EREBUS

EuRopean Extinction BUmp Survey

ALPBACH SUMMER SCHOOL 2017 – TEAM RED

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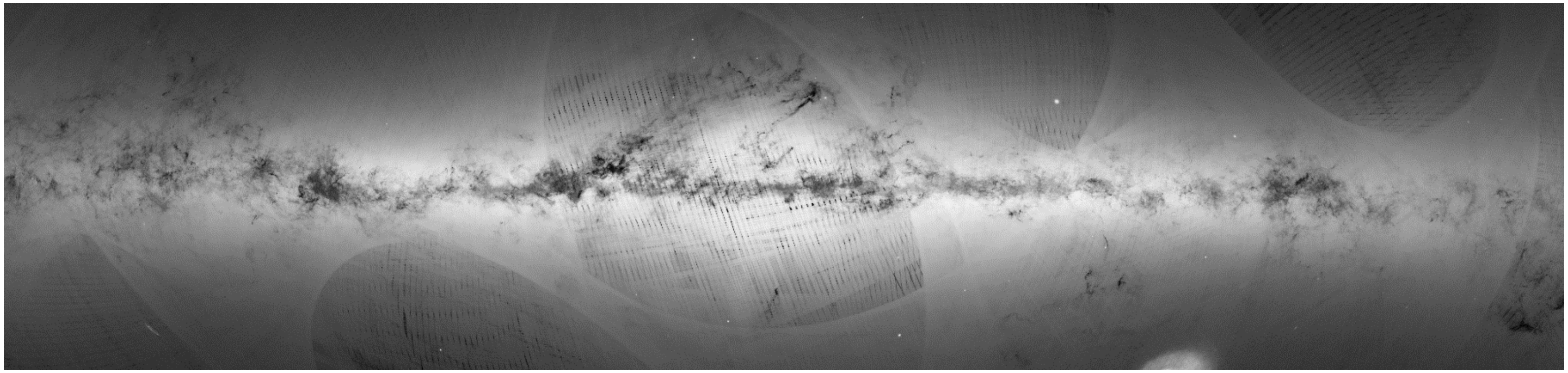
Science

SURVEYING THE UV SKY

Scientific background

Dust has implications in every astrophysical context:

- Dust blocks, scatters and reflects light
- Dust helps build planets, stars and galaxies
- Dust hides gaseous elements
- Dust reveals magnetic fields



Milky Way plane – Credit: GAIA

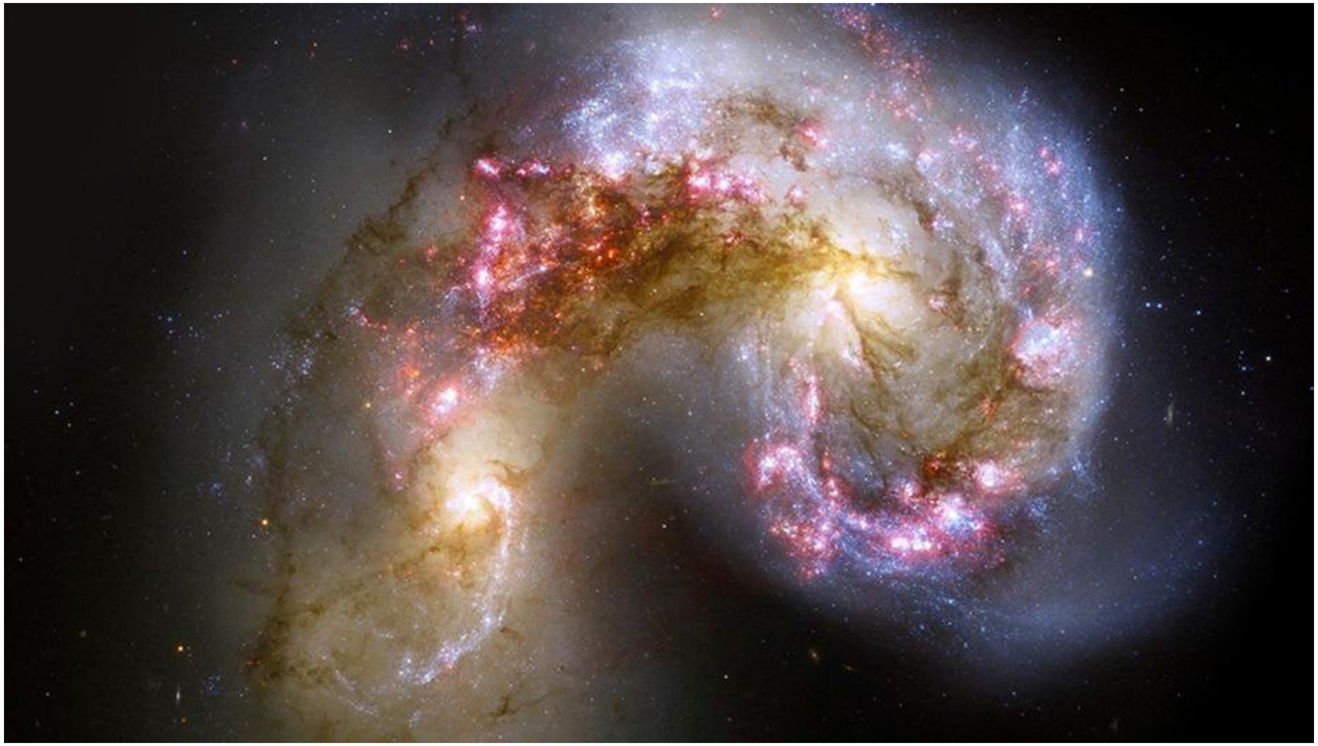
Scientific background

- Dust in the interstellar medium (ISM) is intimately linked to the birth and death of stars
- The dynamic behaviour and composition of ISM are not yet fully understood

Orion nebula - credit: HST

Scientific background

If we do not understand stellar evolution, we do not understand galaxy evolution



Antennae galaxies- credit: HST

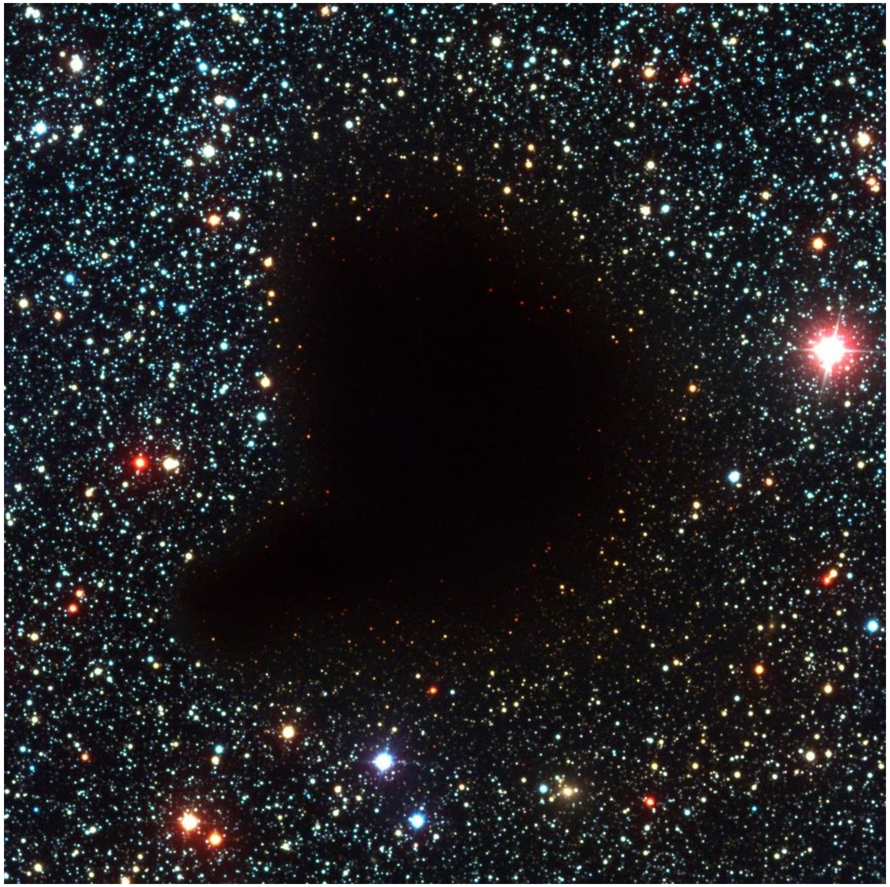
Scientific background

- If we can map the spatial distribution of the composition this will help us understanding the time evolving behaviour of this carrier
- This would constitue a significantly forward in understanding evolution of our Galaxy and of the nearby galaxies

Scientific background

- Compelling evidence for the presence of complex carbonaceous molecules in our Galaxy and in local galaxies
- This component can only be studied in the ultraviolet (UV) band and so our aim is to make observation in this region

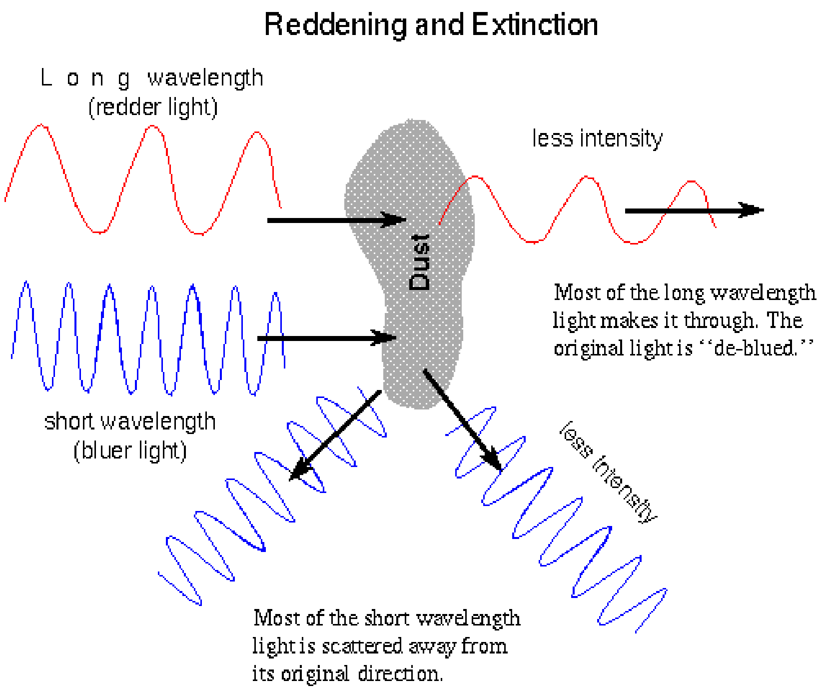
What is extinction?



Barnard 68 dark cloud - credit: ESO

What is extinction?

- Extinction is the *loss of light* due to interstellar dust
- It is related to the *dust particles* the light has to pass through while on its way to us



Credit: Nick Strobel

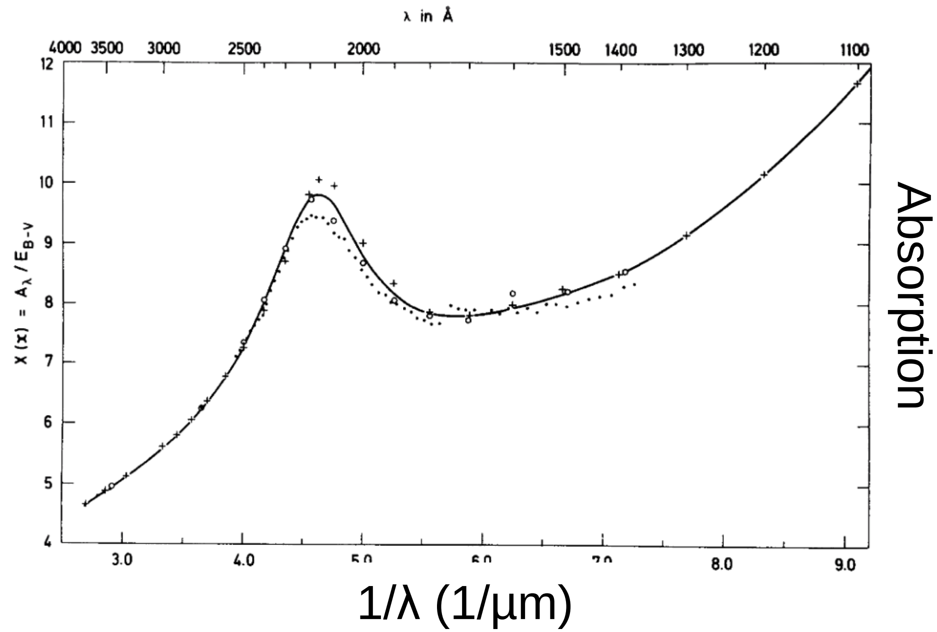
What is the extinction law?

