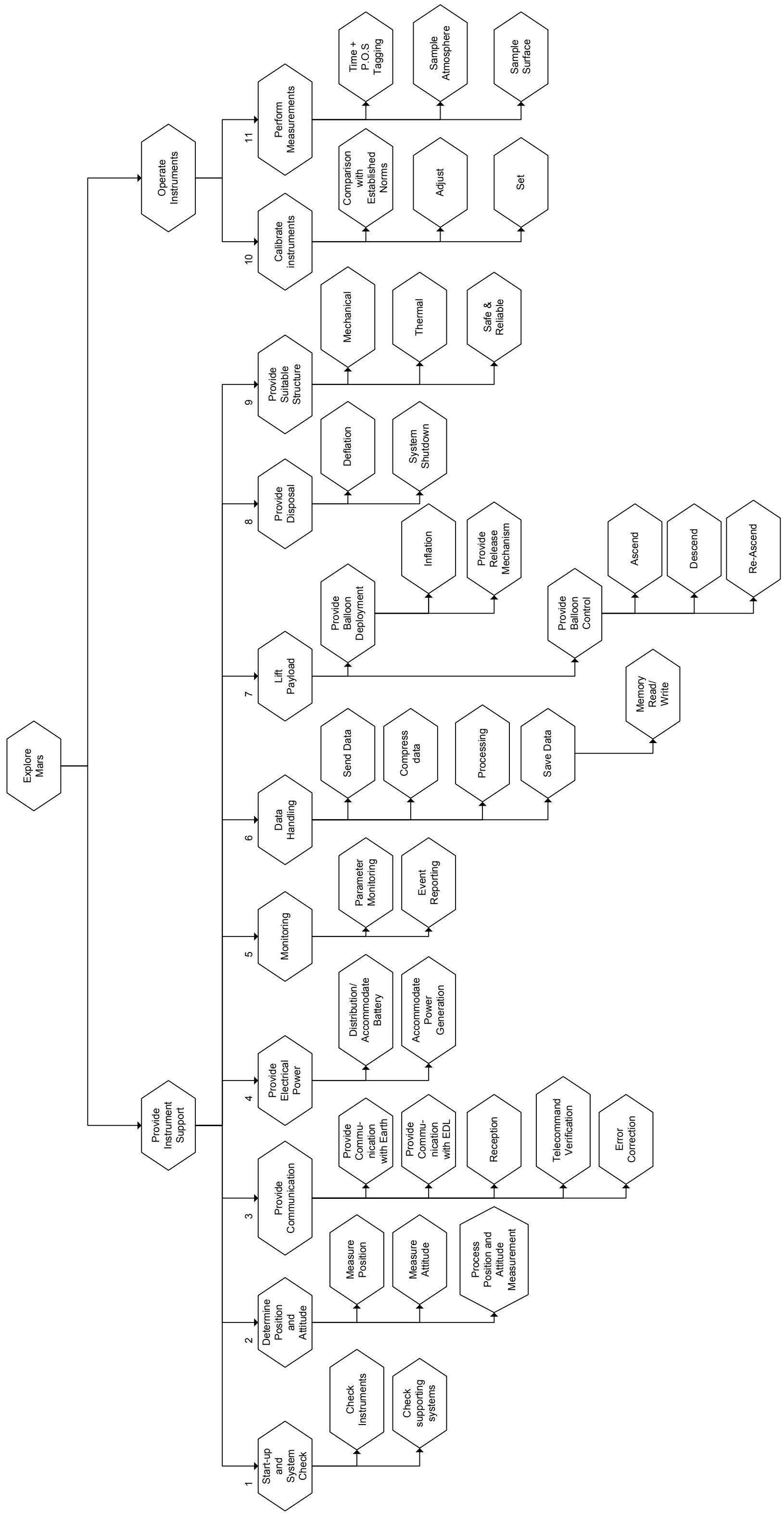


Figure 1.5: Functional Breakdown Structure

- The balloon is able to hover in the air:
  - The balloon can provide lift.
  - The balloon is able to descend.
  - The balloon can be fixed at a desired altitude.
- Considering deployment:
  - The balloon is able to inflate.
  - The balloon possesses the ability to redeploy in an autonomic way.
- The balloon is able to survive the harsh Martian environment:
  - The balloon prevents out-gassing.
  - The balloon material can resist strong radiation.
  - The balloon material is corrosion resistant.
  - The balloon material should not degrade due to the atmospheric composition of Mars.
  - The balloon should withstand thermal loads.
  - The balloon should withstand static loads.
  - The balloon should withstand dynamic loads.
  - The balloon is able to cope with the extreme low pressure conditions on Mars.
- The balloonsystem is compatible with the launch vehicle:
  - The balloonsystem is low risk, safe, reliable and should not interfere with other launcher payload.
  - The mass of the balloonsystem is within the required constraints of the launcher.
  - The balloonsystem should survive the loads imposed during launch.
  - The dimensions of the balloonssytem are compatible with the launcher.
- The balloon complies with the mission requirements:
  - To keep the project costs low, the balloon uses Commercial Off The Shelf (COTS) components
  - The balloon system should not cost more than 1 million dollar.
  - The impact of the balloonsystem on the Martian environment should be minimised and the system should be sustainable.
  - All requirements in the list should be accomplished at least for 90 Martian days (sols).

Chapter 2

System Analysis

The balloon system consists of numerous subsystems. This chapter analyses the different subsystems. Also the Martian environment is discussed in section 2.1. Next the balloon dynamics are described in section 2.2 after which section 2.3 discusses the different substances capable of lifting the balloon. Balloon configurations and materials follow in section 2.4. Next, section 2.5 treats the feasibility of a tethered balloon. Section 2.6 subsequently discusses altitude and position determination. Communications are treated in section 2.7. After communications the power subsystem is reviewed in section 2.8. And finally the thermal subsystem is discussed in section 2.9. The design options in this chapter are still a work-in-progress, yet they give an indication of the progress made.

2.1 Martian environment

This section treats the Martian environment briefly on the basis of earlier research and data. The parameters in the table are discussed below in the text.

Table 2.1

Parameter	Min	Avg	Max	Unit
Gravitational acceleration [27]		3.73		[m s^{-2}]
Temperature [13]	125	218	320	[K]
Air density[1] [6]		0.015		[kg m^{-3}]
Pressure[2] [23] [13]	10		890	[Pa]
Wind velocity [29]		3	10	[m s^{-1}]
Light intensity [36] [31]	493	590	718	[W m^{-2}]
UV [31]		50		[W m^{-2}]
Magnetic field[3] [30]	1	25	>100	[nT]
CO_2 [34]		95.3		[%]
N_2 [34]		2.7		[%]
Ar [34]		1.6		[%]
O_2 [34]		0.15		[%]
CO [34]		0.07		[%]
H_2O [34]		0.03		[%]

The temperature differences in table 2.1 are the maximum differences. The differences are smaller during the Martian summer and vary between 180 and 295 K [29]. This is still a very large difference and most subsystems will have to be protected using a thermal control system. As the thermal inertia is very low on Mars, objects will heat up and cool down very quickly.

The air density of 0.015 kg m^{-3} will decrease with altitude as it does on Earth, and it is dependent on the pressure and temperature, which in their turn are dependent on the altitude.

The pressure and the density vary greatly with altitude, and are given by a model built by NASA. [9] Compared with Earth, the pressure on Mars is extremely low, around 700Pa on the surface which is about 0.7 % of the Earth's surface pressure.

Wind can be very violent on Mars with velocities up to 100 m s^{-1}. During the summer the wind velocity is mostly limited and typically has values not over 10 m s^{-1}. Wind velocity does however greatly vary during the day with minima during the night time and maxima during the day [29]. In combination with dust the wind can form dust devils, which could cut off the power supply of the balloon if solar energy would be used. The wind also provides the general heat circulation on the planet.

Light intensity depends on the distance from the sun. For Mars this means that the lowest light intensity is 493 W m^{-2}, measured when the distance from the Sun is at its maximum. The greatest light intensity which can be measured is 718 W m^{-2} [31] but for calculation purposes the mean value of 590 W m^{-2} is used [36].

The intensity of ultraviolet (UV) light was recently estimated at 50 W m^{-2} [31]. The atmosphere of Mars does not filter UV-C light. This type of UV radiation damages organic matter heavily[2].

