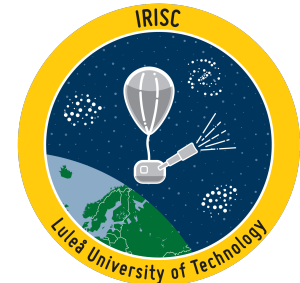




SED

Student Experiment Documentation

Document ID: BX28_IRISC_SEDv1-0_16Jan19



Mission: BEXUS 28

Team Name: IRISC

Experiment Title: InfraRed Imaging of astronomical targets with a Stabilized Camera

Team

Student Team Leader:

Team Members:

Name

Diego Octavio Talavera Maya

Anja Möslinger

Eligius Franciscus Maria Weterings

Kimberly Tuija Steele

Veronika Haberle

Adam Smialek

Ajith Kumar Baskar

Harald Magnusson

Niklas Ulfvarson

Sabina Björk

William Eriksson

University:

Luleå University of Technology

Version:

1.0

Issue Date:

January 16, 2019

Document Type:

Spec

Valid from

January 16, 2019

Issued by:

The IRISC Team

Approved by:

Dr. Thomas Kuhn

CHANGE RECORD

Version	Date	Changed chapter	Remarks
0 1-0	2018-12-06	New Version All	PDR

Abstract:

Keywords:

Contents

CHANGE RECORD	2
PREFACE	7
1 Introduction	9
1.1 Scientific Background	9
1.2 Mission Statement	9
1.3 Experiment Objectives	9
1.4 Experiment Concept	10
1.5 Team Details	11
1.5.1 Contact Point	11
1.5.2 Team Members	11
2 Experiment Requirements and Constraints	14
2.1 Functional Requirements	14
2.2 Performance Requirements	14
2.3 Design Requirements	15
2.4 Operational Requirements	15
2.5 Constraints	15
3 Project Planning	16
3.1 Work Breakdown Structure	16
3.2 Schedule	17
3.3 Resources	17
3.3.1 Manpower	17
3.3.2 Budget	17
3.3.3 External Support	18
3.4 Outreach Approach	18
3.5 Risk Register	19
4 Experiment Design	22
4.1 Experiment Setup	22
4.1.1 Telescope and CMOS sensor	22
4.1.2 Electronics	23
4.1.3 Control system	23
4.2 Experiment Interfaces	24
4.2.1 Mechanical Interfaces	24
4.2.2 Thermal Interfaces	25
4.2.3 Electrical Interfaces	25
4.2.4 Radio Frequencies (Optional)	25
4.3 Experiment Components	26
4.3.1 Electrical Components	26
4.3.2 Mechanical Components	27
4.3.3 Other Components	28
4.4 Mechanical Design	29
4.4.1 Structure	29

4.4.2	Electronic box	29
4.4.3	Gimbal	29
4.4.4	Fixing interface	29
4.5	Electrical Design	30
4.5.1	Block Diagram	30
4.5.2	Critical Component/Part A	30
4.5.3	Critical Component/Part B	30
4.5.4	Critical Component/Part C	30
4.5.5	Schematic	30
4.5.6	PCB Layout	30
4.6	Thermal Design	31
4.6.1	Optothermal considerations	31
4.6.2	Thermal environment	32
4.6.3	Temperature requirements	33
4.6.4	Thermal control	33
4.7	Power System	34
4.8	Software Design	35
4.8.1	Purpose	35
4.8.2	Design	35
4.8.3	Implementation	40
4.9	Ground Support Equipment	41
5	Experiment Verification and Testing	42
5.1	Verification Matrix	42
5.2	Test Plan	44
5.2.1	Planned Tests	44
5.2.2	Test Descriptions	44
5.3	Test Results	50
6	Launch Campaign Preparations	54
6.1	Input for the Campaign / Flight Requirements Plans	54
6.1.1	Dimensions and Mass	54
6.1.2	Safety Risks	54
6.1.3	Electrical Interfaces	55
6.1.4	Launch Site Requirements	55
6.1.5	Flight Requirements	55
6.1.6	Accommodation Requirements	55
6.2	Preparation and Test Activities at Esrange	57
6.3	Timeline for Countdown and Flight	58
6.4	Post Flight Activities	59
7	Data Analysis and Results	60
7.1	Data Analysis Plan	60
7.1.1	Control Images	60
7.1.2	Image Processing and SNR Determination	60
7.2	Launch Campaign	61
7.2.1	Flight preparation activities during launch campaign	61
7.2.2	Flight performance	61

7.2.3	Recovery	61
7.2.4	Post flight activities	61
7.3	Results	61
7.3.1	Expected Results	61
7.4	Lessons Learned	62
7.4.1	Management	62
7.4.2	Scientific	62
7.4.3	Electrical	62
7.4.4	Software	62
7.4.5	Mechanical	62
7.4.6	Thermal	62
8	Abbreviations and References	63
8.1	Abbreviations	63
8.2	References	64
A	Experiment Reviews	65
B	Outreach	66
C	Additional Technical Information	67
D	Standard Operation Procedures	68

PREFACE

The Rocket and Balloon Experiments for University Students (REXUS/BEXUS) programme is realized under a bilateral Agency Agreement between the German Aerospace Center (DLR) and the Swedish National Space Board (SNSB). The Swedish share of the payload has been made available to students from other European countries through a collaboration with the European Space Agency (ESA).

EuroLaunch, a cooperation between the Esrange Space Center of SSC and the Mobile Rocket Base (MORABA) of DLR, is responsible for the campaign management and operations of the launch vehicles. Experts from DLR, SSC, ZARM, and ESA provide technical support to the student teams throughout the project.

The Student Experiment Documentation (SED) is a continuously updating document regarding the BEXUS student experiment IRISC - InfraRed Imaging of astronomical targets with a Stabilized Camera and will undergo reviews during the preliminary design review, the critical design review, the integration progress review, and final experiment report.

Acknowledgements

1 Introduction

1.1 Scientific Background

The universe hides a plethora of information across the entire electromagnetic spectrum. Infrared light is unique as compared to other wavelengths of light in that it can permeate interstellar dust, and corresponds to typically "cold" astronomical phenomena, such as star formation, some nebulae, and older, colder stars, to name a few [3]. Here on the surface of the earth, both visible light and radio waves exhibit near-total transmission through the atmosphere for observation, and experience fewer ill effects from atmospheric interference than other wavelengths, including infrared light, that cannot penetrate the atmosphere at all. The infrared regime lies between visible and microwave radiation, and in an astronomical context this usually corresponds to wavelengths between 0.75 and 300 microns. Within this range, a number of cosmological phenomena can be explored, however only parts of this spectral range are capable of penetrating the earth's atmosphere for observation.

Factors affecting infrared transmission through the atmosphere include molecular absorption (in particular absorption by carbon monoxide, carbon dioxide, water vapour, and oxygen, among others), scattering by dust and other molecules, and distortion of the light by small-scale perturbations in the atmosphere such as pressure and temperature gradients [1]. As with visible light, infrared observations are also not possible on cloudy or overcast nights. To minimise these problems, infrared telescopes are usually situated at very high altitudes, such as the Tokyo Atacama Observatory (TAO) at 5,600 m above sea level [6]. Better still, the Stratospheric Observatory for Infrared Astronomy (SOFIA) is an airborne observatory that flies at an altitude of 13-14 km, thus getting above 99.8% of atmospheric water vapour absorption [2], as well as the majority of scattering and distortion.

1.2 Mission Statement

Studying astronomical targets in the infrared from ground-based observatories is hampered by atmospheric distortion and extinction, limiting the amount and kind of infrared research that can be done. Therefore, having a telescope make observations from above the majority of interfering atmosphere will negate these effects, and improve the SNR and therefore scientific quality of the obtained images. Establishing a functional, low-cost system for performing infrared observations from a stratospheric balloon will help to push the boundaries of infrared astronomy.

1.3 Experiment Objectives

The primary objectives of the experiment can be split into a main scientific objective, and a main technical objective: the primary scientific objective is to establish the SNR improvement (if any) from ground-based observations to stratospheric observations in the infrared. In order to achieve this scientific objective, the primary technical objective is to construct a gimbal system that is capable of stabilising the optics setup to arcsecond accuracy.

Pending success of these primary objectives, secondary scientific and technical objectives include:

- I (Scientific) Observations of globular and open star clusters for the purpose of population studies
- II (Scientific) Observations and evaluation of galaxies and nebulae for fine structure detail and infrared characteristics
- III (Scientific) Comparison of IRISC observations with observations done by other instruments in the same wavelength band
- IV (Technical) Construction of a thermal system suitable for maintaining and optimising operation of a near-infrared camera within the BEXUS environment

1.4 Experiment Concept

The experiment will be comprised of a telescope with baffle, a CMOS sensor, and a gimbal stabilisation system, which will work together to obtain long-exposure images of astronomical targets. The control system is responsible for selecting and tracking the astronomical targets using the position and orientation of the BEXUS gondola. It also stabilises the telescope during exposure using an active feedback control. Sensors include a gyroscope, accelerometer, GPS, and a compass/magnetometer, to ensure all vital information for finding and tracking targets is available to the control system. A small sanity camera will also be used for visual verification of the state of the system, in the event that images provided by the BEXUS telemetry are not as expected. The thermal control system will ensure that an optimal operational temperature is maintained for the duration of the experiment.

1.5 Team Details

1.5.1 Contact Point

Project Manager

Address	Diego Talavera Snårvägen 17 981 42 Kiruna Sweden
IRISC Email	contact@irisc.space
Personal Email	dietal-8@student.ltu.se

Endorsing Professor

Title	Thomas Kuhn Associate professor
Address	Rymdcampus 1 981 92 Kiruna Sweden
Telephone	
Email	thomas.kuhn@ltu.se

1.5.2 Team Members

The IRISC Team consists of twelve people of a number of different educational and personal backgrounds. All team members are studying at the Luleå University of Technology, Kiruna Space Campus.



Diego Octavio Talavera Maya - Management

Current Education: MSc in Space Sciences and Technology (SpaceMaster).

Previous Education: BSc in Aerospace Engineering at the Autonomous University of Baja California (UABC).

Responsibilities: Project Management.



Anja Möslinger - Control system

Current Education: MSc in Space Sciences and Technology (SpaceMaster).