- The extinction law relates the extinction at a certain wavelenght to extinction at a different one
- Should be constant but need to be parametrized with the R_v parameter
- Ground based observations in the infrared band (APOGEE & PANSTARSS1) showed that Rv varies across the sky; we expect deviations in the extinction law

The UV bump

Seaton. 1979

- Strong extinction feature in the UV band, but the carriers are still uncertain
- Laboratory experiments are supporting the assumption that these are carbonate grains

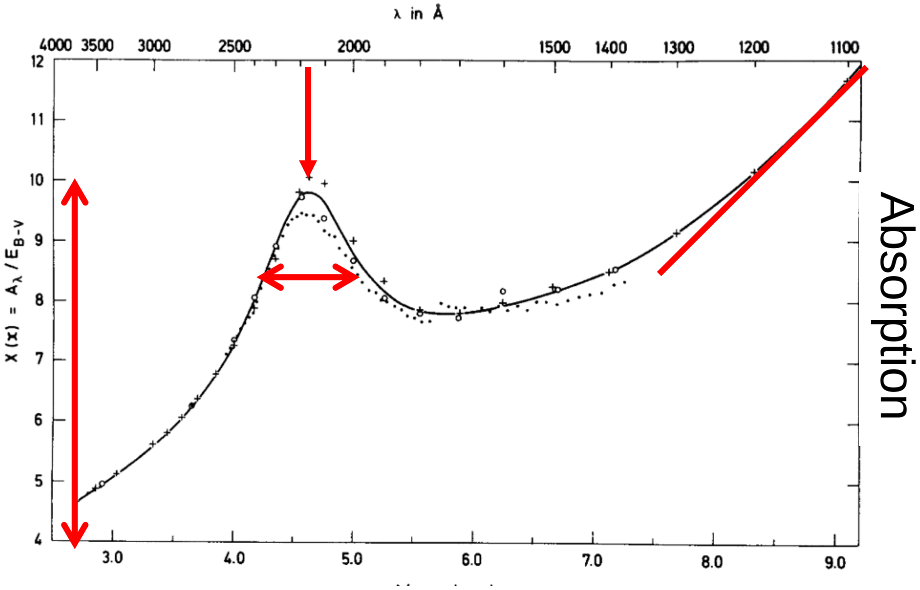


The UV bump

Properties of the bump:

1. Height of the peak: amount of the carriers
2. Width of the peak: grain size
3. Slope of the tails: others components likely grains size
4. Position of the peak: supposed to be stable

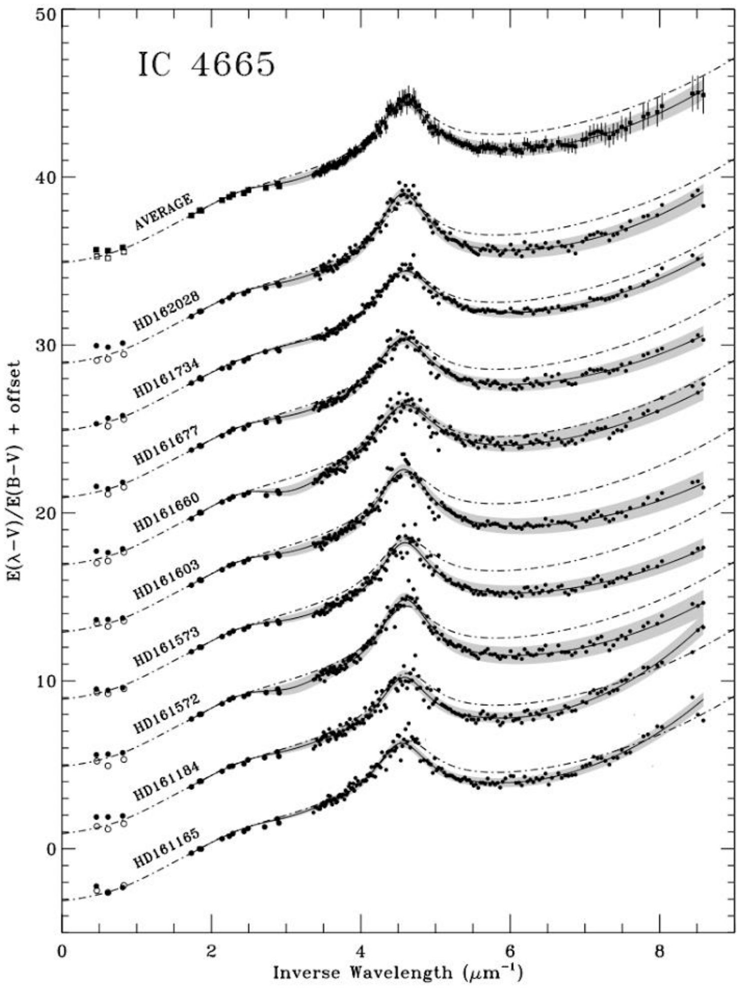
Seaton. 1979



1/λ (1/µm)

The UV bump

Small number of observations of this feature were done by the NASA's IUE space mission between 1970s and 1990s



Fitzpatrick & Massa, 2005

The objectives of EREBUS

- Map the extinction curve variability in the UV band in 3 dimensions in our Galaxy
- Map the extinction law variability in the UV band in 2 dimensions in the Local Group

Observation strategy

Hierarchical Map: from large to fine structures. Iterative process.

MILKY WAY MAP: we define the minimum spatial resolution for the map and it defines the required spatial distribution for the stars to observe. For statistical reasons we need a relevant number of stars in the same volume.

LOCAL GROUP: we define at least 4 points per galaxy

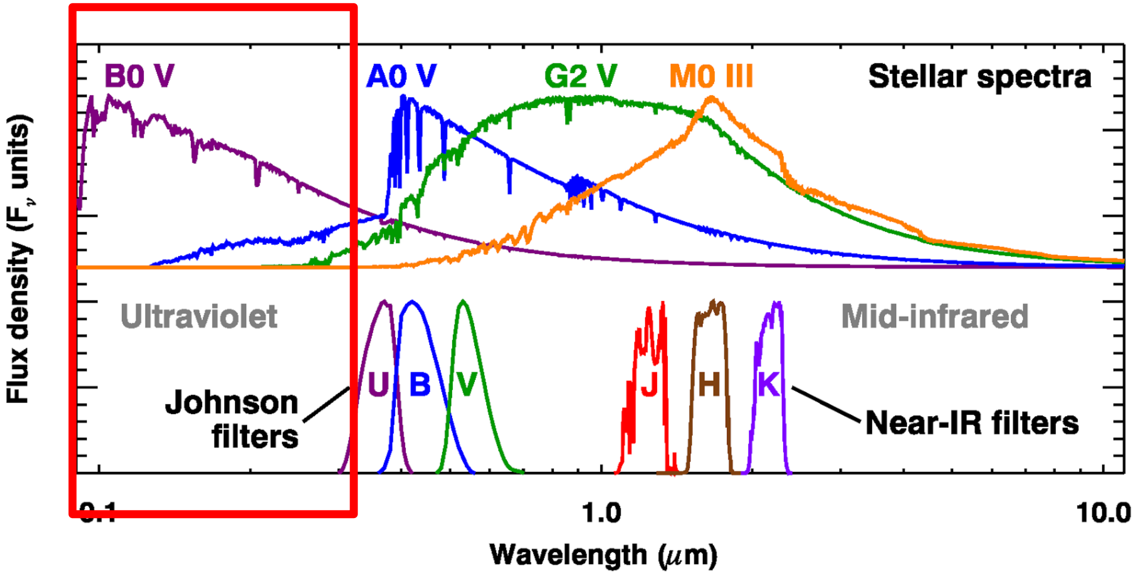
Observation strategy

We defined three classes of targets which will be observed through an iterative grid building process:

- **Class I**: Brightest stars, O-B3. Concentrated in galactic plane. Star forming regions. From SIMBAD catalog: 5115 possible targets.
- **Class II**: B4-A stars. From SIMBAD catalog: 6026 possible targets
- **Class III**: Local group galaxies. From MESSIER: 54 possible targets

How we will do this

Then match we will match the observations with synthetic photospheres put at the distance of the sources, and hence calculate how much light is missing

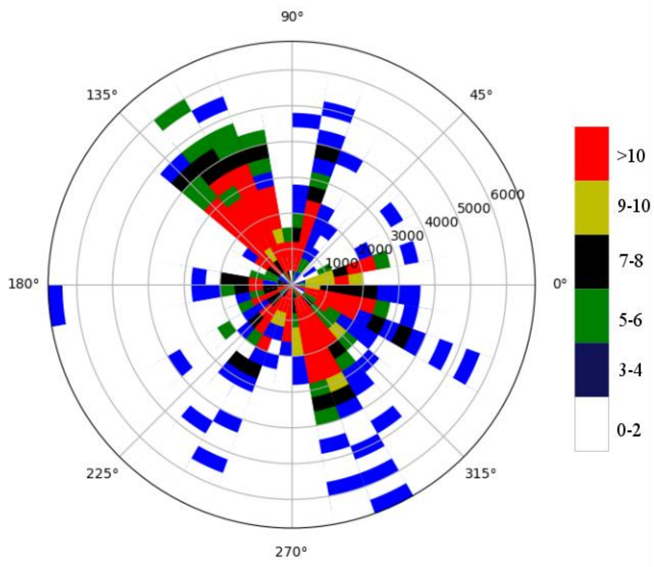


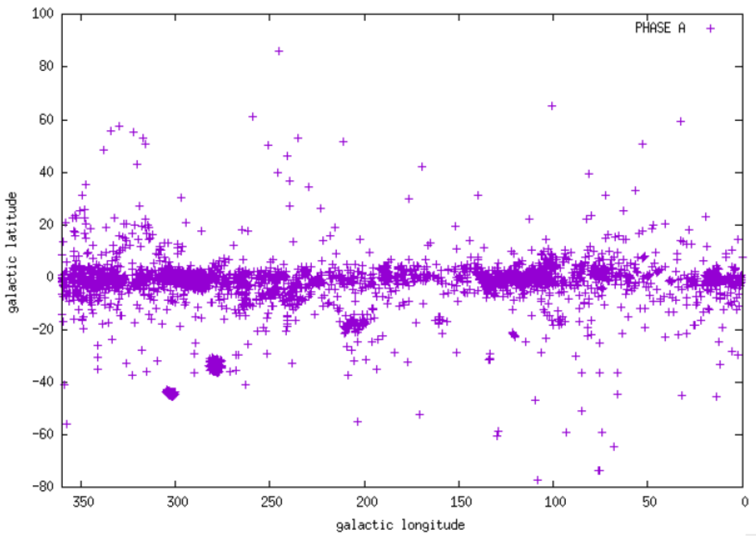
Observation strategy

Optional Phase : Open to call to scientific community, developing countries, outreach, amateurs.

Zero order map – Milky Way

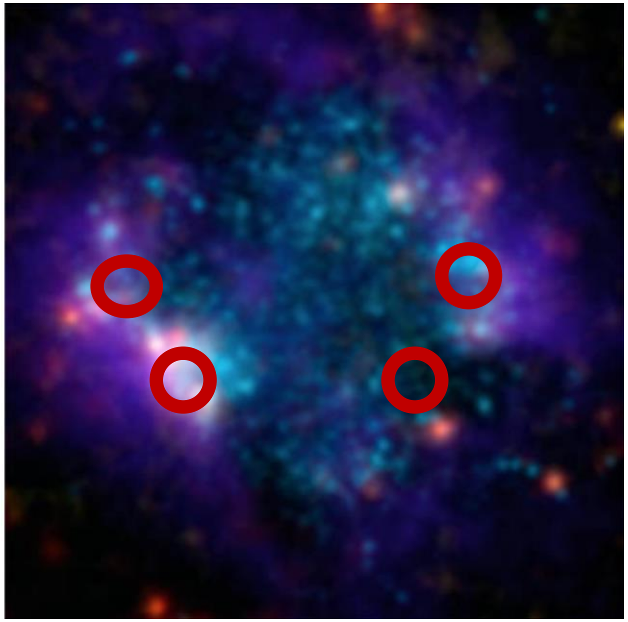
- Define a minimum resolution: the resolution provides the targets
- Baseline selection: +/- 100 pc altitude on the plane – thin disk





Zero order map – Local Group

- 4 points per Galaxy
- The brighter points for each galaxy – based on GALEX



Credit: GALEX

First Iteration

- MILKY WAY: fining our map adding stars to improve statistic and resolution
- LOCAL GROUP: improve the number of points for the larger (on the sky) galaxies

Traceability matrix

Science theme

Science REQs

Instrument REQs

Scientific theme		Scientific sub theme		Scientific requirement		Observational requirement		Instrument requirement		Spacecraft requirement
Understand distribution and evolving behaviour of carbonaceous dust	S01	Understand distribution and evolving behaviour of carbonaceous dust in the Milky Way	SR01	Map stars in 3D	OR01	Identify differences in bump and wing in FUV with uncertainty < 0.1	IR01	Measure spectrum in 100 - 300 nm band	SC01	Internal temperature at 20 C, 1 C drift
	S02	Understand distribution and evolving behaviour of carbonaceous dust in other galaxies in the local group	SR02	Map stars in 2D	OR02	Observe >1 star in grid 10 degree square out to 5 kpc	IR02	Measure spectrum with resolving power > R = 300	SC02	Detector box temp at -100 C, 1 C drift
					OR03	Integrate for at least 6 hours	IR03	Measure photon count in each spectral bin from 120 - 300 nm with mean SNR > 10	SC03	Slew rate > 0.025 deg/s
					OR04	Identify differences in bump and wing in FUV with uncertainty < 0.1	IR04	No order overlap in spectrograph	SC04	Lifetime of essential systems > 5 years
					OR05	Observe >4 points for each galaxy in local group	IR05	Baffle	SC05	Support orbit to minimise airglow impact
							IR06	Detectors at -100 C, drift < 1 C	SC06	Support orbit outside of Van Allen belts
							IR07	Telescope structure at 20 C, drift below 1 C	SC07	Support orbit in low space debris density regime
							IR08	Calibration source		
							IR09	Shutter		
							IR10	Observe with angular resolution > 0.6 arcsec		

Science Subtheme

Observation REQs

S/C REQs

Scientific objectives

- Understand the distribution and evolution behaviour of carbonate dust in Milky Way
- Understand the distribution and evolution behaviour of carbonate dust in Local Group galaxies

Scientific requirements

- SO 1: Map the extinction in 3D
  - SO 1.2: Map the grain size in 3D
  - SO 1.3: Map the carbonate component in 3D

- SO2: Map the dust in the Local Group
  - SO 2.1: Map the extinction in 2D
  - SO 2.2: Map the grain size in 2D
  - SO 2.3: Map the carbonate component in 2D

Observational requirements

- OR1: Identify difference in bump and wing for FUV with uncertetude <0.1 (FOR MW)
- OR2: Observe >1 star in grid 10 degree square at 5 kpc
- OR3: Integrate for at least 6 hours
- OR4: Identify difference in bump and wing for FUV with uncertetude <0.1 (FOR LG)
- OR5: Observe >4 points per galaxy in Local Group

Possible secondary cases

Data taken during the nominal operational phases could be used also to study the SEDs of massive stars

Additional observational phases could investigate:

- Solar mass stars (filling the observation gap between the X-rays and Vis bands)
- Accretion processes in T-Tauri stars
- UV variability in M stars (both vs time and vs spectral type)

Comparison with other missions

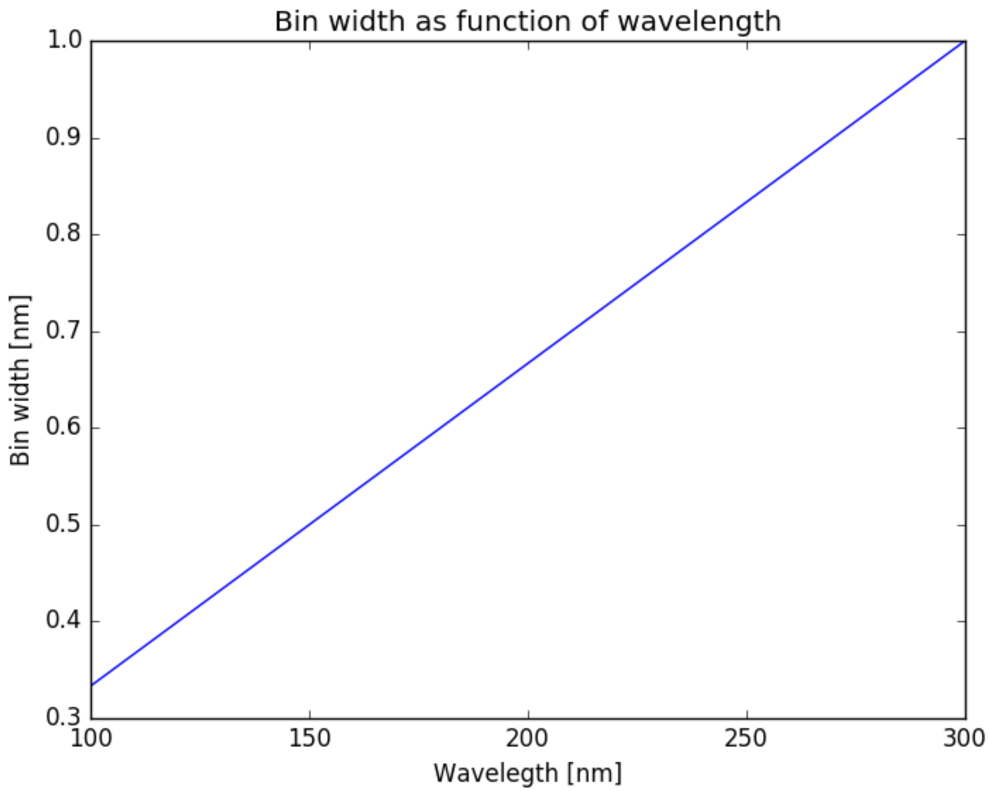
- GALEX (2003-2013): photometric survey
- FUSE (1999-2017): different spectral bandwidth
- IUE (1978-1993): not enough targets to perform mapping