On Mars a very small magnetic field strength can be measured which is negligible with respect to that from Earth. A sharp increase in magnetic field strength can be measured around 30°N, where the terrain is heavily cratered. At 30°N values which are more than four times as high as average can be measured. It is unlikely that this area will be the landing site of any of the coming missions [30].

The composition of the atmosphere is dominated by large concentrations of CO_2, there are however small amounts of O_2 and H_2O. Furthermore there are traces of methane and ozone [34]. The composition is determined around the landing site of the Viking I mission which could be comparable to the landing sites of future missions.

[1] Calculated with a temperature of 218 K and a pressure of 620 Pa

[2] Variation from 0 to 30 km altitude and during a Martian year, pressure at ground level varies between 690 and 890 Pa

[3] The peak values of >100 nT are mainly focussed around 30°N which roughly coincides with heavily cratered and very old terrain which will not be our landing site.

2.2 Balloon dynamics

This chapter of the report focuses on the most important forces working on a balloon. The first of the following two sections will describe the main equations used to calculate forces that work on the balloon. Furthermore, some general figures for the variables in these formulas are given. Several assumptions are made to give some general figures of these variables.This is done in order to give the reader a general overview of balloon dynamics and to simplify these initial calculations. Some of the simplifications made during the calculations in this section will be elaborated upon later in this report. The second section of this chapter will show some examples of calculations of forces that will act on the balloon in the case the balloon will be tethered and in the case it will not be a tethered.

2.2.1 Forces acting on a balloon

There are three main forces acting on a balloon [39]. The first of these forces is obviously the buoyancy force. The second main force that works on the balloon is gravity. Finally, the drag of a balloon in a wind flow plays a major role in balloon dynamics. The following subsections will describe these forces one by one.

Buoyancy Force

The buoyancy force that works on a balloon filled with gas originates from a difference in density between the gas contained in the balloon and the density of the outside atmosphere. The following equation describes the buoyancy force in zenith direction.

$$B_z = (\rho_b - \rho_a) V_b g_0 \tag{2.1}$$

where B_z is the buoyancy force in Newton in Z direction (positive upwards), ρ_b is the density of the gas in the balloon in kilogram per cubic meter, ρ_a is the density of the atmosphere in kilogram per cubic meter, V_b is the volume of the balloon in cubic meters and finally g_0 is the gravity in meters per second squared.

The first unknown one encounters in equation (2.1) is the density of the gas in the balloon. The density of a gas on Earth is different than the density of this same gas on Mars. Therefore, it is necessary to find a method to calculate the density of any gas on Mars. An easy way to do this is to directly use the equation of state. The most simple calculation is done using the relation below.

$$\rho = \frac{MP}{RT} \tag{2.2}$$

where ρ is the density in kilogram per cubic meter, M is the molar mass of the gas in gram per mole, P is the local pressure in Pascal, R is the universal gas constant and T is the temperature of the gas in Kelvin. As this section is just meant to give a rough estimation of forces acting on a balloon, the temperature and pressure and hence the density of the gas inside the balloon are considered constant. The Martian atmosphere is assumed to have a pressure of 762 Pascal and a temperature of 238 Kelvin [43]. This will also approximately be the pressure and temperature of the gas inside the balloon. For now, the assumption is made that the balloon is filled with the gas helium. Helium is chosen as the buoyant gas for this initial estimation because it is a frequently used gas for balloons and blimps used on earth today. Helium has a molar mass of 4.003 gram per mole [50]. The gas constant R is equal to 8.413 $(J)/(K \cdot mol)$ If equation (2.2) is now plugged in with the values defined

in this paragraph, the result is a balloon gas density ρ_b of $1.54 \cdot 10^{-3}$ kilogram per cubic meter.

The second unknown variable in the buoyancy equation is the density of the atmosphere on Mars. The density of the atmosphere on Mars is taken as constant at a value of $0.015 kg/m^3$ [6] for now. The actual value of the density of the Martian atmosphere depends on several factors such as altitude, but those factors are neglected in this initial calculation.

The last of the unknowns in the equation of buoyancy is the gravity g_0. The value of g_0 will be taken as a constant equal to 3.73 meter per square second in the initial calculations [21]. In the experience of the group of authors of this report it is not necessary to take the change in gravity with height or location into account in initial estimations like this one, since the value is insignificantly small. The value of g_0 could later be replaced with an actual estimate of the gravity on Mars if this appears to be necessary after all.

Gravity force

The second force that works on the balloon is not a very complicated one. The gravity force works in nadir direction and is described by

$$W_z = -m_{tot} g_0 \tag{2.3}$$

where the gravity force W_z is in Newtons, the value of the total mass of the balloon system including payload is m_{tot} in kilogram and the value of g_0 is the gravity constant in meter per second squared. The gravity force W_z in Newton shall again be estimated by taking an average value for g_0 following the same reasoning as in the previous paragraph.

The mass of a free balloon will consist out of the mass of the payload M_p and the mass of the balloon M_b, both in kilogram. First of all, the mass of the balloon is calculated. Then, the difference between buoyancy force and gravity force of the balloon mass will be looked at, to get an indication of buoyancy force left to carry the payload. The mass of the balloon is mainly dependent on the area of the skin and thus scales with the following relation:

$$A_b = 4 \cdot \pi \cdot r_b^2 \tag{2.4}$$

where the value of A_b is the area of the balloon material in square meters and r_b is the radius of the balloon in meters. For this initial calculation it is assumed that the material that the balloon is made of is polyethylene film with a thickness of 20 micron and a density of 918 kg/cm^3. These values are taken from a material used in previous experiments by other institutions for balloon tests in the earth's stratosphere [37]. The density of the material is extracted from a data sheet of a producer of polyethylene film LLDPE [42]. Using this data, the weight of the polyethylene skin constitutes to a mass of $M_b = A_b \cdot t \cdot \rho_{skin}$ where t is the thickness in metres and W is the weight in Newton. When plugging in the values of density and thickness into this equation the result is:

$$m_b = A_b \cdot t \cdot \rho_{skin} = A_b \cdot 20 \cdot 10^{-6} \cdot 918 = A_b \cdot 0.0184 \tag{2.5}$$

This function can now be used to calculate the mass of the balloon as a function of the surface area.

Drag force

A final important force to consider in these initial calculations is the drag force. The general equation to calculate drag force is described below.

$$D = -\frac{1}{2} C_d S_b (V_a - V_b)^2 \tag{2.6}$$

where D is the drag in Newton, C_d is the drag coefficient in the direction of the wind flow, S_b is the frontal area of the balloon in the direction of the wind flow, V_a is the velocity of the wind and V_b is the velocity of the balloon.

The drag coefficient will be guessed for this initial calculation. An initial guess of the drag coefficient will be based on the drag coefficients of some common shapes. The Delft2Mars balloon is assumed to have a spherical shape in this initial calculation. The drag coefficient of a sphere is approximately between 0.07 and 0.5 [10]. A drag coefficient of $C_d = 0.2$ will be taken as an initial 'educated guess'. One should note that the drag coefficient of other possible shapes, such as the typical shape of a blimp or Zeppelin, can be just fractions of the drag coefficient of a sphere if designed properly. The frontal area S_b of the balloon will be estimated by assuming a spherical shape. The frontal area can now easily be calculated using the equation

$$S_b = \pi \cdot r_b^2 \tag{2.7}$$

where r_b is the radius of the balloon.

Finally, the values of the velocities of the atmosphere V_a and balloon V_b should be estimated for a relatively bad Martian weather scenario. This should be done in order to be able to make a more accurate calculation of the required cable strength later on in the report. After some initial research done within the group, it appears that 100 meters per second is not a very rare wind speed at Mars [29], and shall therefore be taken as a reference for now. More detailed estimations on this wind speed are definitely required later on in this project.

From this point on it is good to notice that there are two completely different design concepts possible in this project from a dynamic point of view. When the choice is made that the balloon should be tethered, the average velocity of the balloon V_b can now be assumed to be generally (on average) equal to 0 m/s. This would mean that the relative velocity of the balloon with respect to the atmosphere is very large, that the drag force will have a major impact on the forces working on the balloon and that further calculations are likely to show that a strong structure is needed to keep the balloon in place. If, however, the choice is made to have a free balloon, this force will not cause any structural problems.

2.2.2 Samples of calculations

This section is meant to give the reader an insight of the forces that work on a balloon in the Martian atmosphere. Two different cases will be presented. One will show a rough calculation of the forces acting on a non-tethered balloon, and the other will show calculations of a tethered balloon.