Previous Education: BSc in Mechatronics at the Johannes Kepler University (JKU)

Responsibilities: Control system, Stabilisation system, Camera system



Eligius Franciscus Maria Weterings - Electrical

Current Education: MSc in Space Sciences and Technology (SpaceMaster).

Previous Education: BSc in electrical engineering at the University of Rotterdam (HR) with a specialization in computer sciences and mathematics at the University Utrecht (UU).

Responsibilities: Embedded systems, electrical engineering.



Kimberly Tuija Steele - Science and Optics

Current Education: MSc in Space Sciences and Technology (SpaceMaster).

Previous Education: BSc(Astronomy)(Hons)

Responsibilities: experiment scientific background and overall objectives; defining experimental parameters; contacting and collaborating with industry partners that manufacture off-the-shelf optics components; data analysis; interpreting and documenting images; documenting and publishing findings.



Veronika Haberle - Science

Current Education: MSc in Space Sciences and Technology (SpaceMaster).

Previous Education:

Responsibilities: Outreach & data analysis.



Adam Smialek - Control system

Current Education: MSc in Space Sciences and Technology (SpaceMaster).

Previous Education: BSC in Aerospace Engineering at Warsaw University of Technology (WUT) with a specialisation in Automatics and Flight Systems

Responsibilities: Onboard control system & Outreach.



Ajith Kumar BASKAR - Mechanical

Current Education: Master Programme in Spacecraft Design

Previous Education: Bachelor of technology in Aerospace Engineering

Responsibilities: Mechanical engineering.



Harald Magnusson - Software

Current Education: Master Programme in Space Engineering, Luleå University of Technology

Responsibilities: Software (onboard & ground station).



Niklas Ulfvarson - Software

Current Education: Master Programme in Space Engineering, Luleå University of Technology

Responsibilities: Software (onboard & ground station).



Sabina Björk - Electrical

Current Education: Master Programme in Space Engineering, Luleå University of Technology

Responsibilities: Energy technology, electrical engineering.



William Eriksson - Software

Current Education: Master Programme in Space Engineering, Luleå University of Technology

Responsibilities: Software (onboard & ground station).

2 Experiment Requirements and Constraints

A list of requirements and constraints are listed below. The requirements are separated in functional, performance, design and operational requirements.

2.1 Functional Requirements

- F.1 The telescope shall successfully track the celestial bodies of interest.
- F.2 The camera shall take images in the near infrared (NIR) spectrum.

2.2 Performance Requirements

- P.1 The gimbal stabilization system shall point the telescope towards the celestial body with an accuracy of at least 1 arc seconds.
- P.2 The optics shall be cable of making pictures of 0.5-1.5 x 0.3-1 degrees.
- P.3 The NIR camera shall make images in the range of 720-850 to 1200 nm.
- P.4 The NIR camera shall have a resolution of at least 16 MP.
- P.5 The NIR camera shall be able to make images with exposure times between 0.5 and 150 seconds.
- P.6 The experiment shall measure the location and orientation of the gondola.

2.3 Design Requirements

- D.01 The experiment shall be able to operate in the temperature profile of the BEXUS environment.
- D.02 The experiment shall be able to operate in the pressure profile of the BEXUS environment.
- D.03 The experiment shall be able to operate in the vibration profile of the BEXUS environment.
- D.04 The absolute position of the telescope relative to the gondola shall be known with an accuracy of 0.1 degrees.
- D.05 The supporting structure shall not twist by more than 0.1 degrees.
- D.06 The experiment shall never be pointed directly at the sun ± 27 degrees.
- D.07 The experiment shall be able to fly during the entire day.
- D.08 The temperature of the NIR camera shall be held at 0 ± 5 °C.
- D.09 The images obtained shall be sent to a ground station by the E-link system with a maximum data rate of 1000 kilo bits per second.
- D.10 The experiment shall be mounted at the side of the gondola.
- D.11 The experiment shall not consume more power than 250 Wh.
- D.12 The volume of the experiment shall not exceed 65 x 40 x 40 cm.
- D.13 The mass of the experiment shall not exceed 20 kg.
- D.14 The experiment shall be able to run for at least 2.5 hours.
- D.15 The experiment shall be able to function autonomously.
- D.16 The data stored in the experiment shall be able to survive the landing.

2.4 Operational Requirements

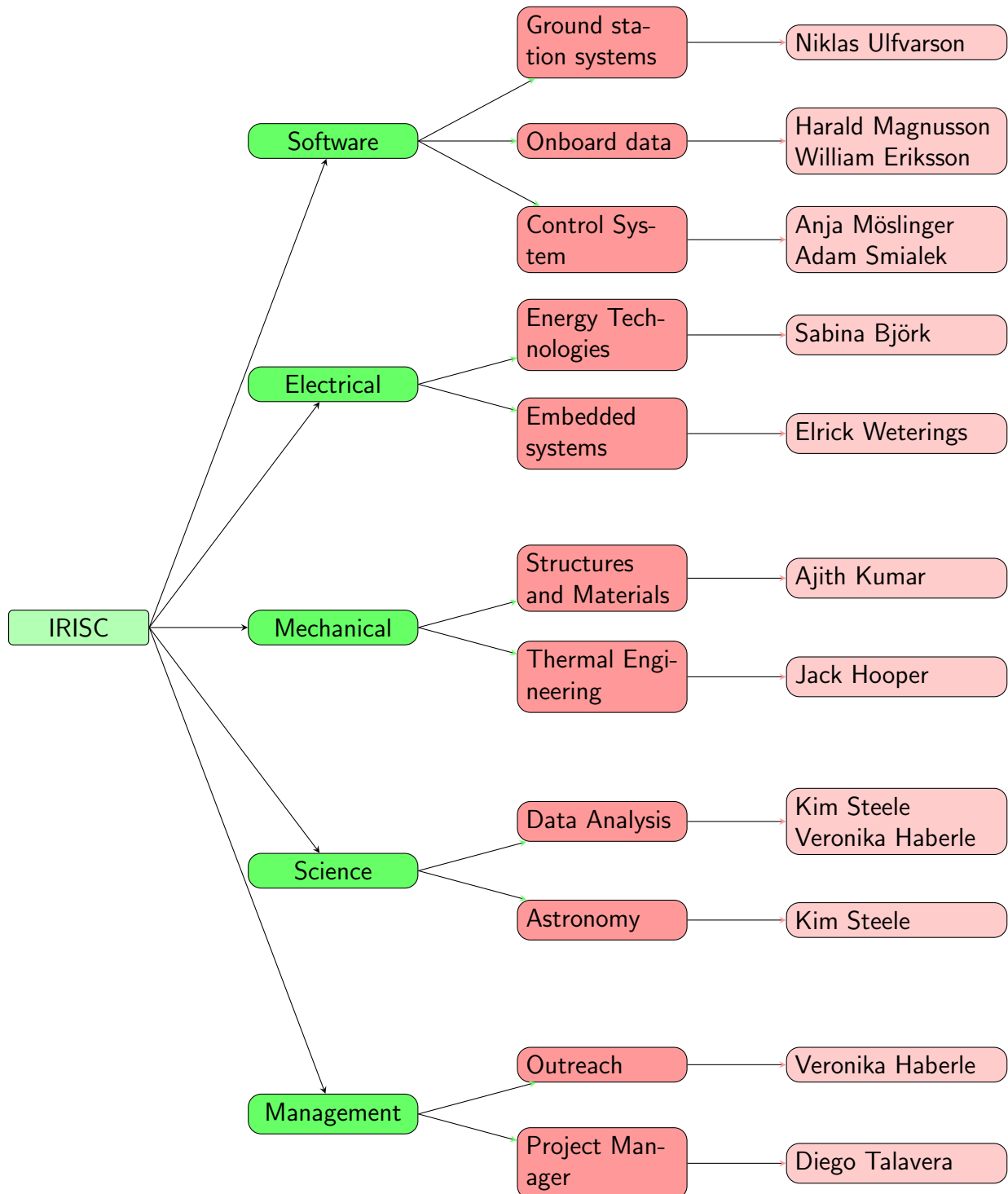
- O.1 The experiment shall be able to be controlled by the ground station when requested.
- O.2 The experiment shall rotate to a 'safe' location while descending.

2.5 Constraints

- C.1 The shared E-link data transfer rates are limited by coverage and quality of reception.
- C.2 There shall be no direct internet connection on the ground station.
- C.3 The mass and volume should fit inside the gondola together with the other experiments.
- C.4 The budget for the experiment is limited by the generous companies and organizations that sponsor IRISC.

3 Project Planning

3.1 Work Breakdown Structure



3.2 Schedule

	BEXUS - IRISC	
		2018
		Dec
Design Phase		
Unit testing		
Manufacturing Phase		
<i>First Prototype</i>		
Complete System Testing		
Launch Campaign		
Data Analysis Phase		

3.3 Resources

3.3.1 Manpower

3.3.2 Budget

Category	Total Mass [g]	Total Price [EUR]
Structure	0.00	00.0
Electronics Box	000.0	0.00
Cables and Sensors		
CAC		
AAC		
Tools	—	
Travel	—	
Contingency	—	
Total without Error Margin		
Shipping Costs and Error Margin		
Total with Error Margin		

Table 3.3.1: Mass and Cost Budget.

3.3.3 External Support

3.4 Outreach Approach

An important focus of the project lays in the topic of outreach. During the whole timeline, updates about the project will be shared with as many people as possible. The most effective way of reaching people is via social media. IRISC is represented on the following social media platforms:

- facebook.com/IRISCBexus
- [instagram](https://www.instagram.com/IRISCBEXUS)
- [twitter/IRISCBEXUS](https://twitter.com/IRISCBEXUS)

Additionally to the social media platforms, the team's website with information about the project is available and updates are blogged there regularly.

Future outreach plans include, but are not limited to,:

- articles at university blog of the technical university of Luleå
- articles in local newspaper
- visibility through posters, flyers, etc at university
- presentations during local events
- applications to grants and awards

3.5 Risk Register

Risk ID

- TC – Technical/Implementation
- MS – Mission (operational performance)
- SF – Safety
- VE – Vehicle
- PE – Personnel
- EN – Environmental
- OR - Outreach
- BG - Budget

Adapt these to the experiment and add other categories. Consider risks to the experiment, to the vehicle and to personnel.

