ESA Summer School Alpbach 2013

PAC^{2}MAN

Photospheric And Chromospheric and Coronal Magnetic field ANalyser

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Mission Statement

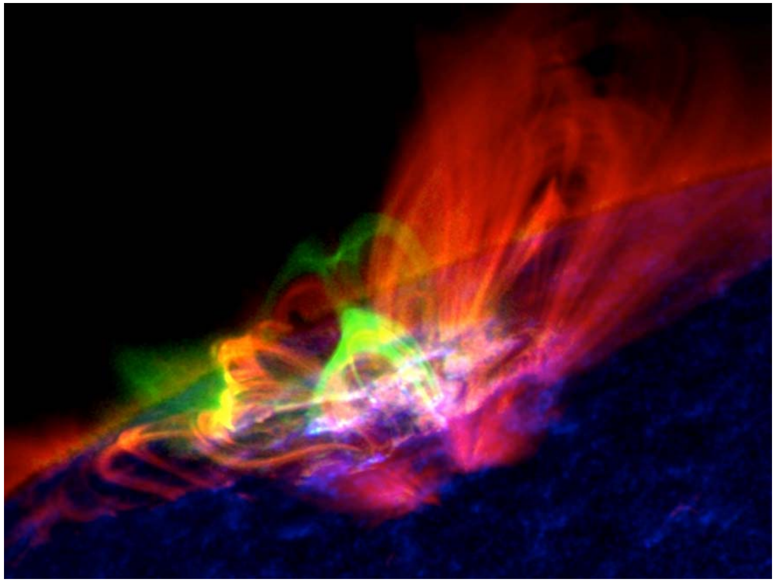
Our mission will study properties of CMEs and flares by observing different layers of the solar atmosphere, as well as the interplanetary space, with emphasis on the generation and further development of CMEs.

Mission Case

Many unanswered questions about CMEs/flares

- How are flares and CMEs initiated?
- What is driving CMEs up to their observed speeds?
- How can we measure the vertical component of B?

→ The key to these questions is the changing magnetic field throughout the solar atmospheric layers



[Su et al., 2013 (Nature Physics)]

Mission Case

- Knowing the physical properties of **magnetic energy build up and release** allow us to **forecast** when flares and CMEs are initiated, and how strong they become
- Currently no (permanent) measurements of **coronal magnetic fields** are available
- To understand why flares and CMEs occur, we need information about the entire process of magnetic energy build up **from photosphere to corona**

Mission Objectives

Primary objective:

To understand and predict the initiation and development of potentially hazardous CMEs and flares.

Secondary objective:

To determine the speed and direction of CMEs in order to forecast in *near real-time* solar wind conditions near the Earth.

A Successful Mission

Measures of a Successful Mission

1) Improve existing models of CME propagation by providing previously unknown data about the **initiation** of CMEs.

2) Determining the likelihood of flare and CME incidences with high statistical significance **within 2-3 days** [Reinard et al., 2010].

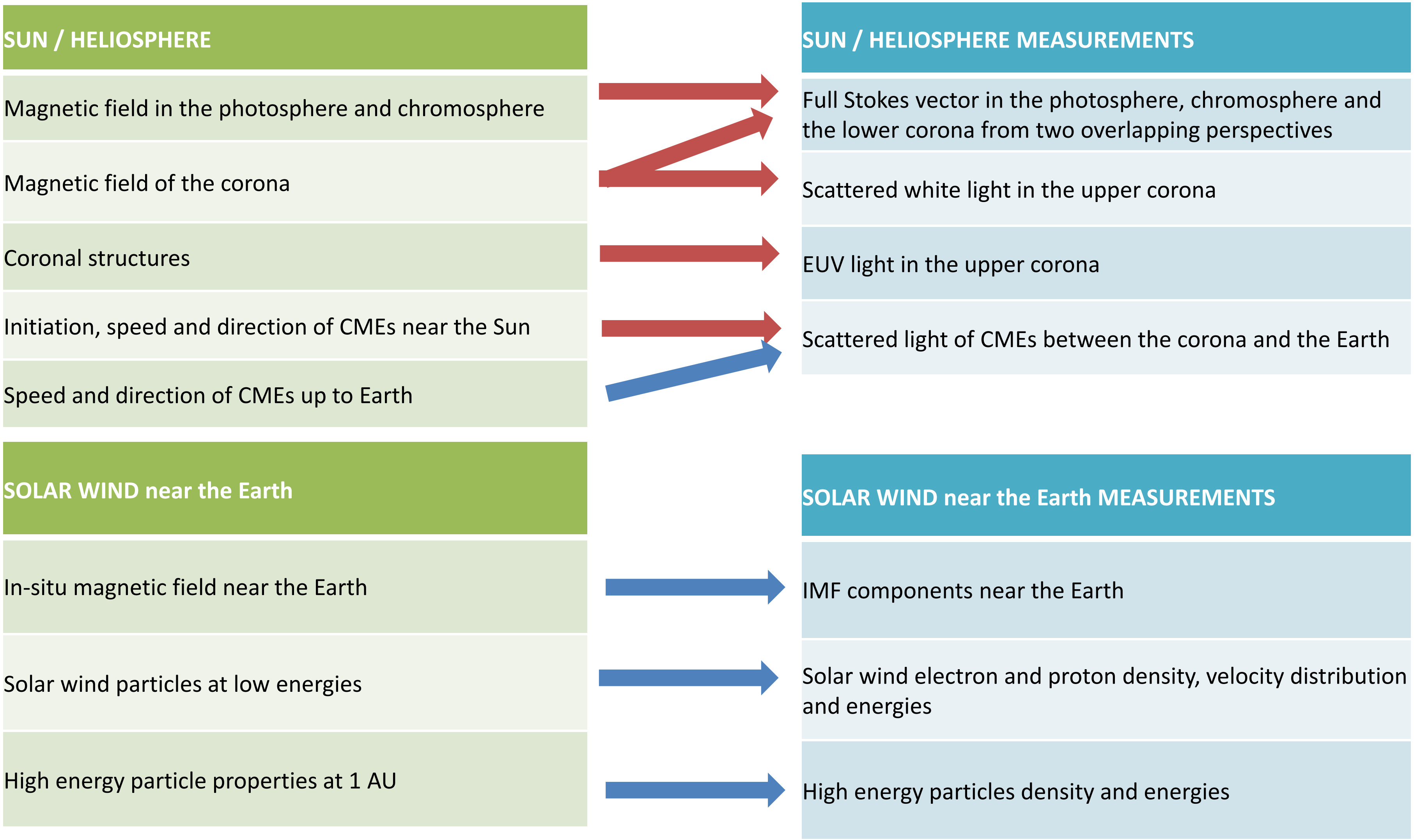
3) Correlate observed events at the solar surface with their effects on the **near-Earth** solar wind (for secondary objective).

Key Achievements (needed to achieve our goals)

1) Measurement of coronal magnetic field **vectors.**

2) Successful **combination of** photospheric, chromospheric transition region and coronal magnetic field measurements.

Scientific Goals and Physical Measurements



SUN / HELIOSPHERE

- Magnetic field in the photosphere and chromosphere
- Magnetic field of the corona
- Coronal structures
- Initiation, speed and direction of CMEs near the Sun
- Speed and direction of CMEs up to Earth

SUN / HELIOSPHERE MEASUREMENTS

- Full Stokes vector in the photosphere, chromosphere and the lower corona from two overlapping perspectives
- Scattered white light in the upper corona
- EUV light in the upper corona
- Scattered light of CMEs between the corona and the Earth

SOLAR WIND near the Earth

- In-situ magnetic field near the Earth
- Solar wind particles at low energies
- High energy particle properties at 1 AU

SOLAR WIND near the Earth MEASUREMENTS

- IMF components near the Earth
- Solar wind electron and proton density, velocity distribution and energies
- High energy particles density and energies

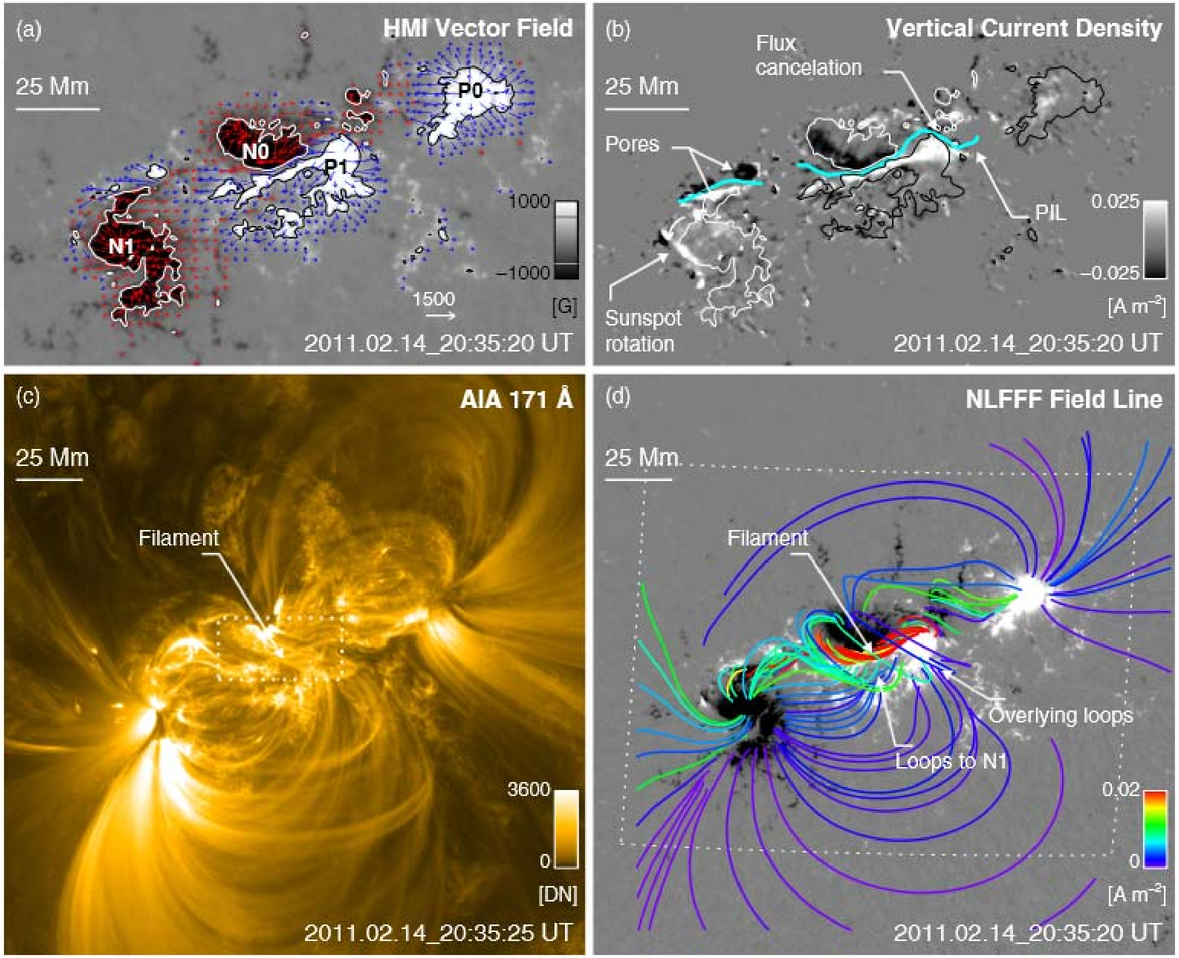
Physical Measurements and Requirements

SUN / HELIOSPHERE MEASUREMENTS	Exposure times	FoV	Reason
Full Stokes vector in the photosphere, chromosphere and the lower corona from two overlapping perspective	1 – 20 s	Full disc up to 2 Rs	To detail the flare initiation, choice of spectral lines
Scattered white light in the upper corona	5 s - 2 min	2 Rs - 30 Rs	Signal to noise ratio vs accuracy
EUV light in the upper corona	5 - 20 s	Full disc up to 1.6 Rs from solar center	Low density
Scattered light of CMEs between the corona and the Earth	50 s	30 Rs - 260 Rs	Low density

SOLAR WIND near the Earth	Sampling times	Measurement ranges	Resolution	Reason
IMF components near the Earth	100 vectors / s	+/- 1000 nT	0.1 nT	Quiet IMF ~10 nT; CMEs ~100 nT
Solar wind electron and proton density, velocity distribution and energies	3 - 30 s	1 eV - 100 keV	ΔE/E ~0.2	3D velocity distribution functions, electrons, protons and heavy ions
High energy particles density and energies	1 min	1 keV - 100 MeV	ΔE/E ~0.2	Flares and CMEs particles

Today’s Instruments

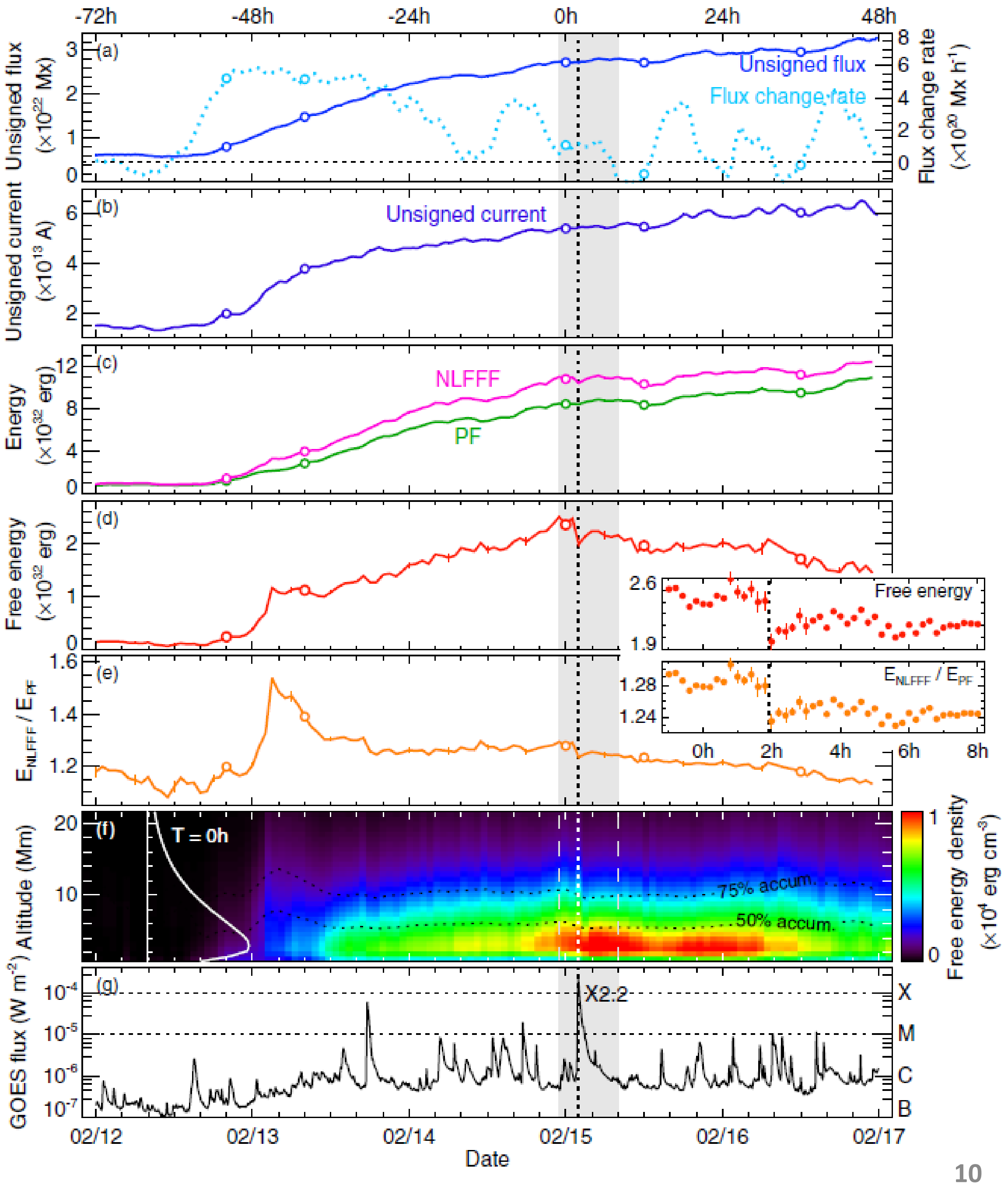
Extrapolation of the chromospheric and coronal field from photospheric measurements



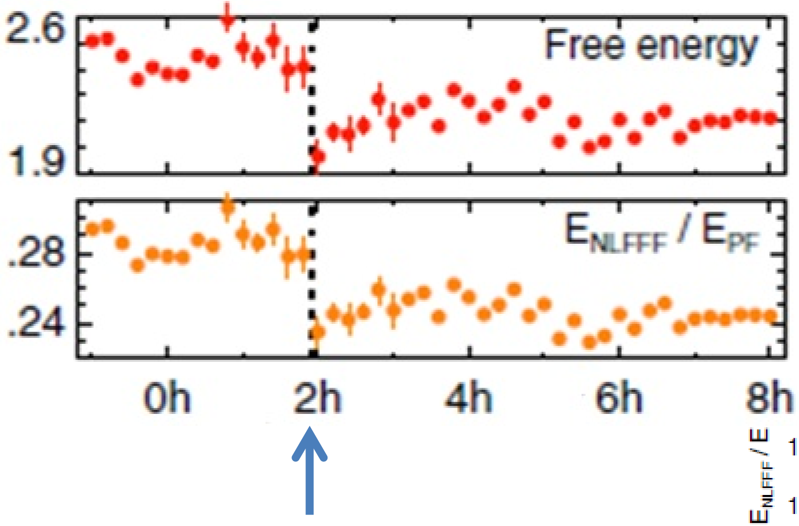
[Sun et al., 2012]

One example:
AR 11158,
February 2011

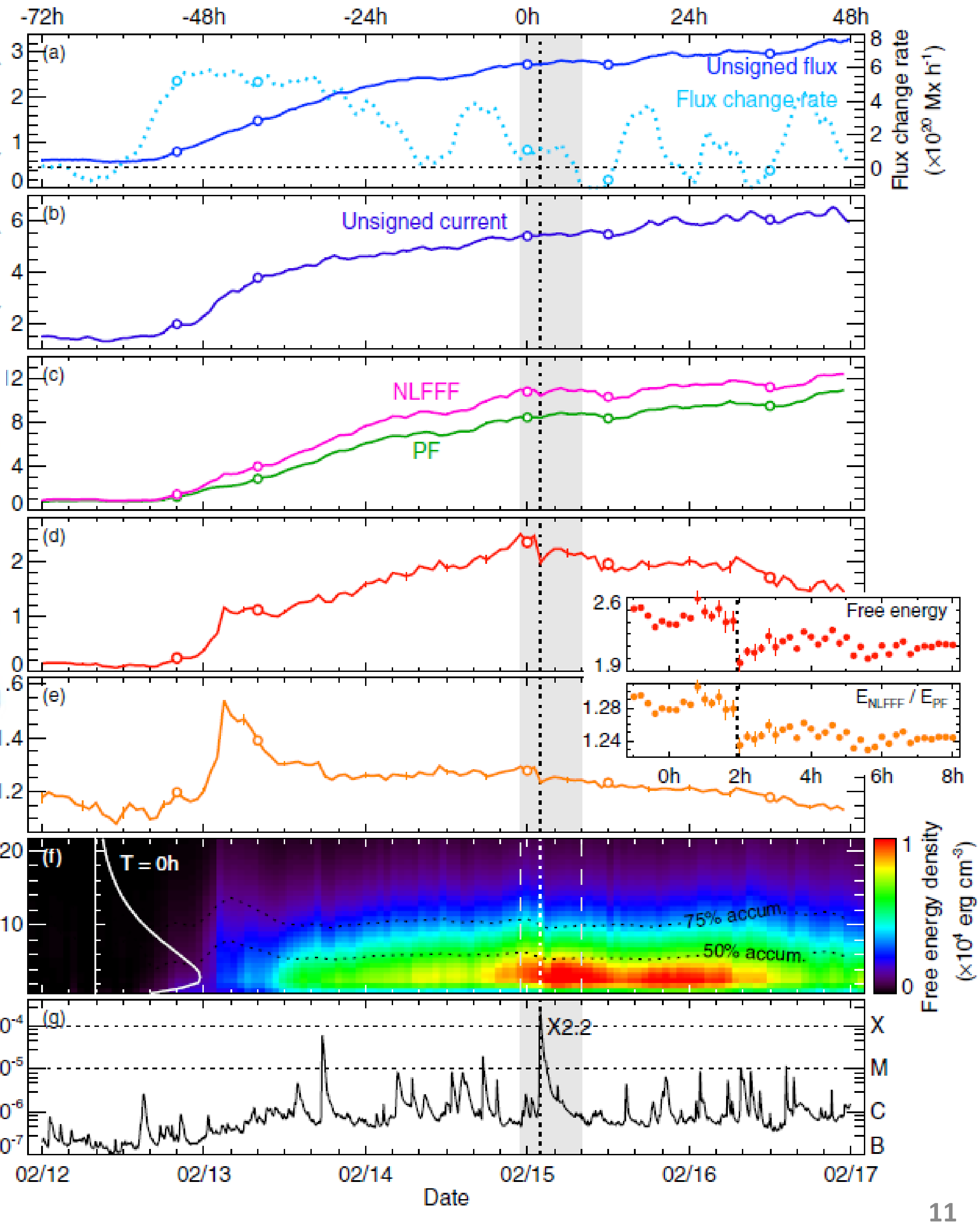
From the extrapolation: computation of the energy which can be released during a flare/CME event



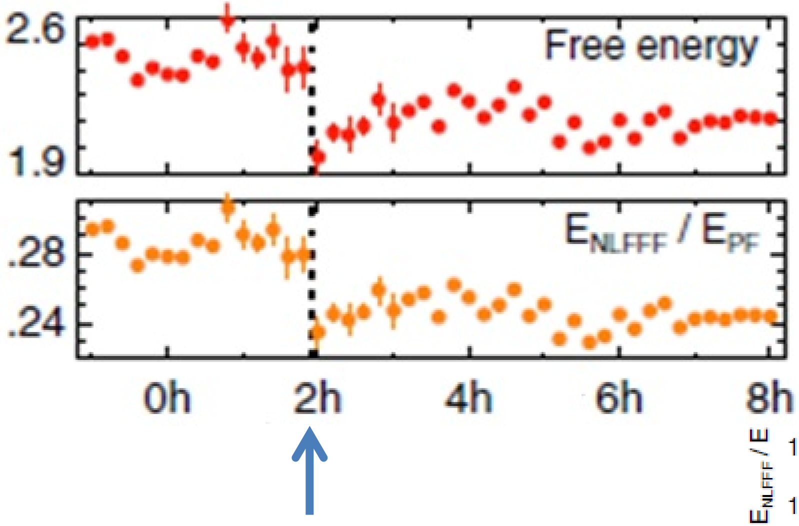
From the extraction: computation of the energy which can be released during a flare/CME event



X-class flare

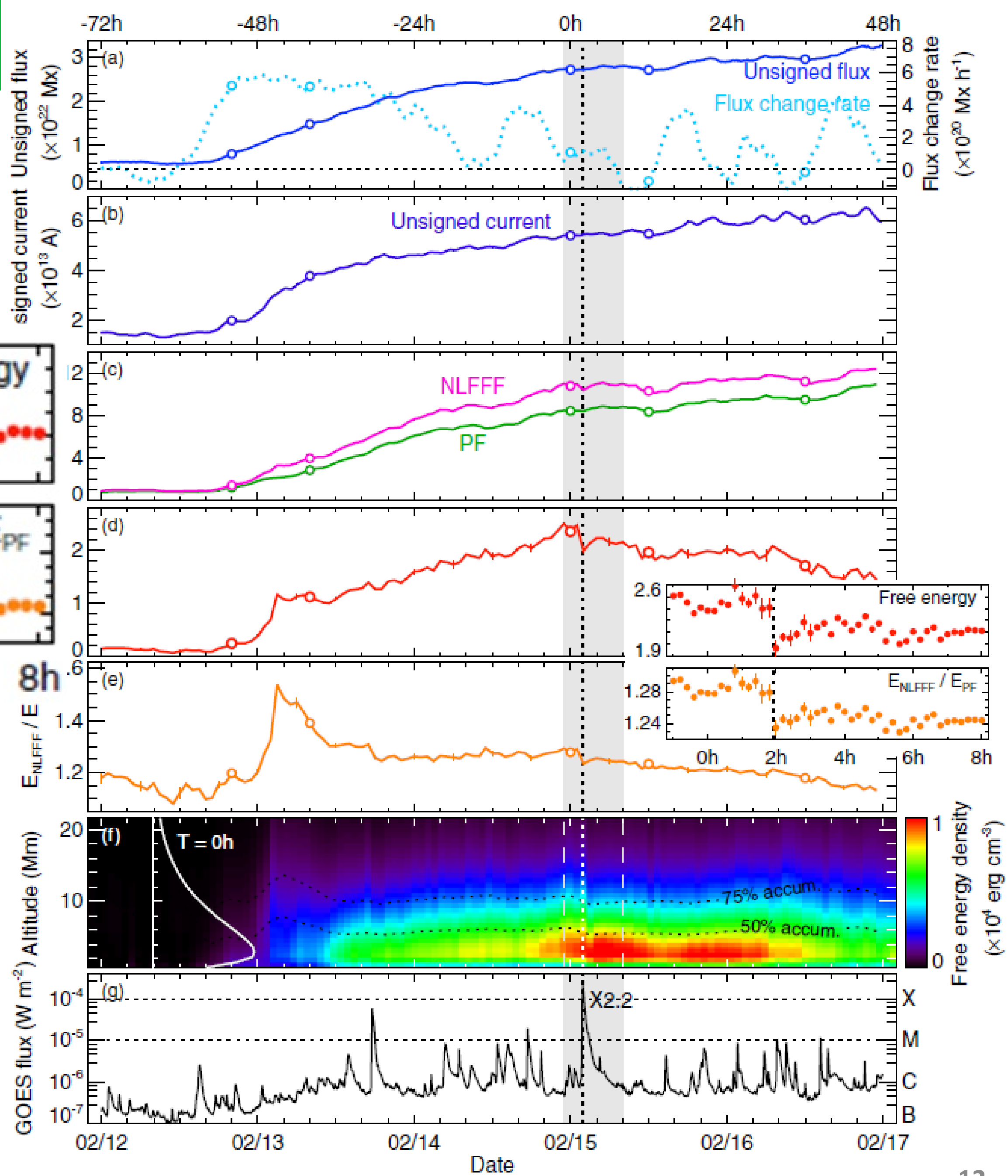


From the extraction: computation of the energy which can be released during a flare/CME event