Non-tethered balloon

This section shows the calculation of the forces on a non-tethered balloon as an example calculation. The initial calculations on a non-tethered or 'free balloon' are easier than the

calculations on a tethered balloon, and shall therefore be done first. This calculation will show the forces acting on a 1000 cubic meter balloon by using the equations described in the previous sections. From some previous estimation calculations, 1000 cubic meter seemed to be around the minimum volume required to be able to give a substantial lifting force. First, the buoyancy force of 1000 m^3 is calculated using the buoyancy equation (2.1).

$$B_z = (\rho_b - \rho_a)V_b g_0 = (0.02 - 0.00154) \cdot 1000 \cdot 3.73 = 68.9N \quad (2.8)$$

Secondly, it is necessary to calculate the radius and area of the skin of the balloon using equation

$$r_b = (\frac{3}{4}\frac{V}{\pi})^{1/3} = 6.200m \quad (2.9)$$

followed by the calculation of the skin area using equation (2.4)

$$A_b = 4 \cdot \pi \cdot r^2 = 483.1m^2 \quad (2.10)$$

Now the skin weight and consequential gravity force will be calculated. Equation (2.11) can be used now.

$$m_b = A_b \cdot 0.0184 = 484.1 \cdot 0.0184 = 8.91kg \quad (2.11)$$

Now it is necessary to calculate the downward force caused by the mass of the balloon using the following relation.

$$N_b = g_0 \cdot m_b = 3.73 \cdot 8.91 = 33.2N \quad (2.12)$$

Finally, the lift remaining to lift the payload is the difference between the buoyancy force and the downward force caused by the weight of the skin.

$$N_p = B_z - N_b = 68.9 - 33.2 = 35.7N \quad (2.13)$$

This force will now be translated to a weight in kilograms in order to give a clear image of how much payload the balloon can carry on Mars.

$$W_p = \frac{N_p}{g_0} = \frac{35.7}{3.73} = 9.57kg \quad (2.14)$$

This calculation shows that a $1000m^3$ free flying balloon filled with helium can carry a payload of approximately $9.57kg$ when flying in the Martian atmosphere.

Some important precautions should be taken when considering the validity of this calculation. First of all, it has appeared that the thickness of the balloon material has a great impact on the amount of buoyancy left for lifting a payload. If the skin thickness is increased, the point at which the 1000 m^3 balloon will not even be able to carry it's own weight quickly approaches. Secondly, the type of gas used in the balloon will also have a major impact on the lifting force. Later on in the report this will be shown in more detail.

Tethered balloon

For the initial calculations for a tethered balloon, the 1000 m^3 balloon with the exact same properties will once again be taken as an example. In this example, the balloon will now be tethered to the ground by a Dyneema cable. The properties of Dyneema cable are 3.5 GPa

strength and a density of 970 kilogram per cubic meter. Later on in this report more details will be given on the different materials available to tether the balloon to the Martian ground and sources of the previously mentioned Dyneema properties.

This calculation starts where the previous calculation ends. It is already known that the balloon can lift approximately 9.57 kilogram. As a start, the forces caused by the relative wind speed are calculated. Afterwards, calculations will be shown in order to give the reader a feeling of the possibilities and constraints related to tethered balloons.

The drag force on a balloon is calculated using equation (2.6).

$$D = -\frac{1}{2}C_d S_b (V_a - V_b)^2 = -\frac{1}{2}0.2 \cdot 121 \cdot (100 - 0)^2 = 1814N \quad (2.15)$$

where the value of S_b is calculated as being the area of a circle with the radius of the balloon. Iterations done before the writing of this report have shown that it is instructive to use a cable of 2 millimetre diameter and 1000 meter length in order to give a good indication of cable strength and weight. The yield strength of a cable can be calculated using the equation

$$F_y = \sigma_y \cdot A_c \quad (2.16)$$

where F_y is the yield strength of the cable in Newton, σ_y is the yield stress in Newton per square meter and A_c is the cross-sectional area of the cable in question. Now equation (2.16) will be plugged in with the values mentioned before.

$$F_y = \sigma_y \cdot A_c = 3.5 \cdot 10^9 \cdot 3.15 \cdot 10^{-6} = 11.0 \cdot 10^3 N \quad (2.17)$$

The weight of the cable in question will be

$$W_c = V_c \cdot \rho_c \quad (2.18)$$

where W_c is the weight of the cable in kilogram, V_c is the volume of the cable in cubic meters and ρ_c is the density of the cable in kg/m ^{3}. The density of Dyneema is 970 kilogram per cubic meter, as mentioned before. The volume of the cable is calculated by multiplying the area of the cable by the length of the cable. In this case, the result is thus $3.14 \cdot 10^{-3}$ m ^{3}. The result of equation (2.18) is now

$$W_c = V_c \cdot \rho_c = 3.14 \cdot 10^{-3} \cdot 970 = 3.05kg \quad (2.19)$$

This would mean that the resulting buoyancy force left to carry payload is now

$$W_p = W_{p,free} - W_c \quad (2.20)$$

where W_p is the weight of the balloon in kilogram, $W_{p,free}$ is the weight the free balloon can carry in kilogram and W_c is the weight of the cable. It turns out that the balloon can now carry 6.51 kilogram.

These initial calculations show that it is feasible to have a tethered balloon at Mars. Even with wind speeds of up to 100 m/s, the Dyneema cable will be able to stand the forces that will occur. It should be noted that Dyneema might have disadvantages related to very low shear strength, meaning a coating could be necessary. This coating will greatly increase the weight of the cable per meter. More on this can be read in the section on cables. Secondly,

it should be noted that it could turn out that a 1000 meter long cable does not reach far enough to gain purposeful measurements of the Martian atmosphere. In this case, the cable length might have to be increased to lengths up to several multiples of the length assumed here. Thirdly, more research has to be done on the change in density with altitude. This calculation is based on the preliminary assumption that the density of the atmosphere is constant. If there is a large density gradient in the Martian atmosphere, it could appear that the forces on the cable will be lower due to a lower drag force. Finally, in this calculation two small fractions of additional forces on the cable are neglected. These are the force caused by the cable's own weight onto itself as well as the tensile force caused by the buoyancy of the balloon. Their effects will be small compared to the force of the wind on the balloon so that they are negligible in calculations in this early stage.

2.3 Balloon lift

A balloon needs to create lift to ascend. This is done by filling the balloon with a substance which has a lower density than the surrounding atmosphere. Five lifting substances are treated in this section: first hydrogen will be discussed, then helium will be presented next, thirdly water is discussed, and finally ammonia, carbon dioxide and methanol are treated.

2.3.1 Hydrogen

The most obvious choice for a lifting gas would be hydrogen, as it is very light. Hydrogen has a molar mass of only 1 g/mol. [22] This results in a density of 0.39 kg/m^3 (using equation (2.2) with M = 1) in the atmosphere of Mars. However, hydrogen has one major drawback: it is highly inflammable.[49] It's flammability might restrict it from being used in this project, since this project needs to be low-risk. From a sustainability point of view, this would be a possibility: although hydrogen does not occur in the Martian atmosphere, it can react with the available oxygen to form water vapour. This does occur naturally. [21]

2.3.2 Helium

Just like hydrogen, helium is a very light gas. It is more dense than hydrogen, with a density of 1.54 kg/m^3 (using equation (2.2) with M = 4 g/mol [50]) at Martian temperatures and pressures, yet the density is low enough to ensure the balloon will rise into the atmosphere. An advantage helium has over hydrogen is the fact that helium is inert, whereas hydrogen is highly inflammable and thus dangerous. Nevertheless, helium has its own risks: the gas has to be compressed when transported from Earth to Mars, because it would simply take up too much space otherwise. Bringing a pressure vessel into space will create an additional risk, as it will have to be very robust to withstand launch loads without failing. Furthermore there is a chance of damage to the launcher should the canister fail on the way to Mars. According to E.J.Grayzeck [21] helium does not occur in any significant amounts on Mars. It is not known what influence introducing helium will have on the Martian environment.

2.3.3 Water

In an attempt to reduce the complexity of the mission introduced by bringing compressed gas canisters to Mars, Zubrin et al.[53] suggest bringing water as a fluid. When the balloon is heated by the sun, the water (which on Mars is only present as a solid or a gas [12]) will sublimate. Following the increase in temperature the pressure and thus the volume of the

balloon will increase. This will cause the density of the water in the balloon to decrease. When the density of the water is lower than that of the Martian atmosphere, the balloon will start to rise, as is shown by equation (2.1). Water occurs in small amounts on Mars [21], thus it is acceptable to leak a small amount of water, needed to lift the balloon, into the atmosphere after completion of the mission.