Probability (P)

- A Minimum – Almost impossible to occur
- B Low – Small chance to occur
- C Medium – Reasonable chance to occur
- D High – Quite likely to occur
- E Maximum – Certain to occur, maybe more than once

Severity (S)

- I Negligible – Minimal or no impact
- II Significant – Leads to reduced experiment performance
- III Major – Leads to failure of subsystem or loss of flight data
- IV Critical – Leads to experiment failure or creates minor health hazards
- V Catastrophic – Leads to termination of the REXUS/BEXUS programme, damage to the vehicle or injury to personnel

The rankings for probability (P) and severity (S) are combined to assess the overall risk classification, ranging from very low to very high and being coloured green, yellow, orange or red according to the SED guidelines.

Whether a risk is acceptable or unacceptable has been assigned according to the SED guidelines. Where mitigation is written for acceptable risks this details the mitigation undertaken in order to reduce the risk to an acceptable level.

ID	Risk (& consequence if)	P	S	P * S	Action
TC10	Optics and/ or camera destroyed due to testing	C	2	Low	There is budget for a spare part, it is quite easy to get and test where it will likely fail (e.g. drop test) will not be done with this part.
TC20	Optics and/ or camera destroyed due to looking directly into the sun	B	3	Low	A model will be made and sufficient testing will make sure that the probability gets very low.
TC30	Software failure	B	3	Low	A watchdog with power-on-reset will be added to the design.
TC40	Motors of the gimbal are uncontrollable	B	4	Low	It will be made sure that a single component failure will not result in this consequence.
TC50	Motors overloaded	A	3	Very Low	Sufficient testing and modeling will be done to decrease the probability.
TC60	PCB failure	B	3	Low	Sufficient testing will be done on each PCB to decrease the probability.
TC70	Single component failure gives unprecedented failure	B	4	Low	A Failure mode and effects analysis (FMEA) study will be done so that single failure components with a high impact will be documented and migrated.
MS10	Target not found	D	2	Low	The ground station will be able to correct this, or send the system to another target.
MS20	Gears get jammed	B	4	Low	Gear will be oiled on the day of the launch.
MS30	Damage to the system on landing	D	1	Low	Optics will move inside a frame for protection.
MS40	Damage to the storage unit on landing	C	2	Low	Data will be send over telemetry
MS50	Storage unit full during flight	A	3	Very Low	Sufficient modeling will be done to decrease the probability.
MS60	BEXUS balloon power failure	A	4	Very Low	-
MS70	BEXUS balloon telemetry failure	B	2	Very Low	The system will be able to function autonomously.
SF10	Components falling off the gondola	A	4	Very Low	All parts sufficiently fastened. Testing conducted to ensure fastening is able to hold all parts in place in case of turbulence. Where possible, add assurance by adding additional fixations.
VE10	Short circuiting	B	3	Low	A fuse is in the power system added.
VE20	Collision of telescope with landing mechanism	A	4	Very Low	The experiment will be inside a frame for protection.

PE10	Miscommunication in the team	B	2	Very Low	The management team should be responsible for ensuring proper information is conveyed to all team members.
PE20	People are not available	C	1	Very Low	An availability sheet is made so a planning can be made. This will be kept up to date during the entire project.
PE30	Management team unavailable to oversee project	C	1	Very Low	There is always someone as a backup.
PE40	Sudden resignation of project members	B	2	Very Low	Management team ensure morale remains high through a variety of techniques (group building activities).
EN10	Rays focused on someone due to damage to the telescope (camera)	A	4	Very Low	Calibration of telescope set properly so that rays do not get misguided

Table 3.5.1: Risk Register.

4 Experiment Design

4.1 Experiment Setup

The experiments mounts a telescope with an attached CMOS sensor inside the gondola, looking out as shown in figure CAD-model of experiment setup is still missing. The telescope is mounted on a gimbal system that provides stabilisation along two axis (three if required, depending on simulation results, hardware is available) and tracking in three dimensions. The sensor/telescope/gimbal system will be shielded from the Sun's radiation and climatized in order to provide the required operation temperatures. This is achieved by using Peltier elements where heating or cooling may be necessary (e. g. the sensor) and heating pads where there is only a chance of freezing (e. g. the moving parts of the gimbal). The individual sections of the experiment are described below.

4.1.1 Telescope and CMOS sensor

The telescope chosen is a Sky-Watcher BKP 130 DS (see figure 4.1.1), a parabolic newtonian reflector with a focal length of 650 mm, an optical diameter of 130 mm and therefore featuring an aperture ratio of $f/5$.

The imaging sensor used is ZWO ASI183MM (mono) (see figure 4.1.2), a CMOS sensor with only one channel (mono, not color) with a resolution of 20.18 MP (5496x3672), a sensor size of 13.2x8.8 mm (diagonal: 15.86 mm) and a pixel size of $2.4 \times 2.4 \mu\text{m}$. To limit the wavelength bandwidth imaged, an IR filter that filters out any wavelengths below 720 nm is used in order to use the sensor as a NIR camera.



Figure 4.1.1: Sky-Watcher BKP 130 DS [5]



Figure 4.1.2: ZWO ASI183MM (mono) [7]

This combination of telescope and sensor features the following specifications:

- **Field of View (FoV):** the field of view determines the astronomical targets that can be observed. It depends on the sensor size and the focal length of the telescope. Naturally, there is a horizontal, a vertical and a diagonal field of view:

$$\text{FoV}_{\text{horizontal}} = \arctan \frac{13.2 \text{ mm}}{650 \text{ mm}} = 1.16^\circ \quad (1)$$

$$\text{FoV}_{\text{vertical}} = \arctan \frac{8.8 \text{ mm}}{650 \text{ mm}} = 0.757^\circ \quad (2)$$

$$\text{FoV}_{\text{diagonal}} = \arctan \frac{15.86 \text{ mm}}{650 \text{ mm}} = 1.382^\circ \quad (3)$$

- **Sensor resolution:** the angular resolution per pixel defines the precision of the scientific data collected.

$$\text{Resolution} = \arctan \frac{2.4 \mu\text{m}}{650 \text{ mm}} = 0.7616'' \quad (4)$$

In order to examine the field of view in case the images sent down via downlink do not show the expected astronomical targets, an additional imaging sensor is installed on a guiding telescope that has a shorter focal length than the main telescope, implying a larger field of view. With the help of these pictures it will be able to correct offset errors in the pointing mechanism of the control system due to e. g. temperature drift of the sensors.

4.1.2 Electronics

The On-Board Computer is hosted by the electronics box that also features the onboard storage as well as the power supply unit, one set of gyroscopes and accelerometers to measure the movement of the gondola in order to provide input data to the control system, a GPS (for the control system, only applicable if there is no real-time access to the GPS data from the BEXUS gondola), temperature sensors for housekeeping data and the heat management system inside the electronics box and heating elements. The sensors are located on a PCB designed by the electronics team, along with the power supply unit.

The CMOS sensor data is transmitted to the On-Board Computer where it is compressed with lossless compression and sent down via E-link and is also stored onboard the BEXUS balloon. The onboard storage is located in the electronics box that is designed considering compatibility with the harsh environmental conditions as well as redundancy. The mechanical structure that features the onboard storage ensures survival in case of shock due to hard impact when landing or if the BEXUS balloon lands in a lake or wetlands.

4.1.3 Control system

The control system is responsible for tracking the target in the sky and stabilising the telescope during exposure. The tracking uses the current orientation of the gondola along the z-axis measured by a magnetometer as well as the orientation of the telescope within the gondola using encoders. Based on the current time and position (measured by the GPS system) as well as the operational field of view, the control system will select and track the target in order to point the telescope towards the astronomical targets and avoid star trails due to the sky's rotation as seen from an observer on Earth. The stabilisation system is responsible for keeping the telescope steady during exposure by counteracting the gondola movements measured by the gyrometers and accelerometers located on the sensor PCB in the electronics box.

currently not included: guiding scope & camera -> needs to be included!

4.2 Experiment Interfaces

4.2.1 Mechanical Interfaces

The experiment mounting platform will be attached to the upper rails of the gondola.

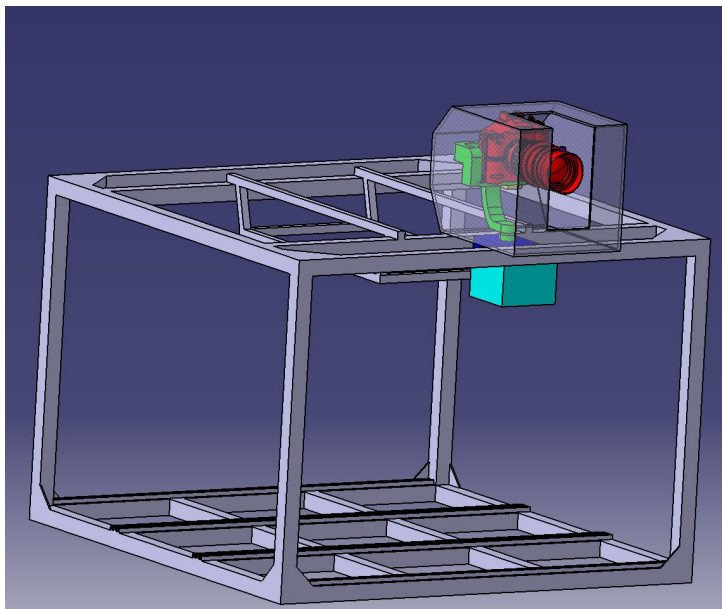


Figure 4.2.1: Instrument position on gondola

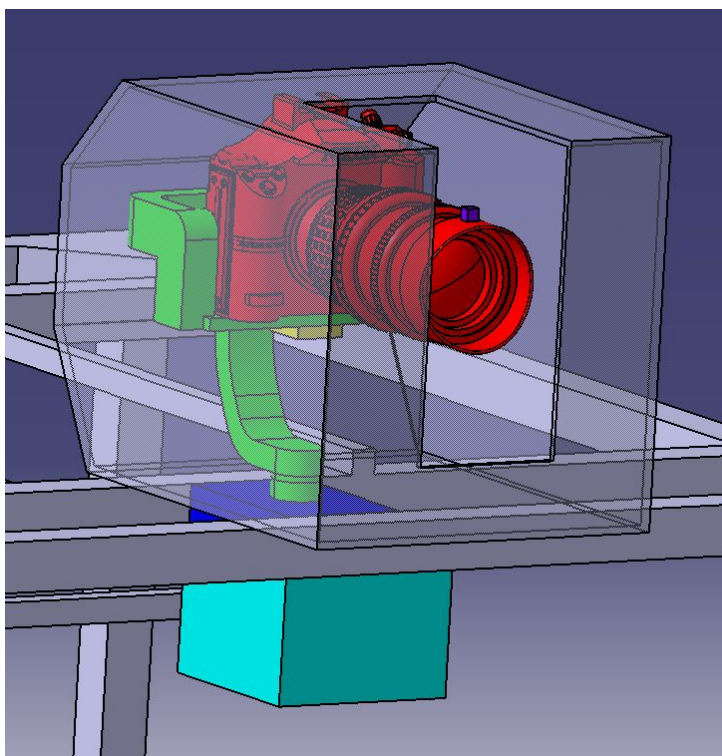


Figure 4.2.2: Close up of the instrument mounting

4.2.2 Thermal Interfaces

4.2.3 Electrical Interfaces

E-link:

The uplink will be used to send occasional commands to control the experiment. One command will be [TBD] in size. The TCP/IP protocol will be used for uplink, so the total size of one transmission will be the data plus the TCP header (maximum 480 bits), the IP header (maximum 480 bits) and the Ethernet frame (144 bits).

$$\text{bits per uplink packet} \leq [TBD] + 480 + 480 + 144$$

The downlink will be used to send science and housekeeping data to the ground station. The data in the downlink packet is estimated to be [TBD]. For downlink, UDP protocol will be used, as the reliability of the data is not as crucial as during the uplink and to compensate for the size of the data packet. The total size of one packet will be the data plus the UDP header (32 bits), the IP header (maximum 480 bits) and the Ethernet frame (144 bits).

$$\text{bits per downlink packet} \leq [TBD] + 32 + 480 + 144$$

Power:

Info about power cables, their length/resistivity and thus power loss, their connection to gondola power relay.

Connectors:

Protection:

Grounding:

4.2.4 Radio Frequencies (Optional)

4.3 Experiment Components

4.3.1 Electrical Components

Table 4.3.1 shows all required electrical components with their total mass and price.

ID	Component Name	Supplier	Supplier Code	Qty	Mass Each [g]	Cost Each [EUR]	Note	Status
E001	Raspberry Pi 3B+	TBD	TBD	1	50	TBD		Defined
E002	Micro SD 32GB	TBD	TBD	1	0.27	TBD		Defined
E003	DC motor	TBD	TBD	3	TBD	TBD		Defined
E004	Encoders/potentiometers	TBD	TBD	1	TBD	TBD		Defined
E005	Buck Converter	TBD	TBD	1	TBD	TBD		Defined
E006	Gyroscope	TBD	TBD	2	TBD	TBD		Defined
E007	Magnetometer	TBD	TBD	1	TBD	TBD		Defined
E008	GPS	TBD	TBD	1	TBD	TBD		Defined

Table 4.3.1: Electrical components.

4.3.2 Mechanical Components

Table 4.3.2 shows all required mechanical components with their total mass and price.

ID	Component Name	Supplier	Supplier Code	Qty	Mass Each [g]	Cost Each [EUR]	Note	Status
----	----------------	----------	---------------	-----	---------------	-----------------	------	--------

Table 4.3.2: Mechanical components.

4.3.3 Other Components

Table 4.3.3 shows other components which contribute to the mass and/or price.

ID	Component Name	Supplier	Supplier Code	Qty	Mass Each [g]	Cost Each [EUR]	Note	Status
O001	ASI183mm	TBD	TBD	1	140	TBD	Mono color camera	Defined
O002	TBD	TBD	TBD	1	TBD	TBD	Guiding camera	Defined
O003	TBD	TBD	TBD	1	TBD	TBD	Sanity camera	Defined
O004	130PDS telescope	TBD	TBD	1	3660	TBD		Defined
O005	NIR filter 1.25"	TBD	TBD	1	TBD	TBD		Defined

Table 4.3.3: Other components.

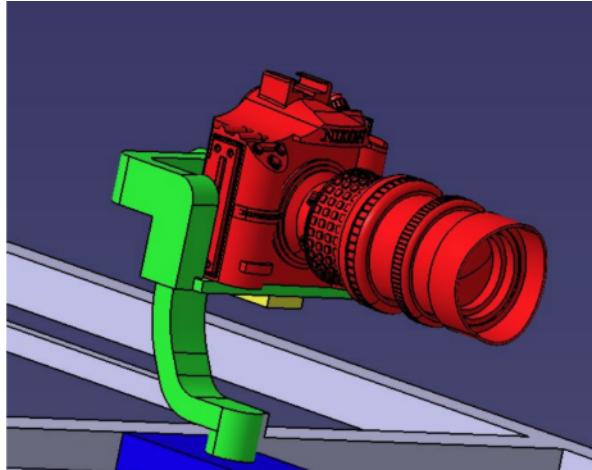


Figure 4.4.1: Gimbal structure

4.4 Mechanical Design

4.4.1 Structure

The experiment itself has only two components that are placed inside the Gondola. Firstly, the electronic box and then the gimbal on which the telescope is mounted. We require the gimbal to be placed at the edge of the Gondola so that we will be able to perform rotating mechanism that pops the telescope out of the gondola while operation.

4.4.2 Electronic box

The electronic box has a dimension 10x10x10 cm which is placed directly inside the gondola. It is estimated to weigh 1.5 kg. The box is made of aluminium side plates with a thick layer of styrofoam placed on the inside of the aluminium plates which protects the electronics. The box has rubber cushion feet that acts as a shock absorber and also thermal insulator from the gondola.

4.4.3 Gimbal

We intend to use a three axis gimbal so we have a maximum field of view. We use CFRP or composites to manufacture the gimbal. The gimbal along with telescope is estimated to weigh around 10kg.

4.4.4 Fixing interface

The telescope itself has certain fixture points. So, we make the gimbal with matching fixture points. The gimbal is directly fixed on the gondola.

4.5 Electrical Design

4.5.1 Block Diagram

4.5.2 Critical Component/Part A

4.5.3 Critical Component/Part B

4.5.4 Critical Component/Part C

4.5.5 Schematic

4.5.6 PCB Layout

4.6 Thermal Design

4.6.1 Optothermal considerations

In order to ensure minimise measurement error in acquiring photographs, the effect of temperature on the optics must be considered, and the temperature must be controlled if needed to ensure that the error is within an acceptable range.

SNR Dark current is small residual currents that are present in the camera, generated irrespective of whether there is incident illumination. This dark current becomes present in the data in the form of random noise that is not trivial to subtract. By decreasing the operating temperature of the camera optics, the magnitude of dark current can be minimised and the signal to noise increased. This relationship between signal to noise and dark current is as follows

$$SNR = \frac{I \times QE \times t}{\sqrt{I \times QE \times t + Nd \times t + Nr^2}}$$

I = Photon flux (photons/pixel/s)

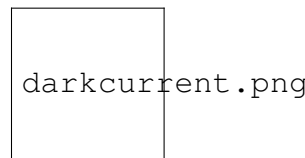
QE = Quantum efficiency

t = Integration time (s)

Nd = Dark current (electrons/pixel/s)

Nr = Read noise (electrons)

The ASI183 camera is specified as having a read noise of 1.6e @30db gain and a Qe peak of 84%. The camera also has the following relationship between dark current and sensor temperature.



As an example, the SNR as affected by dark current at -10C versus 10C is

$$SNR(-10C) = \frac{I \times (0.84) \times (300s)}{\sqrt{I \times (0.84) \times (300s) + (0.00391e/pixel/s) \times (300s) + (1.6e)^2}} =$$

$$SNR(10C) = \frac{I \times (0.84) \times (300s)}{\sqrt{I \times (0.84) \times (300s) + (0.01563e/pixel/s) \times (300s) + (1.6e)^2}} =$$

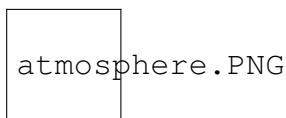
Optothermal stability Another important effect will be the how thermal stresses and subsequent deflections can affect the optics of the camera, in particular the index of refraction, and hence the quality of the collected data. Variation of solar flux over the time of flight and from the heat signatures of the BEXUS module will need to be considered. A thermoelastic analysis should be conducted in finite element analysis software to evaluate the effects of the

thermal environment, and the implication of those results on the validity of the data should be investigated.

Condensation Condensation of water vapor may occur in this cold environment due to heat generation of the camera. This will deteriorate the quality of the detections and must also be mitigated.

4.6.2 Thermal environment

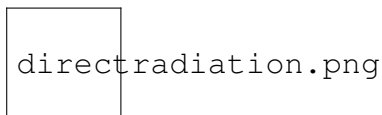
Atmosphere ambient conditions IRISC will ascend to and float in the stratosphere at an altitude of between 25 and 30km, after which it will experience altitude fluctuations of no more than 200m. This is the phase of flight during which the infrared camera will be operational and hence thermal control most necessary in ensuring sound optical performance. This part of the atmosphere is also characterised by relatively low temperatures. Based on the flights of number previous BEXUS missions seen in figure xx, it can be assumed that the atmospheric temperature during float will range between -70C and -50C.



Flight phase	Expected temperature	Duration
Preparation	15 – 25C	4 hours
Launch pad wait	-15 – 0C	3 hours
Ascent phase	-80 – 0C	1.5 hours
Float phase (25-30km)	-70 – -50C	1 – 5 hours
Descent phase	-80 – 0C	30 min
Post-flight phase	-15 – 0C	1 – 2 days

Solar flux The extent of solar irradiance is characterised by several factors, including the sun's height above the horizon, typically low for the polar latitudes that the balloon will be flying at, and the height in the atmosphere and atmospheric conditions, which will cause absorption and scattering of light.

The total solar irradiance, neglecting atmospheric effects, at the Esrange latitude of 68° and assuming a launch date of the 15th of October is demonstrated in figure xxx , with a peak of 500 kW/m² at noon.