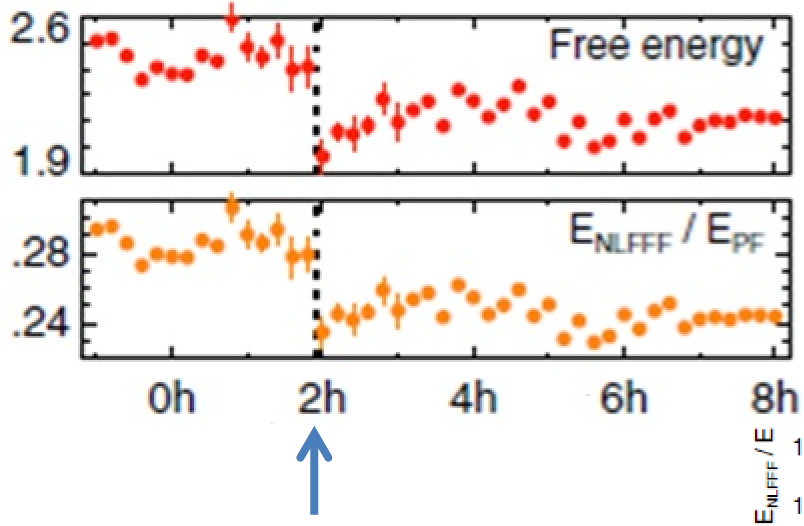


X-class flare

Energy loss = (0.34 ± 0.04) ×10^{32} erg



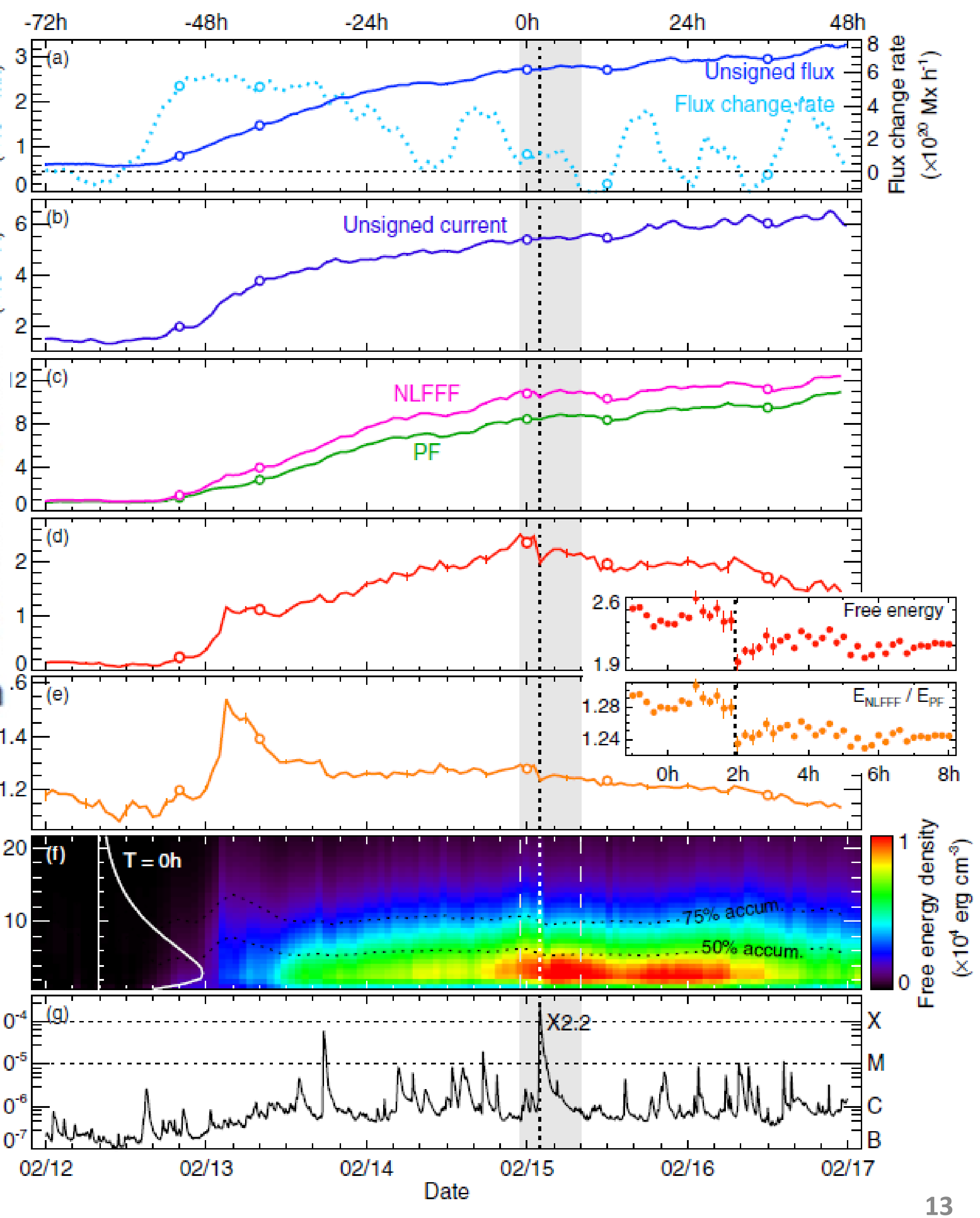
From the extrapolation: computation of the energy which can be released during a flare/CME event



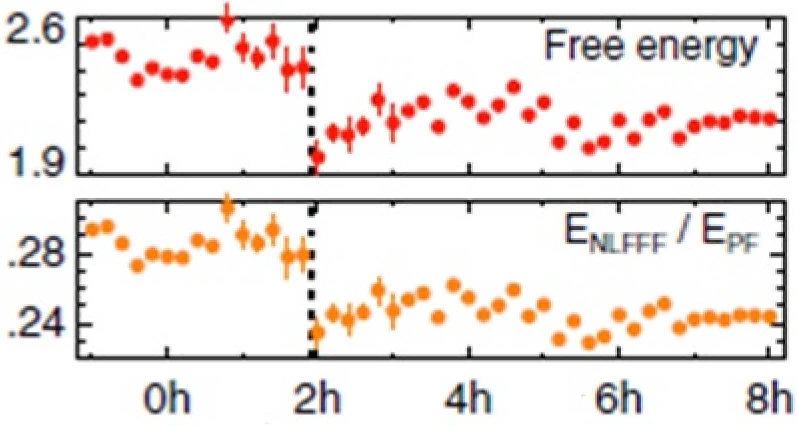
X-class flare

Energy loss = (0.34 ± 0.04) ×10^{32} erg

But energy in accelerated electrons = (0.5 ± 0.2) ×10^{32} erg!



Computation by extrapolating the energy which can be released during a flare/CME event

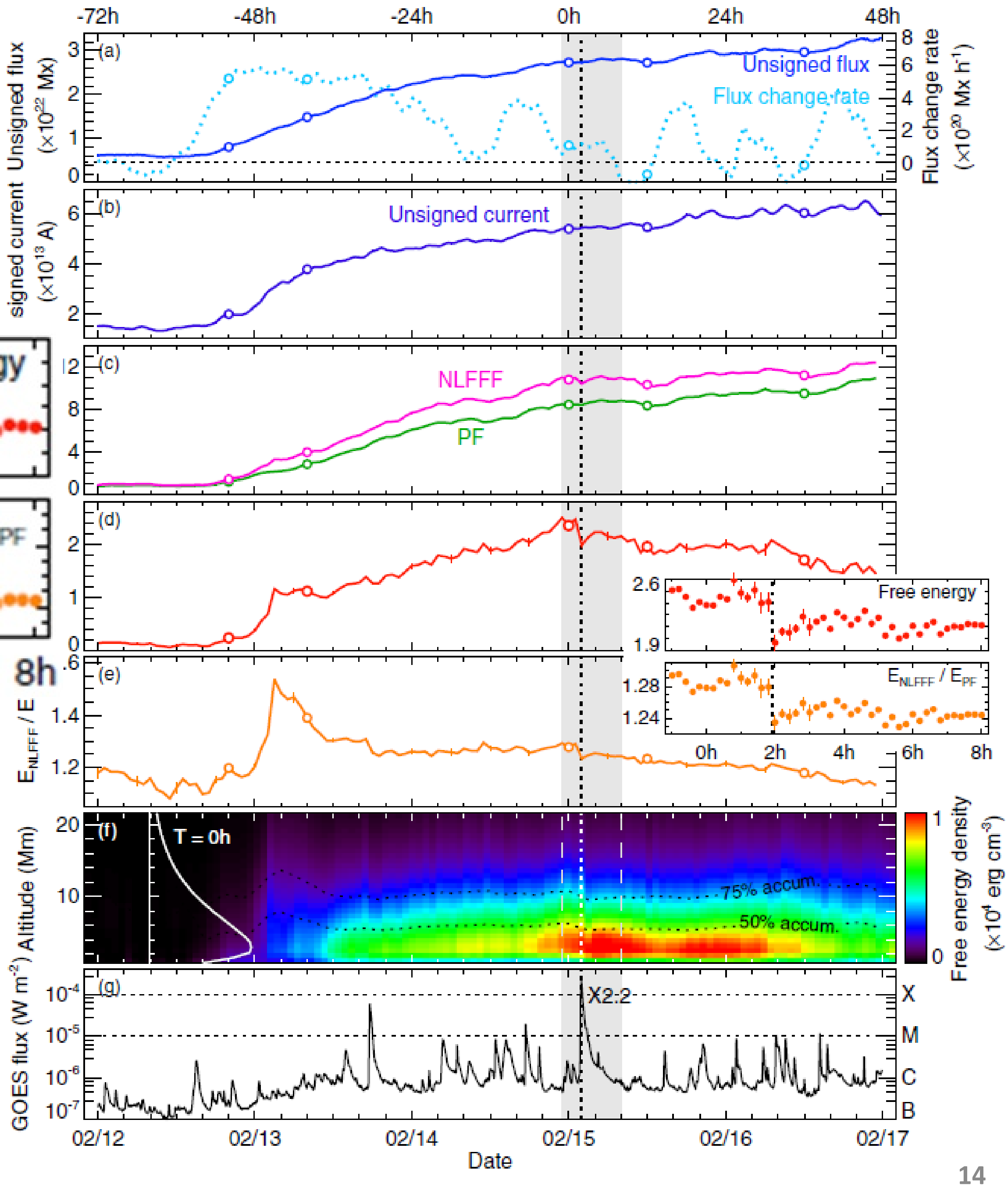


X-class flare

Energy loss = (0.34 ± 0.04) ×10^{32} erg

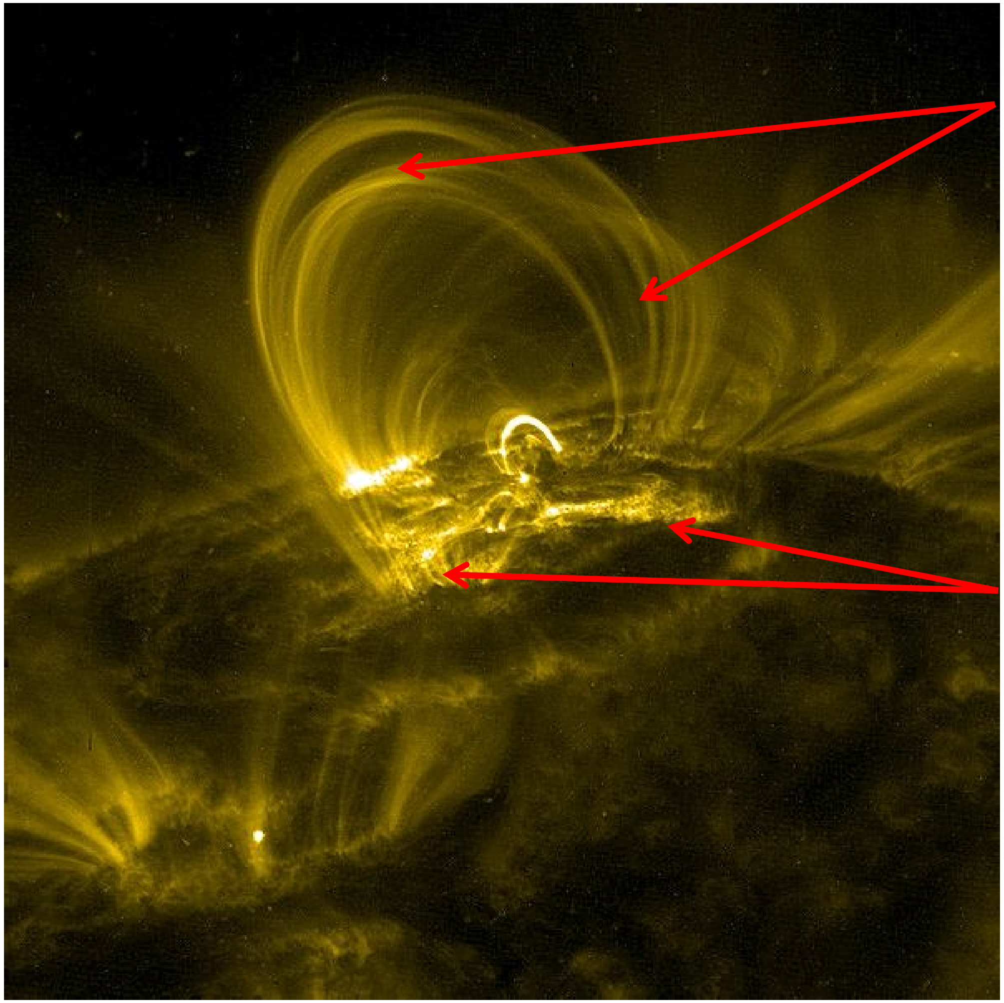
But energy in accelerated electrons = (0.5 ± 0.2) ×10^{32} erg!

(without taking into account kinetic energy of CME!)



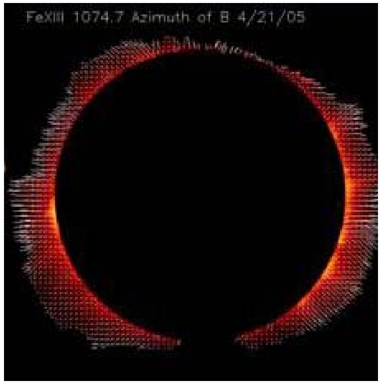
Our Measurements

Vector magnetic field measurements in different layers of the solar atmosphere



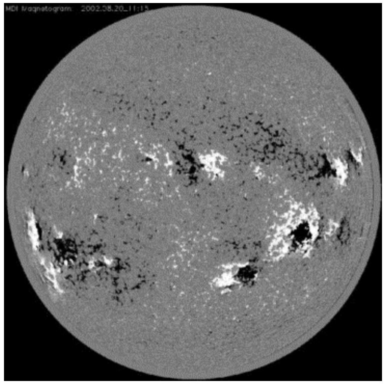
TRACE, 08/09/2005, 11:42

Coronal measurements: Hanle and Zeeman effect, **off-limb**



CoMP

Photospheric and chromospheric measurements: Zeeman effect, **disc centre**



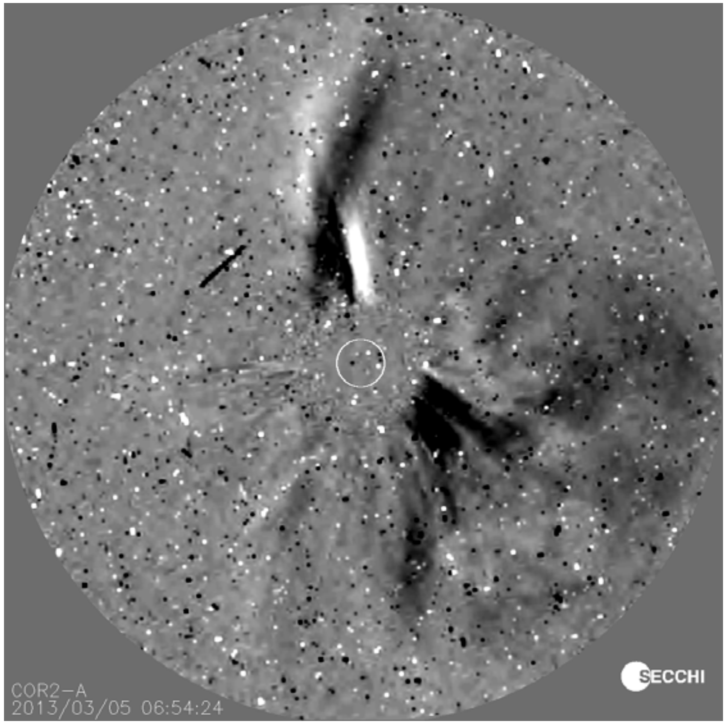
SOHO/MDI

→ **Need for two satellites at 90°**

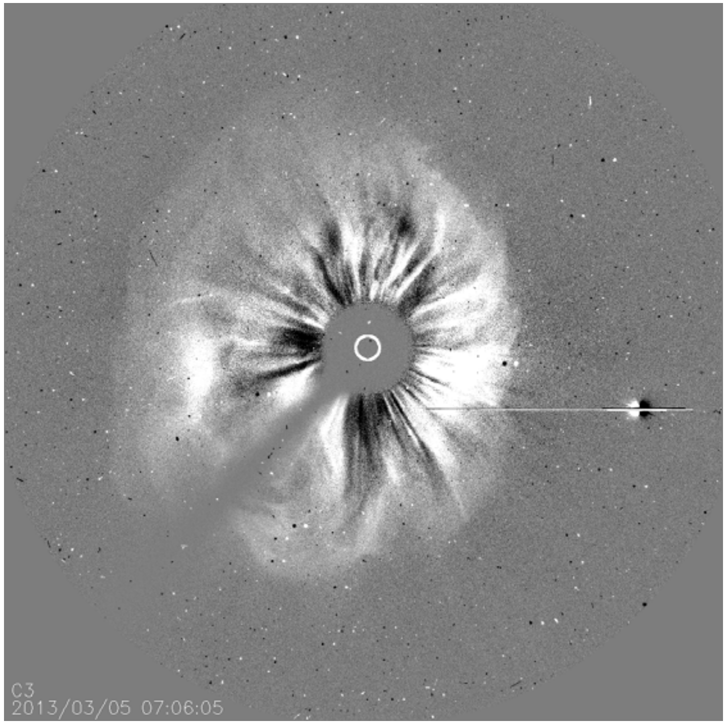
Our Measurements

Measurements of direction, speed and shape of CMEs

STEREO and SOHO coronagraphs: combination of two points of view



STEREO/COR2 AHEAD, 05/03/2013



SOHO/LASCO/C3, 05/03/2013

Need two satellites for a stereoscopic view

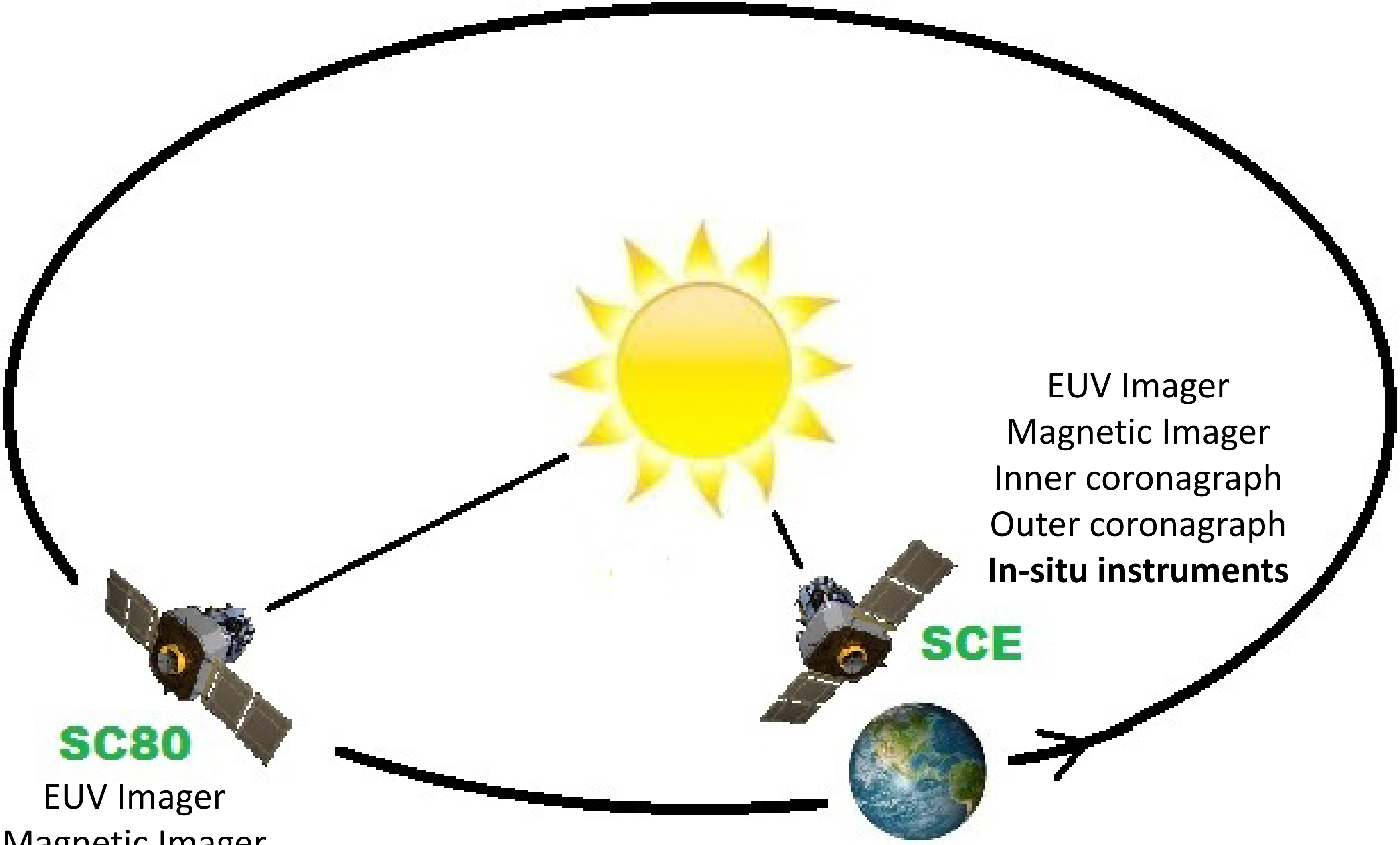
<u>Forecast</u> of speed and direction from the beginning of the mission
Great support to the ESA SSA program

Observation Strategy

Why two satellites with different lines of sight?

- To measure **one** event throughout the entire solar atmosphere:
  - Photosphere, chromosphere from Earth line-of-sight
  - Corona from wide angle
- To measure the **direction** of the CMEs – need two different views for triangulation.
- To observe CMEs propagating towards Earth.

Instruments



EUV Imager
Magnetic Imager
Inner coronagraph
Outer coronagraph
In-situ instruments

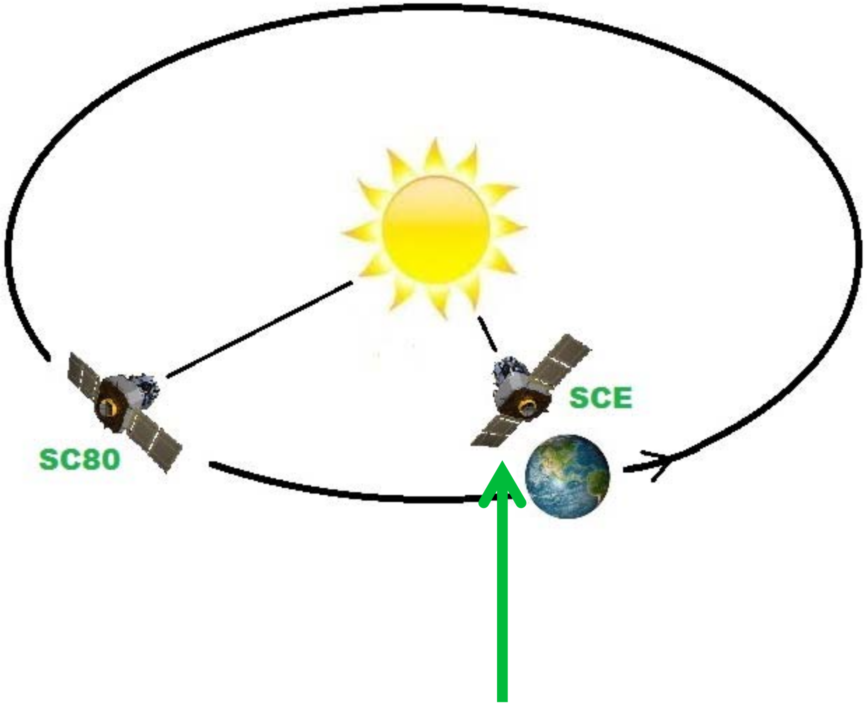
SCE

SC80

EUV Imager
Magnetic Imager
Inner coronagraph
Outer coronagraph
Heliopsheric Imager

Instrument Overview for Spacecraft SCE

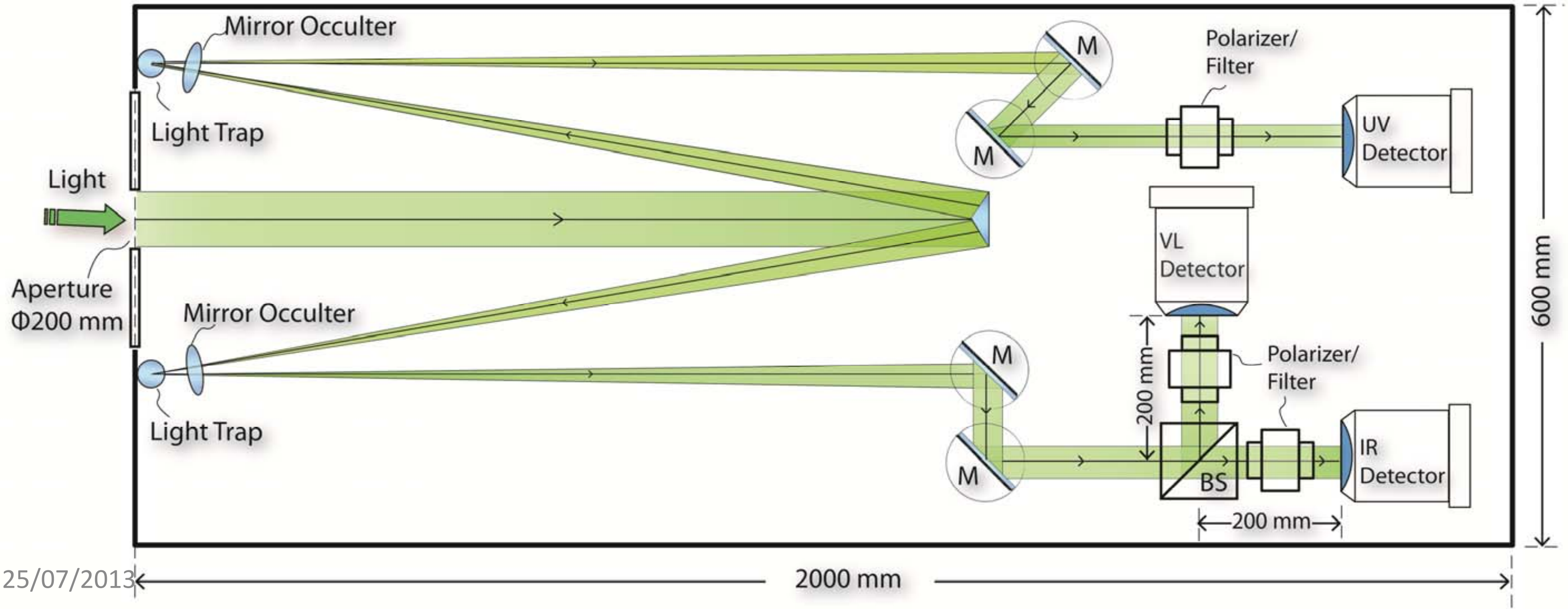
Instrument	Extracted Parameters	Field of View
IR/UV Polarimeter & Coronagraph C1	Magnetic field of lower corona	1.1 – 2 Rs
Multichannel Magnetic Imager (MMI)	Magnetic field of photosphere and chromosphere	1.07 Rs
Coronagraph C2	Observation of CMEs near sun	2 – 30 Rs
EUV Imager	Coronal Structures	1.6 Rs
Fluxgate Magnetometer (FGM)	IMF components near the Earth	N/A
Low Energy Solar Wind Sensors (LEWIS)	Solar wind electron and proton properties	360°, 65° Azimuth and 45° Elevation
High Energy Particle Sensor (HEPS)	High energy particles density, velocity distribution and energies	30°, 22°, 40°, 50°, 60x70°