2.3.4 Other substances suggested by Zubrin et al.

Zubrin et al. applied this same idea to other substances, namely : carbon dioxide, methanol and ammonia.[53] The achievable payload masses for these substances (and water) are summarised in figure 2.1. However some of these substances Zubrin et al. suggest could lead to pollution of Mars: ammonia and methanol do not occur naturally in the Martian atmosphere.[21] Although it is unsure what will happen when ammonia and methanol are released into the Martian atmosphere, no risks should to be taken in this respect. Carbon dioxide is a naturally occurring gas on Mars (95% of the atmosphere [21]), so using carbon dioxide would not influence the environment on Mars.

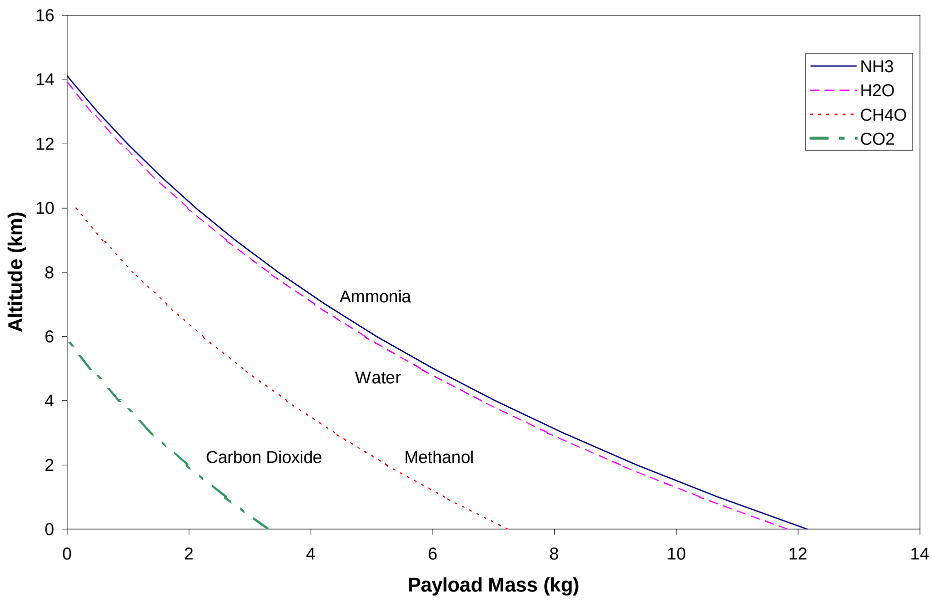


Figure 2.1: Steady-State Altitude vs. Payload Mass for 1529 m^3 COTS Balloon (Coated with Nickel: α_s = 0.4, ϵ= 0.1)

2.4 Balloon configurations and materials

The balloon is designed to lift the envelope and payload by using a lifting gas. The lift is obtained by displacing a sufficient amount of the atmosphere with a lighter gas. There are two types of light gas balloons, namely a zero pressure and a super pressure type. Zero pressure balloons are inflated with the light gas, with an equal gas pressure inside and outside the balloon. They are similar to the balloons used for leisure flights on Earth. The gas expands as the balloon rises to maintain the zero pressure difference, and the balloon's envelope swells. In the Martian environment, however, a zero pressure balloon would probably flip upside down and empty up unless the system is ballasted. The use of a zero pressure balloons therefore

needs ballast weight and therefore this type of balloon could turn out to be unacceptable. The super pressure balloon, in contrast, is ideally suited for long duration flights, as it has a though and inelastic envelope filled with a light gas with a pressure higher than that of the external atmosphere. These balloons float at a constant density altitude, but when the lifting gas is heated by radiation during flight, the pressure of the gas increases. Consequently, the envelope material will become stressed. To provide the required stress resistance, the material strength and durability will have to be sufficient.

2.4.1 Balloon configuration

Spherical super pressure polyester balloons have been manufactured and flown successfully for numerous years in the Earth atmosphere [38]). The volume of this type of balloon is proportional to the radius to the third power and the stress is directly related to the radius. Therefore, the stress will be determined by the volume of gas needed for the mission. A design that successfully distributes stresses in the balloon skin is called a "pumpkin" balloon. It can withstand five times the pressure of a sphere with the same volume. By shortening the seams of a fabric balloon with a sewing machine, excess material in the circumferential direction is introduced. Consequently, the circumferential radius of curvature is reduced and higher pressures can be accommodated. The equilibrium in meridional direction is satisfied by a system of so called "tendons". Both the gores and tendons are visualized in Figure 2.2.

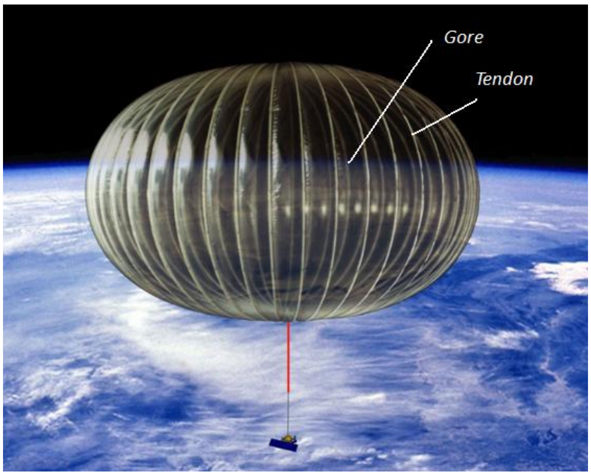


Figure 2.2: A "pumpkin" shaped balloon configuration [1]

As the pressure difference across the film of the balloon is increased, a higher number of lobes will be required which will increase the envelope weight. Still, this weight penalty will be less than that for the corresponding sphere configuration of which the thickness will have to be increased.

2.4.2 Balloon materials

The materials that are suitable for a super pressure balloon on Mars are selected on the premises of their weight. The materials should also have other excellent properties, including low permeability, high toughness at low temperatures and a wide range of sealing temperatures. Mechanical orientation is used to achieve very thin films. Four candidates for material orienting will now be discussed.

1. The most common material used for super pressure balloons is PET (Polyethylene terephthalate) also known as Mylar, the trade name of the material. The density of this material is 1.39 gram per cubic centimeter. This density uses a 6 micron film which is the thinnest standard gauge produced by its manufacturer DuPont-Teijin Films.

2. This manufacturer also produces Kaladex, which is a PEN (polyethylene naphthalate) film with a density of 1.37 g/cc. At this moment, it is commercially available at a thickness of 25 microns, but representatives have indicated that it can be made in any thickness greater than one micron.

3. Another film candidate is nylon 6,6, which is also known Dartek. With a density of 1.14 g/cc, this product is the lightest solution for a given balloon surface. An unusual property of this material is high strength in the machine direction and high elongation in the transverse direction resulting in a significantly increased tear strength.

   All materials discussed above have sufficiently low temperature ductility which is suitable for the Martian environment since it can be concluded from testing that these materials demonstrate adequate elongation at $-100\,^{\circ}$Celsius. Only the nylon film is known to be hygroscopic – it tends to absorb water – which would affect the low temperature failure pattern. However, due to the absence of the any significant moisture in the atmosphere of Mars, nylon can still be considered suitable.

4. The last candidate is linear low-density polyethylene (LLDPE) which has replaced LDPE during the last decade (section [4]). LLDPE has a density of 0.92 g/cc, higher tensile strength, is very flexible and elongates under stress. It can be used to make thinner films and it also has good resistance to chemicals and to ultraviolet radiation.

For the "pumpkin" balloon configuration, tendons will be required to cope with the meridional loading [38]. A tendon material needs to be very lightweight and very stiff. This limits the meridional strains in the gore material. One of the possible candidates is a synthetic fiber made of PBO (Poly(p-phenylene-2,6-benzobisoxazole)) available under the trade name Zylon. With a density of 1.56 g/cc and an ultimate strength of 5800 MPa, this materials is very suitable for a "pumpkin" super pressure balloon (section [3]).