Payload

THE HEART OF EREBUS

Instrument requirements

- Resolving power of 300 from science requirements gives bin size



Instrument sizing

- From Orion data (Simbad), minimum separation between stars of 0.6 arcsec
- In order to avoid source confusion, require minimum aperture size of 12.6 cm

Aperture/duration tradeoff

Target mag in U band (Simbad)

Target mag in UV

Spectral flux density (W/m^2/um)

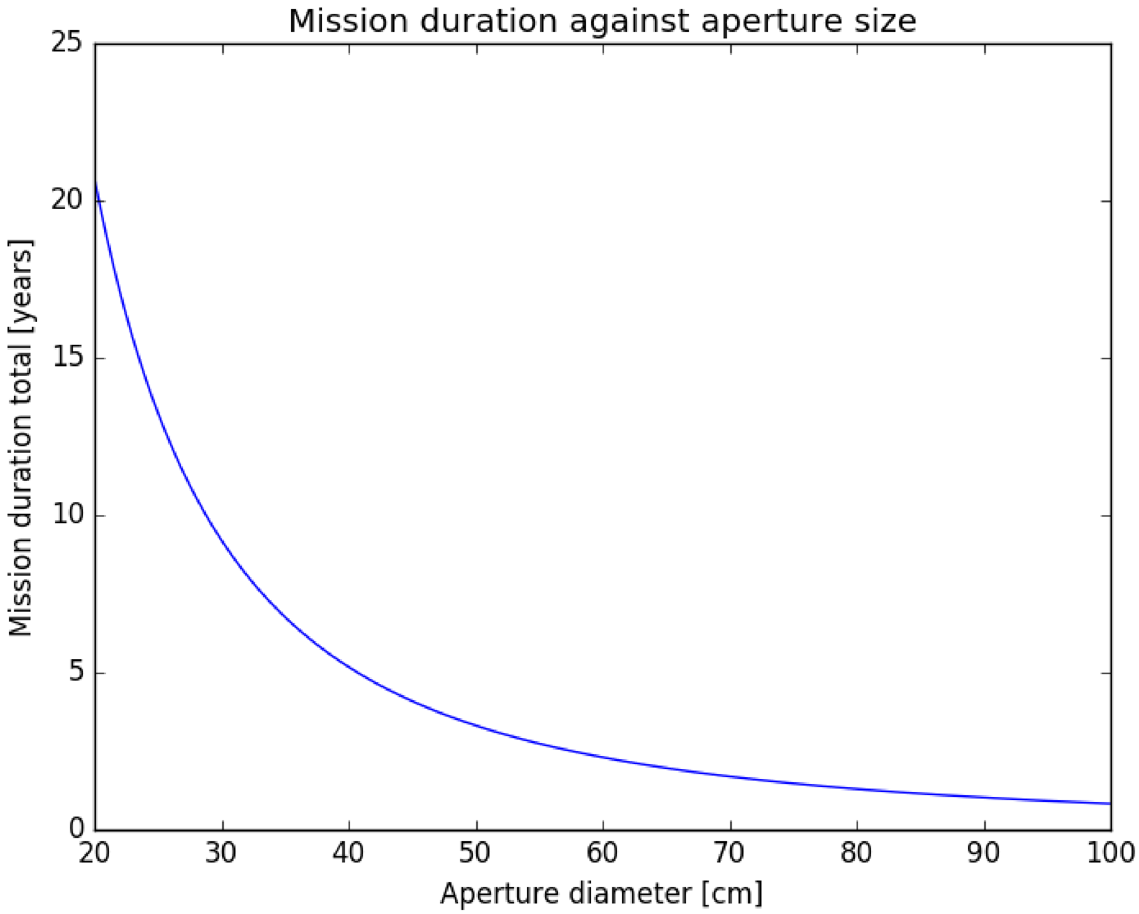
Flux on instrument (W/m^2)

Photon count on inst. (/s/m^2)

Aperture/duration tradeoff

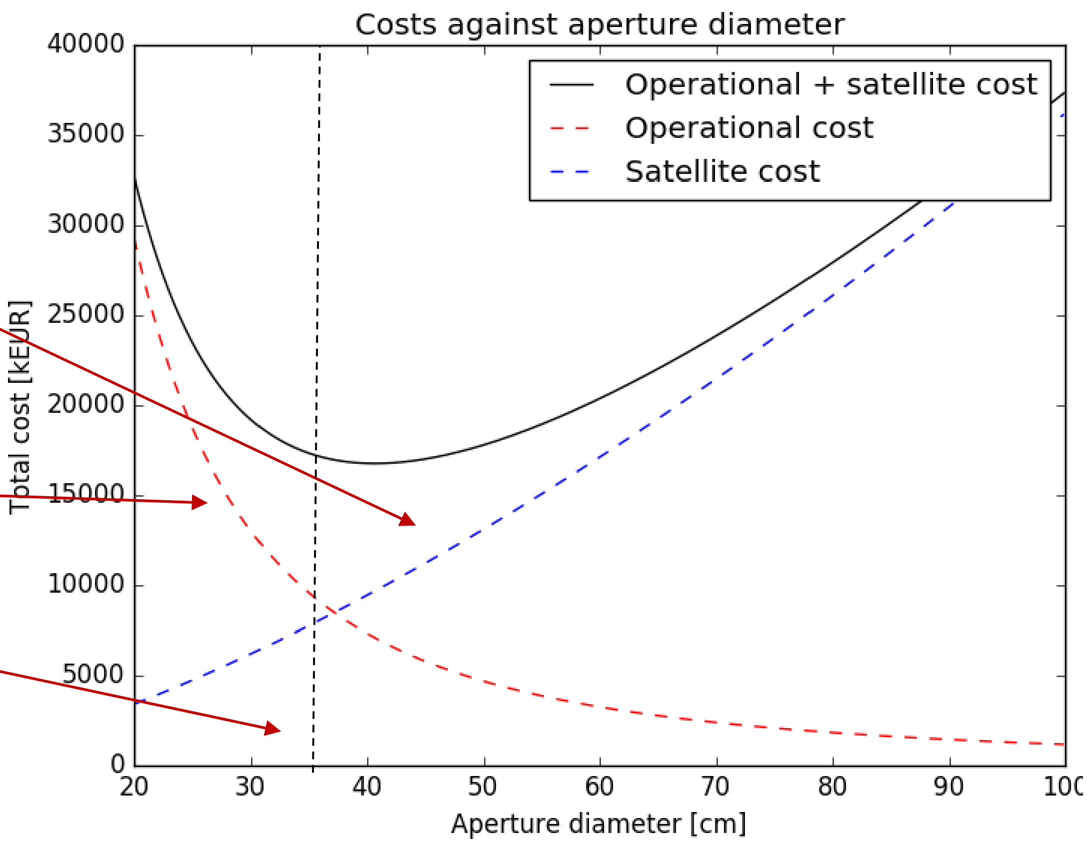
- Photon count on detector array (/s/m^2)
- Photon count per detector (/s/m^2)
- Integration time (s)
- Mission length per aperture size

Aperture/duration tradeoff



Aperture/duration tradeoff

- Satellite cost against aperture size from NASA Instrument Cost Model (Habib-Agahi and Mrozinski , 2014)
- Operational cost per year from SMAD (Wertz, DF Everett, JJ Puschell, 2011)
- 35 cm aperture selected
- Mission duration of 4.2 years

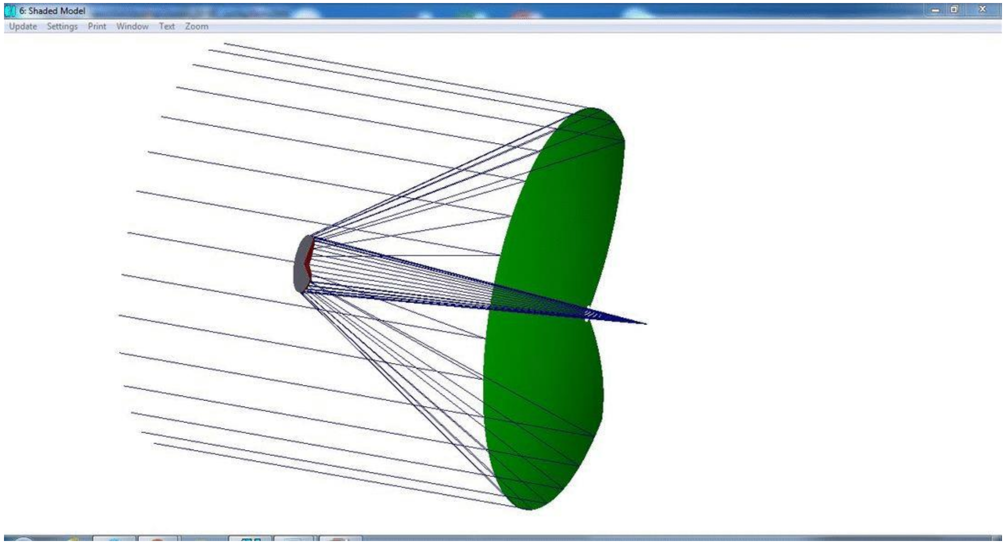


Drivers for telescope design

- Mirror size
- Source have to stay within the field of view during the exposure time
- High dimensional stability
- Low CTE materials
- Thermal stability within 1K during observation

Telescope design

- Cassegrain Ritchey-Chretièn configuration
- 35cm Zerodur primary with Al+MgF_2 coating
- Working f/#=19.7; FoV=0.8“
- Diffraction limited performances
- Airy disk size 0.2“ at 300nm

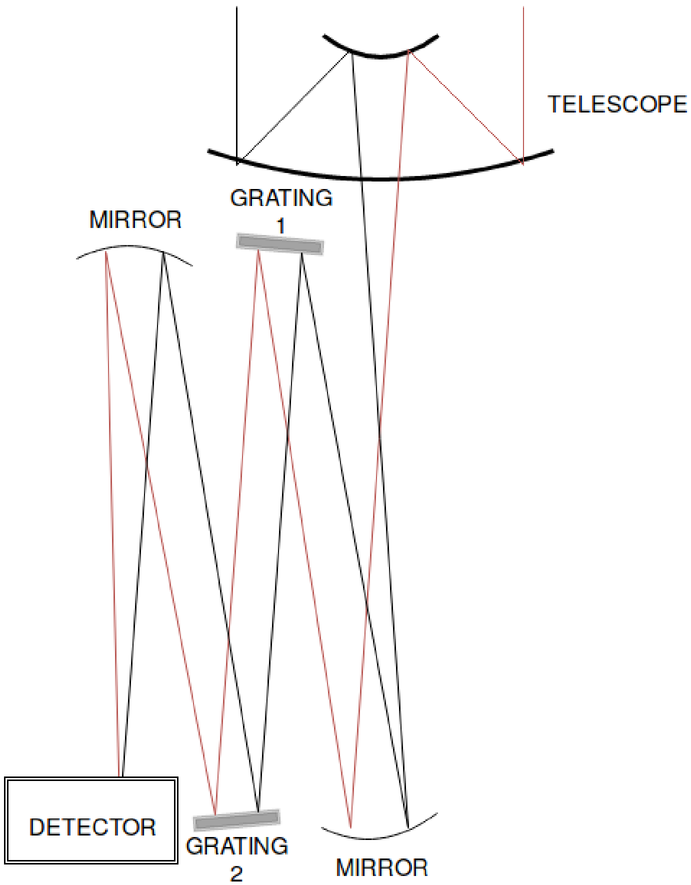


Model done with ray tracing software

Spectrograph architecture

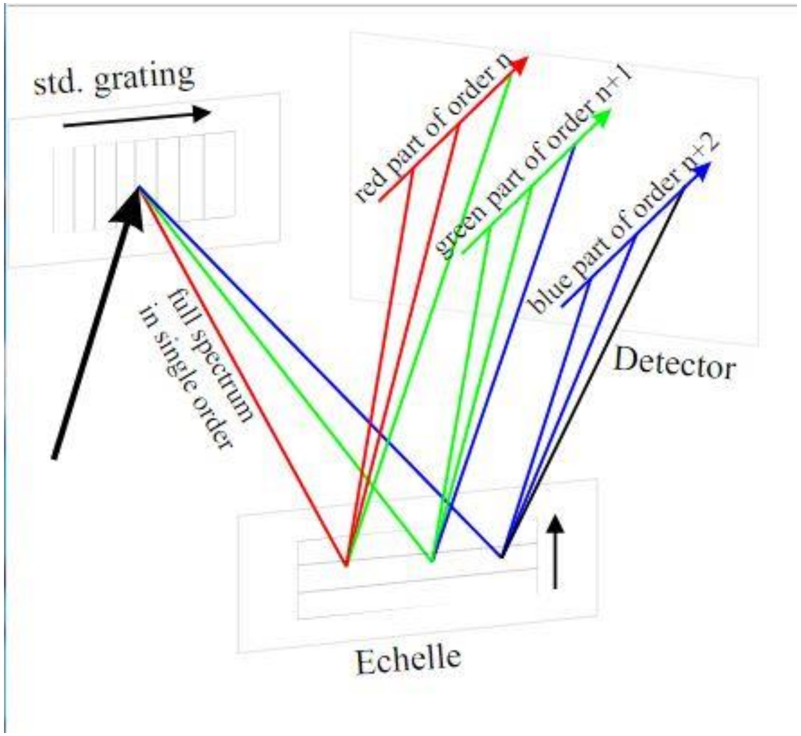
Requirements

- Spectral resolution R=300 in the 100-300nm bandwidth
- Avoid overlap of different orders of the spectrum
- Mean SNR=10 (per bin) over spectral range, in order to identify the flank of extinction region
- Shutter and calibration sources