IR/UV Polarimeter & Coronagraph C1

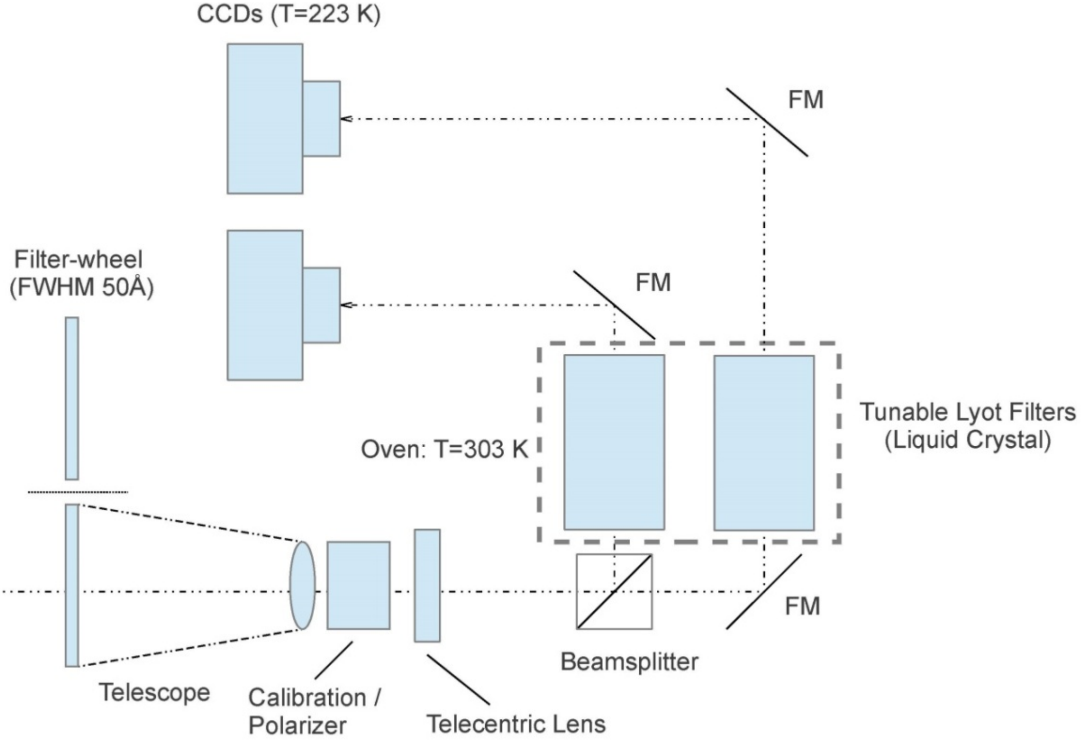
Measurements	Access to weak and strong fields in the corona (off-limb), Measurement of the full Stokes vector
Spectral Range	UV: HI Lyα line at 121.6 nm IR lines: FeXIII 1074.7 & 1079.8 nm , He I 1083.0 nm Visible Light: 560 nm
FOV [Rs]	1.1 – 2.0
Detector Size [pixel]	1024 x 1024

Pixel size [arcsec]	**5**
Mass [kg]	50
Size [cm]	200 x 60 x 25
Power [W]	80
Data Volume per Day	SCE: 4.7 GByte SC80: 238 MByte
Operation Temperature [K]	Detector: 223 IR-Polarimeter: 303



Multichannel Magnetic Imager

Measurements	Magnetic field of photosphere and chromosphere
Spectral Range	Fe 630.15nm Fe 630.25nm Na 589.59nm Na 588.99nm
FOV [Rs]	1.07
Image Size [pixel]	2x: 4096 x 4096
Pixel size [arcsec]	0.5
Mass [kg]	60
Size [cm]	150 x 70 x 30
Power [W]	95
Data Volume per Day	37.8 GByte
Operation Temperature	CCD: 233K Tunable Optics: 300K

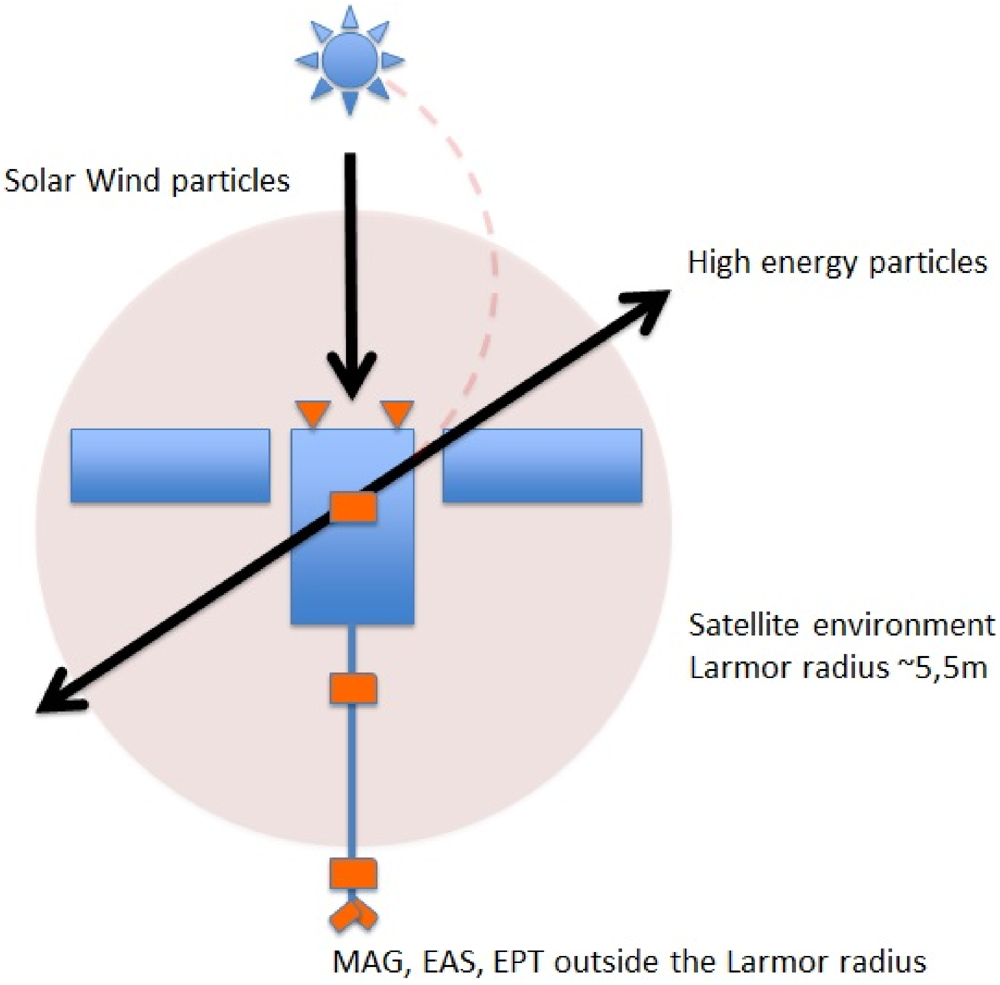


Other Instruments on SCE

Coronagraph C2	
Measurements	Observation of CMEs near sun
Spectral Range	400-850nm
FOV [Rs]	2 - 30
Image Size	1024 x 1024
Pixel Size [arcsec]	56
Mass [kg]	15
Size [cm]	140 x 40 x 32
Power [W]	5
Data Volume per Day	3.84 MByte
Operation Temperature [K]	193
Heritage	SOHO LASCO C3

EUV Imager	
Measurements	Coronal Structures
Spectral Range	17.4 nm
FOV [Rs]	1.6
Image Size	1024 x 1024
Pixel Size [arcsec]	3.2
Mass [kg]	11
Size [cm]	56 x 15 x 12.5
Power [W]	5
Data Volume per Day	21.6 MByte
Operation Temperature [K]	233 - 333
Heritage	PROBA-2 SWAP

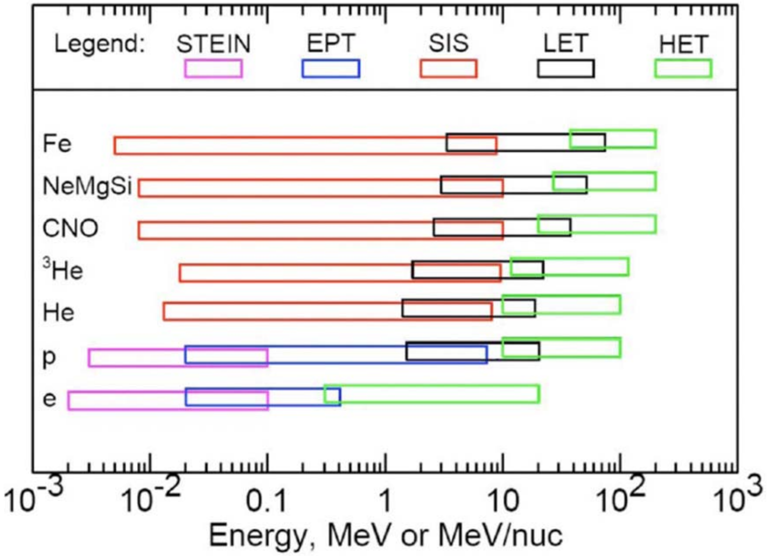
In-Situ Instruments on SCE



Low Energy Solar Wind Sensors (LEWIS)	
Sub-Instruments	EAS, PAS, HIS
Measurements	Solar wind electron and proton properties
FOV	EAS: 360° PAS: 65° Azimuth, 45°Elevation HIS: 96° A, 34° E
Mass [kg]	18.65
Size [cm]	EAS: 11.6 x dia 13.6 PAS: 30 x 20 x 20
Power [W]	15.6
Data Volume per Day	32.7 MByte
Heritage	Ulysses, ACE, STEREO, Solar Orbiter

In-Situ Instruments on SCE

Fluxgate Magnetometer	
Measurements	IMF components near the Earth
Mass [kg]	1.94
Size [cm]	Fluxgate-sensor: 9.75 x 4.9 x 6.7 Electronics: 15.9 x 16.2 x 9.8
Power [W]	4.39
Data Volume per Day	147.7 MByte
Heritage	VEX, THEMIS, Rosette Lander, Double Star, Solar Orbiter

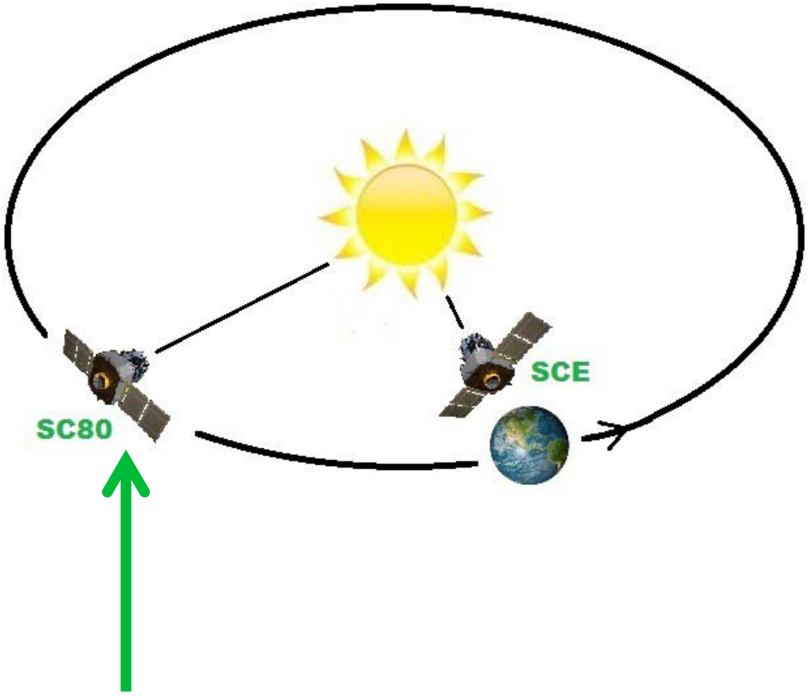


Energy Rate of HEPS [http://www.ieap.uni-kiel.de/et/solar-orbiter]

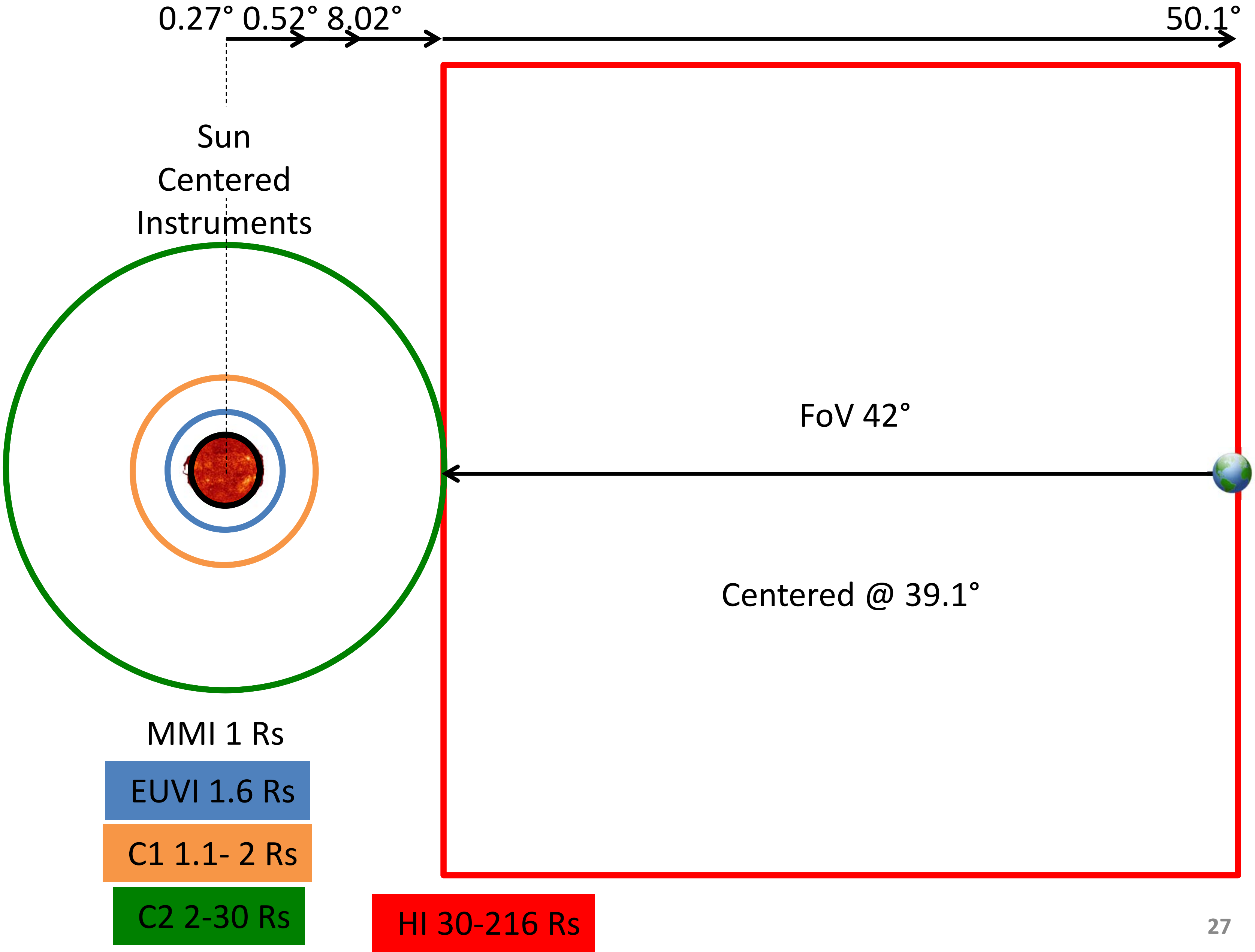
High Energy Particle Sensors (HEPS)	
Sub-Instruments	EPT, SIS, LET, HET, STEIN, CDPU/LVPS
Measurements	High energy particles density, velocity distribution and energies
FOV	EPT: 30°, SIS: 22°, LET: 40°, HET: 50°, STEIN: 60° x 70°
Mass [kg]	15.68
Size [cm]	EPT: 11 x 7 x 12 SIS: 35 x 13 x 11 LET: 22 x 15 x 11 HET: 13.6 x 17 x 16.2 STEIN: 10 x 13 x 13 CDPU/LVPS: 15x15 x10
Power [W]	29.95
Data Volume per Day	10.5 MByte (79.8 MByte in burst mode)
Heritage	STEREO, SOHO, ACE, Solar Orbiter

Instrument Overview for Spacecraft SC80

Instrument	Extracted Parameters	Field of View [Rs]
IR/UV Polarimeter & Coronagraph C1	Magnetic field of lower corona	1.1 – 2
Magnetic Imager	Magnetic field of photosphere and chromosphere	1.07
Coronagraph C2	Observation of CMEs near sun	2 – 30
EUV Imager	Coronal Structures	1.6
Heliospheric Imager (HI)	Properties of the propagation of CMEs through interplanetary space	30 – 216



Combined FoV of SC80



Instruments on SC80

Heliospheric Imager	
Measurements	Properties of the propergation of CMEs through interplanetary space
Spectral Range	400nm – 1000nm
FOV [Rs]	30 - 216
Image Size	2048 x 2048
Pixel Size [arcsec]	148
Mass [kg]	15
Size [cm]	65 x 33 x 20
Power [W]	10
Data Volume per Day	0.42 MByte
Operation Temperature	193K
Heritage	STEREO SECCHI HI

Magnetic Imager	
Measurements	Magnetic field of photosphere and chromosphere
Spectral Range	Fe 617,3nm
FOV [Rs]	1.07
Image Size	4096 x 4096
Pixel Size [arcsec]	0.5
Mass [kg]	73
Size [cm]	120 x 85 x 30
Power [W]	95
Data Volume per Day	645 MByte
Operation Temperature	CCD: 233K Tunable Optics: 300K
Heritage	SDO HMI

Technology Readiness Levels (TRL)

IR/UV Polarimeter and Coronagraph C1	3
Multichannel Magnetic Imager	3
Heliospheric Imager	5
Coronagraph C2	6
Magnetic Imager	7
EUV Imager	7
Low Energy Solar Wind Sensors	7
High Energy Particle Sensors	7
Fluxgate Magnetometer	7

Wide Angle Satellite Orbit Trade Matrix

Parameter	L5	90°	80°	Importance	L5	90°	80°
Field of view	1	5	4	4	4	20	**16**
Communication	5	2	4	3	15	6	**12**
Propellant - cost	4	3	3	1	4	3	**3**
Environment	2	4	4	1	2	4	**4**
Transit time	4	3	3	1	4	3	**3**
					29	36	**38**

Wide Angle Satellite Orbit Trade Matrix

Parameter	L5	90°	80°	Importance	L5	90°	80°
Field of view	1	5	4	4	4	20	**16**
Communication	5	2	4	3	15	6	**12**
Propellant - cost	4	3	3	1	4	3	**3**
Environment	2	4	4	1	2	4	**4**
Transit time	4	3	3	1	4	3	**3**
					29	36	**38**

→ 80° satellite chosen: SC80

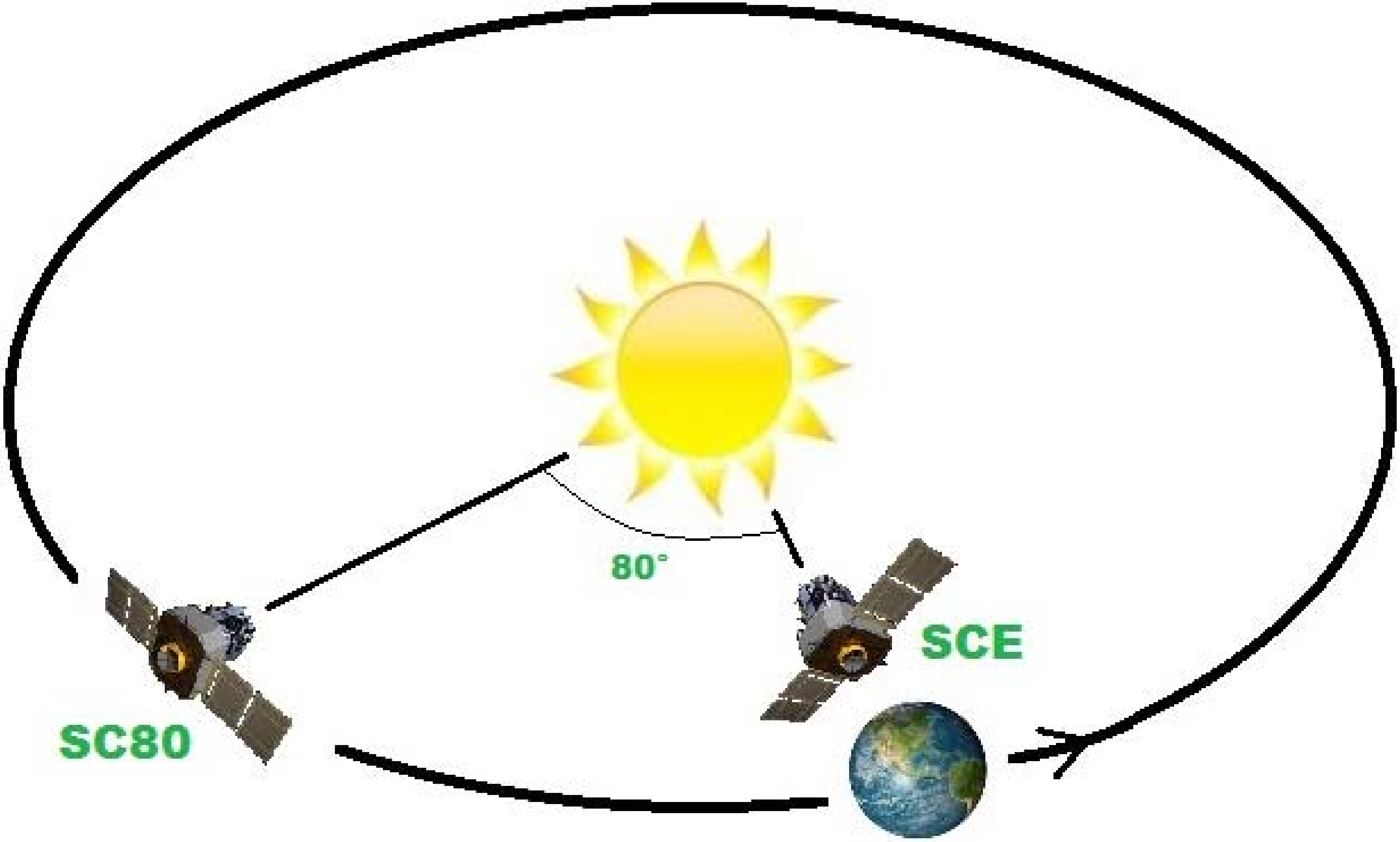
Earth Line-of-Sight Satellite Orbit Trade Matrix

Parameter	L1	SSO	Elliptic	Importance	L1	SSO	Elliptic
Time of observation	10	7.5	5	10	**100**	75	50
Communication	5	10	8	7	**35**	70	56
Propellant - cost	5	9	7	4	**20**	36	28
Environment	9	5	2	5	**45**	25	10
Pointing Stability	10	8	4	7	**70**	56	28
IMF, MM	10	0	3	2	**20**	0	6
ENA	0	1	5	4	**0**	4	20
Plasmasphere	0	0	7	4	**0**	0	28
Aurorae	0	3.5	7	4	**0**	14	28
Exosphere	0	0	5	4	**0**	0	20
					290	280	274

Earth Line-of-Sight Satellite Orbit Trade Matrix

Parameter	L1	SSO	Elliptic	Importance	L1	SSO	Elliptic
Time of observation	10	7.5	5	10	**100**	75	50
Communication	5	10	8	7	**35**	70	56
Propellant - cost	5	9	7	4	**20**	36	28
Environment	9	5	2	5	**45**	25	10
Pointing Stability	10	8	4	7	**70**	56	28
IMF, MM	10	0	3	2	**20**	0	6
ENA	0	1	5	4	**0**	4	20
Plasmasphere	0	0	7	4	**0**	0	28
Aurorae	0	3.5	7	4	**0**	14	28
Exosphere	0	0	5	4	**0**	0	20
					290	280	274

