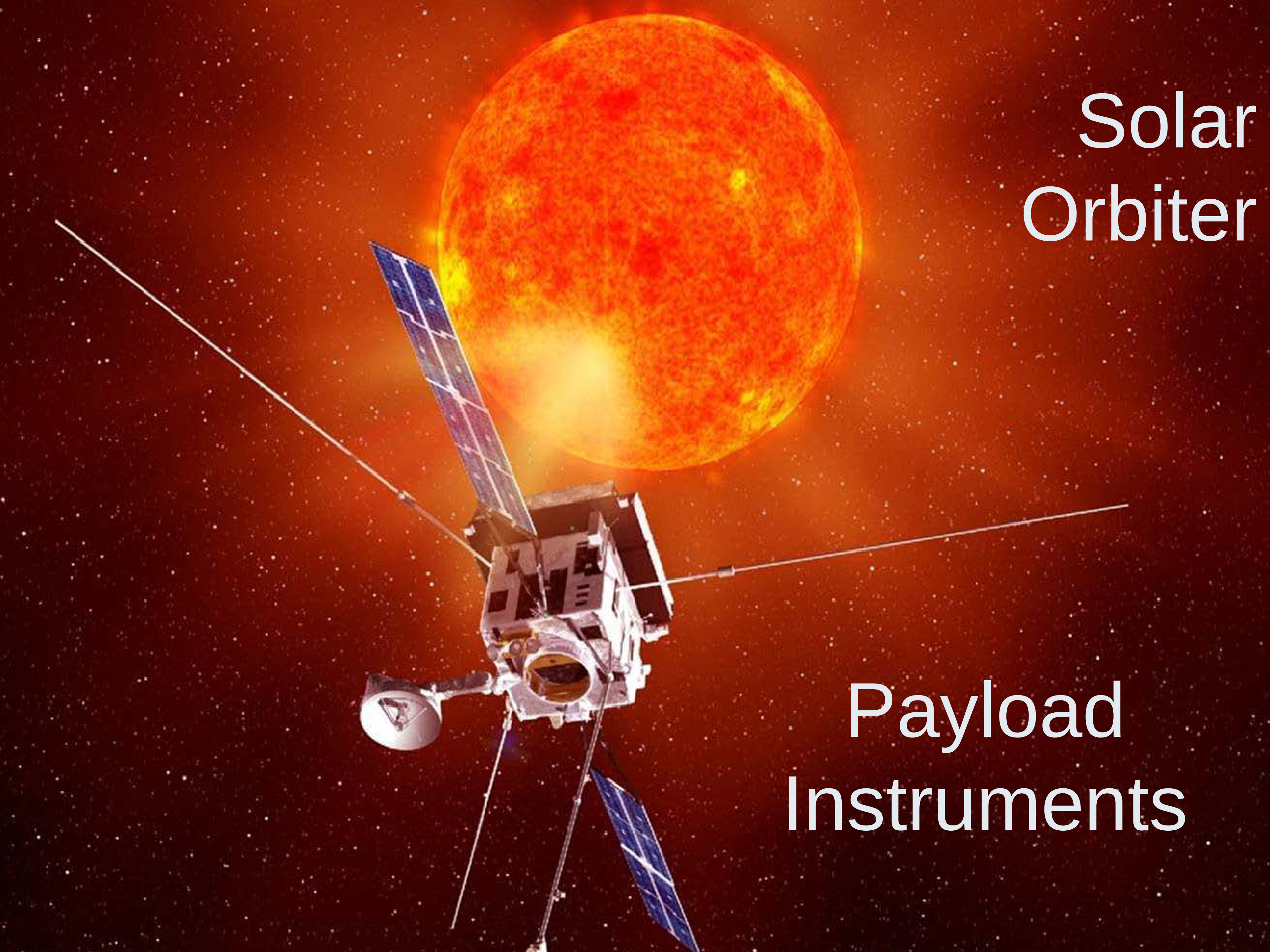
Solar Orbiter and Solar C Mission Concepts and Instrumentation