The degree of attenuation of solar radiation through the atmosphere can be described using the Beer–Lambert law, which relates the transmittance of radiation to optical depth. For an atmosphere with properties that change exponentially with respect to altitude, the optical depth can be estimated to also change exponentially with respect to altitude.

4.6.3 Temperature requirements

Component	Operating temperature
ASI183 camera	-5 – 45C
Camera module for Raspberry Pi 5MP 1080P	-20 – 80C
Igarashi DC Gearmotor 33GN2738-132-GV-5 312:1	0* – 60C
GYRO / ACCELEROMETER 3-AXIS MPU-3050	-20 – 105C
Electronics	-5 – 60C

*0C required to prevent condensation and subsequent freezing on the motors

As the ambient conditions are likely to be very cold, many of the components will need to be heated so that the electronics are able to operate. If the ambient conditions are assumed to be -70C, and the desired temperature for the components 10C, the camera temperature will need to increase by 80C.

4.6.4 Thermal control

In order to heat the electronics to the desired temperature, Polyimide Thermofoil Heaters supplied by Minco can be used, as they are lightweight, and commonly used to protect electronics from cold at high altitudes. A heater will be supplied for each of the three motors, for the camera, and for the electronics box. The heaters can be used to generate temperatures of up to 200C. Temperature sensors will be included next to the heaters to provide feedback that will allow the temperature to be controlled to the desired operating point.

The motor is 37.8mm long with a diameter of 33mm, so the 5572 heater with dimensions 12.7 x 12.7mm and a resistance of 26.5 ohms is selected.

$$P = 5V^2 / 26.5 \text{ ohms} = 0.94W$$

The camera is 73.5mm long with a diameter of 78mm, so the 5587 heater with dimensions 31.8 x 31.8mm and a resistance 13.1 ohms is selected.

$$P = 5V^2 / 13.1 \text{ ohms} = 1.91W$$

The electronics box is 100mm x 100mm x 100mm, so the 5592 heater with dimensions 44.5 x 44.5mm and a resistance 26.3 ohms is selected.

$$P = 5V^2 / 26.3 \text{ ohms} = 0.95W$$

4.7 Power System

A 28.8V/1mA battery package can be provided by the gondola, according to the BEXUS user manual. Which should satisfy IRISCs power needs. One constrain is that the continuous maximum current is 1.8 A. Thus a buck-converter will be needed to step down the voltage, so that the power system will be able to provide the right voltages for the rest of the subsystems.

4.8 Software Design

4.8.1 Purpose

The purpose of the On-Board Software consists of:

- Controlling the tracking and choosing of targets to observe.
- Ensuring that the camera is not oriented towards the sun.
- Reading data from sensors and controlling actuators when needed.
- Processing and storing images taken by camera.
- Logging housekeeping data.
- When possible, send images and housekeeping data to ground station.

4.8.2 Design

a) Process Overview

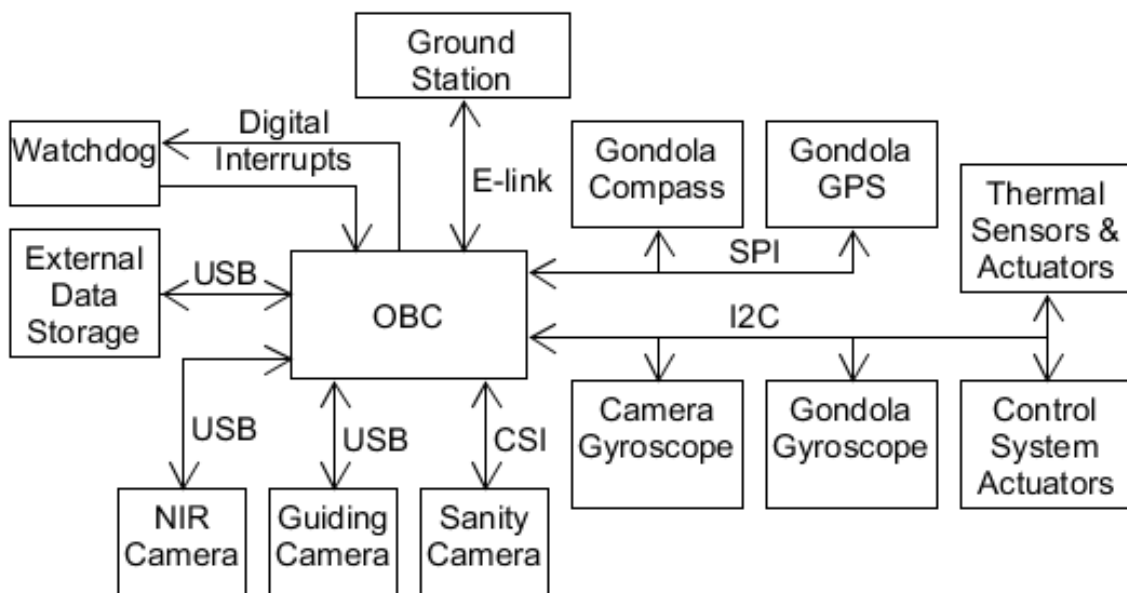


Figure 4.8.1: Relations between On-Board Computer and connected components.

All external components connected to the On-Board Computer and their interface are displayed in figure 4.8.1.

b) General and safety related concepts

To ensure that the software is not erroneous rigorous testing will be done during development and after completion. A watchdog timer will be used to avoid software freezing. This timer will reset the On-Board Computer if it is not itself reset by the software within a certain period. In the case of a reset, the camera shall move to the launch position and tracking restarted.

c) Interfaces

If connection to ground is available, images compressed with a lossless compression will be sent down over the E-link over the course of the experiment. If the storage were to fail on touchdown for any reason, this would mean that not all data is lost.

Component	Interface
Ground Station	E-link
External Data Storage	USB
NIR Camera	USB
Guiding Camera	USB
Sanity Camera	CSI
Watchdog	Digital Interrupts
Gondola GPS	SPI
Compass/Magnetometer	SPI
Gondola Gyroscope	I2C
Camera Gyroscope	I2C
Controller Actuators	I2C
Thermal Sensors & Actuators	I2C

Table 4.8.1: Table showing the interface that each external component is connected with. This is also visually represented in figure 4.8.1.

d) Data acquisition and storage

The main bulk of data handled is the images taken by the camera. Housekeeping data such as positioning, camera direction, time, etc will also be stored along with the images.

As the camera has a resolution of $5496 * 3672$ and a colour depth of 12 bits, the raw image size will be 30.27 MB. For a 4 hour float phase and an exposure time of 30 s a total of 14.53 GB is required in on-board data storage for the images.

With a maximum of 1 Mbit per second data transfer rate to ground it takes at least 145.5 s to transfer one image compressed losslessly to 60% of original size. This means that with little down time between observations and for most exposure times, not all images can be transmitted to ground.

e) Process Flow

Pre-launch tests shall be conducted to ensure that all systems work as expected. Afterwards the system shall enter a sleep mode with the camera in a safe launch position. When the float phase is reached, the system will wake. After wake-up the system shall find its orientation and the position of the sun. Finally tracking and observation can start.

Astronomical targets are prioritised. The software shall track and observe the highest priority target within the field of view with varying camera settings until one of the following events happen:

- Current target leaves operational field of view.
- Target moves too close to the sun for observation.
- A higher priority target enters the field of view.

If one of the aforementioned events happen, the software will switch current target following prioritisation. While observing targets, the On-Board Software shall store images and house-keeping data. If connection to ground is available this data shall be compressed using a lossless compression method and sent to ground.

At the end of the floating phase the camera shall be oriented in a landing position and the system shall shut down. Figure 4.8.2 shows the complete process flow. Figure 4.8.3 shows a simple state diagram for the experiment. Observations are done in the Normal state. In the rare case of a software freeze, it will be reset without entering sleep mode.

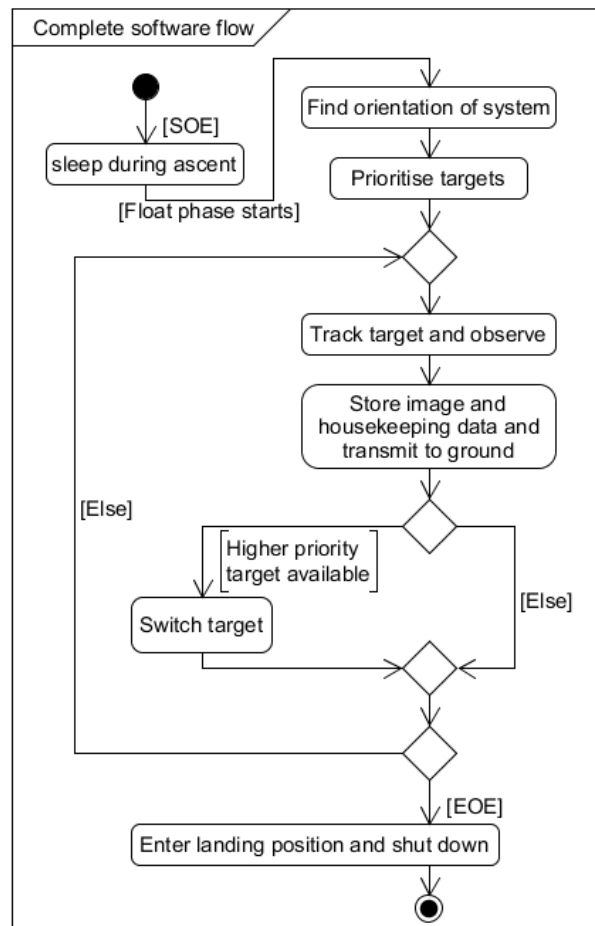


Figure 4.8.2: Activity diagram describing the complete software flow.