Spectrograph architecture

Echelle spectrograph

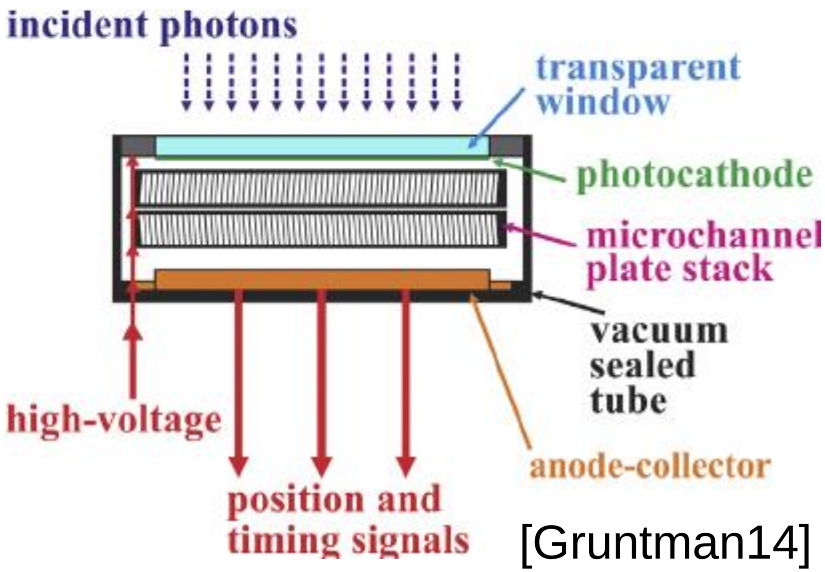


Instrument efficiency

Values @200 nm. Low limit of 120 nm from coatings
Efficiency might increase as new coatings and photocathodes are developed

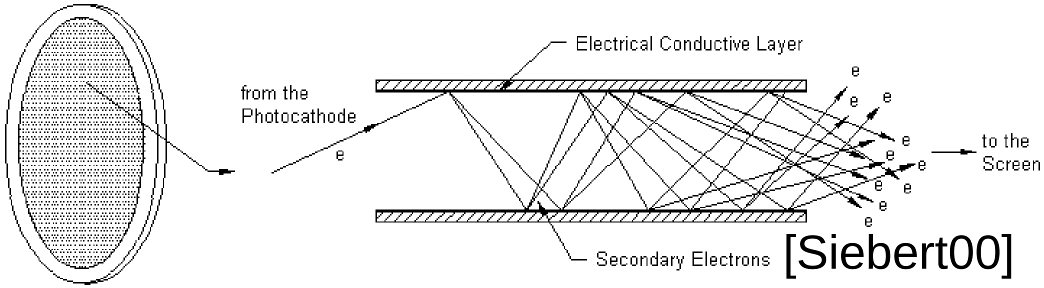
Element	**Value**	**Source**
Cassegrain telescope	$0.85^2=0.72$	2 Al+MgF_2 mirrors, reflectivity from [Bolcar16]
Spectograph mirrors	$0.85^2=0.72$	2 Al+MgF_2 mirrors, reflectivity from [Bolcar16]
Diffraction gratings (Echelle config)	$0.60^2=0.36$	Estimate based on Newport's "Diffraction Grating Handbook"
Detector photocathode	0.40*0.94=0.38	GaN photocathode [Siegmund06], MgF_2 window [Thorlabs] Alternative photocatodes Cs_2Te+CsI (flight-proven but 15-30% efficiency)
Detector OAR	0.90	Funnel OAR [Hamamatsu]
TOTAL	**6.4%**	

Multi-channel Plate Detector (MCP)



[Gruntman14]

- Incoming photon hits photocathode -> emitted e^- -> triggers e^- cascade -> e^- cascade detected by collector (eg. CCD)
- High voltages needed to enable electron cascade
- GaN photocathode
- Needs a MgF_2 window as MCP the photocathode needs to be kept in vacuum



[Siebert00]

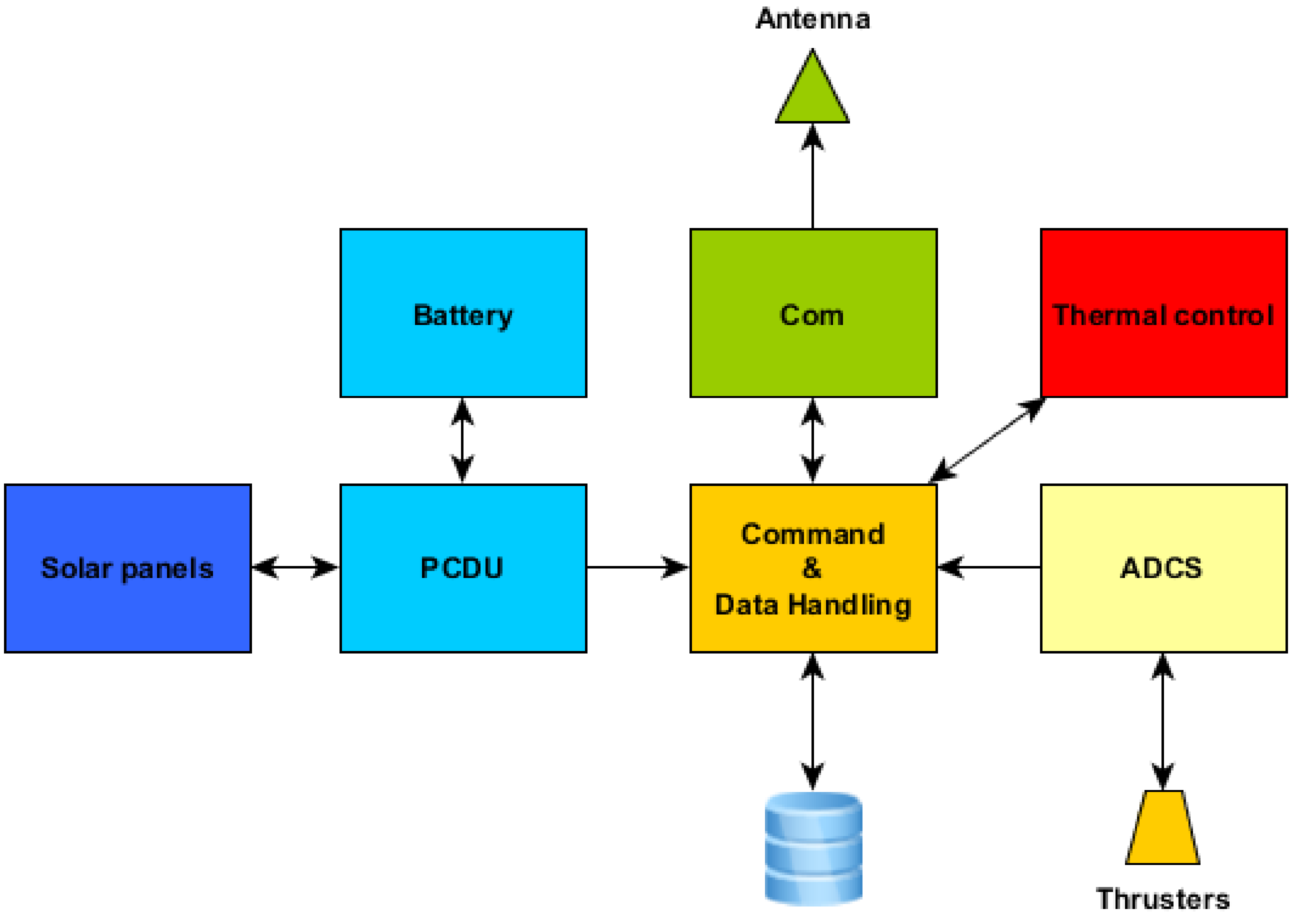
Spacecraft

THE BODY OF EREBUS

System requirements

ID	Description
SC01	Internal temperature at 20 C, 1 C drift
SC02	Detector box temp at -100 C, 1 C drift
SC03	Slew rate > 0.025 deg/s
SC04	Lifetime of essential systems > 5 years
SC05	Support orbit to minimise airglow impact
SC06	Support orbit outside of Van Allen belts
SC07	Support orbit in low space debris density regime

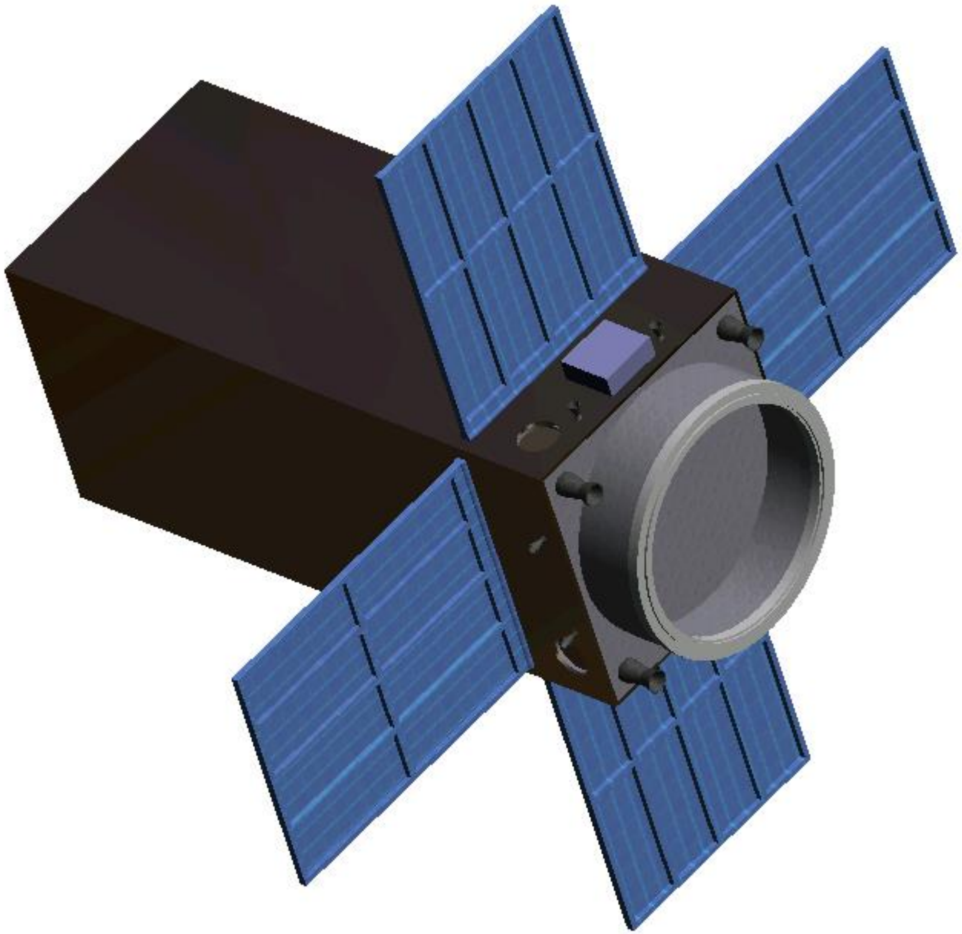
Spacecraft architecture



Satellite operating modes

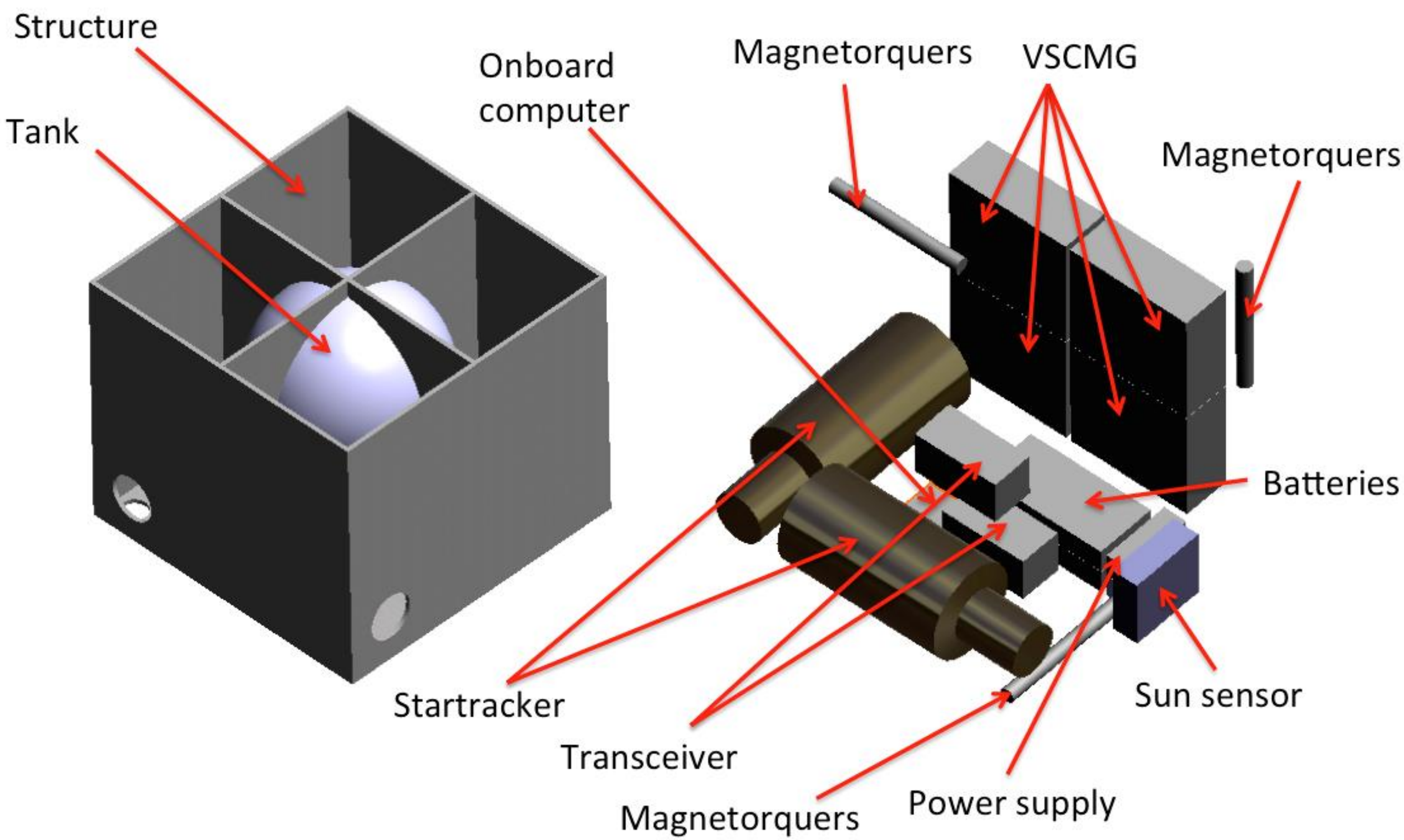
Mode	AOCS	Thermal	OBC	Comm	Payload	Safe AOCS
LEOP	✖	●	●	●	✖	●
Nominal	●	●	●	●	●	●
Safe	✖	●	●	●	✖	●
Orbit keeping	●	●	●	●	✖	●
Eclipse	●	●	●	●	●	●
End of life	✖	✖	●	●	✖	●