→ L1 satellite chosen: SCE


80°
SCE
SC80

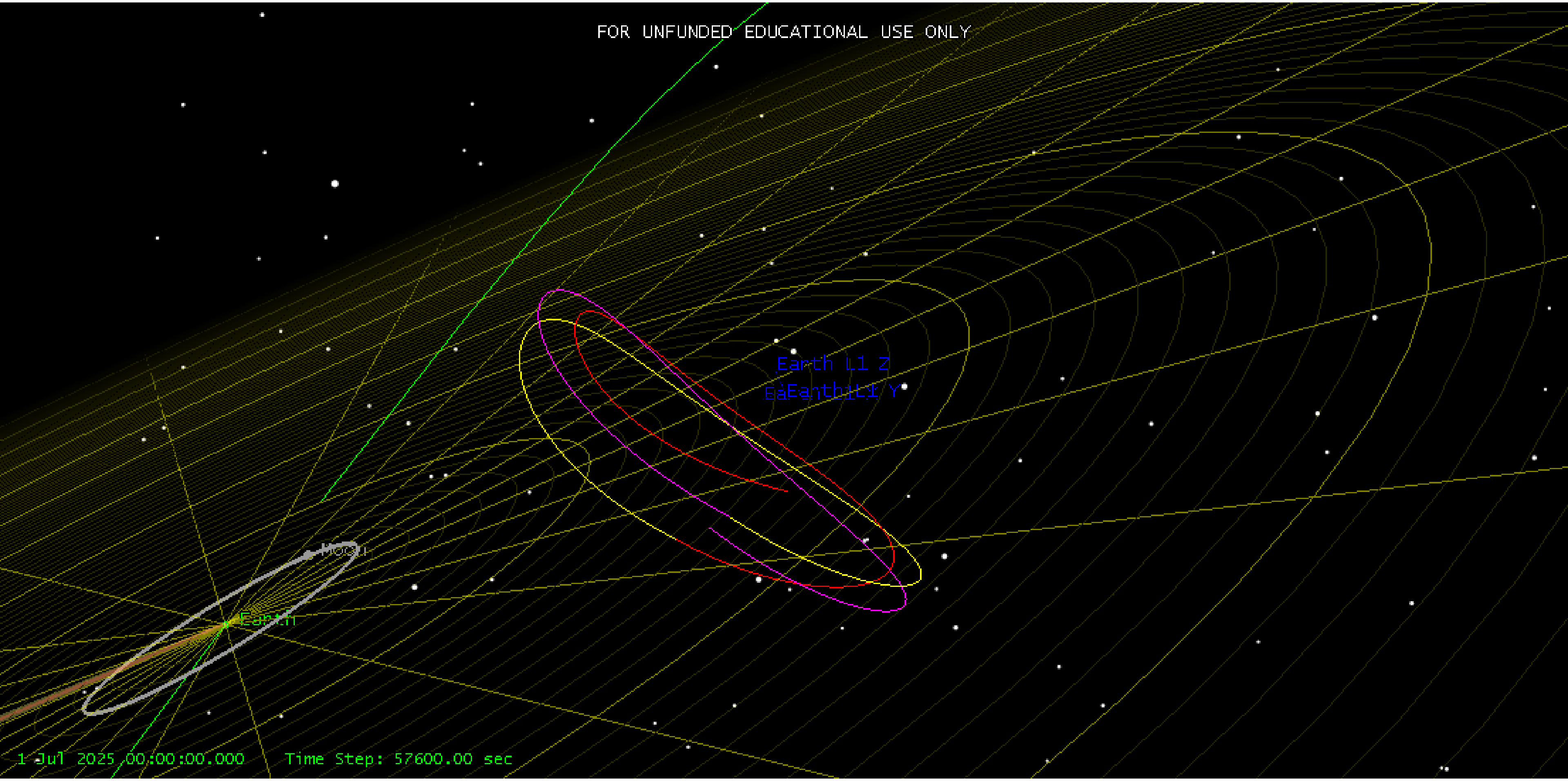
SCE Orbit

Type of orbit: Halo around Lissajous orbit (at L1)

Orbital Parameters
Oscillation period (xy): 177 566 days
Oscillation period (z): 184.0 days
Mean earth-sat distance: 1.5×106 km (L1)
Amplitude of oscillations in E-S distance Ax: 260 000 km
Amplitude of oscillations Az: 400 000 km
Amplitude of oscillations Ay: 828 680 km
Minimum elongation: 14.9°
Estimated transfer time (SOHO): 3.5 months

Delta V budget	SCE [m/s]
Compensation for perigee velocity variation	12
Removal of launcher dispersion	50
Orbit maintenance per year	10 *

SCE Orbit


FOR UNFUNDED EDUCATIONAL USE ONLY
Earth L1 Z
Earth L1 Y
Moon
Earth
1 Jul 2025 00:00:00.000
Time Step: 57600.00 sec

SC80 Orbit

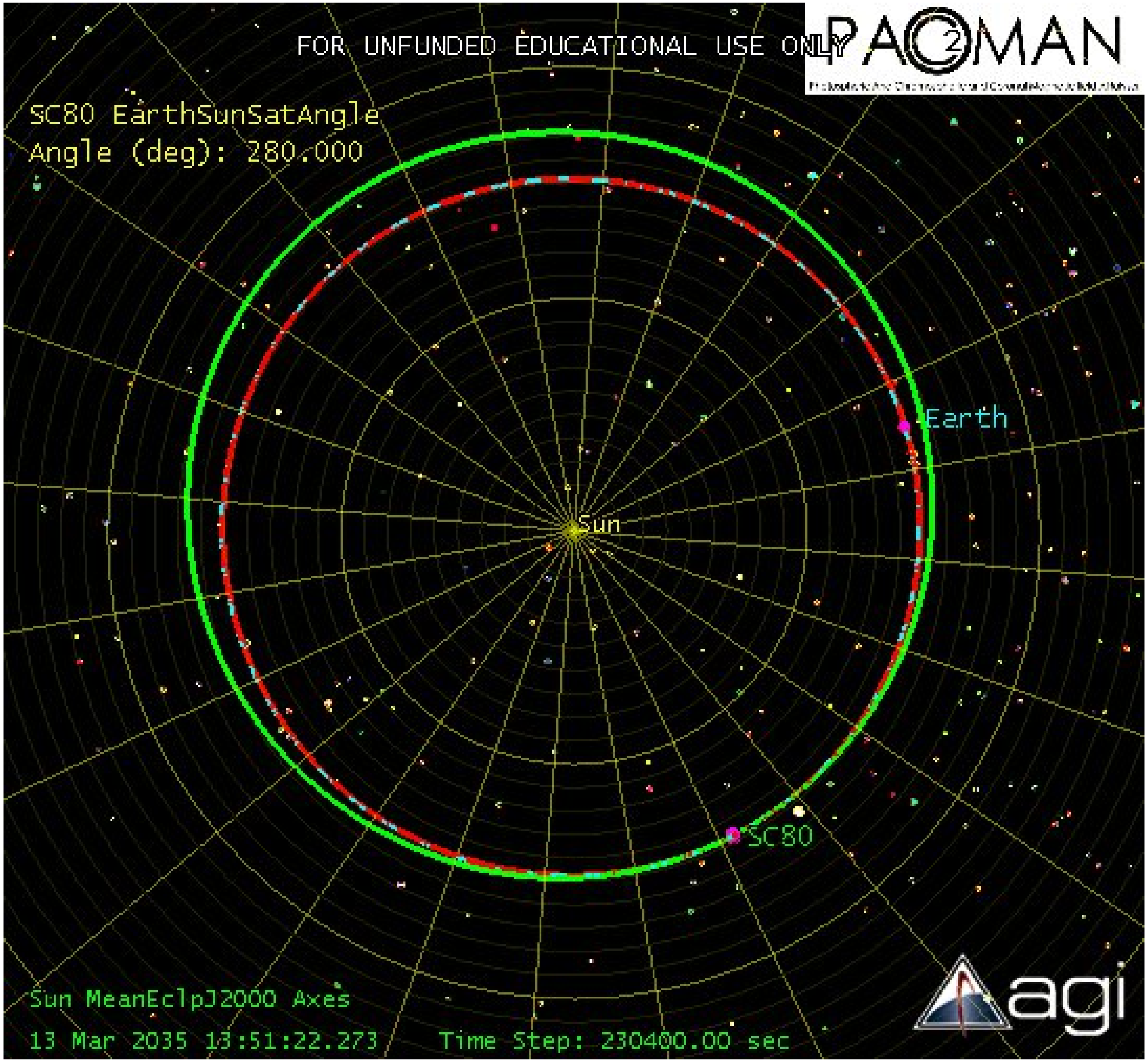
Type of orbit: Elliptical at 1AU trailing the Earth from a tilted angle of 80°

Elliptical transfer orbit
Perihelion: 1AU
Aphelion: 1.15 AU
Semi-major axis: 1.073 AU
Eccentricity: 0.0678
Orbital period 13.3 months
Transfer total time: 26.7 months (2 elliptical lapses)

Delta V budget
Injection into transfer orbit: 1.02 km/s (Soyuz)
Injection into final orbit: 1.02 km/s
Orbit Maintenance: None

Final elliptical Orbit
Maximum oscillation around the 80° tilt: within +/- 3°

SC80 Orbit

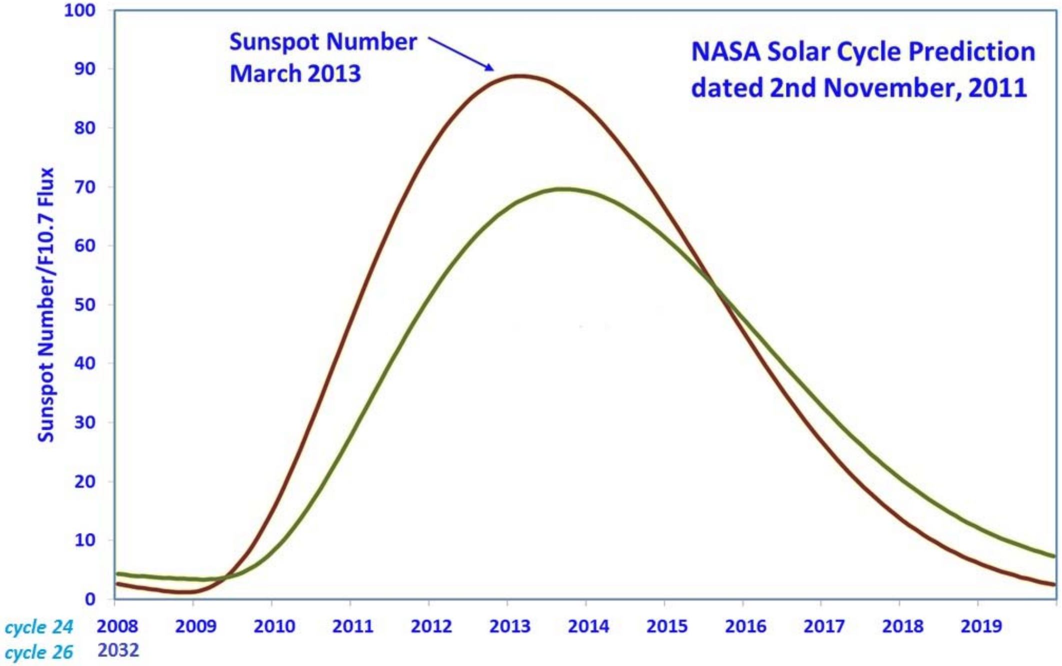

FOR UNFUNDED EDUCATIONAL USE ONLY
PAC2MAN
SC80 EarthSunSatAngle
Angle (deg): 280.000
Earth
Sun
SC80
Sun MeanEclpJ2000 Axes
13 Mar 2035 13:51:22.273
Time Step: 230400.00 sec
agi

Launch and Transfer

When to launch?

- Want to measure over the peak period in solar activity
- Initially plan to be operational over **6 years** with possibility of extension to one whole solar cycle

→ Arrive ~ 3 years before solar maximum



Two Soyuz Launches

Satellite	SCE
Launcher	Soyuz
Launch site	Kourou, French Guiana
Launcher objective	Injection into an Earth escape orbit with c^3=0.08 km^2/s^2
Transfer orbit	Lissajous orbit towards Earth's L1
Delivered payload	2150 kg
Launch date	7 July 2032
Arrival date	22 Oct 2032

Satellite	SC80
Launcher	Soyuz
Launch site	Kourou, French Guiana
Launcher objective	Injection into an Earth escape orbit with c^3=1.15 km^2/s^2
Transfer orbit	Elliptical orbit outside of the Earth orbit
Delivered payload	2100 kg
Launch date	14 Dec 2031
Operation start	22 Jan 2033
Arrival date	1 March 2034

Launch and Transfer Timeline

14 DEC 2031
- SC80 is launched via Soyuz

7 JULY 2032
- SCE is launched via Soyuz

22 JULY 2032
- SC80 begins commissioning

22 OCT 2032
- SCE arrives at L1 and begins commissioning

22 JAN 2033
- SCE becomes operational
- SC80 arrives at 40°, and becomes operational

1 MARCH 2034
-SC80 arrives at 80° final position

Mission drivers

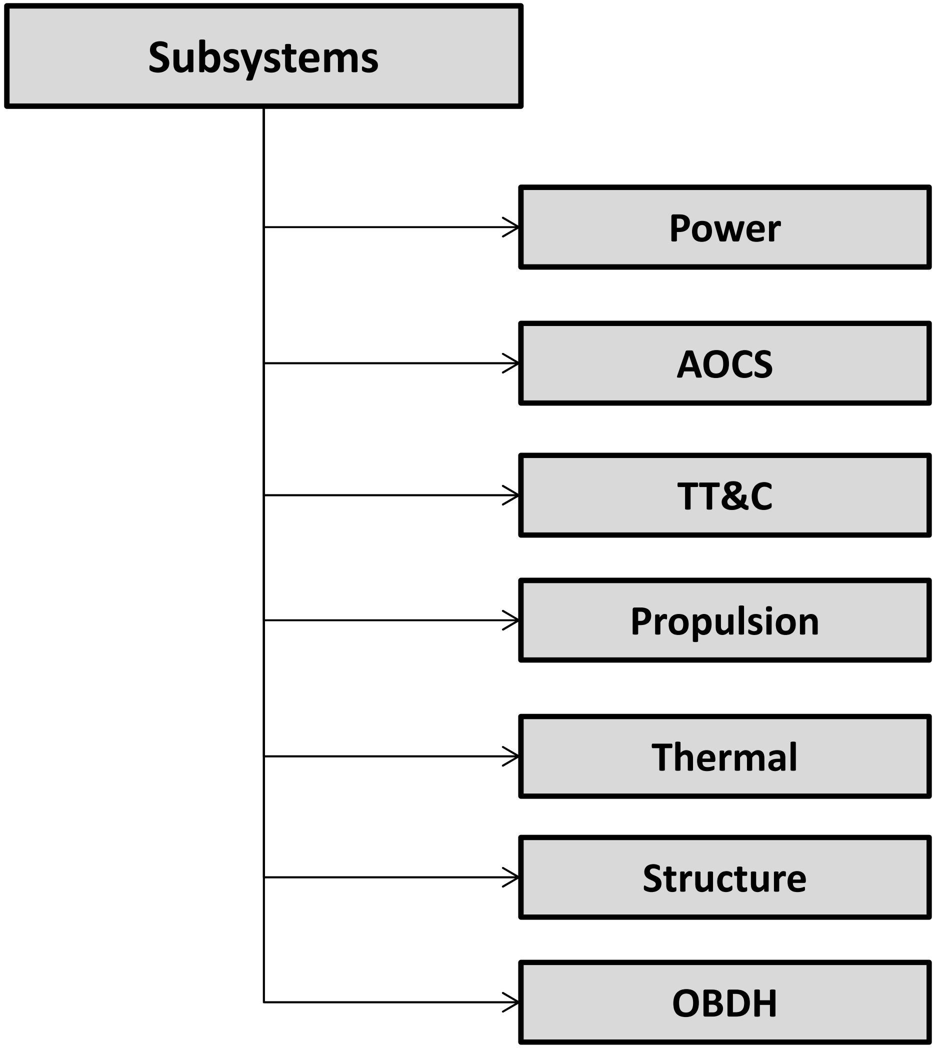
Our technological decisions are based on these requirements:

- High volume of data from SC80
- In-situ probing of the plasma environment in a clean electromagnetic environment
- Communication with both spacecraft for 24/7
- 6 year mission with a possible 6 year extension
- Costs of operations of a Space Weather forecasting system

Quiet Solar Wind Environment at 1 AU

Parameter	**Value**
Electron number density	9 cm^{-3}
Electron temperature	5 eV
IMF magnitude	7 nT
Larmor radius	5,53 m
Electric potential facing the Sun	+10 V
Electric potential in the shadow	-20 V
Solar radiative power	1400 Wm^{-2}
Total ionizing dose (SPENVIS)	30 Krad (Si)

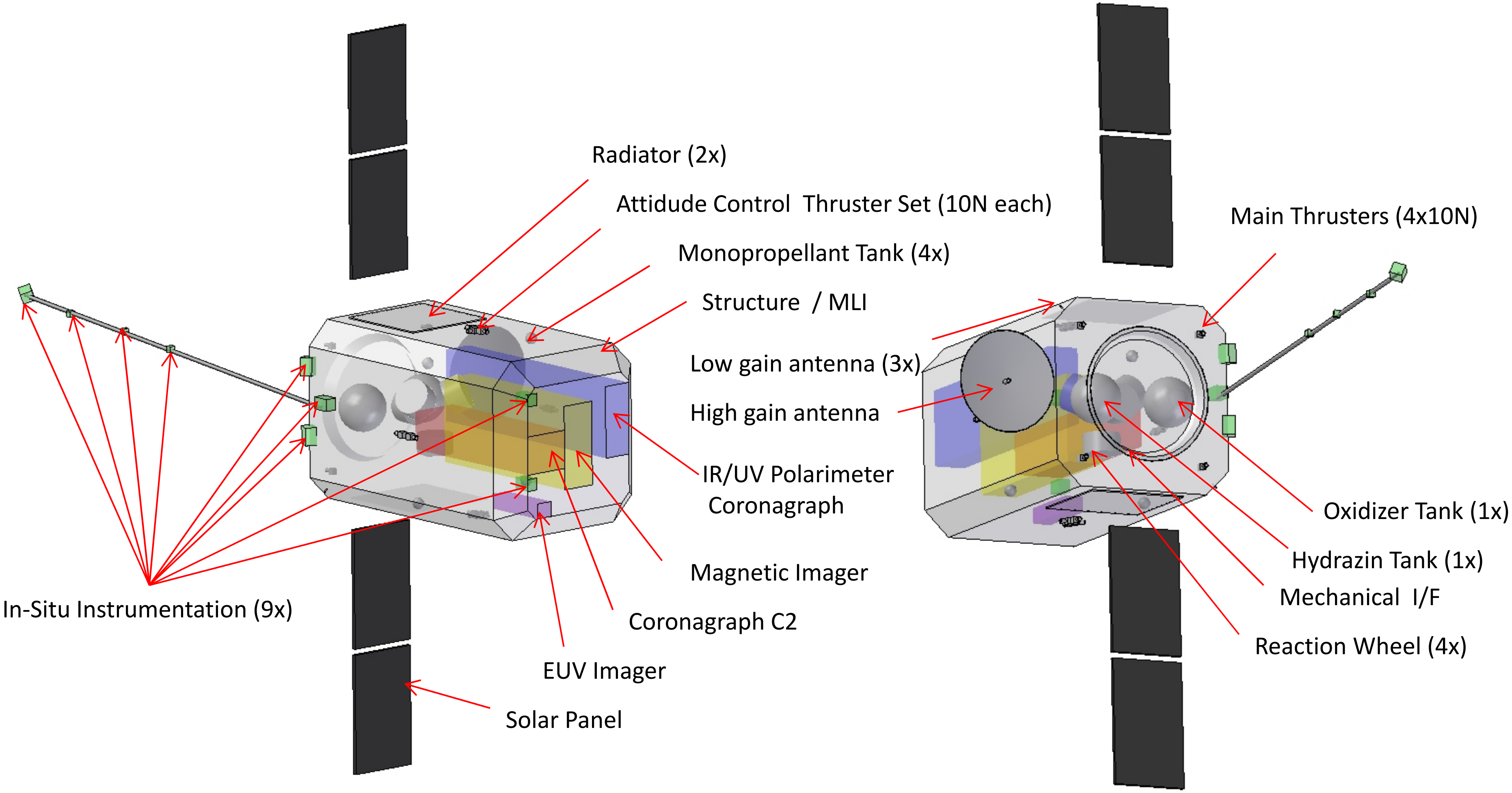
Spacecraft Architecture Design



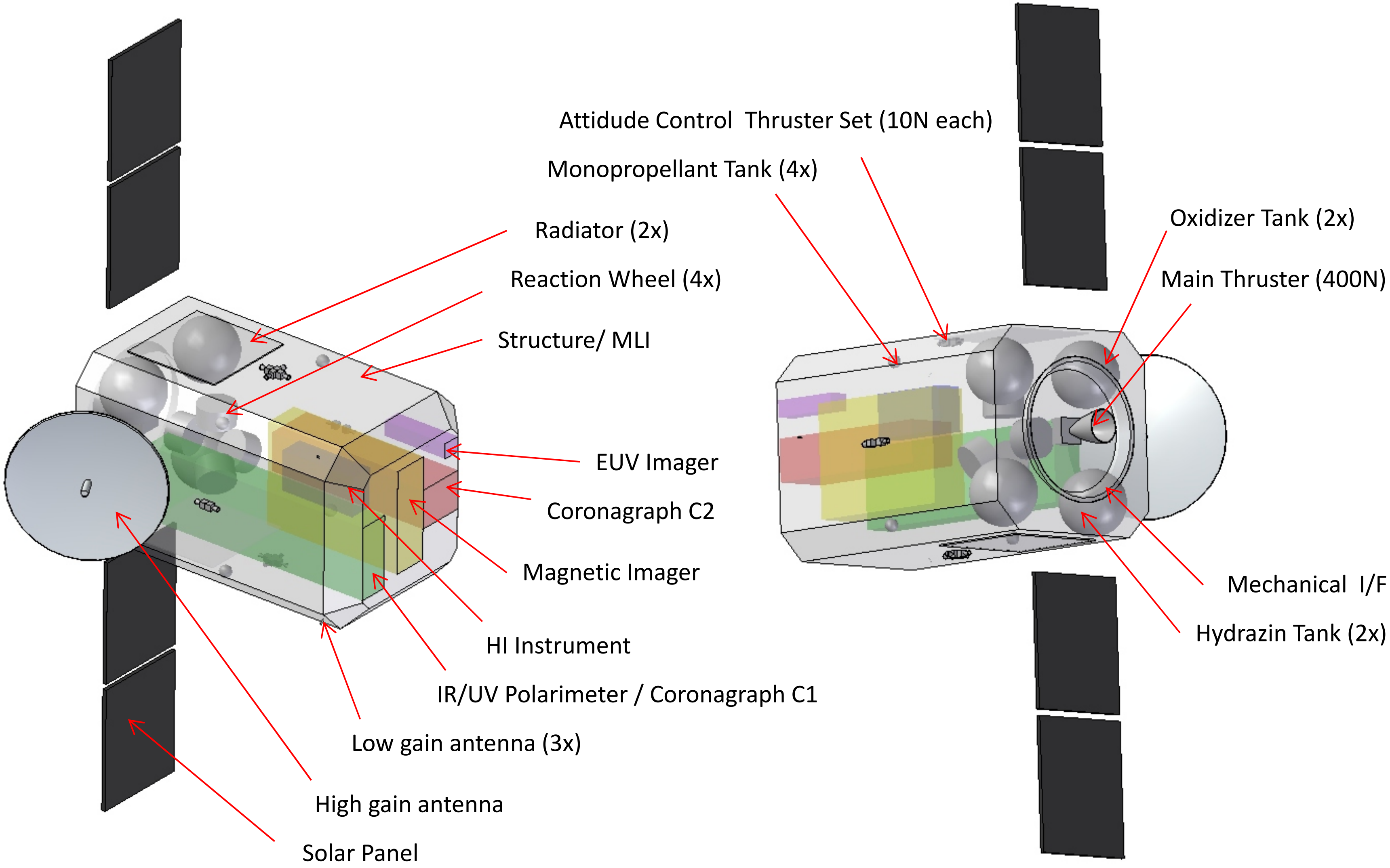
Subsystems

- Power
- AOCS
- TT&C
- Propulsion
- Thermal
- Structure
- OBDH

SCE - Spacecraft Overview



SC80 - Spacecraft Overview



Subsystems

Attitude Control

Attitude Control System (AOCS) requirements:

- To provide a resolution of 0.5’’ over 4 s exposure time (MMI).
- To provide a resolution of 3’’ over a 20 s exposure time (IR-EUV Polarimeter).