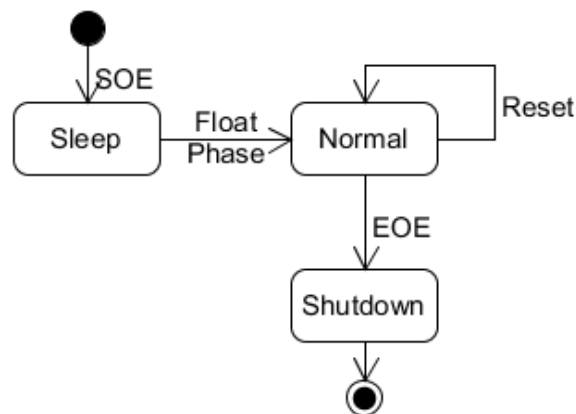


Figure 4.8.3: State diagram for On-Board Software

f) Modularisation and pseudo code

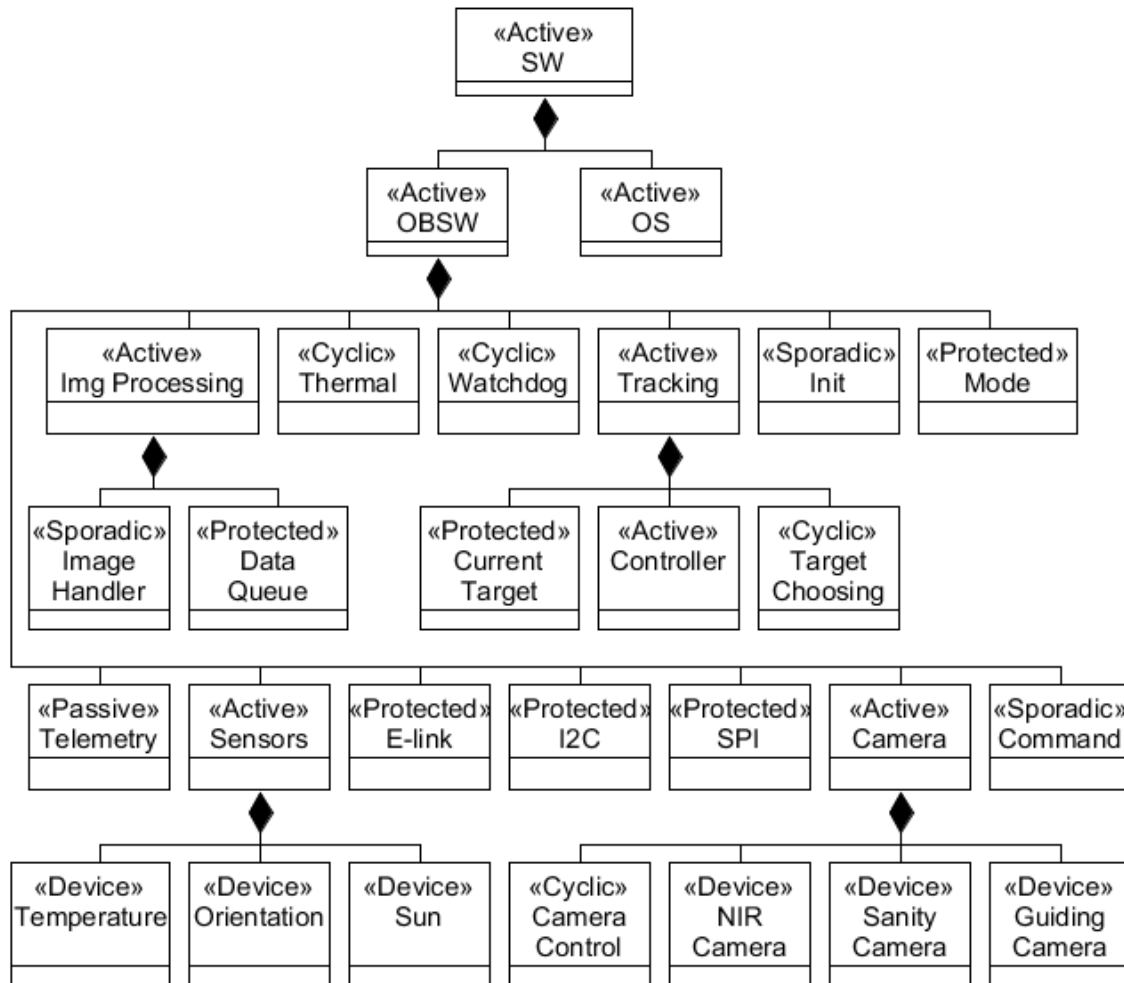


Figure 4.8.4: Composition tree of On-Board Software.

Figure 4.8.4 shows how the complete software is modularised. Each component is described below.

- Img Processing: Image processing, parent
 - Image Handler: Module processing and storing images taken by camera.
 - Data Queue: Buffer to hold camera data until Handler is ready
- Thermal: Module responsible for active thermal control
- Watchdog: Timer to reset external watchdog.
- Tracking: parent
 - Current Target: Module holding the current target to be observed.
 - Controller: Module responsible for keeping camera on target.
 - Target Choosing: Module responsible for keeping track of target prioritisation.
- Init: Module initialising each component.

- Mode: Module responsible for the current state of the software.
- Telemetry: Module responsible for sending telemetry to ground.
- Sensors: parent
 - Temperature: Thermal sensors.
 - Camera Orientation: Module keeping track of camera orientation and location.
 - Sun: Module keeping track of position of the sun.
- E-link: Module responsible for communications over the E-link interface.
- I2C: Module responsible for communications over the I²C bus.
- SPI: Module responsible for communications over the SPI bus.
- Camera: Parent
 - Camera Control: Module responsible for selecting target, camera settings and capturing images.
 - NIR Camera: Communication link to the NIR camera.
 - Sanity Camera: Communication link to the sanity camera.
 - Guiding Camera: Communication link to the guiding camera.
- Command: Module responsible for handling incoming commands from ground.

4.8.3 Implementation

The code for the On-Board Software shall be implemented in C. An operating system will be used to enable the modularisation required. Additional libraries may be needed.

4.9 Ground Support Equipment

A computer on the ground will be connected to the experiment via the E-Link. The ground support software will include a simple GUI which will enable an operator to issue commands to the experiment such as reset, target selection, and moving to landing position. Low resolution pictures will be received by the ground support software, which can be examined to verify nominal operation. The ground support software shall be written in C.

5 Experiment Verification and Testing

5.1 Verification Matrix

The verification matrix is made following the standard of *ECSS-E-10-02A*. [4].

There are four established verification methods:

A - Verification by analysis or similarity

I - Verification by inspection

R - Verification by review-of-design

T - Verification by testing

ID	Requirement text	Method	Reference	Status	Verification result
F.1	The telescope shall successfully track the celestial bodies of interest.	A, T	Tests: 4, 5, 9, 10	A: to be done T: to be done	Not verified
F.2	The camera shall take images in the near infrared (NIR) spectrum.	R	Test: 1	R: to be done	Not verified
P.1	The gimbal stabilization system shall point the telescope towards the celestial body with an accuracy of at least 1 arc seconds.	A, T	Tests: 3, 4, 5, 9, 10	A: to be done T: to be done	Not verified
P.2	The optics shall be cable of making pictures of 0.5-1.5 × 0.3-1 degrees.	R, T	Test: 1	R: to be done T: to be done	Not verified
P.3	The NIR camera shall make images in the range of 720-850 to 1200 nm.	R	Test: 1	R: to be done	Not verified
P.4	The NIR camera shall have a resolution of at least 16 MP.	R, T	Test: 1	R: to be done T: to be done	Not verified
P.5	The NIR camera shall be able to make images with exposure times between 0.5 and 150seconds.	R, T	Test: 1	R: to be done T: to be done	Not verified
P.6	The experiment shall measure the location and orientation of the gondola.	A, T	Tests: 3, 4, 5, 9, 10	T: to be done	Not verified
D.01	The experiment shall be able to operate in the temperature profile of the BEXUS environment.	T	Test: 2	T: to be done	Not verified
D.02	The experiment shall be able to operate in the pressure profile of the BEXUS environment.	T	Test: 2	T: to be done	Not verified

D.03	The experiment shall be able to operate in the vibration profile of the BEXUS environment.	T	Tests: 8, 10	T: to be done	Not verified
D.04	The absolute position of the telescope relative to the gondola shall be known with a accuracy of 0.1 degrees.	T	Tests: 3, 4, 9, 10	T: to be done	Not verified
D.05	The supporting structure shall not twist by more than 0.1 degrees.	T	Tests: 9, 10	T: to be done	Not verified
D.06	The experiment shall never be pointed directly at the sun ± 27 degrees.	T	Tests: 4, 9, 10	A: to be done T: to be done	Not verified
D.07	The experiment shall be able to fly during the entire day.	T	Tests: 9, 10	T: to be done	Not verified
D.08	The temperature of the NIR camera shall be held at $0 \pm 5^{\circ}\text{C}$.	T	Tests: 9, 10	T: to be done	Not verified
D.09	The images obtained shall be send to a ground station by the E-link system with a maximum data rate of 1000 kilo bits per second.	T	Test: 6	T: to be done	Not verified
D.10	The experiment shall be mounted at the side of the gondola.	T	Tests: 9, 10	T: to be done	Not verified
D.11	The experiment shall not consume more power than 250 Wh.	T	Tests: 9, 10	T: to be done	Not verified
D.12	The volume of the experiment shall not exceed 65 x 40 x 40 cm.	I	Test: 7	I: to be done	Not verified
D.13	The mass of the experiment shall not exceed 20 kg.	I	Test: 7	I: to be done	Not verified
D.14	The experiment shall be able to run for at least 2.5 hours.	T	Tests: 9, 10	T: to be done	Not verified
D.15	The experiment shall be able to function autonomously.	T	Tests: 4, 9, 10	T: to be done	Not verified
D.16	The data stored in the experiment shall be able to survive the landing.	T	Test: 8	T: to be done	Not verified
O.1	The experiment shall be able to be controlled by the ground station when requested.	T	Tests: 4, 10	T: to be done	Not verified
O.2	The experiment shall rotate to a 'safe' location while descending.	T	Tests: 4, 9, 10	T: to be done	Not verified

Table 5.1.1: Verification Matrix.

5.2 Test Plan

5.2.1 Planned Tests

The planned tests are as follows:

- Test 01: Optics & Camera;
- Test 02: Thermal & pressure test;
- Test 03: Electronics;
- Test 04: Software with electronics;
- Test 05: Control system;
- Test 06: Data transfer;
- Test 07: Mass & Volume;
- Test 08: Drop test (without optics and camera);
- Test 09: Gimbal mounted on replicated gondola;
- Test 10: Gimbal mounted on a car.