Spacecraft



Size: 700 x 700 x 1700mm

Subsystems & structures



Subsystem - Thermal

- Design based on previous missions
- Radiator design are coated plates mounted on the tube

Description	Value
Overall temperature requirement	293K
Detector temperature requirement (direct connection to radiator)	173K
Heaters	50W
Radiator area	1.6 m^2

Subsystem - ADCS

Requirements

- Slew rate 0.03 deg/sec
- Pointing accuracy 0.001 deg
- Pointing stability 0.0003 deg RMS (over a median exposure time)

Stabilization method: 3-axis control

Subsystem - ADCS

Subsystem	Name	#	Total Mass (Kg)	Total Power (W)	TRL
Sensors	Magnetometers	2	3	3.1	9
	Star tracker	2	4.35	10	9
	Sun sensor	1	0.65	0.2	9
Actuators	VSCMG	4	10	12	5
	Magnetic torquers	3	0.65	1.6	9
	Thrusters 20N	4	15	10	4
	Thrusters 1N	8	0.34	10	9

Subsystem - Power

SOLAR ARRAY	ENERGY STORAGE	POWER DISTRIBUTION
IMM-**α** CIC Multijunction solar cells	Li-Ion Battery	DC bus voltage 28V
Eff.(BOL) 32% Eff.(EOL) 25%	DoD=40%	Buck-boost DC/DC converter
A = 1.5m2	Eb = 278.4 Wh Cb = 10 Ah	D = 0.5
TRL 9	TRL 9	TRL 9

Subsystem - Power

Subsystem	Power [W]
Instrument	25
Power system	0
Launcher	0
AOCS	58,063
Structure	0
Thermal	105
Propulsion	5
Communication	25
OBDH/C&DH	25
Sum of Subsystems	243,063
Sum of components with System Margin	291,6756≃300

On-board data system

- Of the shelf computer system from ÅAC Microtec
- Previously flown (TRL = 9) in small satellites
- Tested for 5 years in LEO

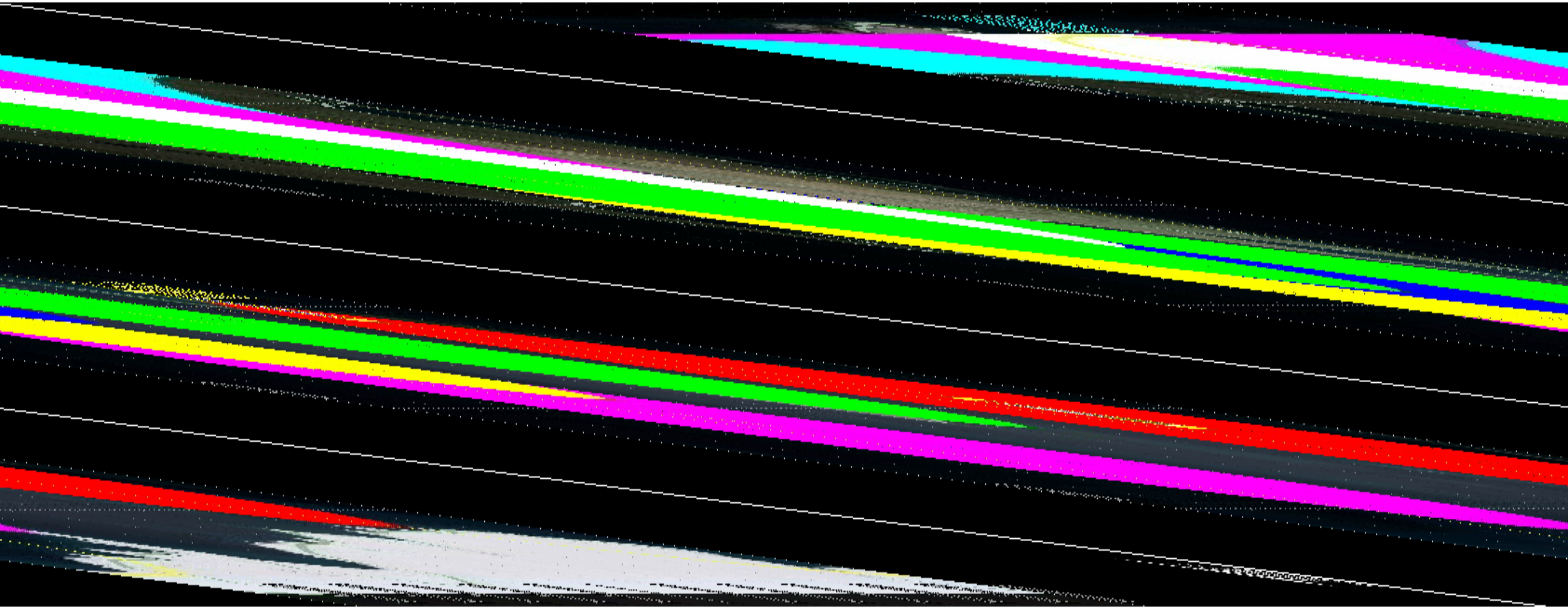
Total mass budget

Mass Budget	Subsystem Margin [%]	Mass [kg]
Instrument	20	27.3
Power system	5	45.2
Launcher	5	1.1
AOCS	10	19.5
Structure	10	83.7
Thermal	5	3.2
Propulsion	10	18.5
Communication	5	6.6
OBDH/C&DH	5	5.8
Nominal Dry Mass	---	211
Total Dry Mass	20	253
Satellite Wet Mass	**---**	**298**

Mission analysis

GETTING EREBUS TO SPACE

Orbits



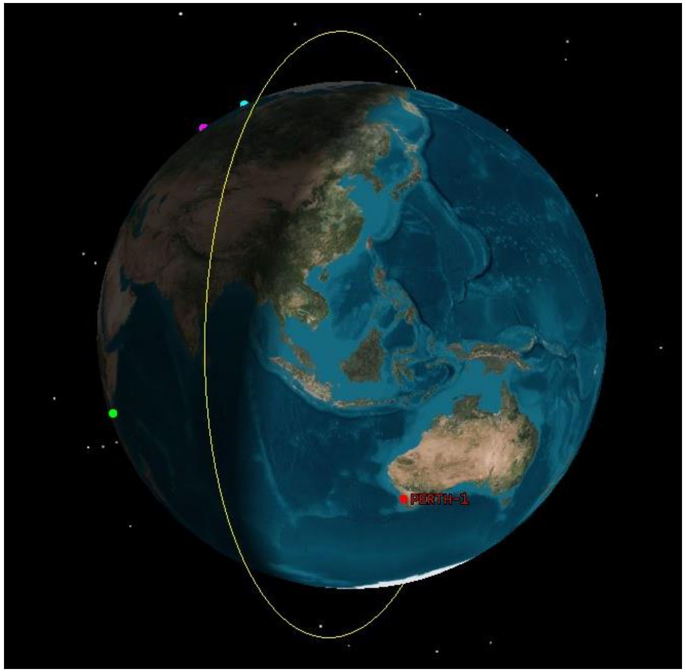
Orbits

- Sun synchronous Orbit
- Altitude: 1200 km
- Max. Eclipse: 1179s

i =100,4°

Orbital period: 109 min

Local time of ascending node:
06:00:00



Launchers

Requirements:

- Avoid airglow from the earth atmosphere
- Outside the Van-Allen-Belt.
- Based on mass budget
- European launchers

Direct insertion into orbit

Launch site: Guiana Space Center (Kourou)

Max Payload mass: 2300 kg (LEO)

Launcher liftoff mass: 210 t

VEGA performance for 1200 km (SSO): ~ 1000 kg

First flight: 2019

Source: ESA, J. Huart

Communications

S band

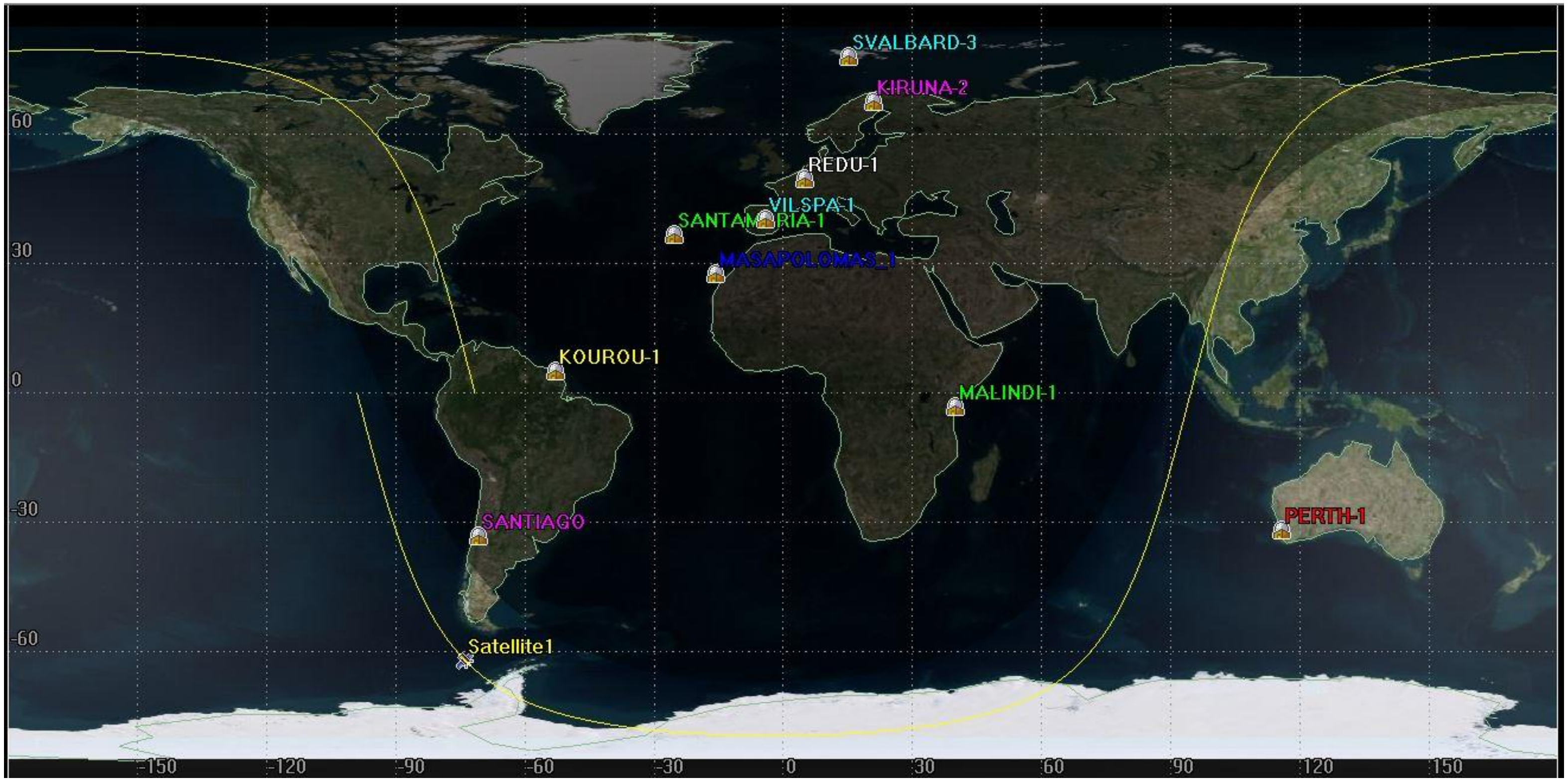
COTS component with flight heritage

4 Antennas for redundancy

Link Budget					[dB]	
EIRP					**16.7**	**dB**
Antenna Pointing Loss	3.00	°			**-0.1**	**dB**
Transmission Loss					**-172.2**	**dB**
Rx G/T					**29.4**	**dB**
Boltzmann's constant (k)			1.38E-23	J/K	**228.6**	**dB**
data Rate (bps)	50,412	bps			**-47.0**	**dB**
Final EB/EN					**55.3**	**dB**