Attitude Control

ACTUATION DEVICES

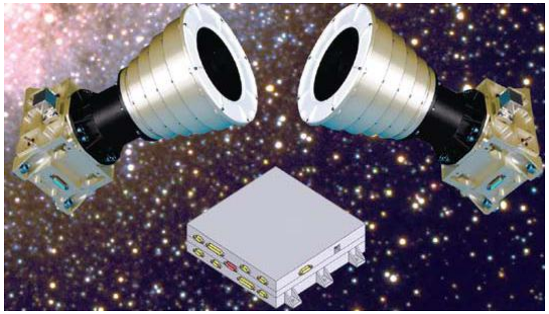
Components	**Rationale**
Reaction wheels	Pitch and yaw axis torqueing Roll passive stability during Science Mode
Hydrazine thrusters	• Pitch, yaw, roll axis torqueing during Safe Mode • Angular momentum dissipation

SENSOR DEVICES

Components	**Rationale**
Sun sensors	• Initial attitude acquisition from unknown orientation • Coarse attitude during pre-Science Mode
Star trackers	Fine attitude during Science Mode
Gyroscopes	Rate error calculations for data processing

Attitude Control - Sensors

Star trackers:	Hast
Number:	1
Provider:	Ball Aerospace & Technologies
Accuracy:	**0.1'' (1σ)**
Legacy:	Chandra Observatory



[http://www.ballaerospace.com/]

Sun sensors:	S3 Smart Sun Sensor
Number:	2
Provider:	SELEX Galileo
Accuracy:	**<0.02 ° (2σ)**
Legacy:	Columbus module (ISS) Lisa Pathfinder

[http://www.selex-es.com/]

Gyroscopes:	Astrix 200
Number:	1
Provider:	Astrium
Bias Drift:	**0.0005''/s**
Legacy:	Pleiades satellites

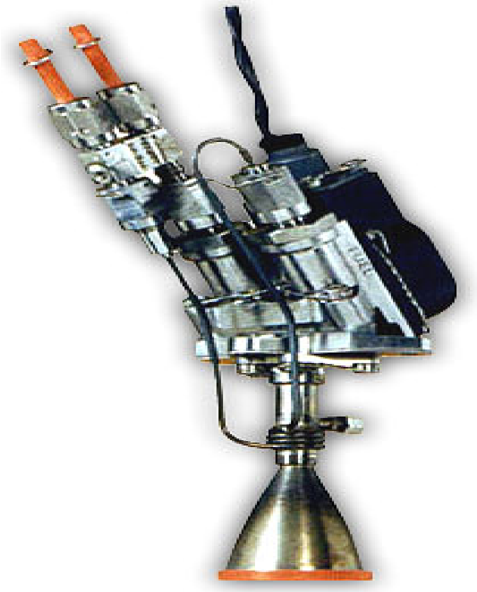
[http://www.astrium.eads.net/]

Attitude Control- Actuators

Reaction wheels	RSI 68
Number	4
Provider	Rockwell Collins
Legacy	Venus Express, Mars Express

[http://www.rockwellcollins.com/]

Thrusters	10 N bi-propellant
Number	16
Provider	Astrium
Legacy	Many missions



[http://www.astrium.eads.net/]

Fuel Usage for AOCS

- **External perturbations (torque)**
- **Solar radiation and Magnetic field**

Assumptions	
Magnetic Field	1-1000 nT
Dipolar Momentum of Space Craft	1 A·m^2
Solar Constant	1400 W/m^2
Reflectivity	0.6
C_m-C_p displacement	0.5m
Margin	50%
Total Torque	31.7 µNm

Thrusters Torque: 7.5 Nm

Fuel Usage: $\frac{T_p}{T_t \cdot F} \cdot n$

T_p: Torque of portubation
T_t: Torque of Thrusters
F: Fluxrate
n: Seconds per year

→ **Total Fuel (+100% margin): 1.12 kg/year**

Attitude control requirements

	SCE	SC80
Mass [kg]	1100	1700
I_x [kgm^2]	532	757
I_z [kgm^2]	900	1324
I_y [kgm^2]	780	1204

$$t=\sqrt{\frac{\theta_{req}}{\alpha}}$$

$$\alpha_i=\frac{T_{pert}}{I_i}$$

θ_{req} = 0.5'' → 10 s
θ_{req} = 3'' → 40 s

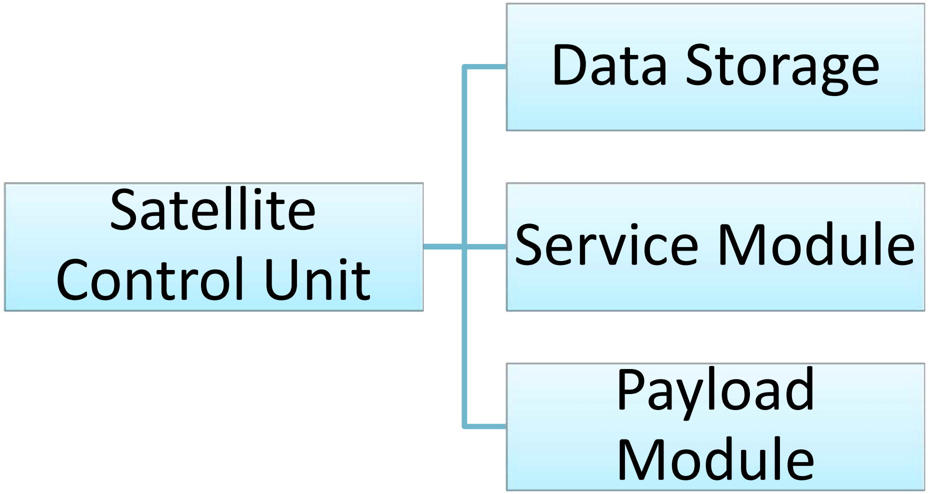
Even with strong perturbations we are able to provide the required accuracy

Control Subsystem

The control subsystem requirements:

The control subsystem needs to provide a reliable, fault-tolerant possibility of operating all subsystems as well as the whole spacecraft.

Control Subsystem



Satellite Control Unit

Data Storage

Service Module

Payload Module

- SCU:
  - Failure Detection and Recovery
  - Command Execution
  - Data Handling
- Service Module (SVM):
  - Operational Control
- Payload Module (PLM):
  - Payload Control
  - Data Processing

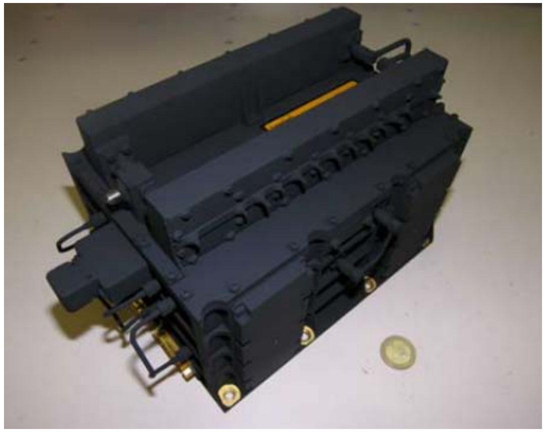
- On-board Communication:
  - SVM: CAN-Bus
  - PLM: SpaceWire

Communication Subsystem

Communication subsystem requirement:

The communication subsystem needs to be capable of transmitting 43.2 GB (SCE)/910 MB (SC80) per day along transmission path with a distance of $1.5 \cdot 10^6$ km (SCE)/$193 \cdot 10^6$ km(SC80).

Communication Subsystem

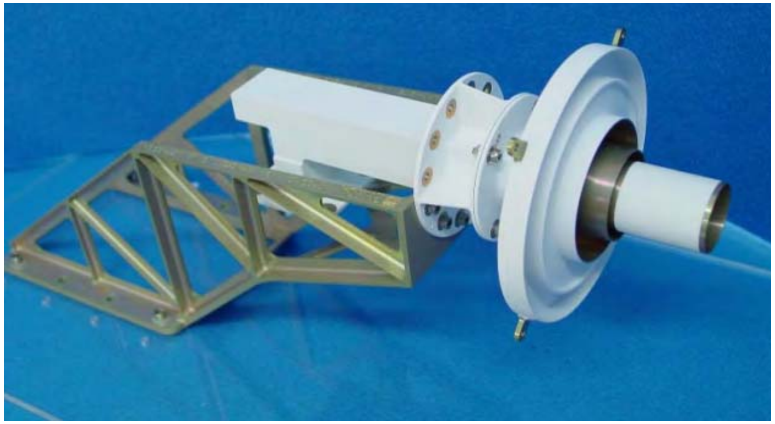


X/X Deep Space Transponder (Thales)

Steerable X-Band HG Antenna (Thales)

	SCE	**SC80**
TWTA – RF Power	15 W	160 W
HGA Diameter	0.5 m	2.3 m
LGA Gain	4.5 dBi	4.5 dBi

TWT Amplifier 160W (Thales)

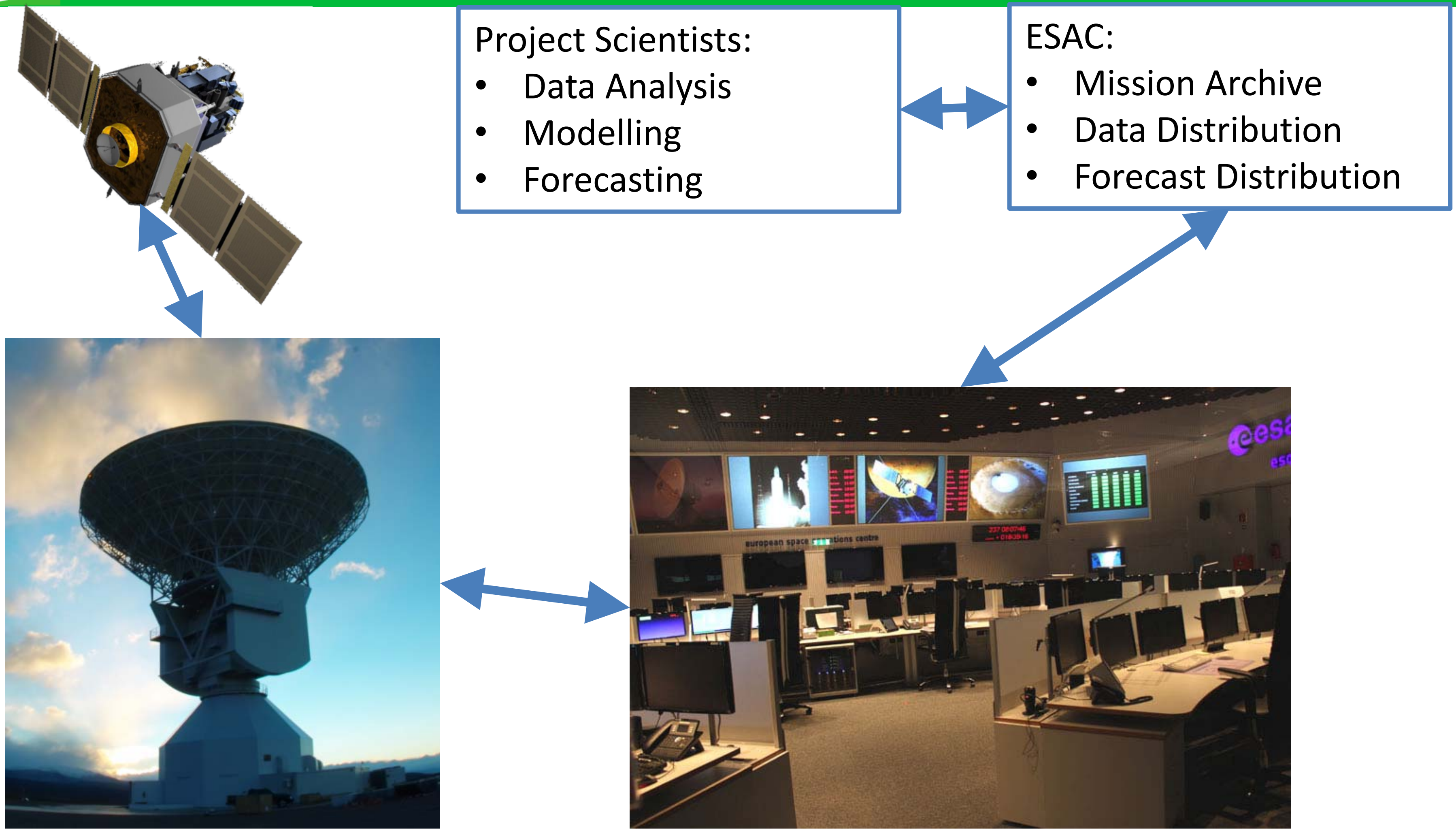


LGA X-Band (MCI)

Communication Subsystem – Link Budget

Link Budget:	**SCE – HGA**	**SCE – LGA**	**SC80 – HGA**	**SC80 – LGA**
Frequency in GHz	8.5	8.5	8.5	8.5
Distance	0.01 AU	0.01 AU	1.29 AU	1.29 AU
Bit Rate in kbps	10500	50	201	0.2
Transmission Power in W	15	15	160	160
Antenna Diameter in m (Satellite)	0.5	0.5	2.3	2.3
Antenna Diameter in m (Ground Station)	15	15	15	15
Coding Gain in dB (CR = ½)	6	6	6	6
Modulation	BPSK	BPSK	BPSK	BPSK
Link Margin	**4.6**	**3.9**	**3.2**	**3.4**

Operations & Ground Segment



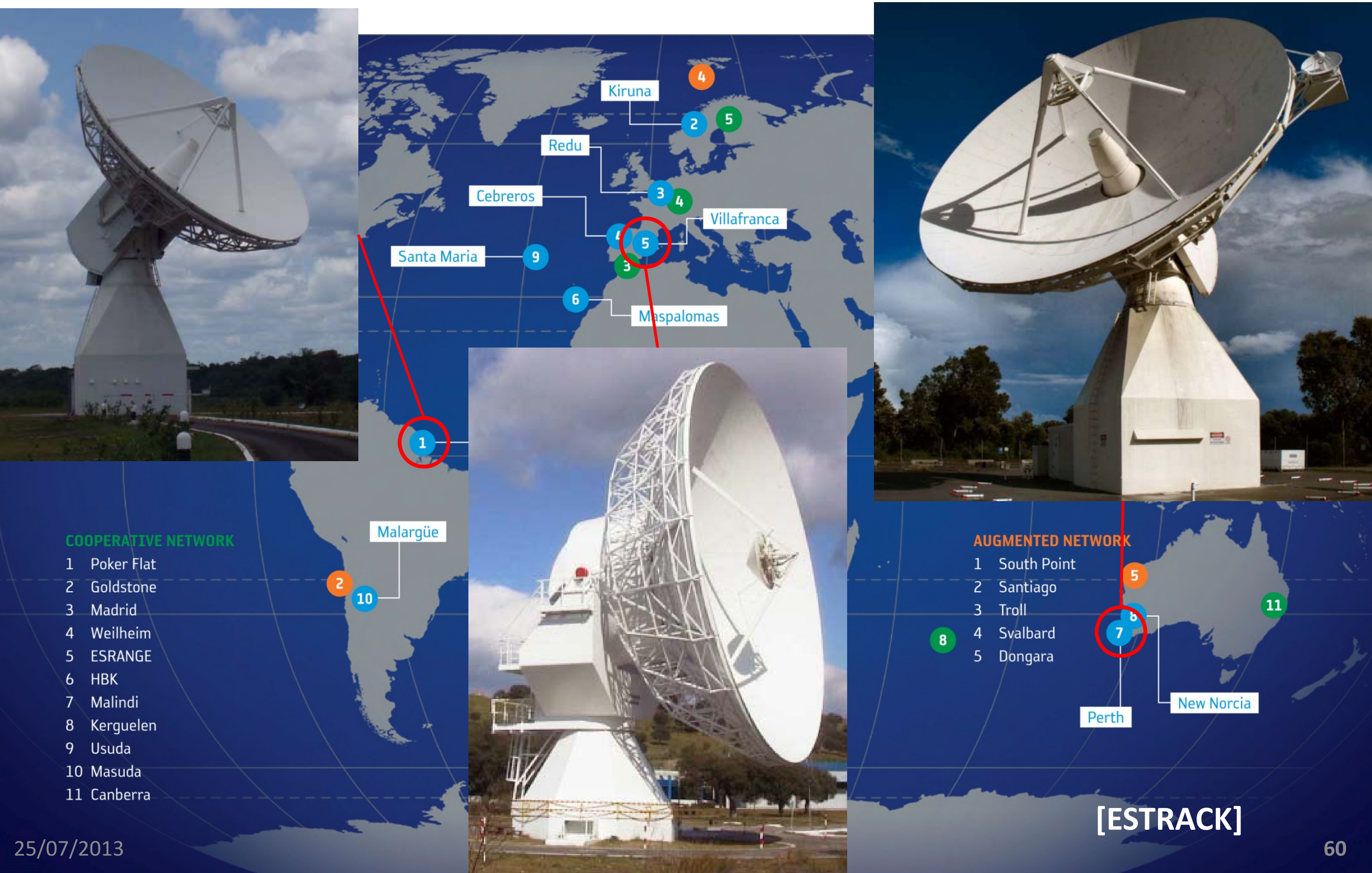
Project Scientists:
- Data Analysis
- Modelling
- Forecasting

ESAC:
- Mission Archive
- Data Distribution
- Forecast Distribution

ESTRACK
Tracking Stations –
Communication

Mission Operations Centre &
Science Operations Centre

Ground Stations



COOPERATIVE NETWORK
1 Poker Flat
2 Goldstone
3 Madrid
4 Weilheim
5 ESRANGE
6 HBK
7 Malindi
8 Kerguelen
9 Usuda
10 Masuda
11 Canberra

AUGMENTED NETWORK
1 South Point
2 Santiago
3 Troll
4 Svalbard
5 Dongara

[ESTRACK]

Thermal

Thermal requirement:

The thermal subsystem shall keep the temperature of each spacecraft at 20 degrees during operations.

Cooling requirement:

Only the detectors of the imaging devices need passive cooling.

Thermal

One side always sun-facing and radiators placed on sides not facing the sun!

Hot case

- Constant case during both s/c final orbits
- 1 AU from the sun
- Negligible radiation from the Earth
- Required radiator area is 1.6m^2

Cold case

- SCE cold case is during its transfer to L1
- SC80 cold case is during its transfer orbit at 1.15 AU from the sun
- SC80 requires an extra 110 W heating power during this cold case

Required heating power taken from TT&C during transfer.

Power subsystem requirements

- The power subsystem shall supply continuous electrical power to spacecraft for peak loads during mission life
- The spacecraft shall survive 12h without external power
- The power subsystem shall support 150 % of nominal required power at end of life
- The power subsystem shall support energy for a deployment time of 2h

Solar Array Dimensions

	Panel Area (Ssa) [m²]	Solar Flux (1 AU) [W/m²]	Cell Efficiency (20-25%)	Coverage ratio (0.9)	Massic efficiency of solar array	Power generated	Mass of solar array [kg]
SCE	2.2	1400	0.25	0.9	30	671.5	22.4
SC80	2.7	1350	0.25	0.9	30	819.2	27.3
Safety Factor	1.5						

Power Storage

	Energy required at spacecraft level [Wh]	Massic energy [Wh/kg]	Depth of discharge [%]	Mass of the batteries [kg]
SCE rechargeable	2726.4	150	0.5	36.352
SC80 rechargeable	3096	150	0.5	41.28

→ Survival Time without external energy: 12h

	Energy required at spacecraft level [Wh]	Massic energy [Wh/kg]	Depth of discharge [%]	Mass of the batteries [kg]
SCE primary	454.4	400	1	1.136
SC80 primary	1076	400	1	2.69

→Deployment time: 2h

$$M_b = \frac{E}{M_e \cdot D}$$

M_b: Mass of batteries [kg]
E: Energy required at spacecraft level
M_e: Massic energy
D: Depth of discharge

Propulsion Systems- Main Engine (SC80)

MMH+N_2O_4 bi-propellant chemical engine

We require a ΔV=1.02 km/s for SC80 orbit injection

We will use one Astrium Apogee Model S400-15 engine

400N

On SC80

- Impressive heritage (40 years of use) – From Galileo to Venus Express → high TRL
- Monomethylhydrazine fuel and pure Di-Nitrogen-Tetroxide N_2O_4 oxidizer
- Supplied as a completely assembled module with supporting structure and thermal shield

Thrust (Nominal)	420 N
Thrust Range	340-440 N
Specific Impulse	318 s
Mixture ratio	1.65
Power	35 W
Coil Voltage	27 V
Single-burn life	1.1 hours
Total-burn life	8.3 hours
Total Engine Mass	3.6 Kg

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Propulsion Systems – Attitude Engines (SCE & SC80)

MMH+N_2O_4 bi-propellant chemical engines

We require a ΔV= 65m/s for orbit injection (SCE) and 10m/s/year for attitude control (SC80 and SCE)

We will use a number of Astrium Model S10-21 engines

10N

On SCE & S80

- 3000+ units have been used in space missions to date → high TRL
- Monomethylhydrazine fuel and pure Di-Nitrogen-Tetroxide N_2O_4 oxidizer
- designed for both long term steady state and pulse mode operation
- single seat valve → 50% reduced mass

Thrust (Nominal)	10 N
Thrust Range	6-10 N
Specific Impulse	291 s
Mixture ratio	1.65
Cycle life	1 million
Single-burn life	15 hours
Total-burn life	70 hours
Total Engine Mass	0.35 Kg

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Propulsion Systems- Fuel and Oxidiser Storage

SC80

350 Kg MMH

Astrium OST 01/X
Shape: Elliptical
Tank mass: 16kg
Diameter: 600mm
Height: 680mm

2x

210Kg N_2O_4

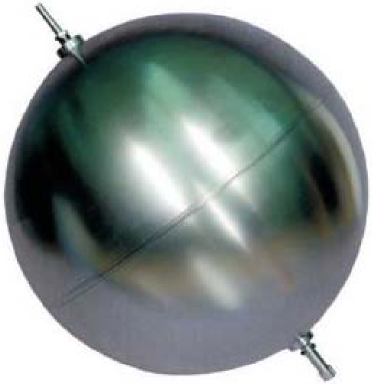
Astrium OST 01/X
Shape: Elliptical
Tank mass: 16kg
Diameter: 600mm
Height: 800mm

SE

60Kg MMH

Astrium OST 31/0
Shape: Spherical
Tank mass: 6.4kg
Diameter: 586mm

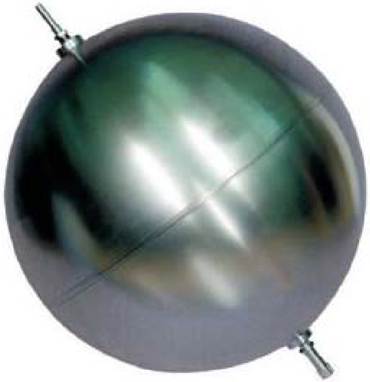
2x



35Kg N_2O_4

Astrium OST 01/X
Shape: Spherical
Tank mass: 6.4kg
Diameter: 586mm

1x



Budgets

Mass Budget - SCE

Element	Mass [kg]	Technology Maturity Margin	Comments
Payload (M_{PL})	**206.7**	**20%**	**15% to 50% of M_{dry}**
Propulsion ($M_{propulsion}$)	14.4	5%	
Attitude Control (M_{gnc})	90.3	5%	
Communications (M_{com})	52.5	5%	
Command & Data Handling (M_{codh})	22.0	10%	
Thermal (M_{th})	41.7	10%	2% to 12% of M_{dry}
Power (M_{ep})	62.2	5%	
Structure & Mechanisms (M_{sam})	125.1	10%	8% to 12% of M_{inj} or 15% to 25% of M_{dry}
Spacecraft Subsystems (M_{SS})	**400.0**		**Sum of subsystems mass**
System margin (M_{mar})	151.7	25%	Including 5 % harness
Spacecraft Dry Mass (M_{dry})	**758.4**		**$M_{dry} = M_{PL} + M_{SS} + M_{mar}$**
Propellant (M_{prop})	86.1	5%	
Loaded Mass (M_{loaded})	**844.5**		**$M_{loaded} = M_{dry} + M_{\_prop}$**
Kick Stage (M_{kick})	0.0		
Injected Mass (M_{inj})	844.5		$M_{inj} = M_{loaded} + M_{kick}$
Adapter ($M_{adapeter}$)	150.0		
Launch Mass ($M_{boosted}$)	**994.5**		**$M_{boosted} = M_{inj} + M_{adapter}$**
Launcher potential mass	2150.0		
Launch margin	1155.5		

Mass Budget – SC80

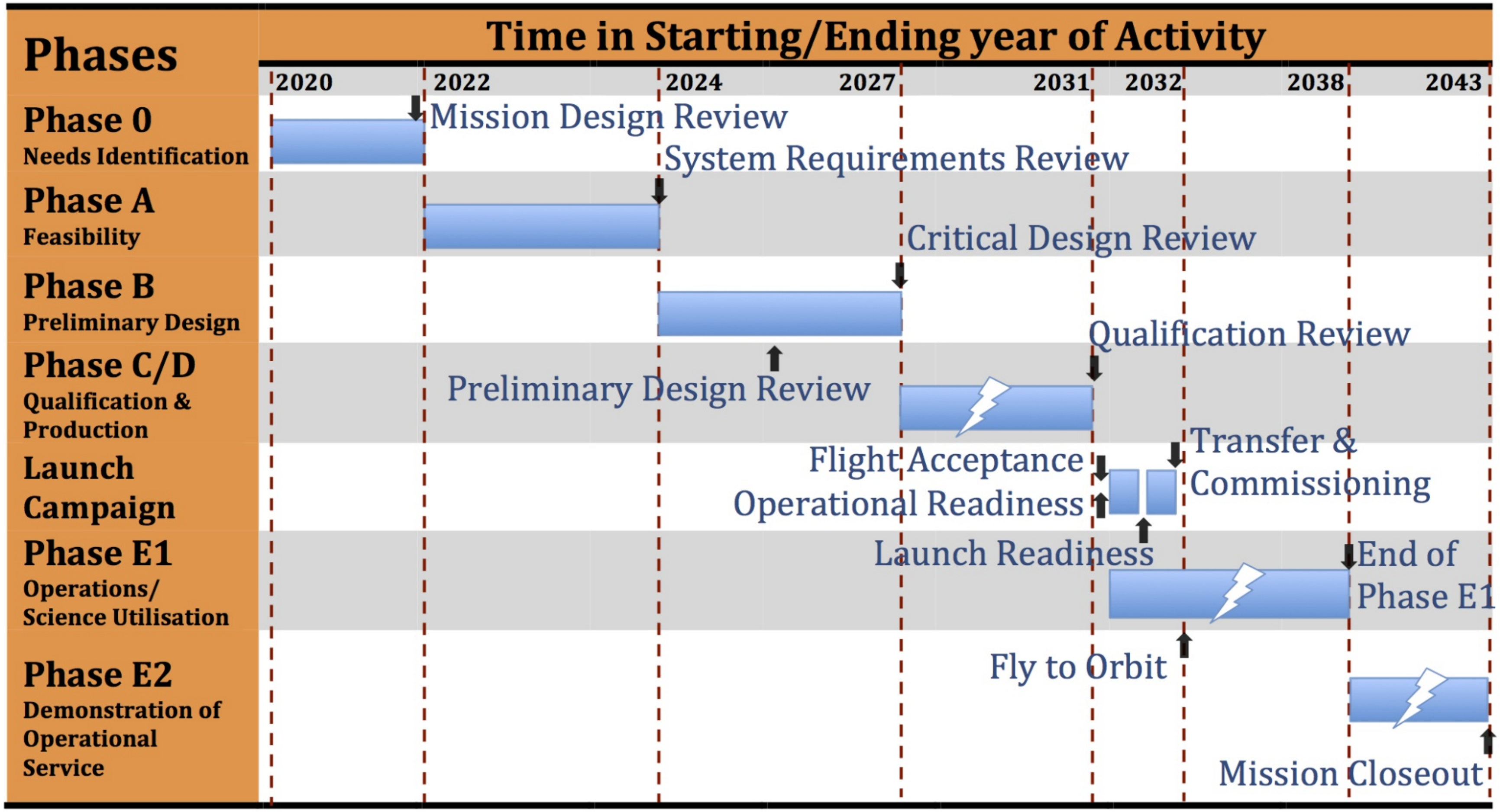
Element	Mass [kg]	Technology Maturity Margin	Comments
Payload (M_{PL})	**196.8**	**20%**	**15% to 50% of M_{dry}**
Propulsion ($M_{propulsion}$)	110.3	5%	
Attitude Control (M_{gnc})	90.3	5%	
Communications (M_{com})	88.0	10%	
Command & Data Handling (M_{codh})	33.0	10%	
Thermal (M_{th})	58.2	10%	2% to 12% of M_{dry}
Power (M_{ep})	130.5	5%	
Structure & Mechanisms (M_{sam})	174.7	10%	8% to 12% of M_{inj} or 15% to 25% of M_{dry}
Spacecraft Subsystems (M_{SS})	**650.0**		**Sum of subsystems mass**
System margin (M_{mar})	211.7	25%	Including 5 % harness
Spacecraft Dry Mass (M_{dry})	**1058.5**		**$M_{dry} = M_{PL} + M_{SS} + M_{mar}$**
Propellant (M_{prop})	565.6	5%	
Loaded Mass (M_{loaded})	**1624.1**		**$M_{loaded} = M_{dry} + M\_{prop}$**
Kick Stage (M_{kick})	0.0		
Injected Mass (M_{inj})	1624.1		$M_{inj} = M_{loaded} + M_{kick}$
Adapter ($M_{adapeter}$)	150.0		
Launch Mass ($M_{boosted}$)	**1774.1**		**$M_{boosted} = M_{inj} + M_{adapter}$**
Launcher potential mass	2100.0		
Launch margin	325.9		

Power Budgets

Subsystem	Nominal [W]	% ON time	% of Total Consumption	SCE
Payload	226	1	0.52	
Propulsion	21	0.1	0.05	
Attidude Control	42	1	0.10	
Communications	60	1	0.14	
Command and Data Handling	21	1	0.05	
Thermal	21	1	0.05	
Power	63	1	0.14	
Total	436		1.00	

Subsystem	Nominal [W]	% ON time	% of Total Consumption	SC80
Payload	101	1	0.18	
Propulsion	24	0.1	0.04	
Attidude Control	47	1	0.09	
Communications	350	0.8	0.64	
Command and Data Handling	24	1	0.04	
Thermal	24	1	0.04	
Power	71	1	0.13	
Total	549		1.00	

Complete Mission Profile



Phases

Time in Starting/Ending year of Activity

2020 2022 2024 2027 2031 2032 2038 2043

Phase 0
Needs Identification

Phase A
Feasibility

Phase B
Preliminary Design

Phase C/D
Qualification & Production

Launch Campaign

Phase E1
Operations/ Science Utilisation

Phase E2
Demonstration of Operational Service

Mission Design Review

System Requirements Review

Critical Design Review

Qualification Review

Preliminary Design Review

Flight Acceptance

Operational Readiness

Transfer & Commissioning

Launch Readiness

End of Phase E1

Fly to Orbit

Mission Closeout

ROM Cost Estimation

Activity	Cost
Launchers	€ 120 million
SCE platform	€ 250 million
SC80 platform	€ 200 million
SCE operations	€ 40 million
SC80 operations	€ 50 million
Ground Segment	€ 100 million
ESA cost	**€ 760 million**
Payload instruments and scientific data processing	€ 420 million
Total cost	**€ 1180 million**
Agency/management (included in the above figure)	€ 130 million

- **Mission Class**

  One L-class mission

- **Cost reduction**

  High S/C similarities, platform heritage, shared launch for SCE, de-scoping

- **Mission extension**

  6 year extension with more operational Space Weather focus will cost an extra € 100 million

Critical Risks

Risk	Likelihood	Severity	Category	Mitigation
IR Polarimeter and Coronagraph not fully developed in time for launch	Low, B	Major, 3	B3	Pre-developement of instruments
Multichannel Magnetic Imager not fully developed in time for launch	Low, B	Major, 3	B3	
Degradation of instruments due to constant solar exposure	Low, B	Major, 3	B3	Shorter planned mission time
Loss of SC80 spacecraft	Minimum, A	Critical, 4	A4	SCE becomes an updated ACE mission
Loss of attitude control during safe mode	Medium, C	Minimum, 1	C1	Special safe-mode programming
Loss of SCE spacecraft	Minimum, A	Major, 3	A3	Investigate alternative satellite measurements at L1

Conclusion

- An early warning system that can evaluate the likelihood of solar events would give people time to prepare!