5.2.2 Test Descriptions

Test Number	1
Test Type	Optics & Camera
Test Facility	LTU (outside), Kiruna
Tested Item	Optics & Camera
Test Level/ Procedure and Duration	Verify the design that pictures are only able to be made in the specified NIR spectrum range, with the specified resolution and angular size. Then put the selected optics with camera on a tripod and make picture of all the selected targets. For these tests the NIR filter may be temperately removed (if possible). But all targets should be photographed at least in the NIR spectrum. Test duration: 8 hours (at night).
Test Campaign Duration	1 day
Test Campaign Date	April
Test Completed	NO
Requirements verified	NO

Table 5.2.1: Test 1: Optics & camera ground tested.

Test Number	2
Test Type	Vacuum & freezer
Test Facility	IRF/ EISCAT, Kiruna
Tested Item	Electronics, optics and camera
Test Level/ Procedure and Duration	The electronics, optics and camera should be placed in a vacuum and freezer to test the components functionality with a simulated environment based on the one we expect to encounter. The pressure should be <5 mbar and temperature -80 °C (or atleast colder than -40 °C if not possible) The components may be tested separately, but should function during the test. Test duration: 15 minutes per test on the specified pressure and temperature.
Test Campaign Duration	1 day
Test Campaign Date	Beginning of June
Test Completed	NO
Requirements verified	NO

Table 5.2.2: Test 2: Vacuum and freezer test of atleast the electronics, optics and camera.

Test Number	3
Test Type	Electronics
Test Facility	LTU, Kiruna
Tested Item	Sensors and Actuators
Test Level/ Procedure and Duration	The sensors should first be read out one by one, without the other sensors connected. If multiple sensors or actuators are located on the same PCB, there should also be a test PCB available with each sensor and actuator separated from the prototype phase. Afterwards, the same is done for each actuator. Then, one by one, each sensor and actuator is added to the system to test the system as a whole. Test duration: 5 hours.
Test Campaign Duration	1 day
Test Campaign Date	Beginning of June
Test Completed	NO
Requirements verified	NO

Table 5.2.3: Test 3: Sensors and actuators test.

Test Number	4
Test Type	Software
Test Facility	LTU, Kiruna
Tested Item	Raspberry pi software with electronics connected.
Test Level/ Procedure and Duration	This test should be done after the functionality of the electronics is verified. Then all sensors and actuators should be tested integrated with the software. Let the gimbal be targeting 4 specific points with a separation of 90 degrees. Test if the gimbal stabilize the system when moved and switches targets based on the field of view. The targets should also be able to be switched on the groundstation. Then add a 5th target which it may never look directly at and repeat the test. Test duration: 5 hours.
Test Campaign Duration	1 day
Test Campaign Date	Beginning of June
Test Completed	NO
Requirements verified	NO

Table 5.2.4: Test 4: Software (onboard and ground) with electronics connected test.

Test Number	5
Test Type	Control system
Test Facility	LTU, Kiruna
Tested Item	Control software.
Test Level/ Procedure and Duration	This test is done in a simulation program. The program verifies that the control system is able to track moving targets realtime in the sky without looking directly at the sun. Test duration: 2.5 hours (real time, simulation might be speed up).
Test Campaign Duration	1 day
Test Campaign Date	Beginning of June
Test Completed	NO
Requirements verified	NO

Table 5.2.5: Test 5:Control system simulation.

Test Number	6
Test Type	Data transfer
Test Facility	LTU, Kiruna
Tested Item	Controller
Test Level/ Procedure and Duration	Send the pictures, made in test 1, over the telemetry channel and monitor the data packages with the program 'Wireshark' or similar. Write down the telemetry data rate including headers and footers. During the test the connection should be resetted and the buffer should make sure all data will be transferred after the connection comes online again. Test duration: 30 minutes.
Test Campaign Duration	0.5 Day
Test Campaign Date	Beginning of June
Test Completed	NO
Requirements verified	NO

Table 5.2.6: Test 6: Telemetry testing.

Test Number	7
Test Type	Mass & Volume
Test Facility	LTU, Kiruna
Tested Item	Entire system
Test Level/ Procedure and Duration	Weigh the project on a measuring scale and write down the total weight. All components that are also included on the BEXUS balloon should be added. The subsystems may be measured individually or as a whole. Then measure the volume of the project and write down the volume. Test duration: 30 minutes.
Test Campaign Duration	1 hour
Test Campaign Date	Beginning of June
Test Completed	NO
Requirements verified	NO

Table 5.2.7: Test 7: Check mass and dimensions of entire system.

Test Number	8
Test Type	Drop test
Test Facility	LTU, Kiruna
Tested Item	Electronics and gimbal
Test Level/ Procedure and Duration	Get the electronics and gimbal and put them off. Put them on the replicated gondola in the preferred positions with the attachment material that will also be used during the BEXUS flight. Drop the experiment from 1, 2 and 3 meters high. After every test the functionality of the system should be tested. At least the data logger should survive. Test duration: 1 hour.
Test Campaign Duration	0.5 day
Test Campaign Date	Beginning of June
Test Completed	NO
Requirements verified	NO

Table 5.2.8: Test 8: Drop test of entire system except optics and camera.

Test Number	9
Test Type	Gimbal performance
Test Facility	LTU, Kiruna
Tested Item	Gimbal, software and electronics
Test Level/ Procedure and Duration	Put the entire system in the replicated gondola and montage the system as would be montaged on the BEXUS flight. Let the system in sleep mode for atleast 2 hours (waiting) plus 1.5 hours (ascending) and simulate that the floating phase is reached. Then let the system work for at least 2.5 hours. Move the system around during the floating phase. Then simulate that the descending phase has started. Monitor the power and data usage during this test. Test duration: 6 hours.
Test Campaign Duration	1 week
Test Campaign Date	End of June
Test Completed	NO
Requirements verified	NO

Table 5.2.9: Test 9: Gimbal with all subsystems mounted on a replicated gondola.

Test Number	10
Test Type	Gimbal vibration test
Test Facility	LTU (outside), Kiruna
Tested Item	Gimbal, software and electronics
Test Level/ Procedure and Duration	Then let the system make images for at least 2.5 hours while being mounted on top of a car. Drive with the slowly car around on a mostly flat survive. Test duration: 5 hours.
Test Campaign Duration	1 week
Test Campaign Date	End of June
Test Completed	NO
Requirements verified	NO

Table 5.2.10: Test 10: Gimbal mounted on a car to test entire system with vibrations.

5.3 Test Results

The results shown here provide the key information obtained from testing. A full report for each test can be found in Appendix ??.

Verification Number	1
Test Type	Optics & Camera
Facility	LTU (outside), Kiruna
Verified item	Sampling System
Verification description	The camera should make pictures in the NIR spectrum with the specified resolution and angular size. This test is also used to obtain ground made pictures from the targets of interest.
Expected results	The camera makes NIR images from the targets of interest.
Obtained results	
Conclusions	Not verified.

Table 5.3.1: Results test 1: Optics & camera ground tested.

Verification Number	2
Test Type	Vacuum & freezer
Facility	IRF/ EISCAT, Kiruna
Verified item	Electronics, optics and camera
Verification description	The electronics, optics and camera withstand a pressure of <5 mbar and a temperature of atleast -40 °C.
Expected results	The system controls the temperature if the temperature almost gets below the minimum temperature specified. The system is also able to survive in a <5 mbar environment.
Obtained results	
Conclusions	Not verified.

Table 5.3.2: Results test 2: Vacuum and freezer test of atleast the electronics, optics and camera.

Verification Number	3
Test Type	Electronics
Facility	LTU, Kiruna
Verified item	Sensors and actuators
Verification description	The specified range and accuracy of each sensor and actuator are being met, even after integration. The sensors are read out by the same board that is used for the onboard control system and read out on a display.
Expected results	Each sensor and actuator works separated and integrated together within the specified accuracy.
Obtained results	
Conclusions	Not verified.

Table 5.3.3: Results test 3: Sensors and actuators test.

Verification Number	4
Test Type	Software
Facility	LTU, Kiruna
Verified item	Raspberry Pi software with electronics connected.
Verification description	Program four targets of interest and move the gimbal around. Determine if the targets are being followed. Then add a 5th point that the gimbal should never point, or around with the specified angle, and determine that this never happens. Connect the ground station and check if the system can be controlled remotely.
Expected results	The gimbal is able to chose targets and keeps it tracked and a specific target will never be looked directly at or nearby.
Obtained results	
Conclusions	Not verified.

Table 5.3.4: Results test 4: Software (onboard and ground) with electronics connected test.

Verification Number	5
Test Type	Control system
Facility	LTU, Kiruna
Verified item	Control software
Verification description	In a simulation program the control system is verified. The targets with movement are inserted in this simulation.
Expected results	The gimbal is able to chose the specified targets and keeps it tracked and a specific target (sun) will never be looked directly at or nearby.
Obtained results	
Conclusions	Not verified.

Table 5.3.5: Results test 5: Control system simulation.

Verification Number	6
Test Type	Data transfer
Facility	LTU, Kiruna
Verified item	Controller
Verification description	The data packages will be monitored by 'Wireshark' or a similar program and the data rate is below the specified data rate. The data gets buffered while being connection is lost.
Expected results	The data rate is below the specified data rate and the data gets buffered while the connection is lost.
Obtained results	
Conclusions	Not verified.

Table 5.3.6: Results test 6: Telemetry testing.

Verification Number	7
Test Type	Mass & Volume
Facility	LTU, Kiruna
Verified item	Entire system
Verification description	The mass and volume of the experiment gets measured.
Expected results	The mass and volume are below the specified values.
Obtained results	
Conclusions	Not verified.

Table 5.3.7: Results test 7: Check mass and dimensions of entire system.

Verification Number	8
Test Type	Drop test
Facility	LTU, Kiruna
Verified item	Electronics and gimbal
Verification description	The electronics and gimbal get dropped, mounted on a replicated gondola, from a height of 1, 2 and 3 meters and atleast the data logger survives.
Expected results	The data logger survives but the gimbal might break depending on the impact.
Obtained results	
Conclusions	Not verified.

Table 5.3.8: Results test 8: Drop test of entire system except optics and camera.