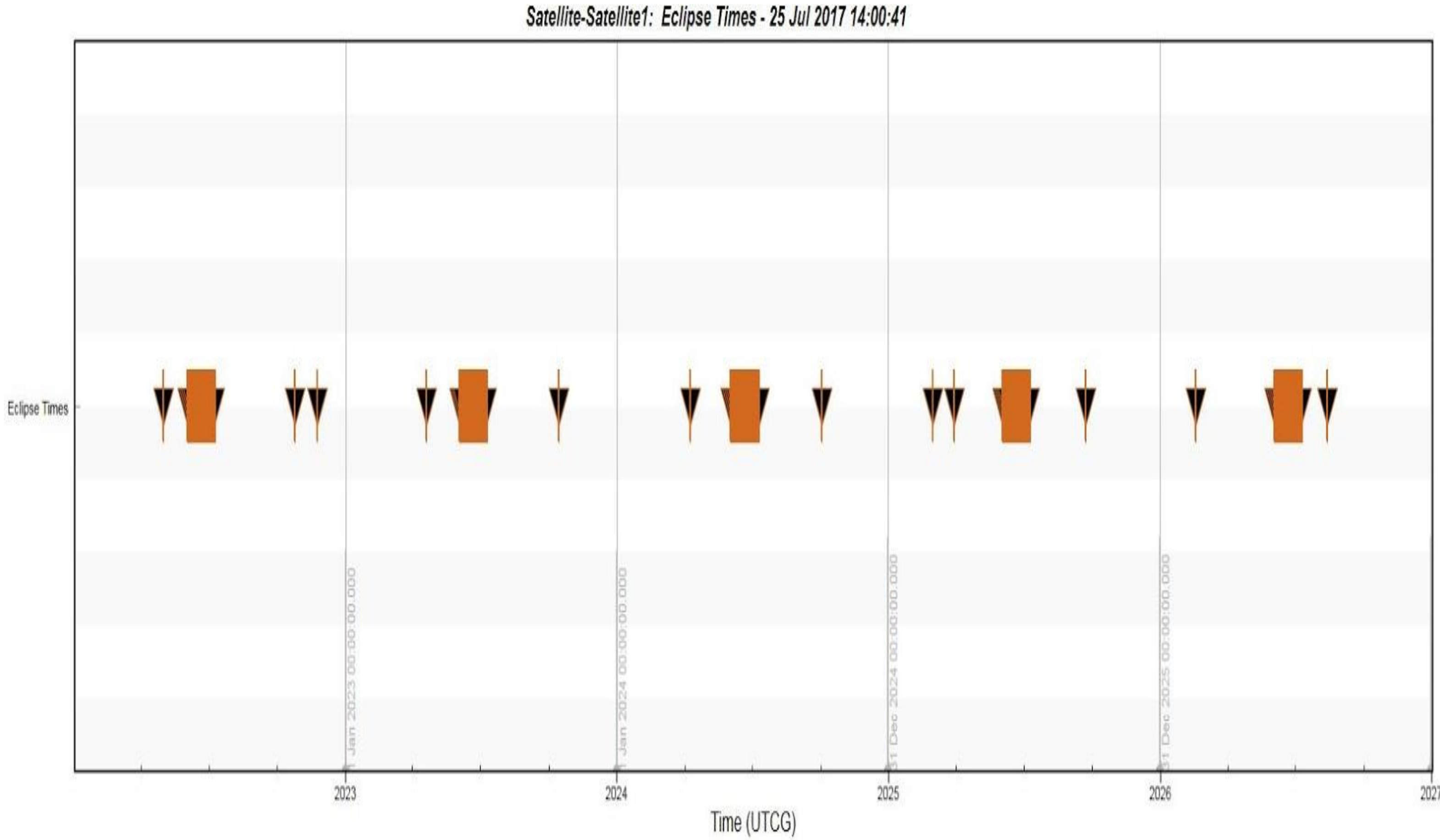
Ground segment

Baseline: all ESA Tracking Stations (ESTRACK) in the S-band

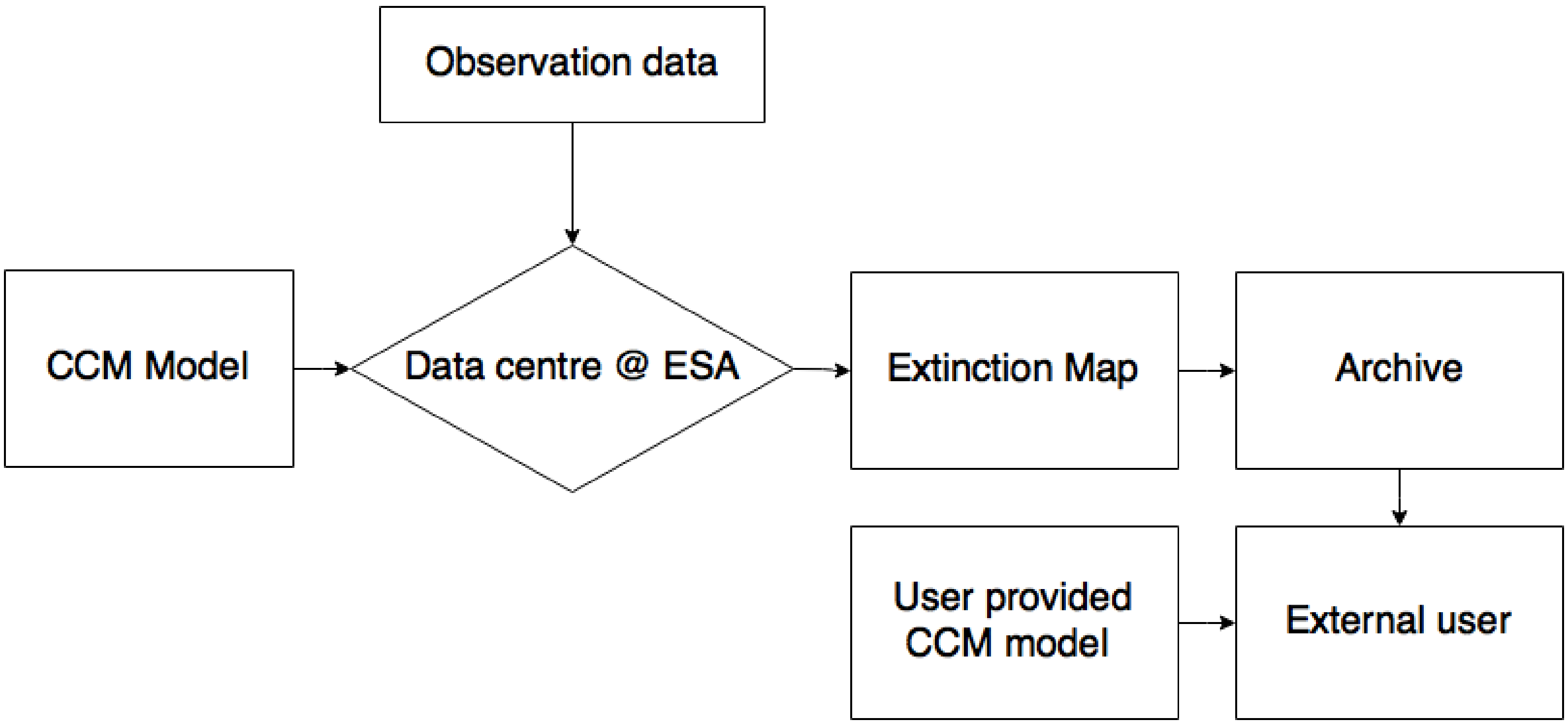


Ground segment

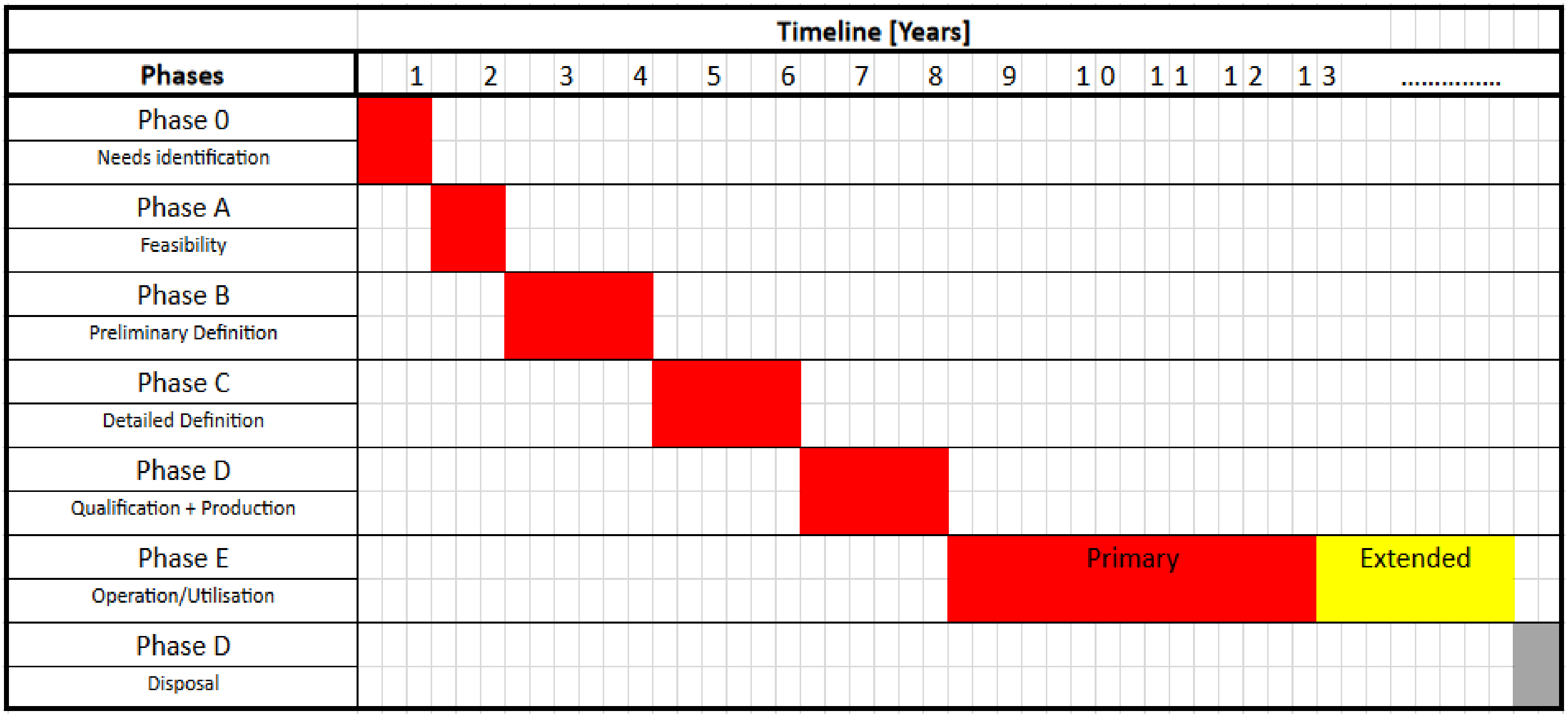
Eclipse times (determines battery size) calculated in STK



Ground segment



Mission phases



Cost assessment

CATEGORY	AMOUNT (M Euro)
Launch	25
Payload	50
Service	40
Project group	23
Operation	27.6
Total cost + 20 % margin	**198.72**

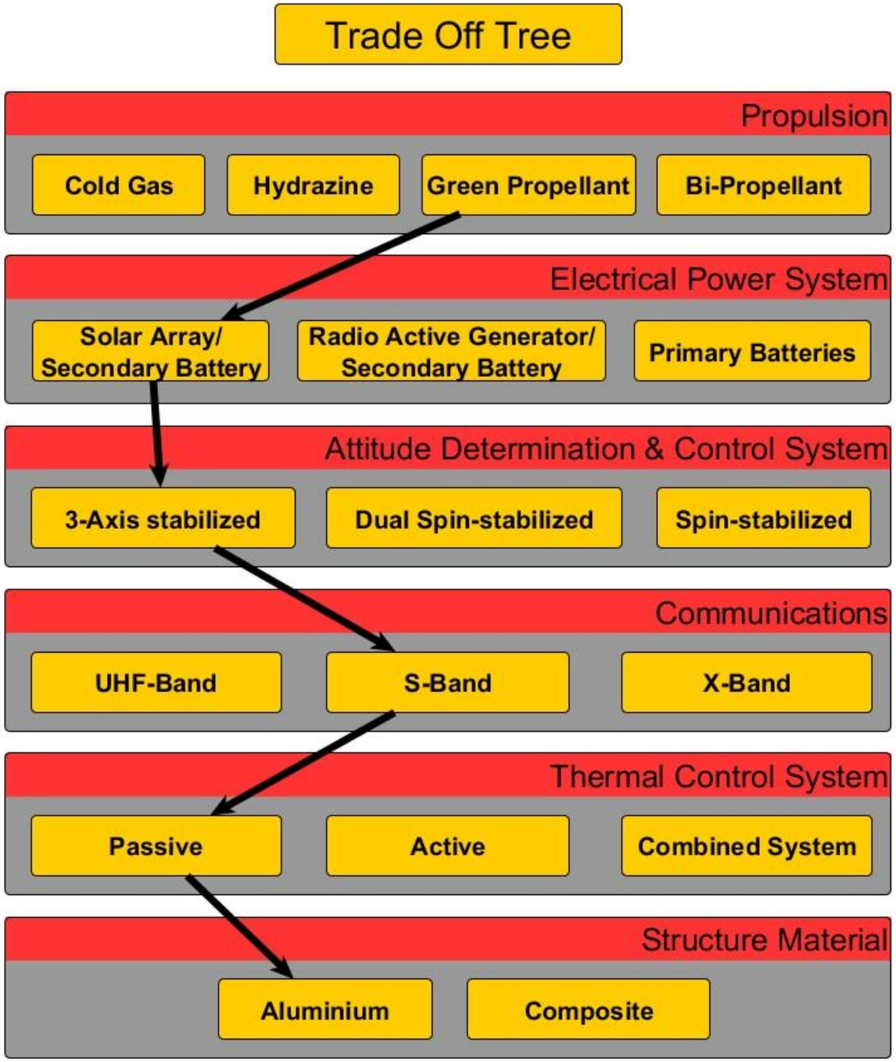
Risk assessment

ID	Name	Prob.	Impact	Mitigation	Mit. Prob.	Mit. Imp.
R1	Expose instrument to the sun, moon and earth	A	4	Telescope shutter closes when ADCS failure is detected	A	2
R2	Calibration source mirror stuck in optical path	B	2	Extensive testing of mechanism reliability	B	1
R3	Calibration shutter of spectograph is stuck in optical path	B	4	See above	B	1
R4	Failure of high voltage power supply for the multi channel plate detector	A	3	Double redundancy	B	2
R5	Calibration source failiure	A	3	Use callibration stars	A	2

Descoping & cuts

Observe less sources

Trade-off table



Outreach

- Provide observation time to amateur astronomers and scientists from developing countries in later phases of the mission
- Seek cooperation with educational institutions e.g. schools
- Provide easy data access to the general community via virtual observatory projects e.g. H2020 VESPA

  http://europlanet-vespa.eu/

- Cooperate with ESA education?
- Summer school for PhDs
- Use social media to promote the mission and the science behind it