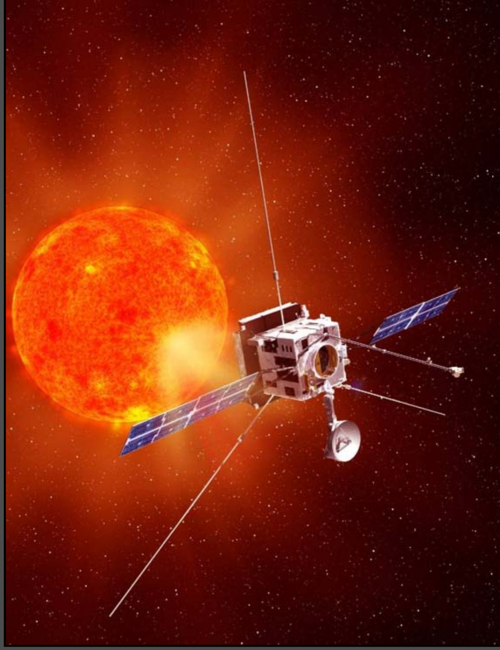
Udo Schühle, Luca Teriaca



Solar Orbiter

Payload Instruments

Mission requirements



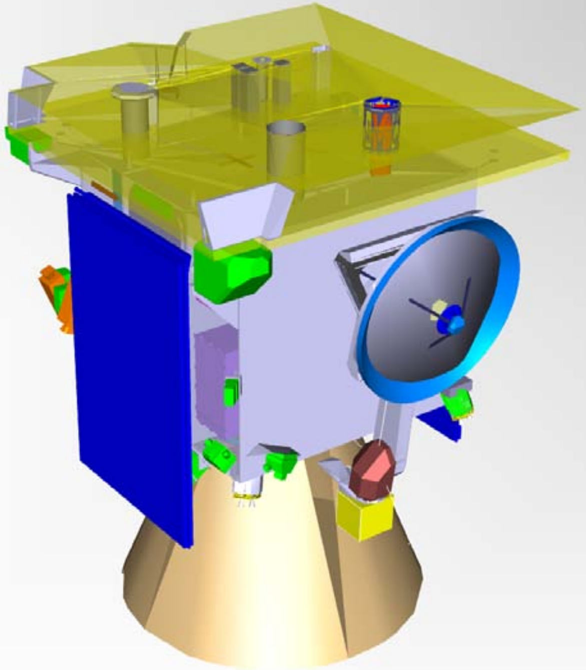
Requirements on the orbit:

1. Go closer to the Sun (within 0.30 AU)
2. Go out of the ecliptic (~ 30°)
3. Have periods of near co-rotation
4. Characterize conditions in dependence on latitude, longitude and distance

Requirements on the spacecraft:

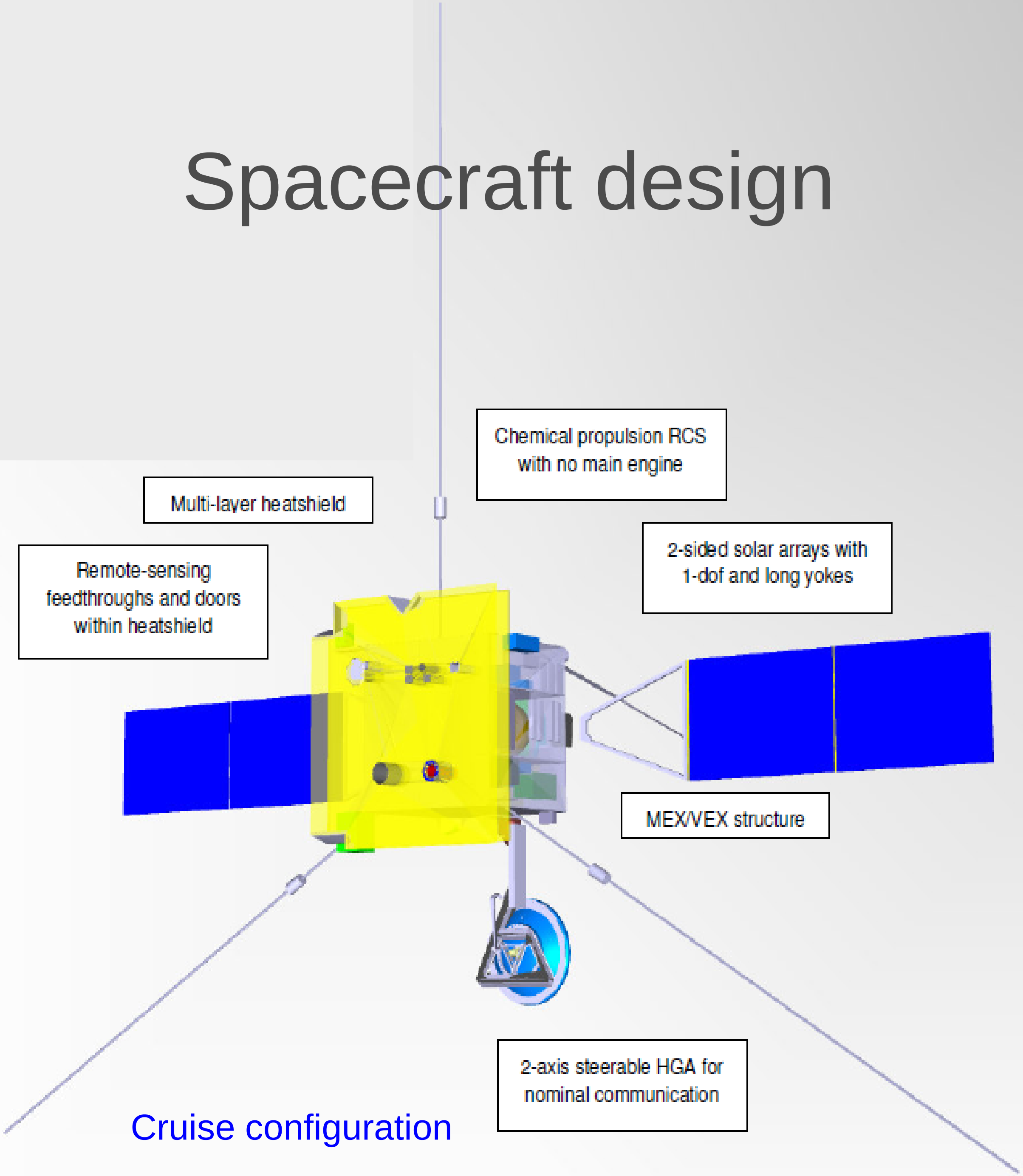
1. Use a three-axis stabilized S/C with sufficient pointing accuracy for imaging and spectroscopy
2. Satisfy electromagnetic cleanliness for plasma wave and magnetic field measurements
3. Enable three ten-days operational periods per orbit near perihelion for close-up views

Spacecraft design



Launch configuration

Reuse of elements from BepiColombo and Express Series



Multi-layer heatshield

Chemical propulsion RCS with no main engine

Remote-sensing feedthroughs and doors within heatshield

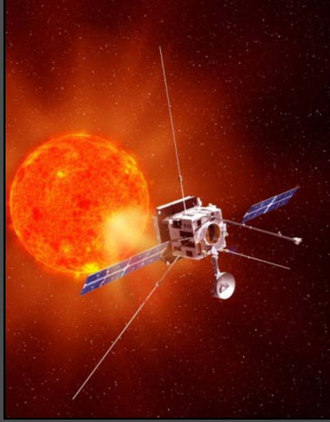
2-sided solar arrays with 1-dof and long yokes

MEX/VEX structure

2-axis steerable HGA for nominal communication

Cruise configuration

Science payload



Instruments have already been selected in a competetive process in response to AOs issued by ESA and NASA.