- Some of the economical sectors that would benefit from this early warning system include:
  - the telecommunications networks
  - the Galileo/GPS positioning systems
  - the electric generation industry

- All these sectors of the economy directly affect the lives of all the people around the world.

THE

PAC2MAN

Photospheric And Chromospheric and Coronal Magnetic field ANalyser

MISSION

will be an important
part of the solution

THE END

Thank you for listening!

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Instruments Overview

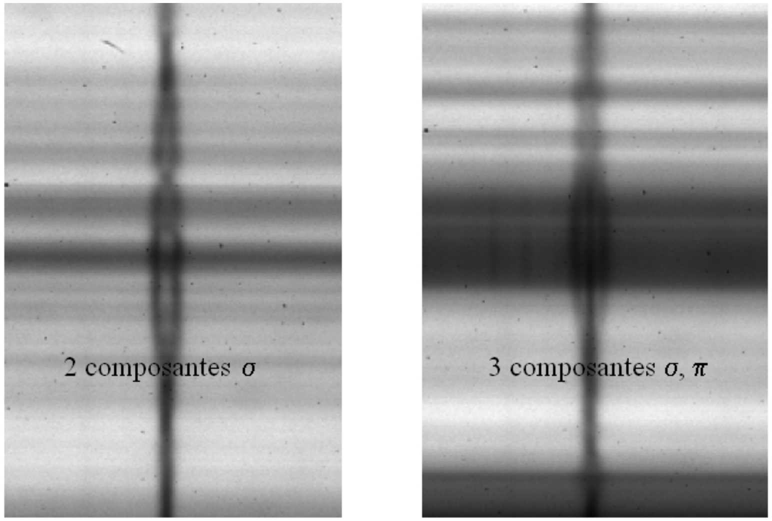
	SCE	SC80	Wavelength	FOV [Rs]	Detector Size in Pixel	Pixel Size [arcsec]	Mass [kg]	Size [cm]	Power [W]	Data Volume per day	Operation Temperature [K]	Heritage
IR/UV Polarimeter & C1	x	x	UV: HI Lyα line at 121.6 nm IR lines: FeXIII 1074.7 & 1079.8 nm , He I 1083.0 nm Visible Light: 560 nm	1.1 – 2	1024 x 1024	5	50	200 x 60 x 25	80	SCE: 4.7 GByte SC80: 238 Mbyte	Detector: 223 IR-Polarimeter: 303	
MMI – Multichannel Magnetic Imager (SCE)	x		Fe 630.15nm Fe 630.25nm Na 589.59nm Na 588.99nm	1.07	2x 4096 x 4096	0.5	60	150 x 70 x 30	95	37.8 Gbyte	CCD: 233 Tunable Optics: 300	
Magnetic Imager (SC80)		x	Fe 617.3nm	1.07	4096 x 4096	0.5	73	120 x 85 x 30	95	645 Mbyte	CCD: 233 Tunable Optics: 300	SDO/HMI
Coronagraph C2	x	x	400-850nm	2 – 30	1024 x 1024	56	15	140 x 40 x 32	5	3.84 Mbyte	193	SOHO LASCO C3
HI		x	400-1000nm	30 – 216	1024 x 1024	148	15	65 x 33 x 20	10	0.42 MByte	193	STEREO SECCHI HI
EUV Imager	x	x	17.4nm	< 1.6	1024 x 1024	3.2	11	56 x 15 x 12.5	5	21.6 MByte	233-333	PROBA 2/SWAP

	Subinstruments	FOV	Mass [kg]	Size [cm]	Power [W]	Data Volume per day	Operation Temperatur [K]	Heritage
Low Energy Solar Wind Sensors (LEWIS)	EAS, PAS, HIS	EAS: 360° PAS: 65°A, 45° E HIS:96° A 34° E	18.65	EAS: 11.6 x dia 13.6 PAS: 30 x 20 x 20	15.6	32.7 MByte	248 - 338	Ulysses, ACE, STEREO, Solar Orbiter
High Energy Particle Sensors (HEPS)	EPT, SIS, LET, HET, STEIN, CDPU/LVPS	EPT: 30° SIS: 22° LET: 40° HET: 50° STEIN: 60° x 70°	15.68	EPT: 11 x 7 x 12 SIS: 35 x 13 x 11 LET: 22 x 15 x 11 HET: 13.6 x 17 x 16.2 STEIN: 10 x 13 x 13 CDPU/LVPS: 15 x 15 x 10	29.95	10.5 MByte (79.8 MByte in burst mode)	233 - 333	STEREO, SOHO, ACE, Solar Orbiter
Fluxgate Magnetometer (FGM)		N/A	1.94	Sensor: 9.75 x 4.9 x 6.7 Electronic: 15.9 x 16.2 x 9.8	4.39	147.7 MByte	233 - 333	VEX, THEMIS, Rosette Lander, Double Star, Solar Orbiter

Zeeman effect (photosphere)

Magnetic field → splitting of spectral lines (3 components with different polarizations)

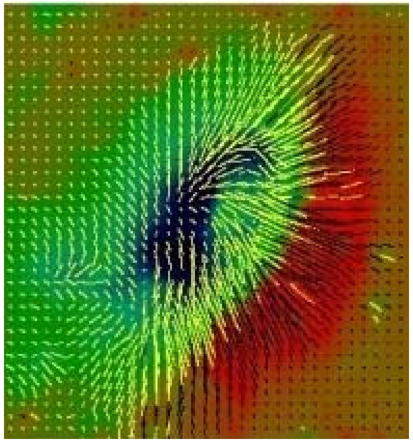
Zeeman effet in the FeI 6173 line in a sunspot



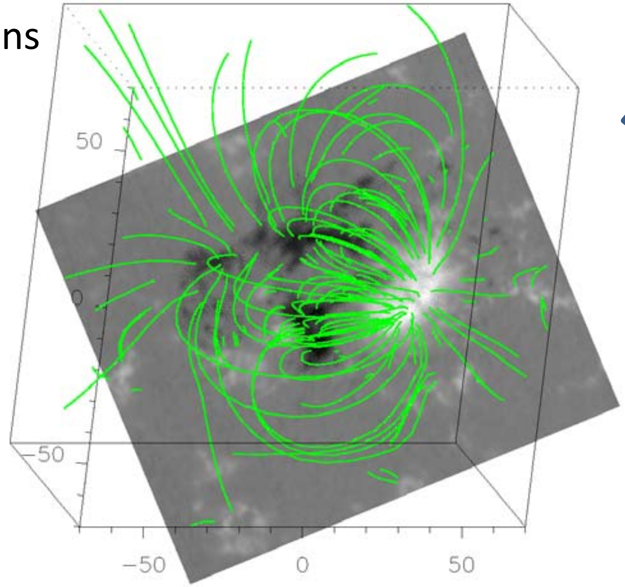
Longitudinal magnetic field

If transverse magnetic field, the 3 components have only a linear polarization

Magnetic field vector in a sunspot

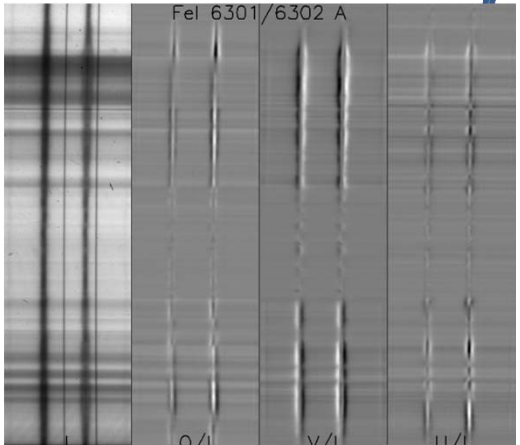


Extrapolation of the **coronal** magnetic field using photometric measurement as boundary conditions

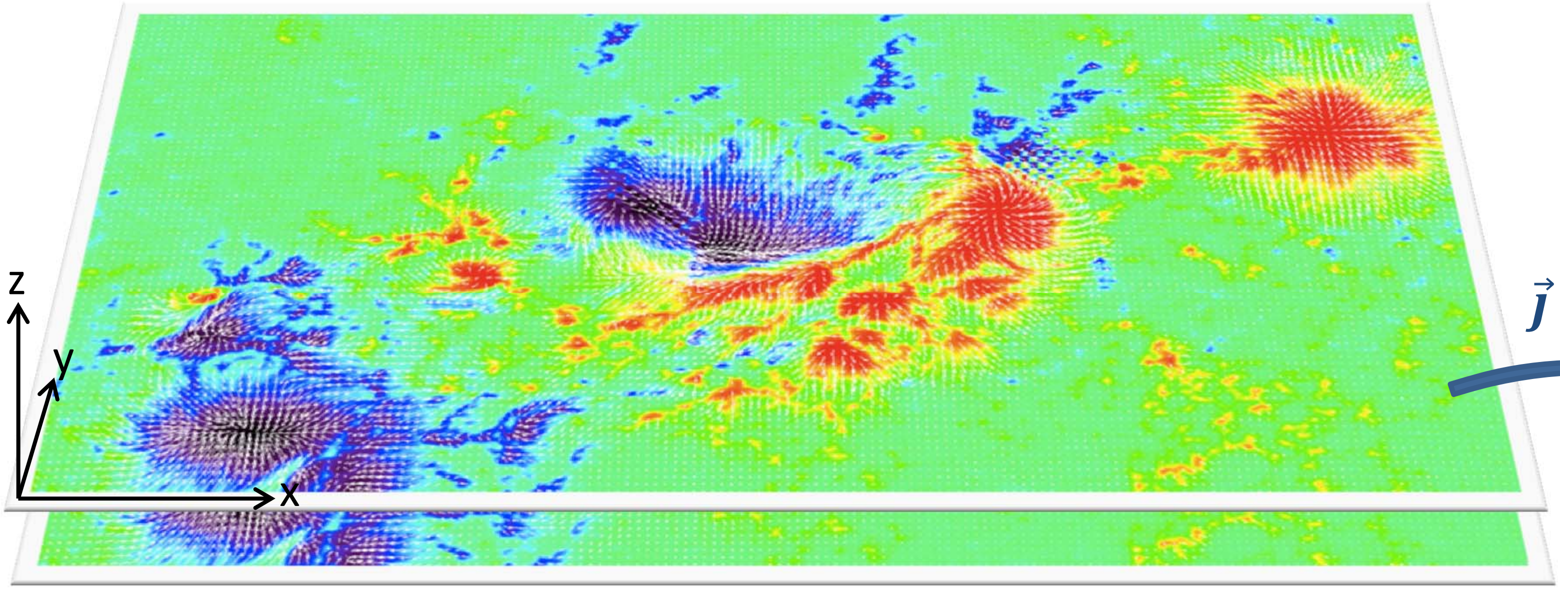


Spectropolarimetric measurements

Stokes parameters profiles in two spectral lines

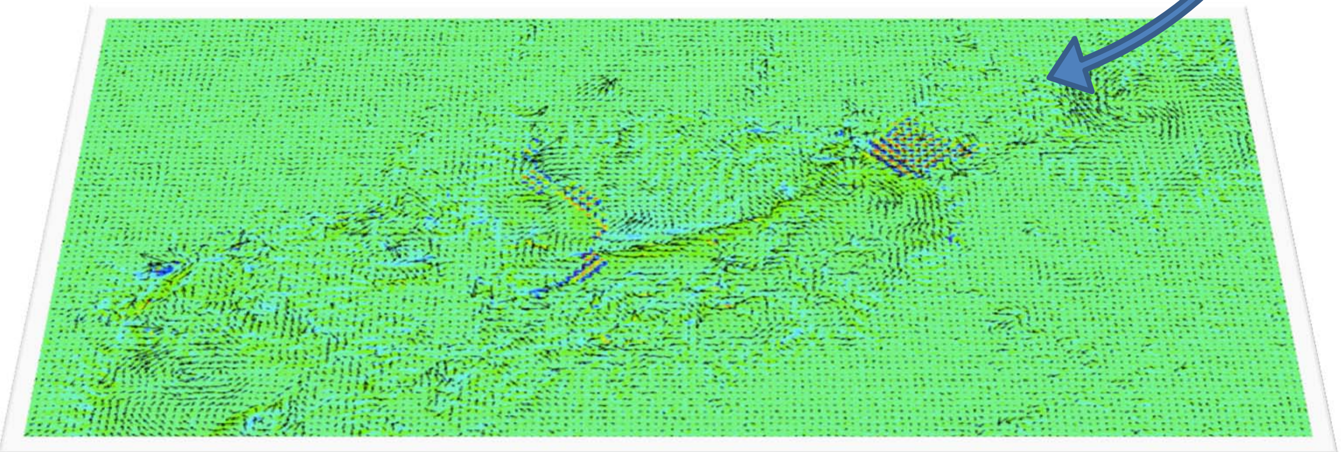


Vector magnetic field and vector current density in the photosphere with Hinode/SOT



$$\vec{j} = \frac{1}{\mu_0} rot(\overrightarrow{B})$$

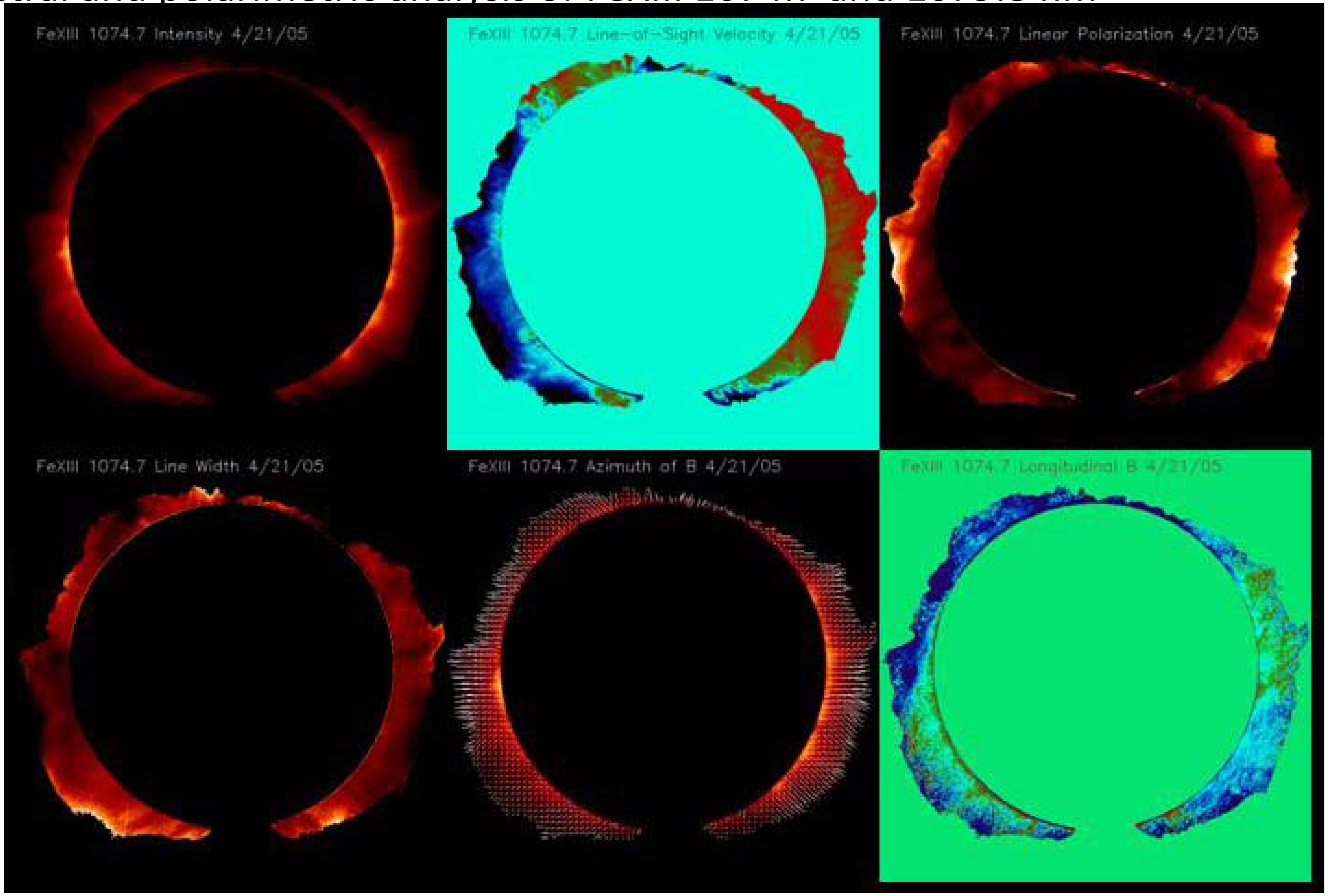
Observation in two close spectral lines ➔ Current density vector calculation !



Zeeman effect in the corona

- Difficult, because large linewidth due to high temperature!
- ***If magnetic field strong enough***:

  spectral and polarimetric analysis of FeXIII 1074.7 and 1079.8 nm



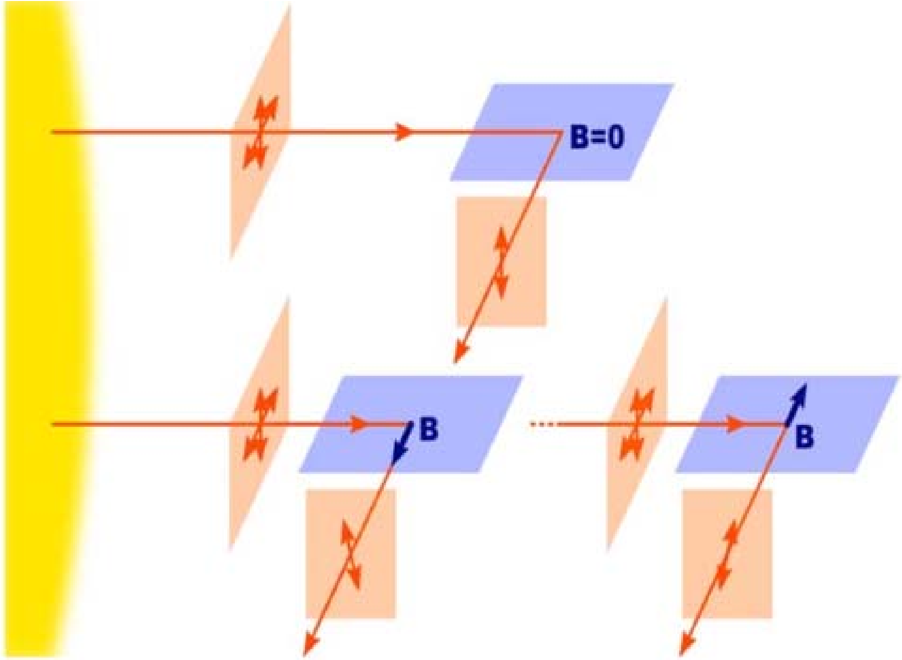
Clockwise from top left: the intensity, velocity, degree of linear polarization, LOS magnetic field, field azimuth and line-width as observed by the CoMP instrument on 4/21/05.

Hanle Effect (Corona, off-limb)

Light scattering → Linear polarization at 90°
Magnetic field → « de-polarization »

- ***Weak magnetic field in the coronan, off-limb***:

Polarimetric measurement of the scattered light (in the Lyman alpha line)



To measure the vector magnetic field:
Observation in 2 lines of different sensibility;
e.g. HI Lyman alpha and He I D3

(Bommier et al. 1994)

Illustration of the modification of the polarization degree and polarization plance of a resonantly scattered coronal line by the presence of a horizontal magnetic field (adapted from Trujillo Bueno et al., 2005)

Infrared Magnetic Imager

- Access to strong fields > 40 G in the corona (off-limb)
- Measurement of the full Stokes vector
- Need polarimetric accuracy of 10^{-4}
- FOV : 1.1 – 1.5 solar radius
- 2 min cadence
- Time exposure : 5 sec
- Lines: FeXIII 1074.7 and 1079.8 nm

and He I 1083.0 nm

- 60 kg
- 50 W
- 180x50x25 cm^3

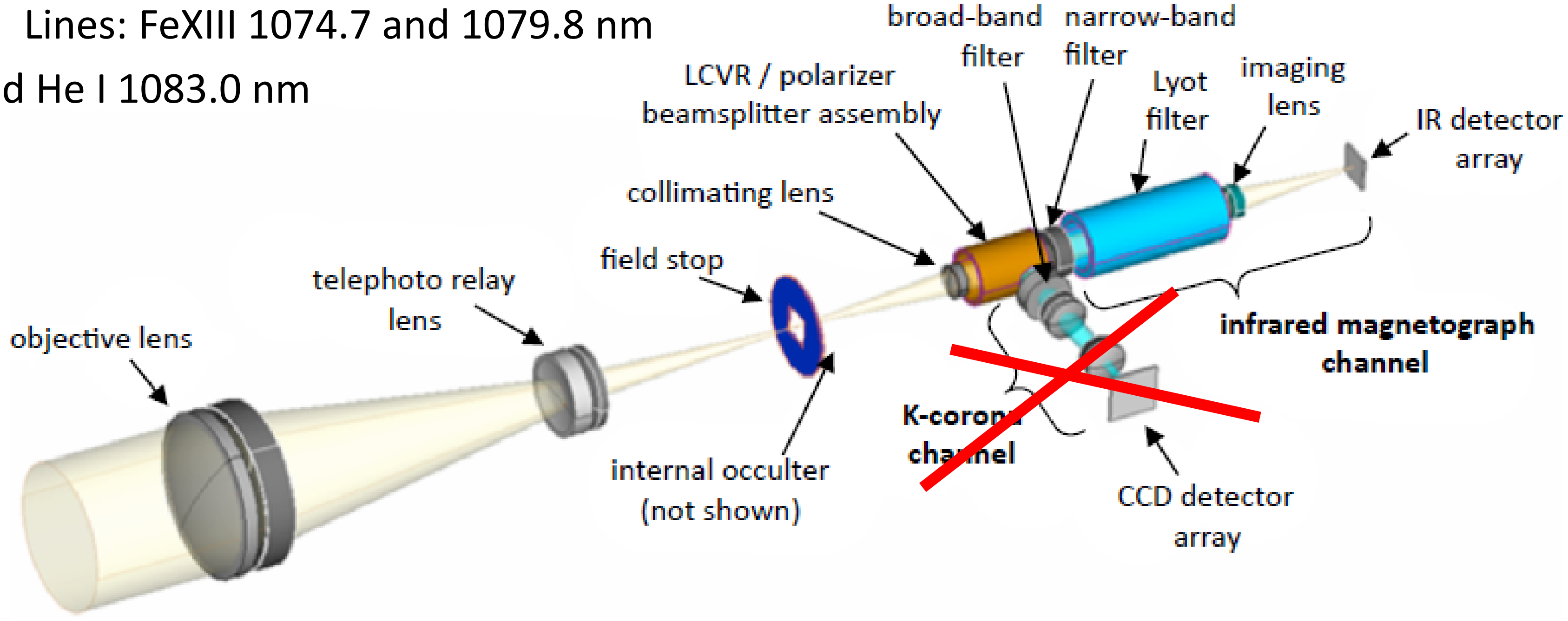


Fig. 14 Schematic optical layout of the Visible light and IR Coronagraph (VIRCOR).