Do not forget to follow us on Twitter: @EREBUSMission

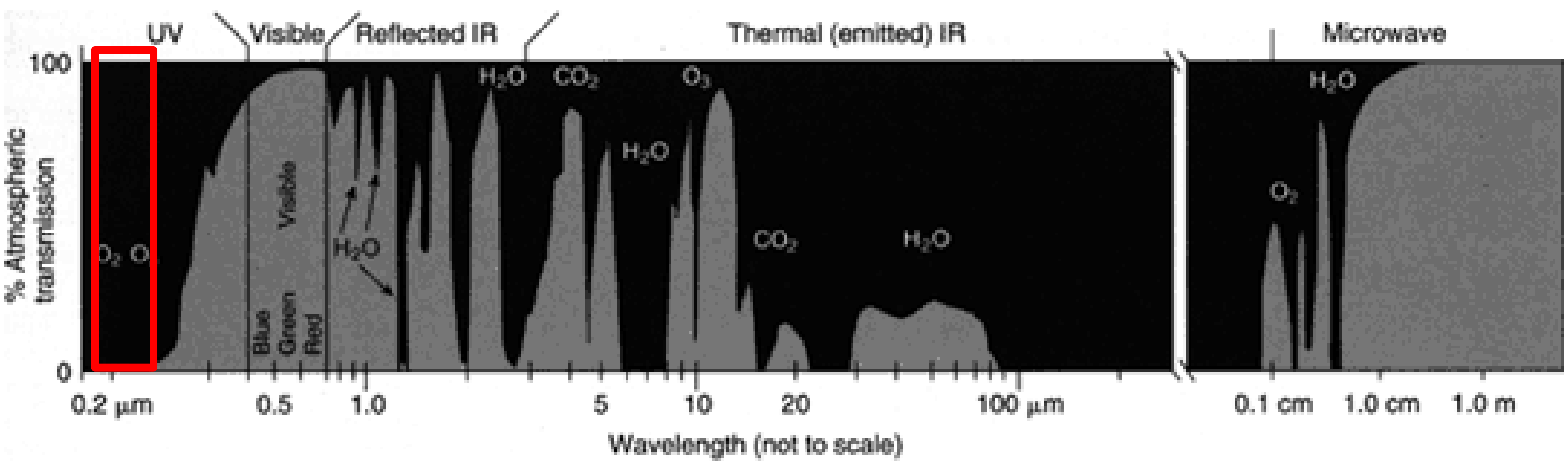
EREBUS

A UV spectral survey to leap forward our understanding of makes up our galaxy

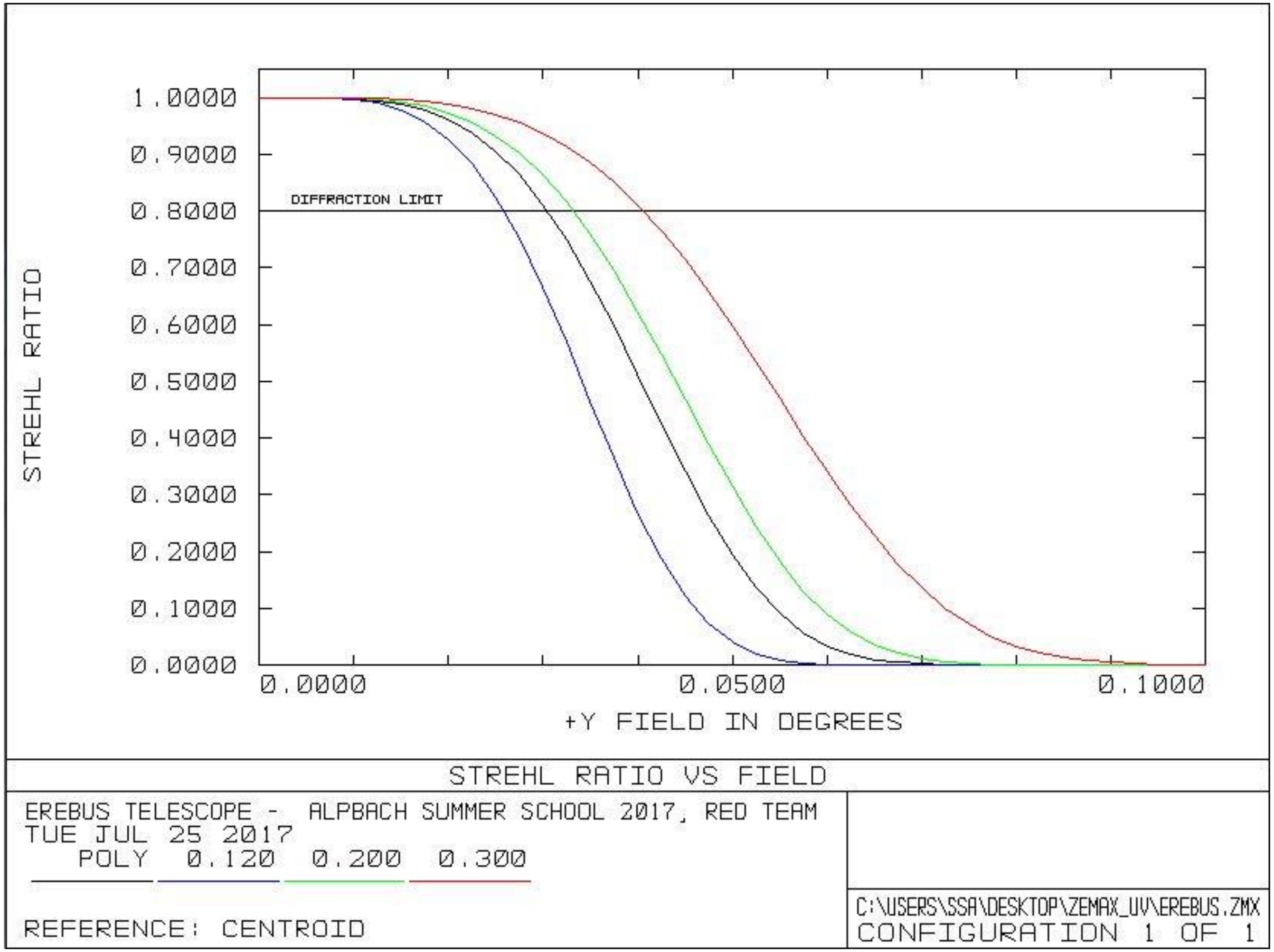
BACKUP SLIDES

Atmospheric transmission

In wavelength regime of interest there is 0% transmission



Telescope optimization



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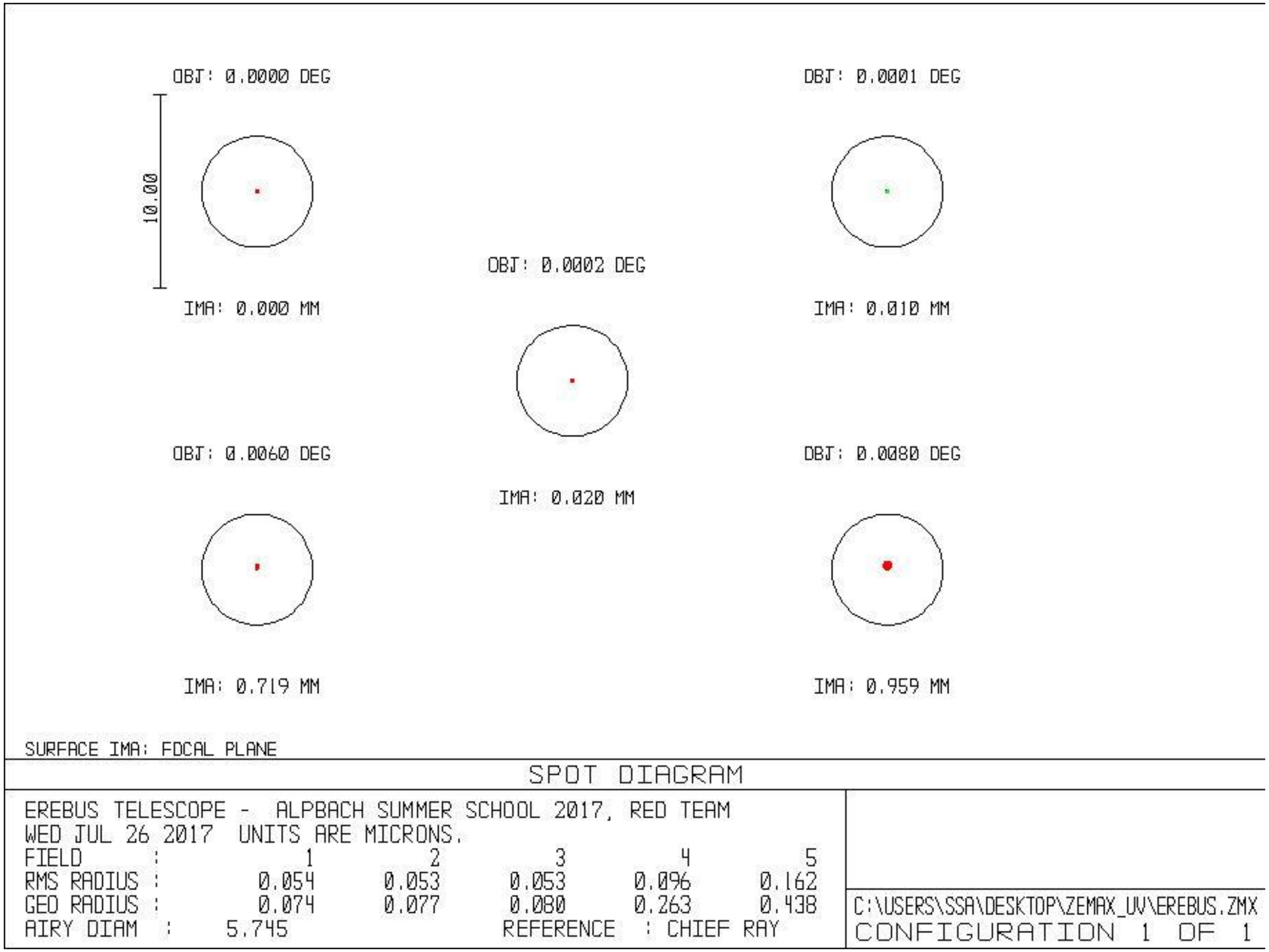
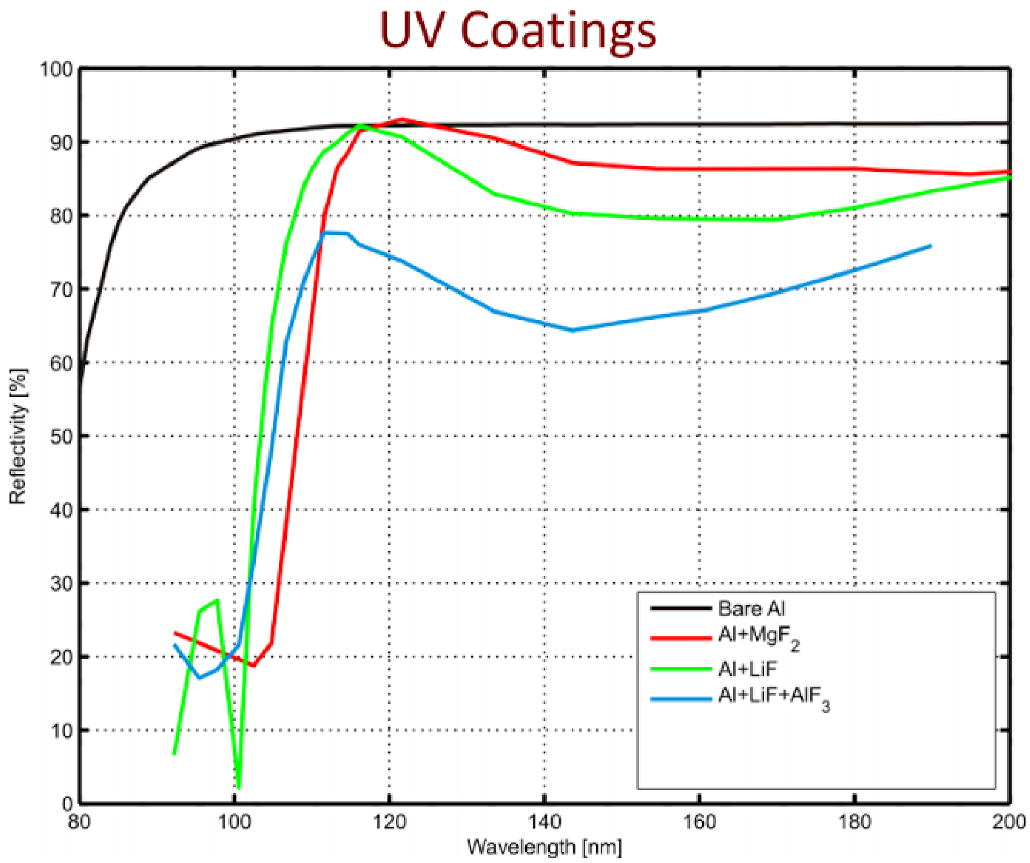
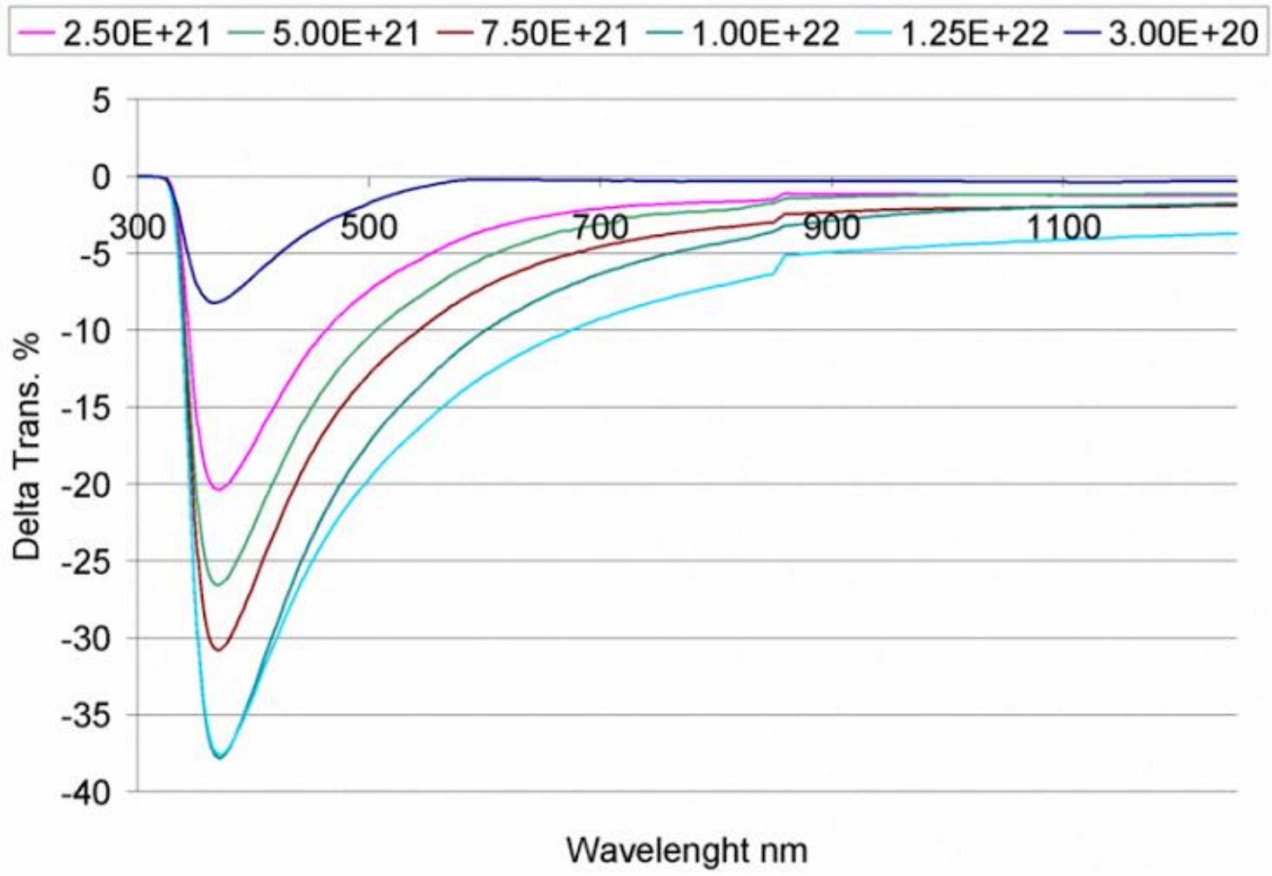