- Resource-efficient instrumentation (e.g., remote-sensing instruments to be "1-m size, 1 arcsec resolution" class)
- Resource envelopes of all instruments were given in ESA‘s payload definition document
- The selected proposals are ensured being funded by the national European space agencies and NASA
- The 10 PI-led hardware investigations on Solar Orbiter include
  - 6 Remote-sensing solar instruments
  - 4 In-situ measuring heliospheric instruments

Mass 180 kg, power 180 W, telemetry 110 kbps

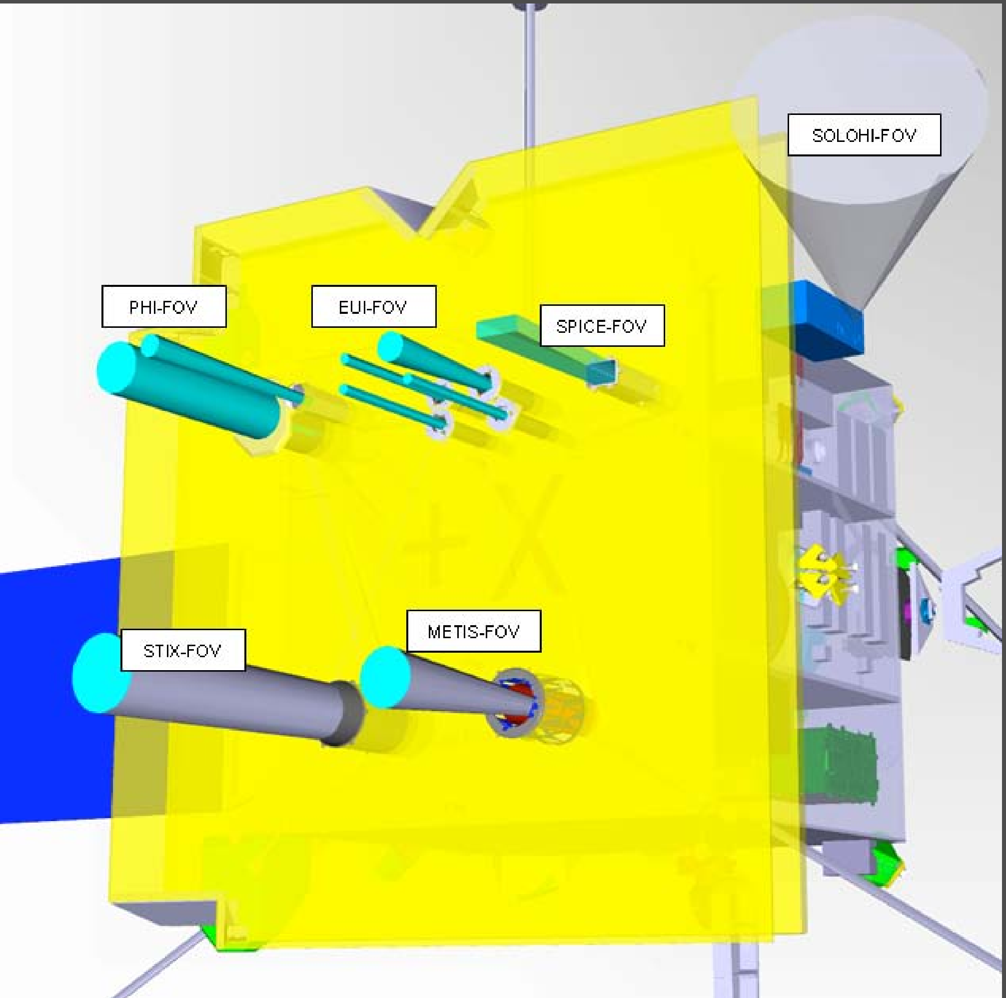
Solar Orbiter Instruments

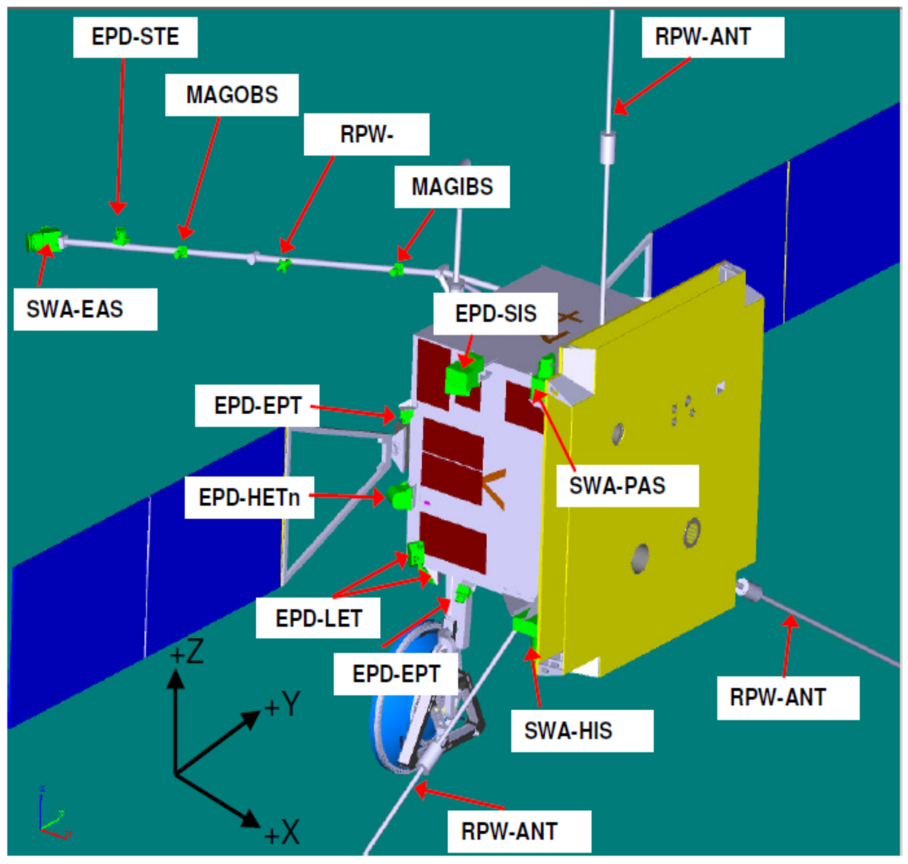
Investigation	Measurements
Solar Wind Analyzer (SWA)	Solar wind ion and electron bulk properties, ion composition (1eV- 5 keV electrons; 0.2 - 100 keV/q ions)
Energetic Particle Detector (EPD)	Composition, timing, and distribution functions of suprathermal and energetic particles (8 keV/n – 200 MeV/n ions; 20-700 keV electrons)
Magnetometer (MAG)	DC vector magnetic fields (0 – 64 Hz)
Radio & Plasma Waves (RPW)	AC electric and magnetic fields (~DC – 20 MHz)
Polarimetric and Helioseismic Imager (PHI)	Vector magnetic field and line-of-sight velocity in the photosphere
EUV Imager (EUI)	Full-disk EUV and high-resolution EUV and Lyman-α imaging of the solar atmosphere
Spectral Imaging of the Coronal Environment (SPICE)	EUV spectroscopy of the solar disk and corona
X-ray Spectrometer Telescope (STIX)	Solar thermal and non-thermal X-ray emission (4 – 150 keV)
Coronagraph (METIS/COR)	Visible, UV and EUV imaging of the solar corona
Heliospheric Imager (SolOHI)	White-light imaging of the extended corona