Coating is a concept that also needs to be taken into account [53]. Carrying large amounts of high pressure life gases followed by automated inflation at the Martian atmosphere will lead to a large increase in both mass and complexity. The increase in mass and complexity can be eliminated by developing a solar balloon, in which a metal coating is used capture solar energy in order to raise the temperature of the interior of a bag. The interior of the bag increases the temperature of the gas inside the balloon, which could be the most common gas on Mars, namely CO_2. There are numerous possibilities such as Aluminium, Titanium, Nickel, Chromium, Gold and steels to coat the skin of the balloon. Especially Gold is suitable, as it has excellent corrosion resistance and reasonable optical properties. Gold is also a very good conductor and has an extremely low emittance that can be easily degraded by dust or other contaminants in the Martian atmosphere.

2.5 Feasibility tethered balloon

To tether a balloon up to 11 kilometres high in the Martian atmosphere, a careful choice of material must be made. As one can read in section 2.2, the cable has to carry a load and

should be as light as possible. An easy and relatively cheap solution would be the use of a steel cable to deal with the high tensile strength and robustness. If necessary power and/or data could be sent through the cable to the balloon. But when one considers weight as a critical factor, the density of the material becomes important. A solution can be found in aramid polymers. These polymers do not conduct electricity, but possess the highest tensile strength to weight ratio.

Two aramid polymers are Kevlar and Dyneema fibre, both often used for space applications. [28] The service temperature of Dyneema ranges from 75 K to 375 K. Temperatures lower than 75 K will make the material very brittle, while the material will come to close to its melting temperature above 375 K. This wide temperature range is acceptable for the Martian environment [48]. Next to these excellent temperature properties, Dyneema can withstand ultraviolet radiation and is not effected by harsh environments during extended periods of time due to its resistance to most chemical agents. [18]

Another similar fibre is Kevlar, produced by DuPont. The properties of Kevlar are similar to those of Dyneema, with minor differences. Kevlar can withstand higher temperatures for longer periods of time than Dyneema. The chemical resistance is comparable, but the main advantage of Kevlar is that it has already been used on Mars and is thus a proven technology. [20] As one can see, the density of Dyneema fibre is lower compared to Kevlar, while the tensile strength is comparable. [18] [46] [20] The most important properties are summarized table 2.2.

Table 2.2: Characteristic values for potential cable materials

Material	Tensile strength [GPa]	E-modulus [GPa]	Density [kg m^{-3}]
Alloy steels [5]	2.0	210	7850
Dyneema [24]	3.5	110	970
Kevlar [19]	3.0	124	1440

2.6 Altitude and position determination

For all measured data it is important to know where the data was obtained to gain any insight in the Martian atmosphere. Therefore, the altitude and position are important parameters that should be attached to all of the acquired data. For both a tethered and a free balloon concept there are different possibilities for determining the altitude and position.

One option for a tethered balloon is to use the characteristics of the cable to determine the position of the balloon. If the length and tension of the cable are known, as well as the angle of the cable with respect to the lander, the altitude and distance from the ground station can be determined by mechanical analysis and modelling of the cable sag. The main advantage of this system is that no additional instruments are needed on the balloon. The obvious disadvantage is that the local height of the balloon will not be determined because the landscape is not taken into account. Also, the modelling of the sagging is especially difficult when the wind velocity varies with altitude. Furthermore a sensor has to be applied to determine the angle the cable makes with the horizontal.

One option can be used for both a tethered and a free balloon: this technique is based on laser ranging. Laser ranging can be used for determining of the local altitude of the balloon.

An advantage of this is that it is potentially very precise. On the other hand, very accurate clocks are needed to achieve this, as the following equation shows [40]:

$$T_t = \frac{2 \cdot H}{v_g} \tag{2.21}$$

where H is the height of the instrument; v_g represents the group velocity and T_t is the travel time. With v_g in the order of 10^9 and H in the order of 10^3, T_t becomes really small: 10^{-6} seconds.

This way to determine the altitude can be complemented with analysis of photographs taken by the balloon to establish the location. Using a detailed map, photos can be compared to the map and the location can be determined. Advantages are that photos in itself are interesting and can be used for other purposes as well, yet it is uncertain whether this can be as accurate as laser ranging. The attitude of the balloon will have an influence on the angle at which the photographs are taken, thus influencing the accuracy.

Another method that could be used is radar altimetry, comparable with the laser altimetry [44]. The altimeter sends a radar signal and computes the time the signal needs to travel back and forth. One problem that could occur is instability of the balloon. If the radar is in the off-nadir direction, the travelled signal must be corrected using the off-nadir angle. One should stabilise the balloon such that the radar is in nadir direction. The results could also be affected by local topography.

According to Wnuk [52], satellites already orbiting Mars cannot be used for positioning because their own position is not known to great accuracy, but then of course the question remains how accurate the position must be determined.

2.7 Communications

For this balloon system there is the need for one or two communication systems, depending on the design concept. The first of the upcoming two sections will describe how the measurement data could be transmitted from Mars to Earth (section 2.7.1). Secondly, a section will follow that explains the possibilities for the data link between the balloon and a Martian ground system (section 2.7.2). In this second section, the possibilities for communication clearly depend on the chosen design concept.

2.7.1 Mars to Earth communication

The communications requirements are dependent on the requirements of the instrument package The requirements of the instrument package have not yet been determined at this stage in the project. To get an estimate of the requirements on data rates, power budgets and mass budgets, the properties of the ExoMars [8] lander and rover communication systems are taken as a starting value. The scope of the balloon mission is much more limited than that of the ExoMars mission, and it is therefore safe to assume that requirements obtained from the rover missions are stricter than the communication requirements for the Delft2Mars mission. For example, the balloon does not need to be commanded because it will be a self-contained system, while the ExoMars mission does need two way communication. Furthermore, the instrument package is likely to be smaller than that of the rover, which has multiple cameras, spectrometers, etc. [7]. The requirements on data rate, power, and mass are largely dictated by the relay method that is used. There are two options for relaying the data to Earth, and each of these options is discussed shortly.

- **Orbiter as relay**
The ExoMars rover uses this method to transfer it's data to Earth. The ExoMars rover has a static antenna and an Ultra High Frequency (UHF) transceiver, which weighs 1.6 kg all together, for communicating with the ExoMars orbiter. This orbiter relays all data received from the rover to Earth using its own communications subsystem. A data link from the rover to the orbiter of 256 kbps requires 21 W of power [8]. The total amount of data that can be transmitted through this system depends on the orbit of the relay satellite. In the case of the ExoMars system it would be about 90 Mb worth of measurements per day, with a contact time of 20 minutes per day.

- **Direct Mars to Earth**
As a backup, the ExoMars rover features a communications system which uses a direct link to Earth. This link works at 10 kbps and requires 40 W of power. The steerable antenna required for the X-band communication weighs 0.6 kg [8]. This link can also send about 90 Mb worth of measurements per day, but makes use of the longer contact time with Earth compared to the orbiter (3.6 hours versus 20 minutes per day). The antenna should be pointed in the right direction, which means mounting this system on the balloon might prove impossible as the balloon may be spinning. Therefore, this option can only be mounted on a ground station. This would require an additional communication system between the balloon and the EDL.

There might be a possibility to use the EDL communication system to send data to Earth. The advantage of using the communications subsystem of the EDL is that the balloon system does not need to bring its own hardware, and thus this will save weight. On the other hand, the balloon would need to be tightly integrated with the EDL, and the data rate is limited by the hardware of the lander. Furthermore, the power capabilities of the lander may not be sufficient to communicate for extended periods of time (i.e., the balloon mission duration of 90 Martian days (sols)). To ensure sufficient power is available, the balloon system would need to be coupled to the lander, increasing the difficulty of integration. This option requires a second communication system, namely that between the balloon and the EDL. At this moment, very little is known about the EDL communications system, so it does not provide much guidance for the general design of the balloon system. Therefore, only the known data of the relay station and dedicated link communication systems of the ExoMars rover can be relied upon.

From a power budget point of view, the relay system clearly wins. The energy required for a day's worth of communication can be calculated with the equation $t \cdot P = E$ where t is time in seconds, P is power in Watt and E is energy in Watt-hour. Much less power is required for the relay link ($\frac{20}{60} \times 21 = 7$ Wh), than for the direct link ($3.6 \times 40 = 144$ Wh). As has been explained earlier, the data rate requirements of the balloon system are likely lower than for the ExoMars rover, this mainly results in lower power requirements. Regarding the mass budget, the references are not unanimous. According to [8], the X-band antenna weighs 0.6 kg and the UHF transceiver weighs 1.6 kg, implying that the transceiver would still be needed if only a direct link to Earth would be considered. Another source [35] states that the relay communications system weighs 1.6 kg and that the direct connection requires 0.6 kg. Even if the latter would be the case, the increased power requirement of the direct communication system would probably not weigh up to the additional mass of a relay communication system.