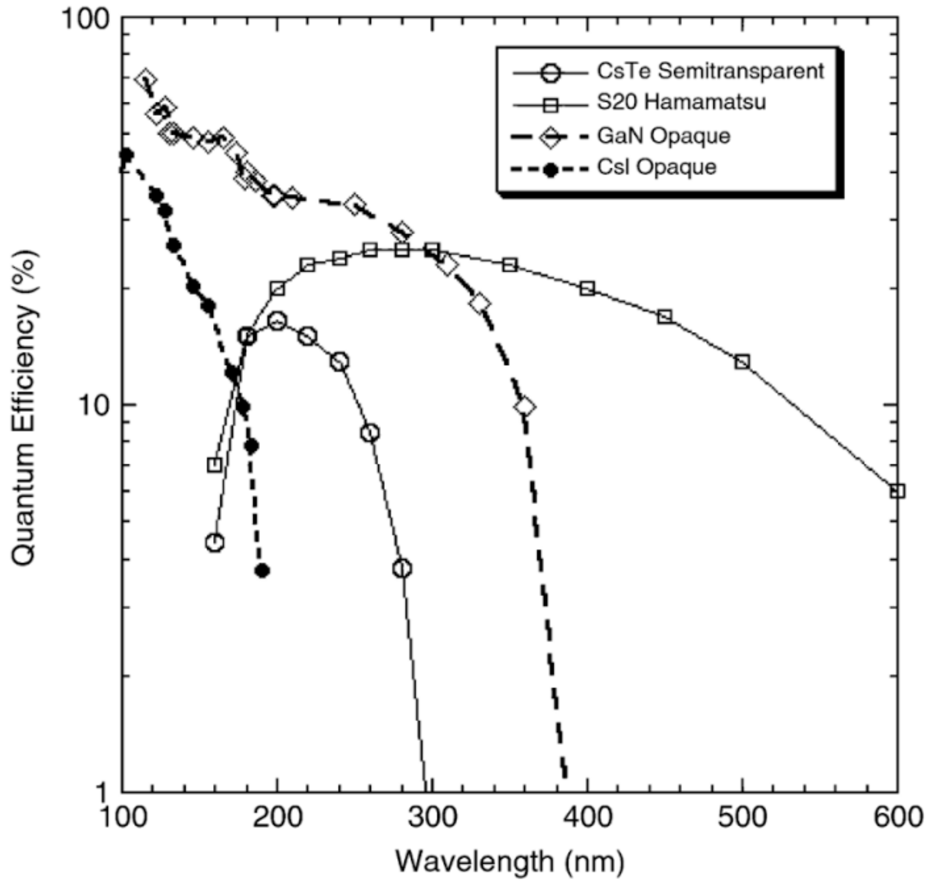
Mirror coating - efficiency



Mirror coating – degradation from AO



Photocatods



MCPs vs CCDs

Multi-Channel Plate Detectors	Charged Coupled Devices
10nm up to 350nm (without added electric field)	200nm to 600nm
Gain of 10^4 up to 10^9 (depending on config.)	Gain of 10^4 at maximum
Already flown on several missions	Already flown on several missions
No sensitivity to visible light	Sensitive to visible light
Operation only under vacuum	Operation under pressure possible
Cathode coatings sometimes sensitivity to air	-

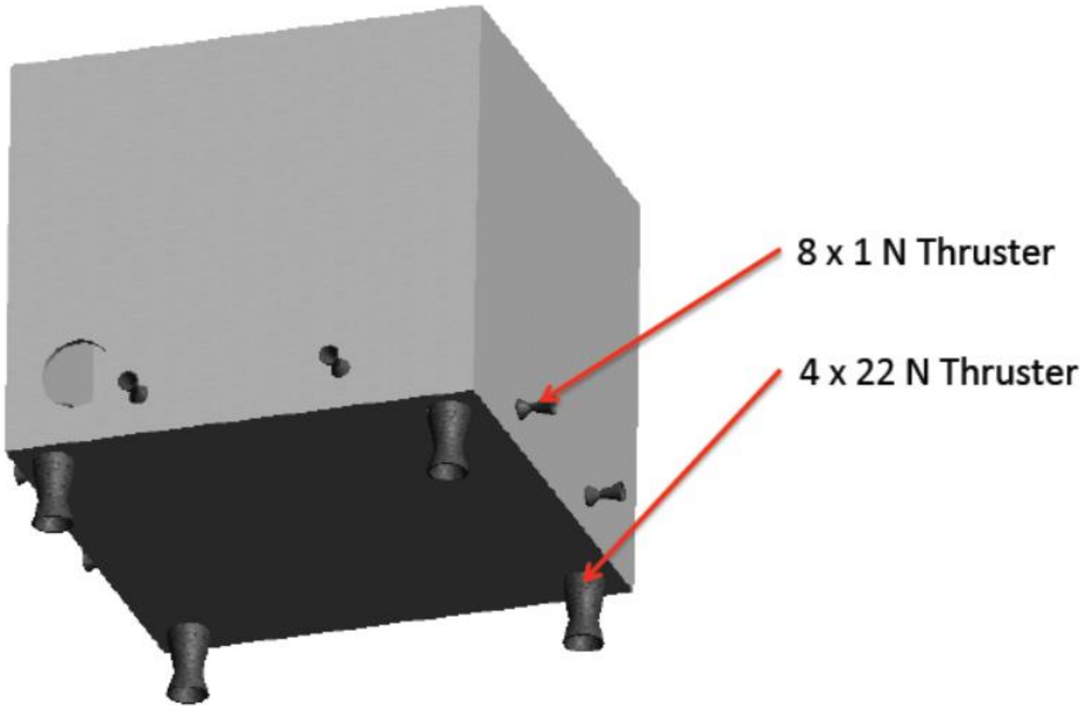
Why not FUSE configuration?

Operational modes

Various modes have been defined depending on various parameters:

- Spacecraft location
  - Sunlight
  - Eclipse
- On-board systems
  - Reset
  - Calibration
  - Low-power mode
  - Observation
  - Safe mode
- Spacecraft science
  - Target observing
  - Repointing
- End of life (EOL)

Subsystem - ADCS



ADCS

Why were these sensors and actuators chosen?

Star trackers – Very high pointing accuracy

Sun sensor – If spacecraft becomes desoriented, will be able to reposition it quickly.

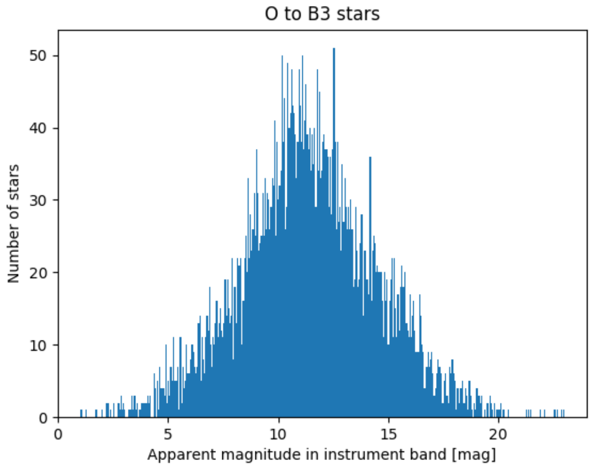
Magnetometer – Measures Earth‘s magnetic field for magnetic torquers to use.

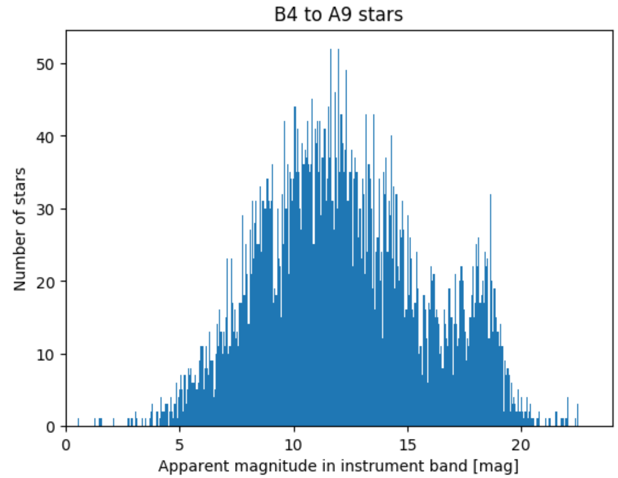
VSCMGs – Way of changing attitude fast and accurately using just one type of actuator.

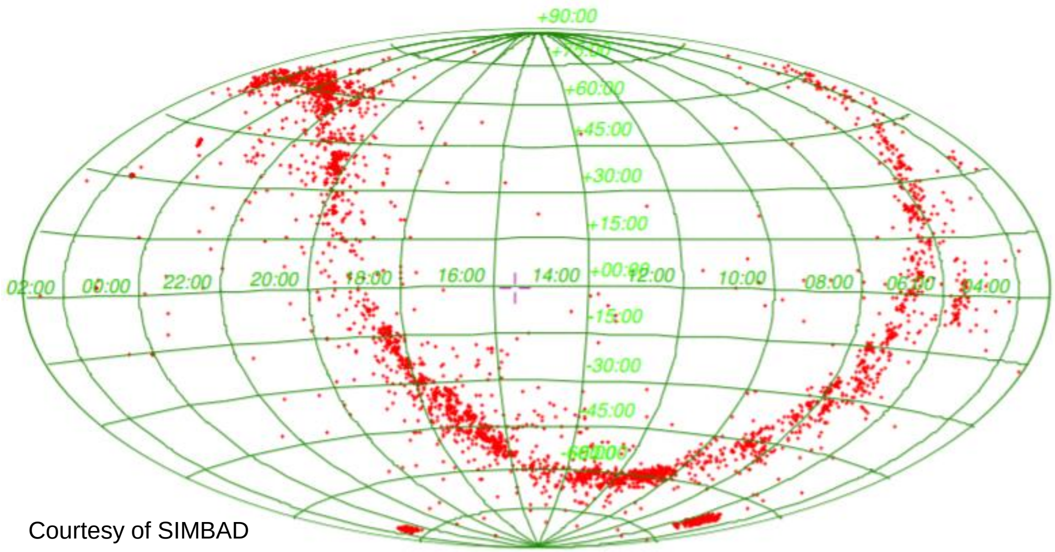
Magnetic torquers – Desaturate CMGs from built up momentum without using expendable propellant from thrusters. They are also lightweight and don‘t use too much power.

Thrusters – Necessary both as a backup actuator for attitude control and for desaturating CMG‘s. Also needed for EOL manoeuvres.

Some useful distributions



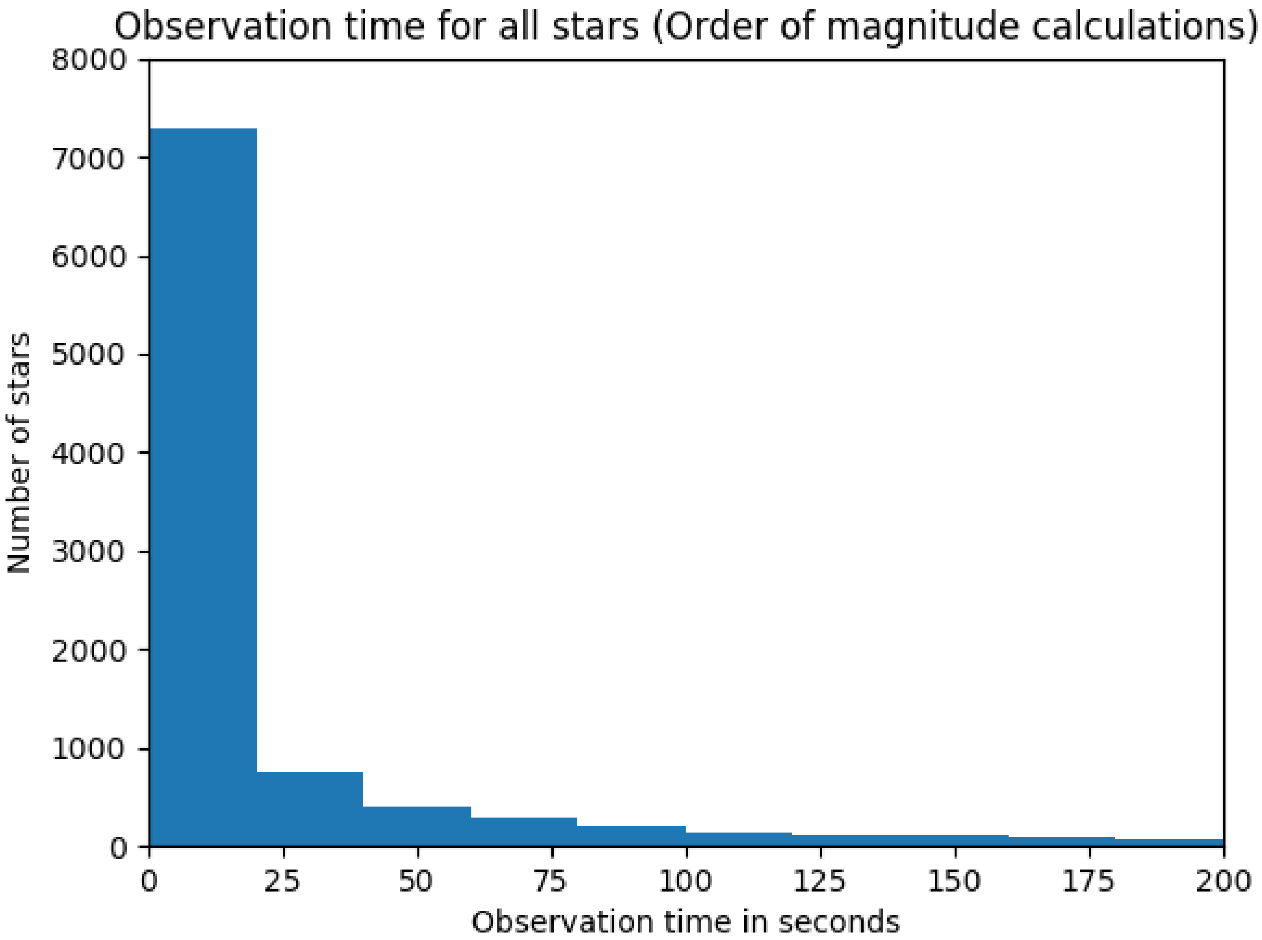




Courtesy of SIMBAD

- O to B3 stellar distribution
- We see gaps that can be filled with B4 to A stars

Some useful distributions



Future missions

There are quite a few planned and proposed missions that will investigate similar bandwidths as EREBUS. These are thoroughly discussed in a paper about the World Space Observatory—Ultraviolet (WSO-UV)[1].

Here follows the main competitors:

- TAUVEX (Tel Aviv University Ultraviolet Explorer): Specifically aims to study the 2175 Å peak the EREBUS plans to study, but only in the band 1400Å and 3200Å, whereas our mission plans to do 1000Å - 3000Å. Moreover TAUVEX is only studying stars brighter than 14 magnitudes within 2 kpc of our solar system.
- Astron-2: Newly proposed mission by the Russian community. All-sky telescope for spectral and photometric surveys in the UV. Aperture size of 2m.
- HORUS (High-ORbit Ultraviolet-visible Satellite): Developed by NASA to continue the success of the Hubble Space Telescope. HORUS will have a 2.4m aperture to do spectroscopy and imaging in UV and visible bands.

[1] "Scientific problems addressed by the Spektr-UV space project (world space Observatory—Ultraviolet)", 2015, url: https://goo.gl/TvdFWe

Zerodur

Extremely low thermal expansion
(down to 0 ± 10^{-8}/K)

Lightweight

Can be polished precise enough to work in FUV

Flight-proven