🟨 —— major hardware contributions of MPS

Instruments accommodation

Remote-sensing instrument locations and fields of view

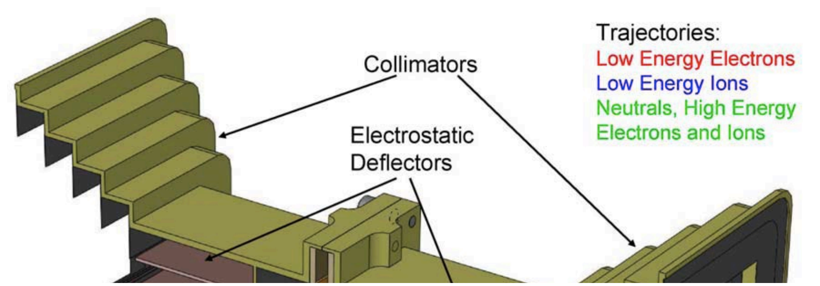




In-situ instrument locations on the spacecraft

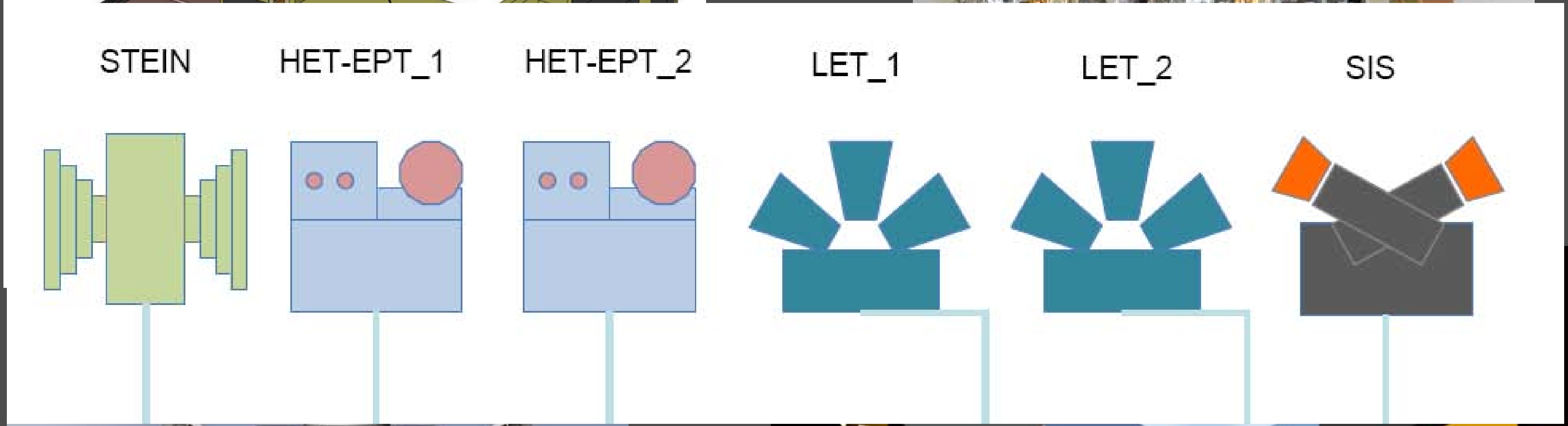
In-situ instruments (I)