2.7.2 Balloon to Mars surface communication

The transfer of data gathered by the instruments in the balloon could be done in two ways: the balloon itself could have a direct data link to Earth (through the use of a relay satellite), or the balloon could relay the data through the balloon ground system. The second case will be discussed here. The transmission of data from the balloon to the ground system can either take place over a wired or wireless connection. Critical aspects of these two methods will now be discussed.

In the case of a wired communication line, different materials for the cable should be considered. Critical aspects that should be taken into account are the density and conductivity of the material, as these aspects dictate the required transmission power. Foreseeable problems are the twist and stretch of the cable due to the balloon movements. Later on in the project it will be attempted to find a solution to these problems.

The wireless link also introduces several design problems. First of all, the distance between the non-tethered balloon and the ground system is not known beforehand. This could lead to high power requirements, as the balloon could go anywhere. If the balloon travels too far from the ground station, the balloon loses line-of-sight contact. As with the Mars to Earth link, the possible pointing requirements (due to the use of a more powerful directional antenna) might collide with the dynamics of the balloon. All these problems either lead to high power requirements or make communicating impossible. Wireless communication could only be an option in the case of a tethered balloon, as the travel distance is fixed.

In conclusion, both balloon to ground station communication options have their own advantages and disadvantages. This will definitely be a main focus during the trade off in the upcoming project period.

2.8 Power subsystem of balloon

The power subsystem of the balloon is made up of several components. It contains a primary power source connected to the power distribution system to deliver energy to all parts requiring electrical power. The subsystems that require power are: energy storage, power distribution, communication subsystem, thermal subsystem and finally the payload (instruments). All the subsystems requiring power contribute to the total power budget needed for the mission. Using the total power budget the individual components of the power subsystem can be sized, starting with the primary power source in section 2.8.2. This section is followed by section 2.8.3 dealing with the distribution and regulation of power.

2.8.1 Power budget of the balloon

The different instruments comprising the payload of the balloon each have different power requirements. The power requirements for the main parts of the balloon are given in table 2.3. For the communications subsystem, the required power is calculated in section 2.7.1. Whereas the power requirement for the payload is assumed to be 25 W, since the exact payload is not known yet. In table 2.3 the total energy requirement for the balloon is listed, after which the sizing of the power subsystem can take place. The energy requirements of thermal heaters have been omitted in this table.

Table 2.3: Power requirements for different subsystems

Subsystem	**Power required [W]**	**Hours per sol [Hr]**	**Energy requirement [WHr]**
Communication	21	$\frac{20[min]}{60[min]}$	7
Payload	25	8	200
Total	**46**	**8.33**	**207**
Power distribution[1]	2.3	8.33	10.35
Power budget	48.3	8.33	217

[1]Power distribution is about 5% of total power used [41]

2.8.2 Primary power source options for balloon

From the total energy requirement, different options for the primary power source of the balloon will be discussed. Three main options for power generation for a balloon are using solar cells, a battery pack or a radioisotope thermoelectric generator (RTG).

Solar cells convert the energy of the sun into electrical power. A consideration using solar cells is that power can only be generated during daytime hours, which means that power storage is required to use power at night. Power production is lower when using solar cells are used on Mars compared to Earth, because the solar radiation of the Sun at the edge of the Martian atmosphere is on average 590 W/m^2 [16], whereas on Earth the average is 1367 W/m^2. The solar radiation on the surface of Mars is not constant due to dust particles in the atmosphere, which means that solar cells could provide less power than expected. If this happens during the mission a decision needs to be made concerning which instruments need to be turned off to ensure enough energy is supplied to critical subsystems, such as data storage.

If a battery pack is considered as a primary power source there is one major drawback: the mission can only be of small duration ($<$ 1 week) since a battery back can either only supply enough energy for a couple of Martian days (sols), or would add an unrealistic amount of weight to the system.[26] The intention of this project is that the balloon mission will last for at least 90 sols, thus choosing a battery as a primary power source means the mission needs to be shortened. A more powerful battery pack could of course be taken along but will introduce more mass leaving a smaller mass budget for the payload.

As a final option a RTG could be used for the balloon mission. RTG's are capable of producing electricity regardless of sunlight, enabling them to supply energy constantly. This means battery power storage is not required to operate during the night on Mars. Two major drawbacks of RTG's are first of all that a RTG is a radioactive source, thus shielding is a critical component, and the residual radioactive materials left on Mars after the mission might not be acceptable from a sustainability point of view. Beside this the specific cost of a RTG per Watt is in the range of 16k$ - 200k$, compared to solar cells which have a specific cost between 800-3000 per Watt [26]. Since the mission budget is based on university funds a RTG would mean making tough design decisions for this project.

2.8.3 Power distribution and regulation

All electrical components in the balloon need to be connected and supplied at the right voltage to operate correctly, thus power distribution and regulation is necessary. The power distribution is simply a network of wires connecting all components. These electrical wires

need to be protected from the environment, and should also be shielded against radiation.

The exact payload is not known yet, but there is a good possibility that power regulators are needed to provide different voltages.

2.9 Thermal Subsystem

The thermal subsystem of the Delft2Mars balloon has not been given very much attention so far. There are, however, some thermal problems anticipated already. After a conversation with engineers from the Concurrent Design Facility at European Space Research and Technology Centre (ESTEC), Noordwijk, it can be concluded that two main thermal problems have to be dealt with.

First of all, the low temperatures during the Martian night can cause problems. Most instruments have minimum temperatures below which they will fail [14]. Therefore it is necessary to think of how the instruments and electronics will be kept warm during the night. According to the previously mentioned sources at ESTEC, it is not possible to use sufficient power from the lander in order to keep the instruments of the balloon warm at night. The lander needs most of the available power to keep its own systems warm. Heating needs a great amount of power for a long period of time and the energy used for this heating can not be stored in batteries due to weight constraints. From the ESTEC engineers it is understood that the use of a nuclear cell is not uncommon to heat the system. It appears that this method is a very reasonable solution to the cold night problem, even though this nuclear heating solution should be carefully reviewed in the light of sustainability concerns. During the day some power can be obtained from the lander and therefore the night will especially create problems with regard to the instruments.

Second of all, there are certain thermal factors to take in to account during the voyage to Mars. Three factors that could cause problems during this phase of the mission are known so far. The first problem will be caused by the use of helium or another substance as a balloon gas. A high pressure helium tank will have to be kept at a low temperature during transport to Mars due to structural requirements. Secondly, heat required during the voyage to Mars could easily be delivered by the solar panels of the launcher. Finally, if the nuclear heating unit mentioned in the previous paragraph is used, this unit will somehow have to be cooled during the trip to Mars because, as the engineers at ESTEC told us, these devices generally create to much heat for this phase.

Chapter 3

Mission analysis

The desired goals of the Delft2Mars mission will be explained in this chapter. Risks that may form a threat to these goals being achieved are analysed, and where possible a solution is presented. First, the mission design concepts are given. In this section several possible concepts are discussed. Also, interesting parameters to be measured are given. Secondly, a risk analysis is carried out in order to reduce the amount of unexpected failures. This can greatly increase the reliability of the mission. Finally, restrictions on contamination are given along with thoughts on sustainability, this section mainly concerns limitations on cleaning procedures and regulations.

3.1 Mission design concepts

As a vehicle that is send to Mars can only be set-up once on the Earth, a predefined mission is needed. This chapter will discuss possible mission concepts, and which parameters would need to be measured.

3.1.1 Atmospheric model

Currently a rough atmospheric model of Mars exists that is determined by indirect measurements of the relevant parameters [25]. The model could be made more accurate by measuring the relevant parameters directly. There are several reasons to determine an accurate atmospheric model of Mars, three of which will be stated below.

1. When designing a lander for Mars it is very important to have information on the aerodynamics of the lander during descent on Mars. As the aerodynamics depend strongly on the atmosphere, an accurate model allows more efficient designs to be made.

2. The model can also be used to increase understanding of the weather phenomena on Mars [15]. This understanding can lead to the possibility of predicting the weather on Mars. These predictions can prevent landers and other Martian vehicles to be damaged by the Martian weather, for example by timely detecting bad weather.