Peter et al., 2011

UV Magnetic Imager + Visible light

- Access to weak fields in the corona (off-limb)
- Measurement of the full Stokes vector
- Need SNR 100-200
- FOV : 1.1 – 3.0 solar radius
- 5 min cadence
- Time exposure: 60-120 sec
- HI Lyman alpha line at 121.6 nm
- Visible Light 560 nm

- 26 kg
- 48 W
- 75x55x30 cm^3

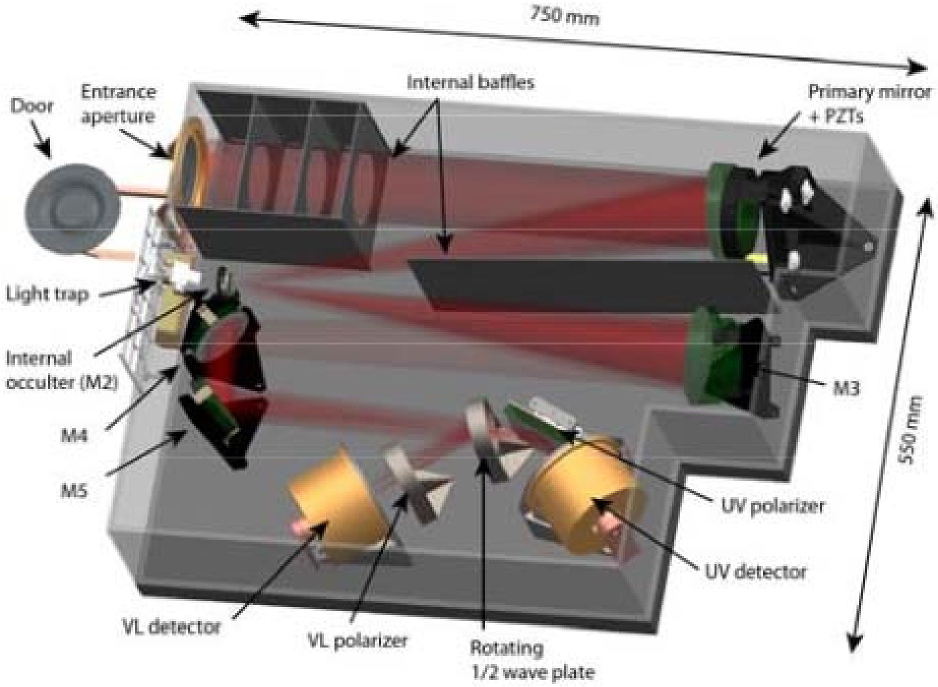


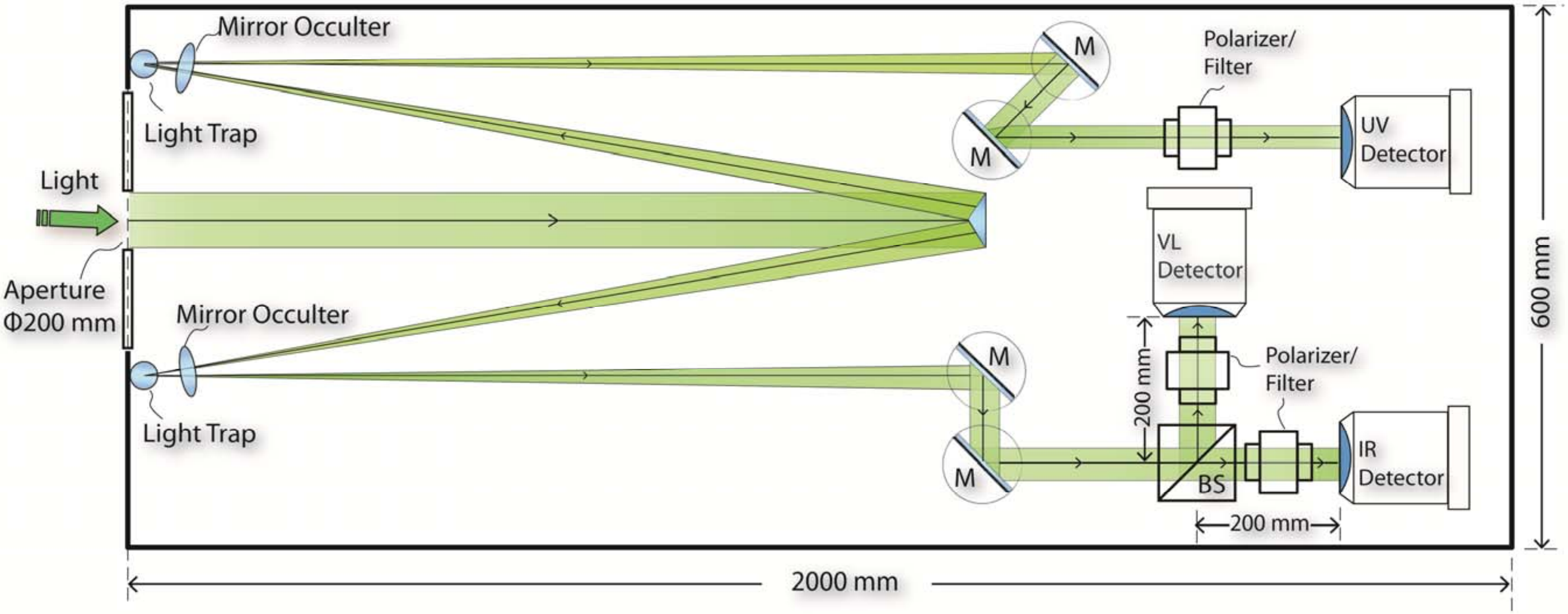
Figure 2-13. Schematic view of MAGIC

Auchère et al., LYOT proposal

Proposition : 2 in 1 (Coronograph for magnetic imaging)

- Access to weak and strong fields in the corona (off-limb)
- Measurement of the full Stokes vector
- FOV : 1.1 – 2.0 solar radius
- 15 min cadence (UV and VL) and 60 min cadence (IR)
- Time exposure: 10-20 sec (UV), 10 sec (IR), 1 sec (VL)
- UV: HI Lyman alpha line at 121.6 nm
- IR lines: FeXIII 1074.7 and 1079.8 nm, He I 1083.0 nm
- Visible Light 560 nm
- Polarimetric accuracy (infrared): 10^{-4}
- SNR UV: 20-100

- 50 kg
- 80 W
- Aperture 20 cm
- 200x60x25 cm^3
- 5’’/pix



Filters and polarimeters

- **Infrared device:**

Liquid Crystal Variable Retarder (polarimetry and tunable wavelength selection)

Narrow-band tunable filter

Six-stage birefringent filter: nested thermal control loops (30°C with variation < 5mC in 24h)

- **Lyman alpha device:**

Rotation 121.6 nm ½ wave plate

High reflectivity Brewter’s angle linear polarizer

- **Visible light device:**

Tunable broad-band filter

Dichroic linear polarizer

Accuracy of pointing

- Constrained by the occulation (1.15 solar radius /15)
- Accuracy = 72’’
- Stability = need 3’’ over 120 s

Detectors

- **Infrared device:**

Teledyne Imaging HgCdTe 2048x2048, pixel size 15 µm

Passive cooling to -50°C

- **Lyman alpha device:**

APS sensor 2048x2048, pixel size 15 µm

Passive cooling to -50°C

- **Visible light device:**

APS sensor 2048x2048, pixel size 15 µm

Passive cooling to -50°C

- **Infrared device:**

Images in 4 states of polarization, in 5 wavelengths for both lines.

One set of measurements in 7 minutes, each hour.

Ground-based calculation of the vector magnetic field.

- **Lyman alpha device:**

Images in 3 states of polarization in one line.

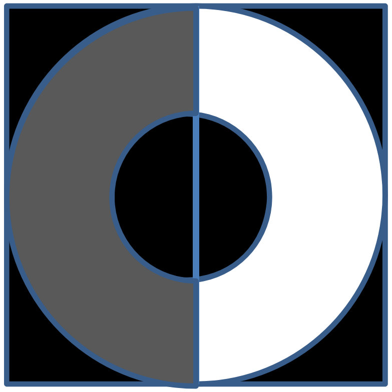
Each set of images in 5 minutes, every 15 minutes.

Ground-based calculation of the vector magnetic field, if the geometry of the source is known.

- **Visible light device:**

K corona

One image every 15 minutes



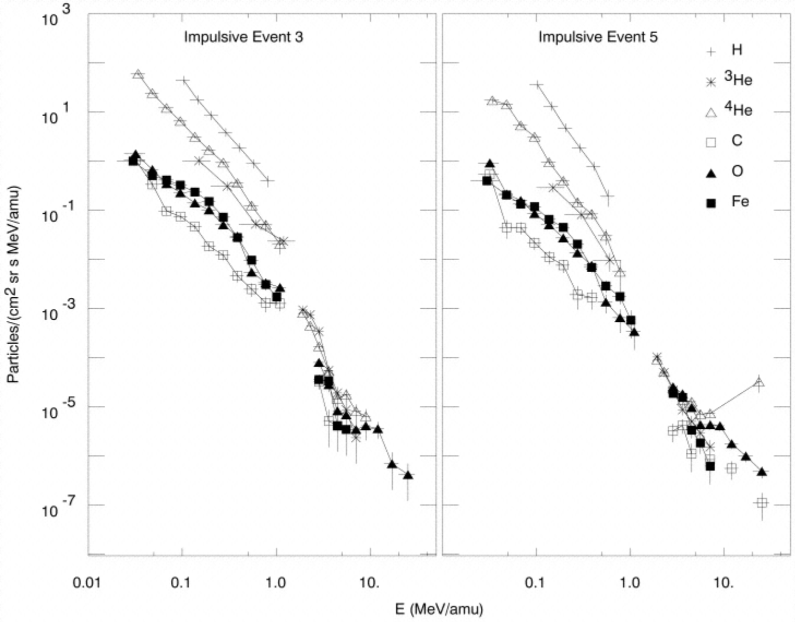
On board processing:

- Substract mean dark
- Normalization by mean image
- Remove useless pixels (see figure) and bad pixels

FOV really transmitted to Earth

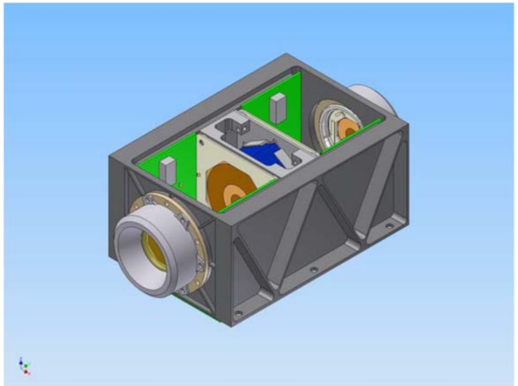
High Energy Particle Sensors (HEPS)

- STEIN
- SIS
- EPT
- LET
- HET



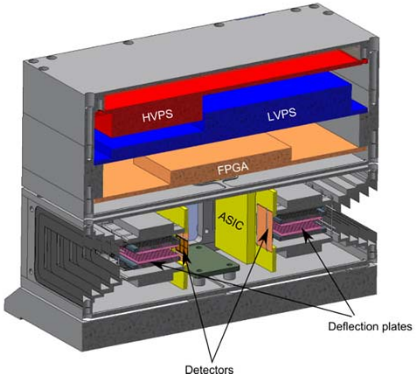
HET-High Energy Telescope

- covers the high-energy particle range
- protons: up to 100 MeV
- heavier ions: 200 MeV/nuc for O and heavier species



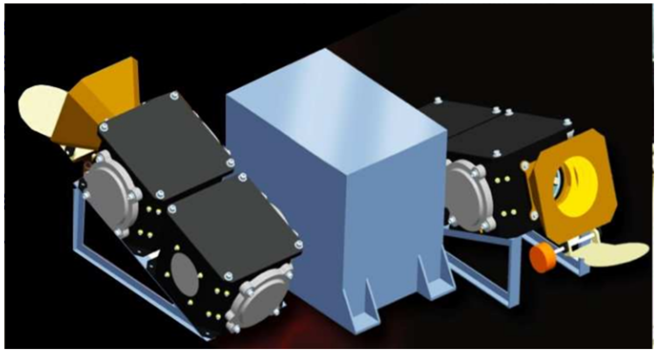
Stein- Supra-thermal Electrons, Ions and Neutrals

- measure suprathermal particles
- ˜3–100 keV
- Double-ended telescope, utilizing passively cooled silicon semiconductor detectors (SSDs)



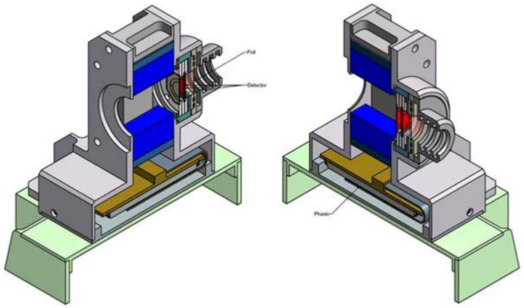
SIS- Supra-thermal Ion Spectrograph

- measures the composition of heavy ions (He-Fe)
- ˜8 keV/n–10 MeV/n
- identifies particles by time-of-flight (TOF) mass spectrometry



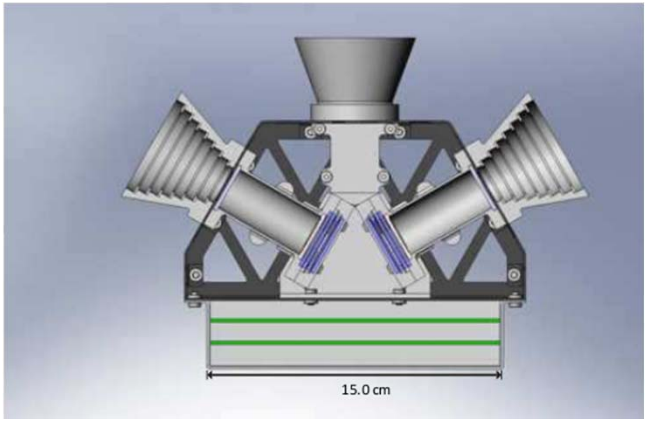
EPT-Energetic ParticleDetector

- measures electrons and protons as well as their anisotropies
- electrons (20 keV to 700 keV)
- protons (20 keV to 9 MeV)
- combines the dE/dx-E method with the magnet/foil technique



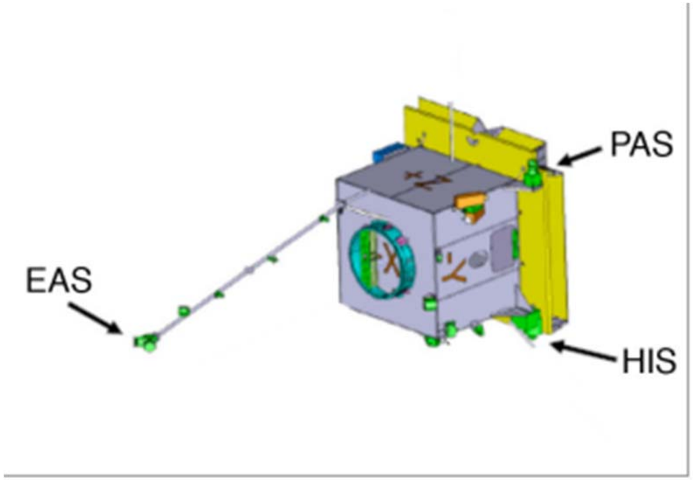
LET-Low Energy Telescope

- measures the species H-Ni
- ˜1.5–60 MeV/n
- dE/dx-E method

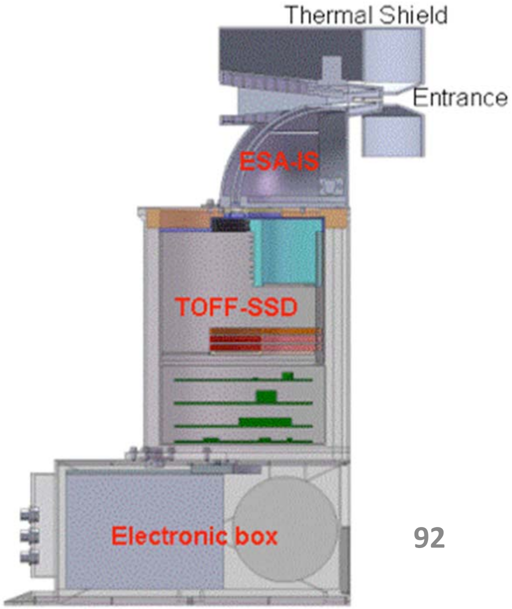


Low Energy solar WInd Sensors (LEWIS)

- HIS
- EAS
- PAS



HIS – Heavy Ion Sensor

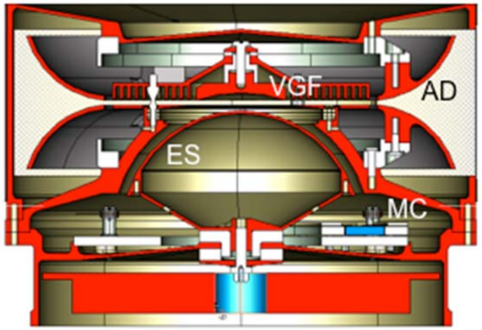


measure five key properties for all ions:

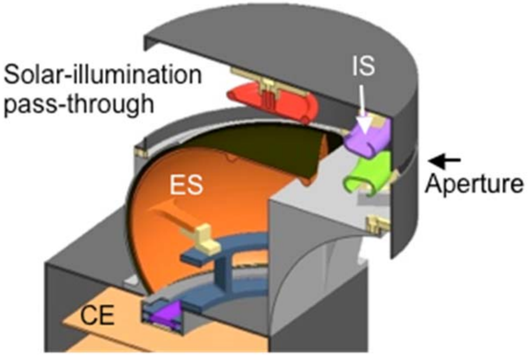
- mass in the range 2-56 amu/q
- charge (q)
- energy in the range 0.5–100 keV/q (for azimuth)
- 0.5–16 keV/q (for elevation)
- direction of incidence (θ, ϕ)

EAS- Electron Analyzer System

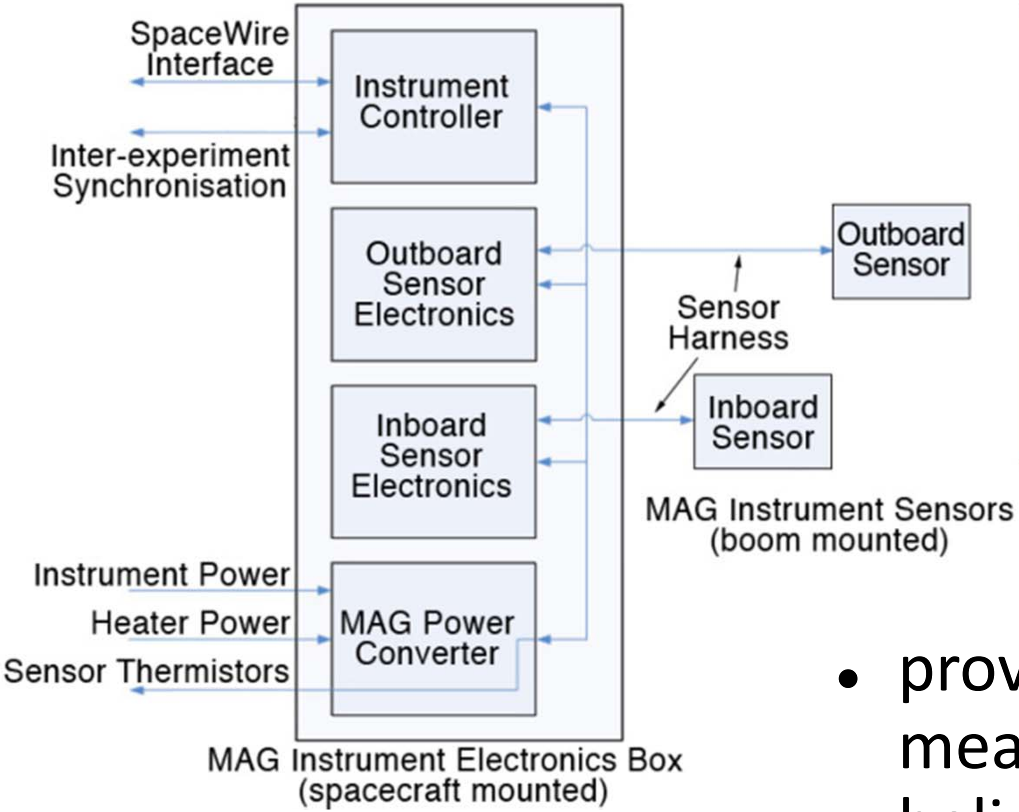
- measure electron fluxes
- ~1 eV - 5 keV
- a pair of top-hat electrostatic analysers with aperture deflection plates

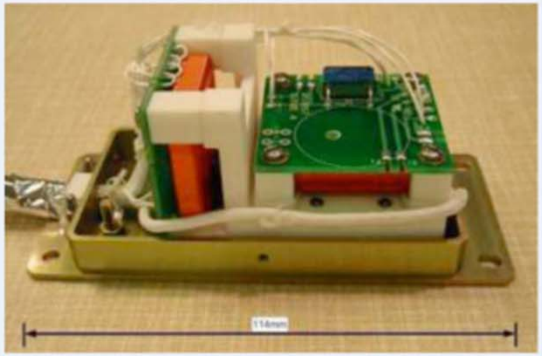


- protons and alpha particles
- ≤ 0.2–20 keV/q
- top-hat electrostatic analyser (EA)



Fluxgate Magnetometer (FGM)

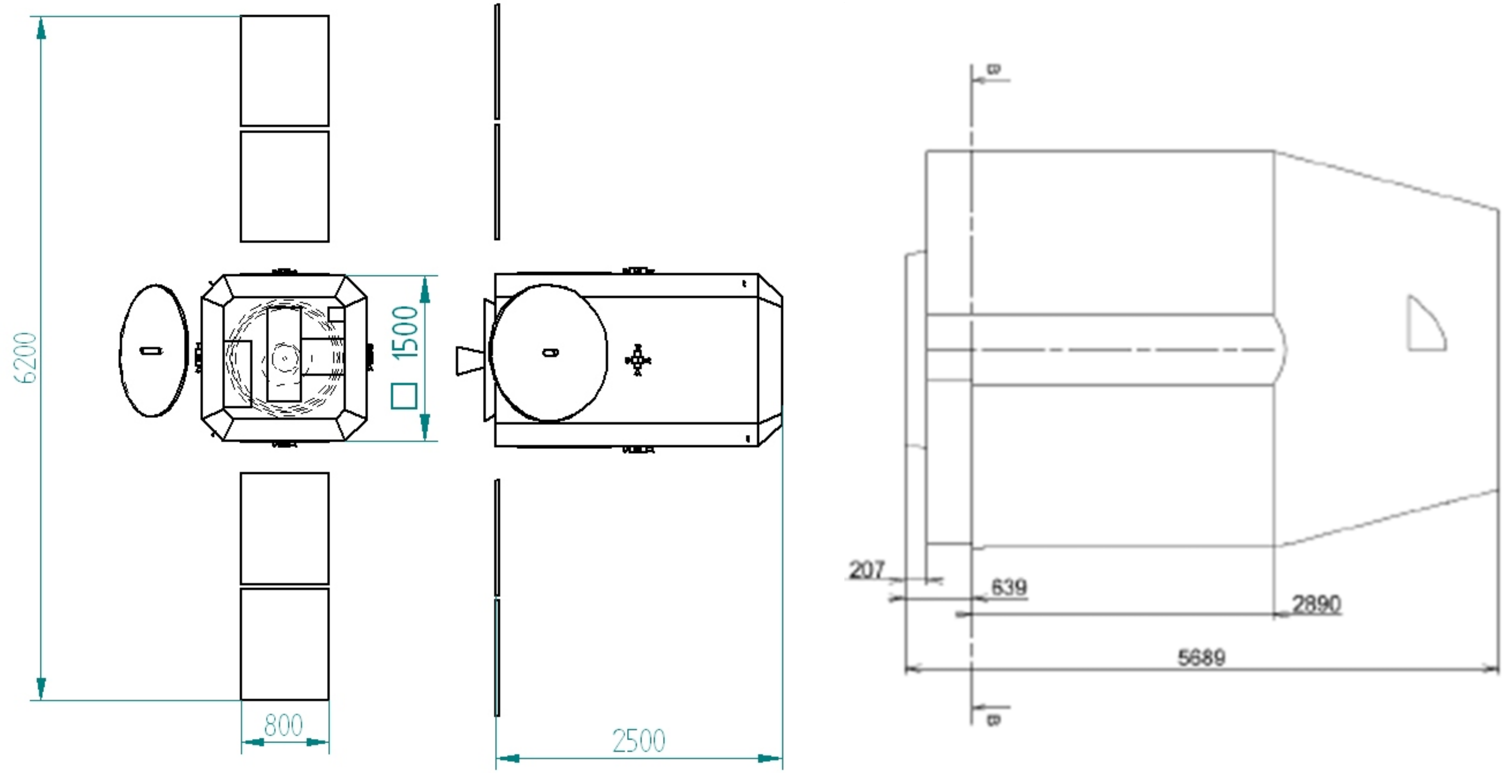




Fluxgate Sensor
(cover removed)

- provide in-situ measurements of the heliospheric magnetic field
- ±23-2040 nT

Spacecraft vs. Launcher usable volume



Details of Attitude Control System

Components	**Type**	**Mass (kg)**	**Dimension (m)**	**Power (W)**	**Mounting considerations**
Momentum wheels	RSI 68 Angular momentum (nominal speed) : 15 N.m/sec T loss : -20 mN.m	-7.7 x4	0.3 x 0.16	Steady state -15 W, Max T (nominal speed) <90 W	Provider : Rockwell Collins
Sun sensors	S3 Accuracy: <0.02^{O} 2 σ Resolution: <0.005^{O} FOV: 128^{O} x128^{O}	0.3 x2	0.1 x 0.01 x 0.04	0.7 W to 1 W	Provider: SELEX Galilleo
Star trackers	HAST: 2 Star Sensor Heads (SSH), 1 Star Sensor Electronic Unit (SSEU), Shutters and Sun-Shaders Accuracy : Boresight 0.1 arcsec 1 σ	SSH 13.5 x 2 SSEU 6.8 S & SS 4 In Total : 38.5 kg		-120 W over any 1-min interval	Provider : Ball Aerospace & Technologies Corp. We can use less size tracker and use pixel binning
Thrusters	16 x 10 N bi-propellant thruster (Hydrazine)	16 x 0.36		14 for each thruster	Provider: Astrium

Why is our mission better than previous ones?

Solar-C: We have an additional coronagraph and therefore measurement of magnetic field in corona.

STEREO: We have continuous stereoscopic look on the earth-facing coronal layers, and we always cover the space between Sun and Earth.

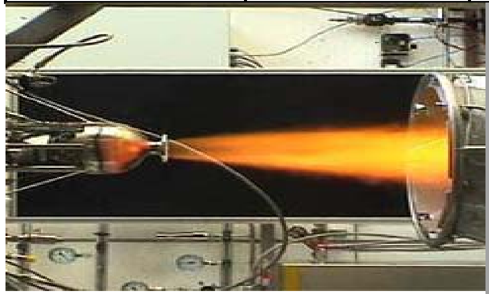
Solar Orbiter: We have continuous observations of photosphere/chromosphere/corona, unlike S.O. due to it's elliptical/inclined solar orbit. We also have coronal magnetic field measurements.

SolmeX: We also have the magnetic field for the photosphere, and can also observe the magnetic field of earth-facing events.