Verification Number	9
Test Type	Gimbal performance
Facility	LTU, Kiruna
Verified item	Gimbal, software and electronics
Verification description	The test is run for atleast 6 hours. The system is slightly moved during the last 2.5 hours, while the images are made. The power and data usage is monitored during the test.
Expected results	The system is able to work for atleast 6 hours with the specified power and data usage. The images are the same as made from a static point.
Obtained results	
Conclusions	Not verified.

Table 5.3.9: Results test 9: Gimbal with all subsystems mounted on a replicated gondola.

Verification Number	10
Test Type	Gimbal vibration test
Facility	LTU (outside), Kiruna
Verified item	Gimbal, software and electronics
Verification description	The entire system including the replicated gondola is mounted on top of a car and the images takes are compared to the images taken while being static.
Expected results	The system is able to work with the vibrations and movement from the car, the images obtained are the same.
Obtained results	
Conclusions	Not verified.

Table 5.3.10: Results test 10: Gimbal mounted on a car to test entire system with vibrations.

6 Launch Campaign Preparations

6.1 Input for the Campaign / Flight Requirements Plans

6.1.1 Dimensions and Mass

The data shown in Table 6.1.1 below is based on the design presented in Section 4.4.

	Telescope	Electronics	Gimbal	TOTAL
Experiment mass [kg]	5	1.5	5	13
Experiment dimensions [m]		0.1x0.1x0.1		
Experiment footprint area [m^2]		0.1		
Experiment volume [m^3]		0.1		
Experiment expected COG position	$X = cm$ $Y = cm$ $Z = cm$	$X = cm$ $Y = cm$ $Z = cm$	$X = cm$ $Y = cm$ $Z = cm$	

Table 6.1.1: Experiment Summary Table.

6.1.2 Safety Risks

Table 6.1.2 contains the risks of all stages of the whole campaign and project.

Risk	Key Characteristics	Mitigation
Moving telescope lens	A telescope is stabilized in three axis. Therefore there is the risk that the motor will start turning uncontrollable.	Adding additional components that at least a double component failure should occur before there is any risk.
Sharp edges, machines aluminum	Sheet and tubing, some sharp edges exist after machining.	Deburr edges where possible. Contain sharp edges in tough material. During transportation, use protective gloves when handling if sharp edges are still present.
Massive bulky structure	The mass of the assembly poses risk of trapped and damaged digits or feet being crushed.	Order of assembly should be well thought out and practiced. At least two people are present during assembly and that there is a dedicated space for assembly.
Parts dropping from gondola	Parts are heavy enough to cause harm if they fall onto people.	All parts sufficiently fastened. Testing conducted to ensure fastening is able to hold all parts in place in case of turbulence. Where possible, add assurance by adding additional fixations.

Table 6.1.2: Experiment safety risks.

6.1.3 Electrical Interfaces

Please refer to Table 6.1.3 for details on the electrical interfaces with the gondola.

BEXUS Electrical Interfaces		
E-link Interface: Yes		
	Number of E-link interfaces	2
	Data rate - Downlink	[TBD]
	Data rate - Uplink	[TBD]
	Interface type (RS232, Ethernet)	Ethernet
Power system: Gondola power required? Yes		
	Peak power (or current) consumption:	[TBD]
	Average power (or current consumption)	[TBD]
Power system: Experiment includes batteries? No		

Table 6.1.3: Electrical Interface Table.

6.1.4 Launch Site Requirements

Prior to launch, in the case that ice has appeared on the experiment prohibiting free motion for the controller, a small electric heater fan will be needed to remove the ice.

Post launch a laptop PC will be used to send and receive data to the experiment. For this a desk and chair will be needed, along with a power outlet and ethernet cable for E-link connection.

6.1.5 Flight Requirements

The flight requirements for the IRISC experiment are stated below.

- **Desired float altitude:** A height of >20 km is adequate for this experiment. However, a higher altitude will improve the signal to noise ratio.
- **Desired float duration:** We need a floating time of at least 90 min in order to collect sufficient amount of data. A longer floating time would be desirable.
- **Required launch time:** A partial night flight would be preferable because there is less interference with the sun and a wider range of view. However, the system will be designed to be able to function during the entire day.

6.1.6 Accommodation Requirements

Assuming that the experiment is able to be mounted to an outer side of the gondola, the objective end of the telescope *must* be able to point outside of the gondola for the entirety of the

float phase, preferably vertically to an angle of 60 degrees above the horizontal. Additionally, it should be able to move such that it has a viewing angle of 45 degrees horizontally in either direction. The telescope requires a "slewing area" of approximately 650 mm wide, 350 mm deep and 350 mm high within the gondola.

6.2 Preparation and Test Activities at Erange

When arriving at Erange the the ground station and e-link will be set up and tested. The control system will be checked, and a picture will be sent in order to ensure functionality of all components. The experiment will then be stowed and a protective cap will cover the lens.

Time	Altitude	Events
T-1H	0m	Lens cover is removed
T-1H	0m	Experiment is switched on
T-1H	0m	Experiment goes to Standby mode
T=0	0m	Lift-off
T+1s	~5 m	Experiment is stowed and not operational during ascent.
T+~1.5H	~25 km	Float Phase, experiment starts operating autonomously.
CUT-OFF-5MIN	~25 km	Data collection stops and experiment moves to safe position.
CUT-OFF	~25 km	Cut-off, experiment returns to safe stowage position.
Touchdown	0m	Experiment recovery begins.

Table 6.3.1: Countdown and Flight Estimated Timeline.

6.3 Timeline for Countdown and Flight

Table 6.3.1 is the estimated timeline during countdown and flight.

6.4 Post Flight Activities

As no component of the experiment is hazardous, no special precautions are needed for recovery. If possible, the whole experiment should be collected as is.

If it is not possible to collect the whole experiment due to external damage or otherwise, then the on-board data storage SD-card shall be collected. The experiment will be designed with this as a consideration, and the data storage unit will be removable in a non-invasive manner. Instructions will be provided on securing that the gimbal is locked in the stowage position, and that no actuators are powered. Manual shutdown will be possible, should the automated shutdown have failed.

The data will then be taken off site for further analysis.

7 Data Analysis and Results

7.1 Data Analysis Plan

In a best-case scenario, where there are no pointing errors, the CMOS sensor experiences no malfunctions and all astronomical targets are imaged as planned with images delivered in RAW, then the only data analysis to be done is to compare the SNR of the control images to the flight images, and then to images of the given targets in the same wavelength from other instruments, if applicable. Images to be processed and analysed are expected to be delivered in RAW and at full resolution for a size of 20-30 MB each, and will therefore require substantial computing power to stack and process.

7.1.1 Control Images

A set of control images is necessary to establish a baseline SNR to compare to the flight images. To obtain these control images, the entire apparatus should be functional in order to as closely simulate the BEXUS gondola inertial environment as possible (temperature and pressure conditions do not need to be the same). In order to image the same targets as will be available during the BEXUS campaign, daylight constraints and the positions of the targets require that attempts begin 4-6 weeks before the experimental instrumentation needs to be completed in full. Should this window be missed, imaging attempts after the launch (provided that the instrumentation survive the landing) can continue for another 6-8 weeks before the targets move out of sky view.

7.1.2 Image Processing and SNR Determination

In astrophotography, there are four main kinds of images that contribute to a final image:

- **Light Frames:** the image of the target itself, with no modifications or corrections yet applied.
- **Dark Frames:** images taken at the same settings and under the same conditions as the light frames, but with the aperture blocked of light.
- **Flat Frames:** these determine the brightness balance of the sensor– a lot of sensors are 'brighter' toward the middle of the frame and 'darker' toward the edges.
- **Bias Frames:** these are taken at as fast an exposure time as possible, with the lens cap on, to remove the readout noise due to the sensor.

These four kinds of images need to be sequentially divided and subtracted from the light image to remove as much noise as possible from the final image. Quantitative determination of the SNR of each image will occur once all frames have been processed through appropriate software, e.g. SIPS, Deep Sky Stacker or RegiStax.

7.2 Launch Campaign

7.2.1 Flight preparation activities during launch campaign

The flight preparations can be found in Section 6.2.

7.2.2 Flight performance

7.2.3 Recovery

7.2.4 Post flight activities

7.3 Results

No results have been produced yet. More information will be provided following the launch campaign in a later version of the SED.

7.3.1 Expected Results

It is expected that since atmospheric interference is a large contributor to the reduction of target light intensity and increased noise in the final images, flight images will display increased clarity and finer detail, as well as an increased SNR as compared to images taken on the ground.

7.4 Lessons Learned

7.4.1 Management

- Friendship
- Sleep deprivation

7.4.2 Scientific

- Increased familiarity with astrophotography systems and instrumentation
- Increased familiarity with CMOS sensors and infrared detection

7.4.3 Electrical

- Friendship
- Sleep deprivation

7.4.4 Software

- Friendship
- Sleep deprivation

7.4.5 Mechanical

- Friendship
- Sleep deprivation

7.4.6 Thermal

- Friendship
- Sleep deprivation

8 Abbreviations and References

8.1 Abbreviations

8.2 References

- [1] Eric Chaisson and Steve McMillan. *Astronomy Today*. Pearson Education, 2014.
- [2] Alfred Krabbe, Dorte Mehlert, Hans-Peter Roser, and Cecilia Scorza. "sofia, an airborne observatory for infrared astronomy". *European Journal of Physics*, 34:161–177, 2013.
- [3] NASA. Sofia overview, 2018.
- [4] ECSS Secretariat. *Space Engineering: Verification*. ESA-ESTEC, Requirements & Standards Division, ESTEC, P.O. Box 299, 2200 AG Noordwijk, The Netherlands, Nov 1998.
- [5] Sky-Watcher. Sky watcher bkp 130 ds, 2018.
- [6] Yuzuru Yoshii, Tsutomu Aoki, Mamoru Doi, Toshihiro Handa, et al. The university of tokyo atacama observatory 6.5m telescope project. *SPIE*, 7733(773308-1), 2010.
- [7] ZWO. Zwo asi183mm (mono), 2018.

Appendix A Experiment Reviews

Appendix B Outreach

Appendix C Additional Technical Information

Appendix D Standard Operation Procedures