3. The atmospheric model could also be used for correction of surface measurements done by a satellite. When a satellite orbiting Mars is probing the surface using signals, the signals will be modified by the atmosphere. If the atmospheric state at that moment is known the signals can be corrected.

For an atmospheric model the following parameters need to be measured [17]:

- **Density**
This parameter is needed because it has a big influence on the aerodynamics of landers and other aerial vehicles on Mars. The density could be measured by using the dynamic pressure, but only if the velocity is known. To determine the velocity accurate positioning systems are required. More about this can be found in section 2.6.

- **Temperature**
The speed of sound is directly related to temperature. Some remote measurement methods, like the Doppler method, need the speed of sound as an input. The accuracy of measurements using this method then depends on the accuracy with which the speed of sound is known. The temperature can also be used to determine the flow of particles through the Martian atmosphere. This flow can give valuable information about the transport of atmospheric particles. A simple commercial off-the-shelf (COTS) temperature sensor would suffice for the measurement of this parameter.

- **Pressure**
As with the temperature this parameter can offer general information about the airflow in the atmosphere. Pressure predicts the direction of winds and therefore is very useful for a general weather model of Mars.

- **Height**
The advantage of using a balloon is that the atmosphere can be sampled at different altitudes. At each altitude the measured parameters will be slightly different. By sampling at as many different altitudes as possible the atmospheric model will be more complete and precise. The measurement method depends on the design of the balloon. In section 2.6 more about the measurement method can be found.

This mission concept can be executed with both a tethered and a free balloon. The tethered balloon gives a more accurate measurement of a limited area, with the possibility to measure changes over time, but the free balloon gives a more overall image and could be used to map an area for example.

3.1.2 High resolution surface imaging

Right now there are surface vehicles present on Mars. Compared to a surface vehicle on Mars a balloon can travel several times faster. This is because it is not hindered by a rough surface, steep hills and rocks. Also, because of the low altitude of the balloon, it can be used to take high resolution pictures of the Martian surface. When something interesting is visible on the photo, a surface vehicle can be send-out to investigate. This working method increases the efficiency of the limited resources of a rover. The only measurement device necessary for this observation mission would be a high-resolution camera. The observation mission can be combined with other mission concepts, but this will increase the mass of the balloon system significantly.

3.1.3 Atmospheric composition

By determining the composition of the atmosphere at different locations a map can be produced which shows what the gas composition on a certain location is. As there is an unknown methane source on Mars [11] it is interesting to find such a composition map, as after all

methane could imply that there is life on Mars. By carefully examining the methane concentrations on different locations the source could be found. The map of the atmospheric composition can also function as a calibration map for other atmospheric measurements.

For measurements of the atmospheric composition there will be a difference in accuracy depending on whether the balloon is tethered or free. When the balloon is tethered a predefined area will be explored several times. A free balloon is uncontrollable but will cover a larger area. This is a trade-off which has to be done later.

3.1.4 Ultraviolet radiation measurements

Because it is a possibility that a manned mission will be sent to Mars in the future, it is important to map the possible hazards on Mars. One of the hazards is the ultraviolet (UV) radiation present on Mars. There is not much information available about this, so this mission could be a good opportunity to measure that radiation. An inherent problem with measuring the radiation is that if the balloon hangs above the instruments, it will block out the UV radiation partially. To execute this mission an alternative balloon system should be designed where the instrument is placed above the balloon.

3.2 Risk assessment

In this section an assessment will be made of the technical risks the mission faces. All conceivable risks (as detailed as the progress of the project allows) will be listed along with the associated failure. For each failure the impact on the mission, ways to prevent the failure from happening, and possible remedies are listed.

1.	**Risk**	Fabric failure.
	Description	Failure of the balloon fabric due to loading and/or radiation.
	Impact	Mission lost.
	Prevention	Use fabrics that are strong enough to handle all conceivable loads, or possibly make use of self-healing materials. Coatings should be applied for thermal and radiation protection. Another option is to use a redundant balloon concept where the balloon is made up of several compartments.
	Remedy	Use of self-healing materials and/or coatings.
2.	**Risk**	Launch failure.
	Description	Failure of the launch vehicle.
	Impact	Mission lost.
	Prevention	Select most reliable launcher available (using statistics).
	Remedy	None, loss reduction by insuring the system.

3.	**Risk**	Lander failure.
	Description	Failure to land the system properly on Mars.
	Impact	Mission lost.
	Prevention	Select most reliable lander system available (using statistics or risk analysis if no track record is available).
	Remedy	None.
4.	**Risk**	Deployment failure.
	Description	Failure to deploy the balloon system.
	Impact	Mission lost.
	Prevention	Redundant deploying systems.
	Remedy	Design the system such that measurements can also be taken from the ground, preventing the system from becoming completely useless if deployment fails.
5.	**Risk**	Delivery system failure.
	Description	Failure during transport from Earth to Mars, for example because of debris collision or failing to reach orbit.
	Impact	Mission lost.
	Prevention	Use of protective shielding against debris, use of debris charts.
	Remedy	None, loss reduction by insuring the system.
6.	**Risk**	Electrical failure.
	Description	Failure of the electronic systems.
	Impact	Either loss of function or mission lost.
	Prevention	Use redundant electrical systems (double wiring, multiple power sources).
	Remedy	None.
7.	**Risk**	Dust storm damage.
	Description	Damage due to dust particles entering the system, and wear and tear of fabrics.
	Impact	Either loss of function or mission lost.
	Prevention	Avoid landing during the dust storm season, insulation of the system from dust particles, using redundant systems, corrosive resistant materials or self-healing fabrics.
	Remedy	None.
8.	**Risk**	Cable failure.
	Description	Breaking of the cable (in case of a tethered balloon) due to wear and tear or high loads.
	Impact	Mission lost.
	Prevention	Selecting a wear-resistant material capable of handling all conceivable loads. Landing during storm season should be avoided.
	Remedy	None.

9.	**Risk**	Computer failure.
	Description	Failure of computer systems, such as memory.
	Impact	Either loss of function or mission lost.
	Prevention	Shielding of computer systems, using redundant systems, using simple systems (no unnecessary complexity).
	Remedy	Ability to remotely reboot system, possibly reprogram the system from Earth.
10.	**Risk**	Communications failure.
	Description	Failure of the communications system.
	Impact	Either loss of function or mission lost.
	Prevention	Use of redundant systems.
	Remedy	None.

3.3 Sustainability

The committee on space research (COSPAR) has issued a planetary protection policy in which it is stated that:

> "Although the existence of life elsewhere in the solar system may be unlikely, the conduct of scientific investigations of possible extraterrestrial life forms, precursors, and remnants must not be jeopardized" [45].

To prevent the contamination of other planets with organic material from Earth, space probes have to be cleaned thoroughly. Different categories are distinguished based on the likeliness of life on the investigated body.

For Mars, category IV applies. Category IV missions consist of certain types of missions to a target planet for which biological contamination could jeopardize future scientific research on the presence of life. For Mars, category IV is subdivided in missions which search for life, past or present, and missions that do not search for life. Taking these subdivisions into account category IVa applies to our balloon mission which states:

> "Lander systems not carrying instruments for the investigations of extant Martian life are restricted to a biological burden no greater than Viking lander presterilization levels" [45]

This means that the total bioburden is restricted as follows: fewer than $3 \cdot 10^5$ spores are allowed on the surface with a maximum of 300 spores per square meter [32].

Next to these organic contamination risks and regulations there are also ethical problems with contamination that have to be addressed [51]. The system which will be deployed on Mars will be left on the planet, resulting in contamination of the Martian surface. At least some form of contamination is impossible to avoid if one wants to advance knowledge about Mars. However, the contamination on Mars should be minimised. This includes using a lifting substance that either is already present on Mars or can be shown not to harm the environment. How these contamination issues will further be addressed is not clear at this moment and will have to be addressed in the future of this project.

Bibliography

[1] Retrieved Thursday, April 29 ,2010 from http://regmedia.co.uk/2009/01/09/nasa_pumpkin_balloon.jpg.

[2] A primer on uv-c light. Retrieved on Thursday, April 29, 2010 from http://hygienitech.com/Hygienitech%20UV-C%20Light%20Primer.pdf.

[3] Zylon (pbo fiber) technical information, 2005. Retrieved on Thursday, April 29, 2010 http://www.toyobo.co.jp/e/seihin/kc/pbo/Technical_Information_2005.pdf.