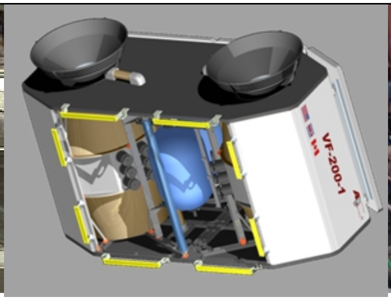
Analysed Propulsion Options

Best solutions comparison

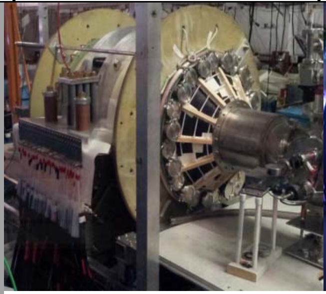
	Chemical Rocket	VASIMR Variable Specific Impulse Magnetoplasma Rocket	FDR Fusion Drive Rocket	ELF Electrodeless Lorenz Force	HALL Effect Ion Engine
SPI Specific Impulse	321 s	4,800 s	10,000 s	6,000 s	8,000 s
TRL Technology Readiness Level	9	5 (7 in 2014 – use for ISS orbit correction)	5	4	6
Fuel Mass	800 kg	50kg Argon/Krypton	20kg Ar/Kr + 5kg Li	40kg Ar/Kr	30kg
System Mass	100 kg	100kg solar panels 200kg batteries 200kg engine (est.)	100kg solar panels 100kg batteries 300kg engine (est.)	100kg solar panels 50kg batteries 100kg engine (est.)	50kg batteries 50kg engine (est.)
Other	High mass fuel required Low single burn life	No in-situ magnetic measurements possible whist engine is on Allow big orbit changes	No in-situ magnetic measurements possible whist engine is on Allow big orbit changes	No in-situ magnetic measurements possible whist engine is on Allow big orbit changes	No in-situ magnetic measurements possible whist engine is on Allow big orbit changes



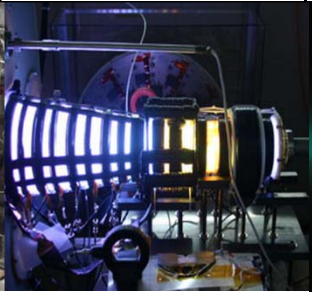
© Astrium



© Ad Astra Rockets



© Washington University



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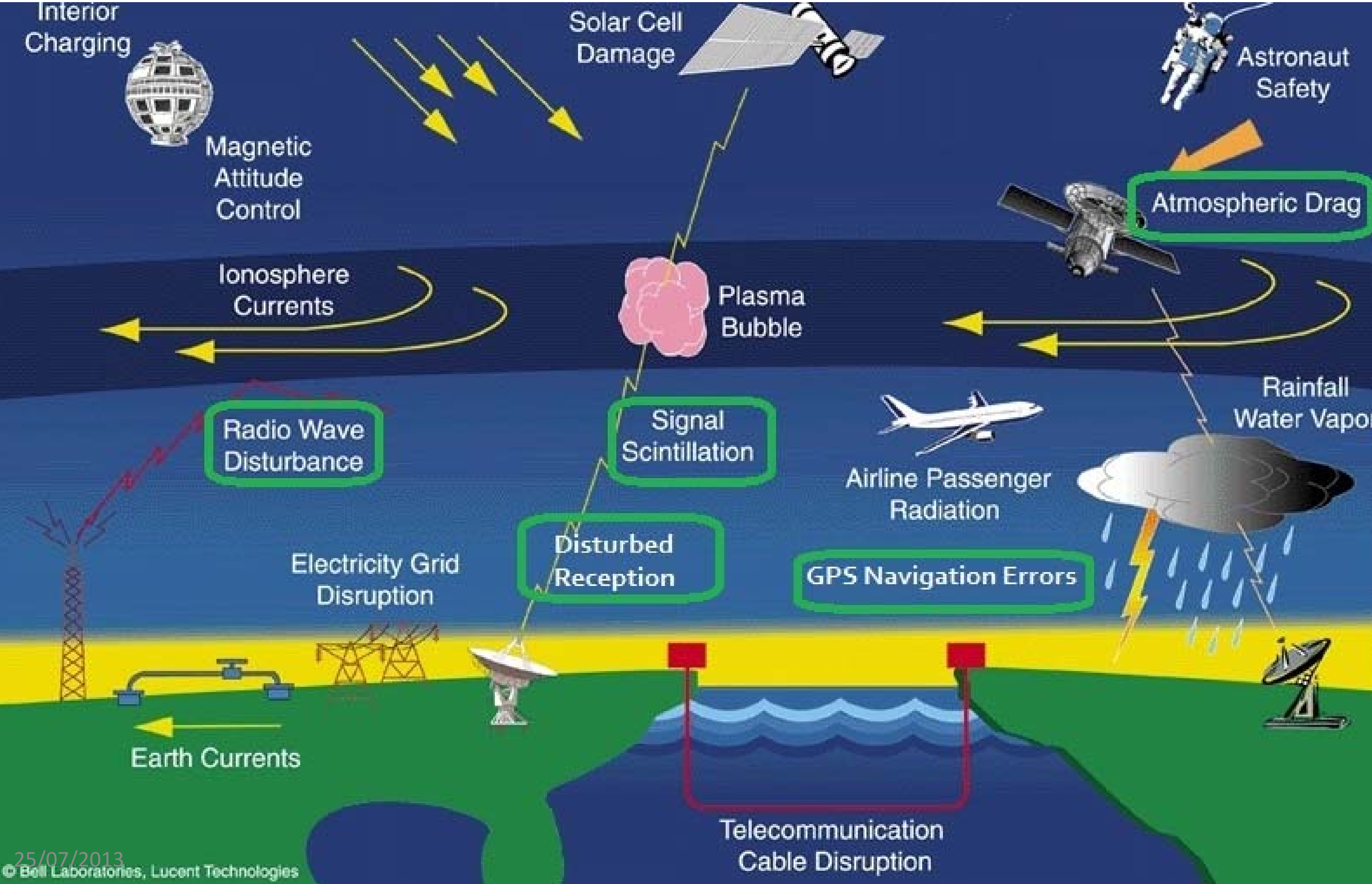
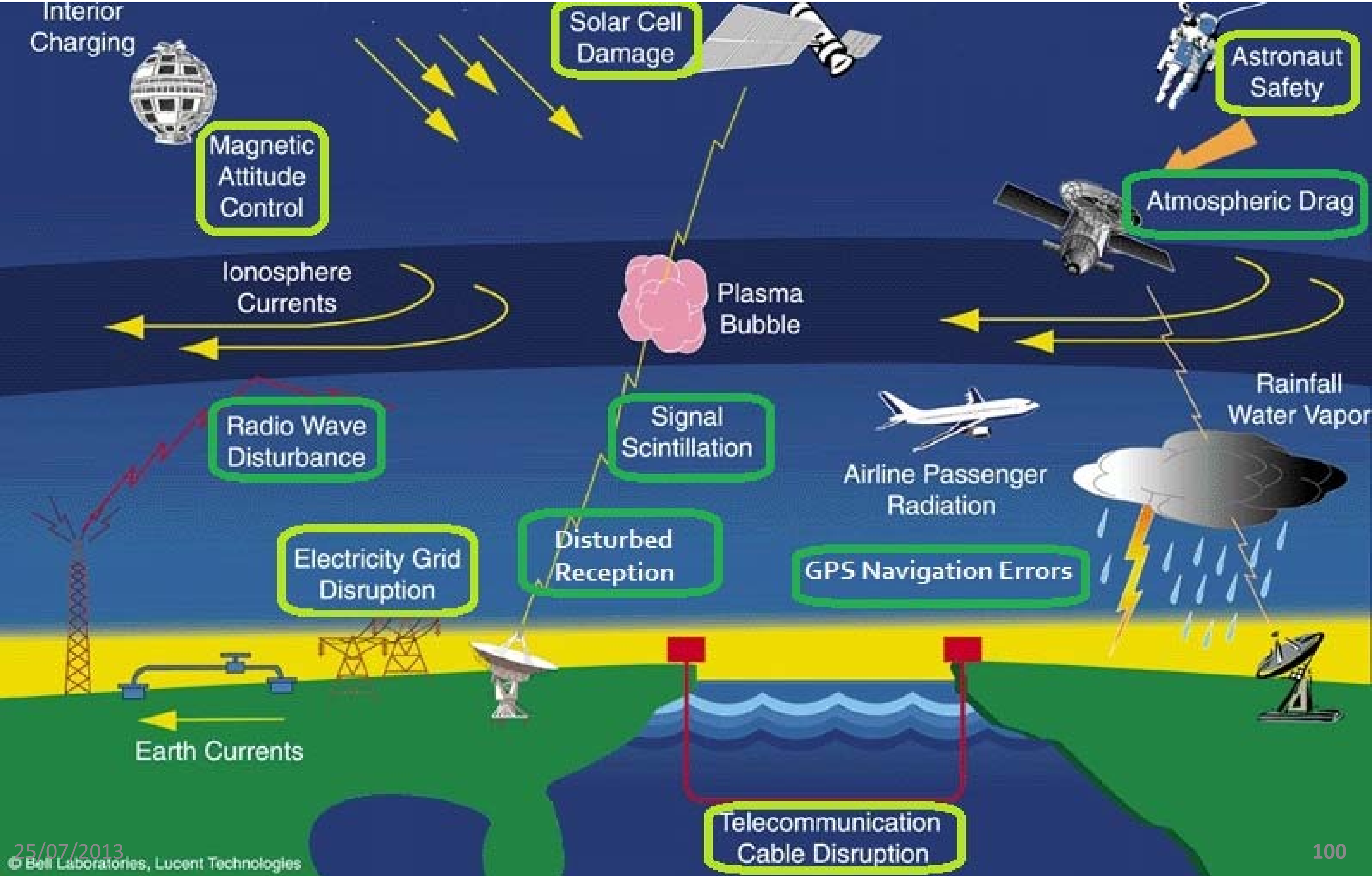
Considering the 2030 launch date TRL 5 engines have been also analysed

Flares


Interior Charging
Solar Cell Damage
Astronaut Safety
Magnetic Attitude Control
Atmospheric Drag
Ionosphere Currents
Plasma Bubble
Rainfall Water Vapo
Radio Wave Disturbance
Signal Scintillation
Airline Passenger Radiation
Electricity Grid Disruption
Disturbed Reception
GPS Navigation Errors
Earth Currents
Telecommunication Cable Disruption
© Bell Laboratories, Lucent Technologies

Flares and CMEs



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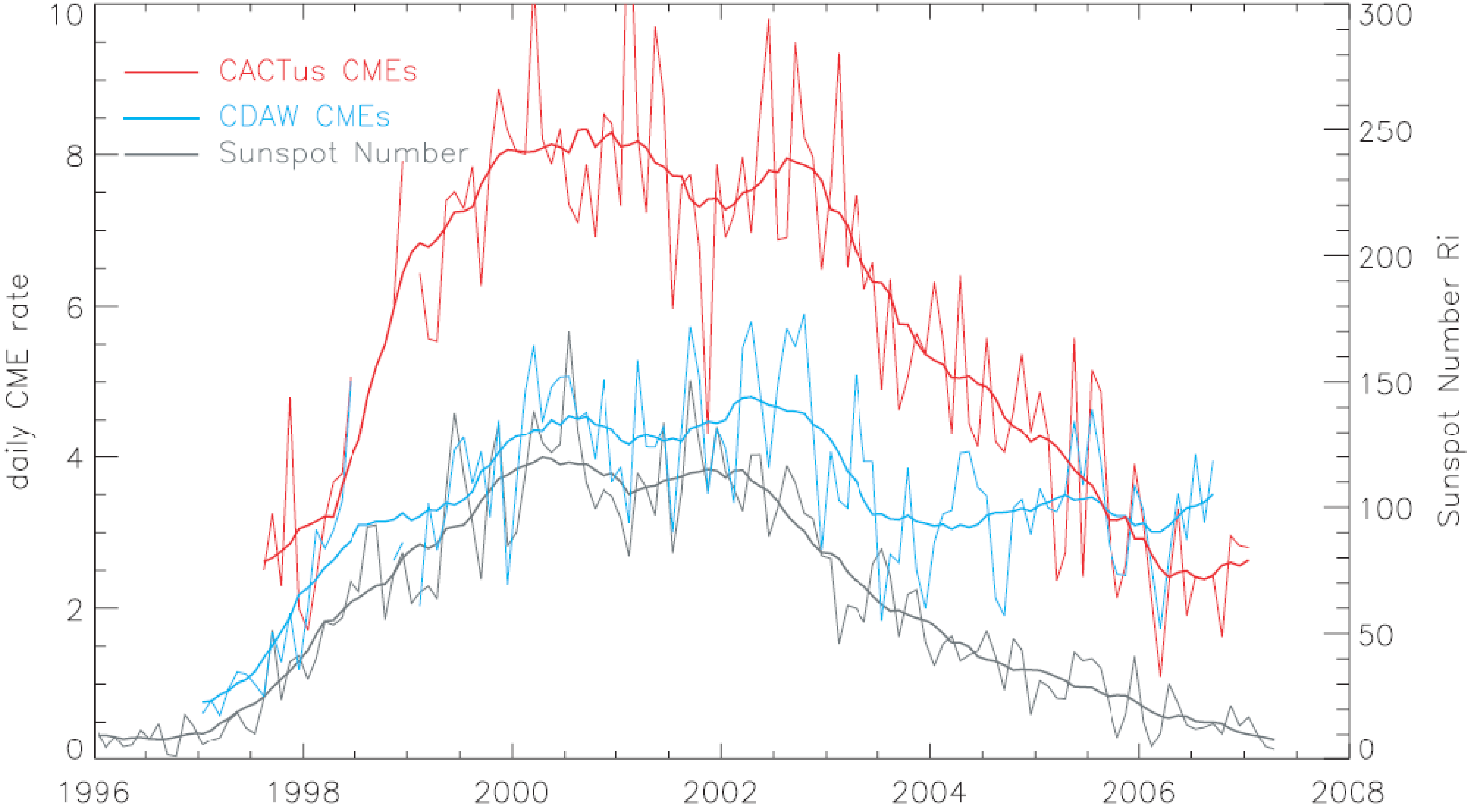
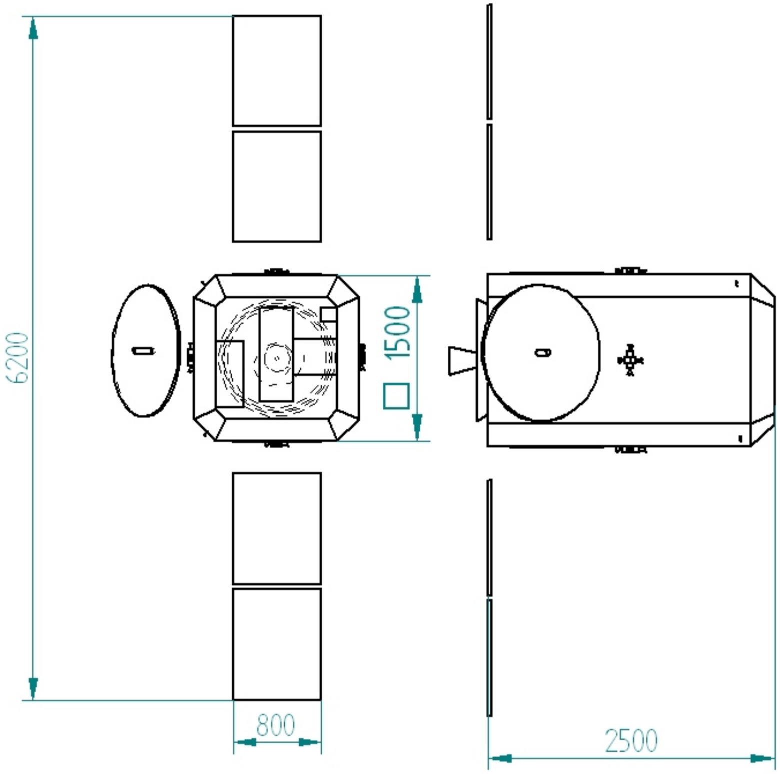
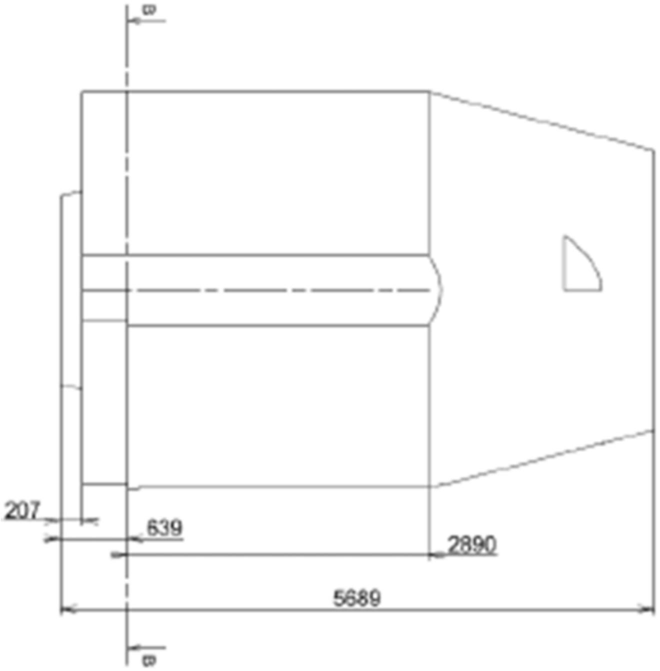


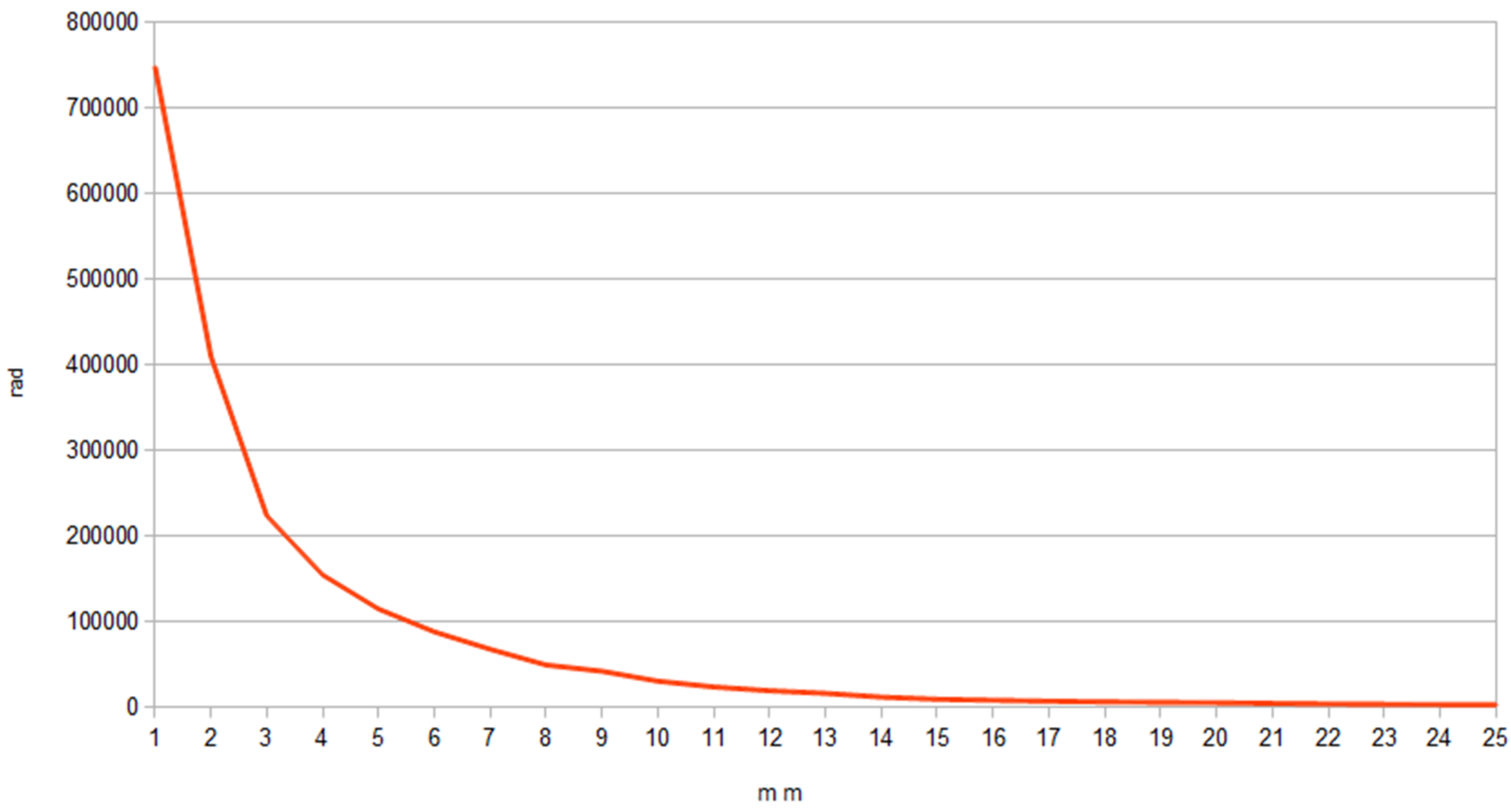
[Robbrecht Berghmans, 2006]

- at cycle maximum, 6 CMEs/day
- at cycle minimum, 0.5 CMEs/day [Gopalswamy et al., 2003]

Spacecraft vs. Launcher Usable Volume



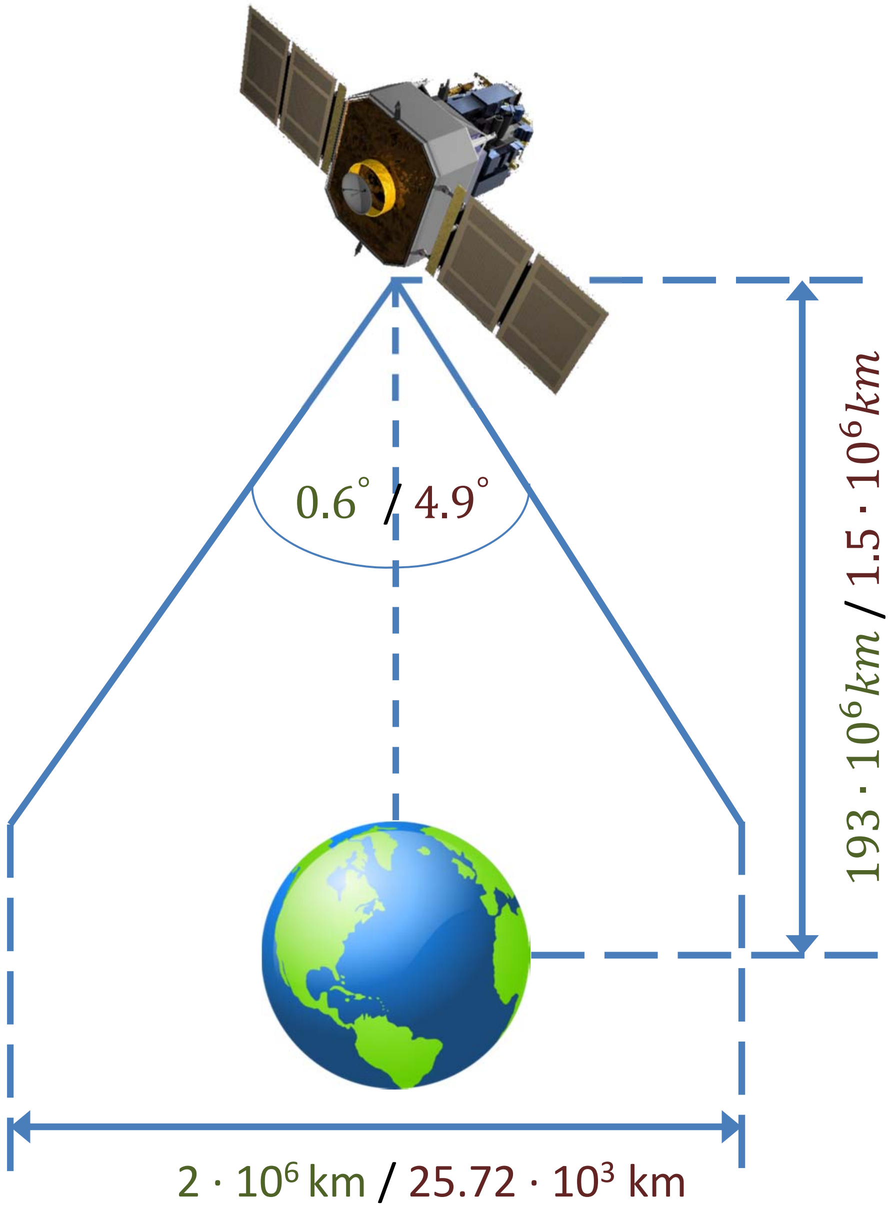




Radiation dose vs Al slab thickness

Generated with spenvis

Appendix-Half Power Beam Width of **SCE** and **SC80**



- HGA:
  - Narrow Beam Antenna
  - Steerable (2dB Loss)
- Pointing Demands:
  - **0.54° (SCE)**
  - **0.15° (SC80)**

Appendix - Communication Subsystem – Link Budget

- Losses
  - Path Loss
    - Frequency – X-Band
    - Distance – $1.5 \cdot 10^6\ km$ (SCE) / $193 \cdot 10^6\ km$ (SC80)
  - On-board and Steering Losses
  - Received Noise
- Bit Energy to Noise Demands
  - Modulation (BPSK)
  - Bit Error Rate Demands
- Data Rate
  - Scientific and Control Data (+ Overhead)
  - Code Rate
- Transmission Power
- Antenna Gains
  - Antenna Diameter
  - Frequency
- Coding Gain

Appendix - Ground Stations

Name	Country	Diameter	Band (T/R)
Malargüe	Argentina	35m	X/XKa
Cebreros	Spain	35m	X/XKa
New Norica	Australia	35m	SX/SX (Ka planned)
Kourou	French Guiana	15m	SX/SX
Kiruna	Sweden	15m	SX/SX
Perth	Australia	15m	SX/SX

- SC80:
  - DSA (Deep Space Antenna) needed (35m)
  - 3 DSAs for continuous communication (120°)
- SCE
  - 15m Antennas
  - 3 for continuous communication (120°)

De-scoping: Instrument priorities

Action	Impact	Comments
Removing solar wind measurements	Failure of secondary objective	Don’t remove, makes good usage of extra s/c resources.
Reduce telecommunication requirements, e.g. From 24h/day to 8h/day or 8h/2days	Reduced SW operational capabilities for forecasting, mainly CME propagation. Science objectives are still achievable.	Possible, but the coronagraphs can provide excellent SW predictions from operation start and this critical information would be lost.
Cut one spacecraft	Failure of primary objective, regardless of spacecraft	Would still produce new science, but is strongly not recommended.