[4] Linear low density polyethylene, 2008. Retrieved on Thursday, April 29, 2010 http://plastics.sabic.eu/_scripts/gradeselector.pl?material=f8c66b8e-ff72-4a0e-8cf2-678b04769dc0&template=material.

[5] Typical properties of steels, 2010. Retrieved on Thursday, April 29, 2010 from http://www.efunda.com/Materials/alloys/alloy_home/steels_properties.cfm.

[6] European Space Agency. Preparing a mission to mars. Retrieved on Tuesday, April 27, 2010 from http://esamultimedia.esa.int/docs/edu/Exercises/Preparing_%20a_%20mission_%20to_%20Mars.pdf.

[7] European Space Agency. The exomars instruments, February 2008. Retrieved on Thursday, April 29, 2010 from http://www.esa.int/esaMI/ExoMars/SEMSZIAMS7F_0.html.

[8] D. Barnes, E. Battistelli, and others. The exomars rover and pasteur payload phase a study: An approach to experimental astrobiology. *International Journal of Astrobiology*, 5(3):221–241, 2006.

[9] T. Benson. Atmosmodeler simulator, July 2008.

[10] T. Benson. Shape effects on drag. March 2009.

[11] D. Brown. Discovery of methane reveals mars is not a dead planet, January 2009. Retrieved on Thursday, April 29, 2010 from http://www.nasa.gov/home/hqnews/2009/jan/HQ_09-006_Mars_Methane.htmll.

[12] M. Chaplin. Water phase diagram, August 2009. Retrieved on Wednesday, April 28, 2010 from http://www1.lsbu.ac.uk/water/phase.html.

[13] R. T. Clancy, B.J. Sandor, et al. *An intercomparison of ground-based millimeter, MGS, TES, and Viking atmospheric temperature measurements*. American geophysical union, 2000.

[14] L. Coe. Solving flight problems on mars. September 2005.

[15] D. Crisp, J.R. Murphy, et al. In-situ environmental measurements needed for future mars missions. page 84. NASA Headquarters and Lunar and Planetary Institute, July 2000.

[16] D. Crisp, A. Pathare, and R. C. Ewell. The performance of gallium arsenide/germanium solar cells at the martian surface. *Acta Astronautica*, 54(2):83 – 101, 2004.

[17] Dr. Dieter and K. Bilitza. U.s. standard atmosphere 1976, December 2005. Retrieved on Thursday, April 29, 2010 from `http://modelweb.gsfc.nasa.gov/atmos/us_standard.html`.

[18] DSM. World's strongest fiber, n.d. Retrieved on Thursday, April 22, 2010 from `http://www.dyneema.com/`.

[19] DuPont. Kevlar aramid fiber, technical guide. Retrieved on Thursday, April 29, 2010 from `http://www2.dupont.com/Kevlar/en_US/assets/downloads/KEVLAR_Technical_Guide.pdf`.

[20] DuPont. The miracles of science, n.d. Retrieved on Thursday, April 22, 2010 from `http://www2.dupont.com/Kevlar/en_US/`.

[21] E. Grayzeck. Mars fact sheet. November 2007. Retrieved on Wednesday, April 28, 2010 from `http://nssdc.gsfc.nasa.gov/planetary/factsheet/marsfact.html`.

[22] T.J. Greytak, C.A. Swenson, and A.L. Kohl. *Hydrogen*, pages 285 – 287. McGraw-Hill, 2004.

[23] S. L. Hess, R. M. Henry, and J. E. Tillman. *The seasonal variation of atmospheric pressure on Mars as affected by the south polar cap.* American geophysical union, 1979.

[24] R. Marissen. Composites for durable structures, 2009. Lecture notes AE4-633.

[25] D. J. McCleese, J. T. Schofield, et al. Remote sensing of the atmosphere of mars using infrared pressure modulation and filter radiometry. *Applied Optics*, 25(23):4232–4245, 1986.

[26] J. K. McDermott. *Space Mission Analysis and Design*, chapter Spacecraft Subsystems, pages 410 – 418. Microcosm Press and Kluwer Academic Publishers, third edition, 1999.

[27] K. Miller. Mars mice, April 2004. `http://www.nasa.gov/vision/earth/livingthings/20jan_marsmice.html` Last visited April 27 ,2010.

[28] M.Ott and J. Plante. Fiber optic cable assemblies for space flight applications: Issues and remedies, February 1997. Retrieved on Wednesday, April 28, 2010 from `http://nepp.nasa.gov/DocUploads/F72F2489-FFBA-4021-88428C5A85930D38/cabass.pdf`.

[29] Y. Moudden, J.C. McConnell, et al. Meteorological results from the global mars multiscale model at the viking 1 lander site. *Advances in Space Research*, 36:2169–2175, 2005.

[30] M. H. Acu na J.E.P. Connerney et al. *Magnetic field and plasma observations at Mars.* Science, 1998.

[31] W. L. Nicholsona, A. C. Schuergerb, and P. Setlowc. The solar uv environment and bacterial spore uv resistance. *Mutation research*, pages 249–264, 2005.

[32] National Academy of Sciences. *Preventing the forward contamination of Mars.* The national academies press, 2006.

[33] COSPAR/IAU Workshop on Planetary Protection. Cospar planetary protection policy, March 2005. Retrieved on Wednesday, April 28, 2010 from `http://cosparhq.cnes.fr/Scistr/Pppolicy.htm`.

[34] M. R. Patel, J. C. Zarnecki, and D. C. Catling. *Ultraviolet radiation on the surface of Mars and the Beagle 2 UV sensor.* Elsevier Science Ltd., 2002.

[35] C. Pillinger, M. Simsand, et al. A combined exobiology and geophysics mission to mars, 2009. `sci.esa.int/science-e/www/object/doc.cfm?fobjectid=36781`.

[36] J. B. Pollack. Climatic change on the terrestrial planets. *Icraus*, 37:479–553, 1979.

[37] J. L. Rand and W. J. Sterling. A constitutive equation for stratospheric balloon materials. *Advances in Space Research*, 37:2087–2091, 2004.

[38] J.L. Rand and M.L. Phillips. A superpressure balloon for mars observations. *Advances in Space Research*, 30(5):1245–1250, 2002.

[39] E. Ras, S. Boer, et al. Simulation of hot air balloon flights. 2009.

[40] W.G. Rees. *Physical Principles of Remote Sensing.* Cambridge University Press, second edition, 2001.

[41] E. I. Reeves. *Space Mission Analysis and Design*, chapter Spacecraft Design and Sizing, pages 332–335. Microcosm Press and Kluwer Academic Publishers, California, third edition, 1999.

[42] SABIC. Sabic lldpe 118n linear low density polyethylene for blown film. 2008. Retrieved at Wednesday, April 28, 2010 from `http://plastics.sabic.eu`.

[43] A. Seiff and D. B. Kirk. Structure of the atmosphere of Mars in summer at mid-latitudes. *Journal of Geophysical Research*, 82:4364–4378, September 1977.

[44] J. Sparks. Radio altitude: The instrument of choice, July 2008. Retrieved on Thursday, April 29, 2010 from `http://amtonline.com/publication/article.jsp?pubId=1&id=1337`.

[45] J. D. Rummel P. D. Stabekis et al. Cospar's planetary protection policy: a consolidated draft. *Advances in space research*, pages 249–264, 2005.

[46] T.Moyer. Comparative testing high strength cord, unknown 2000. Retrieved on Friday, April 23, 2010 from `http://www.xmission.com/~tmoyer/testing/High_Strength_Cord.pdf`.

[47] E. van Hinte and M. van Tooren. *First Read This.* 010 Publishers, 2008.

[48] R. Vennix. Matbase. Obtained Thursday, April 19, 2010 from `http://www.matbase.com/material/fibres/synthetic/dyneema/properties`.

[49] Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek. Chemiekaarten, 2010.

[50] M. E. Wieser. Atomic Weights of the Elements 2005. *International Union of Pure and Applied Chemistry*, 78:2051–2066, 2006.

[51] M. Williamson. *Space ethics and the protection of the space environment.* Elsevier Ltd., 2006.

[52] E. Wnuk and S. Breiter. *The motion of natural and artificial satellites in Mars gravity field.* Elsevier Science Ltd., 1991.

[53] R Zubrin, G. Snyder, et al. Mars micro balloon probe, n.d.