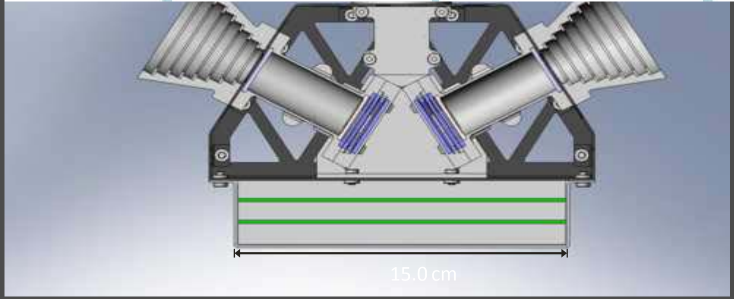
EPD Energetic Particle Detectors

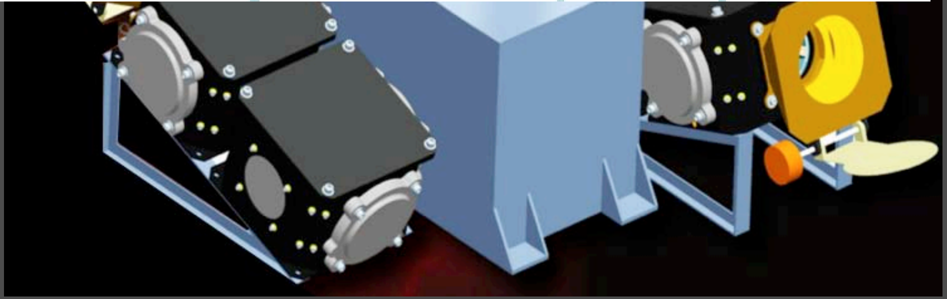


EPT

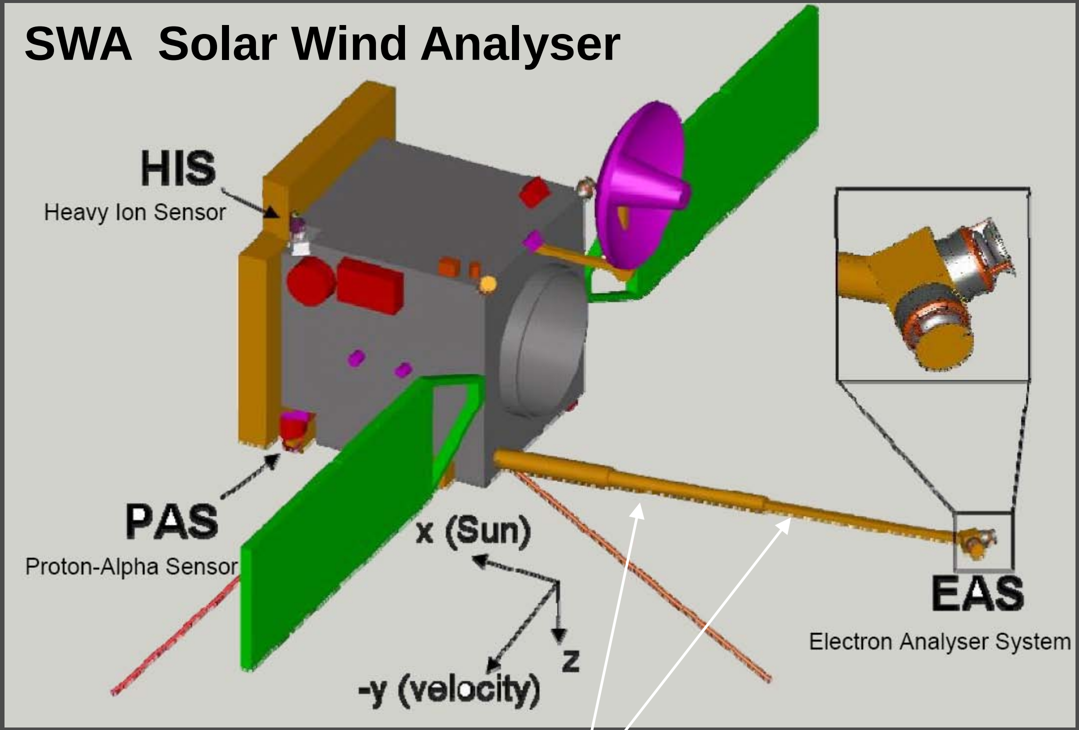
Electron Proton Telescope



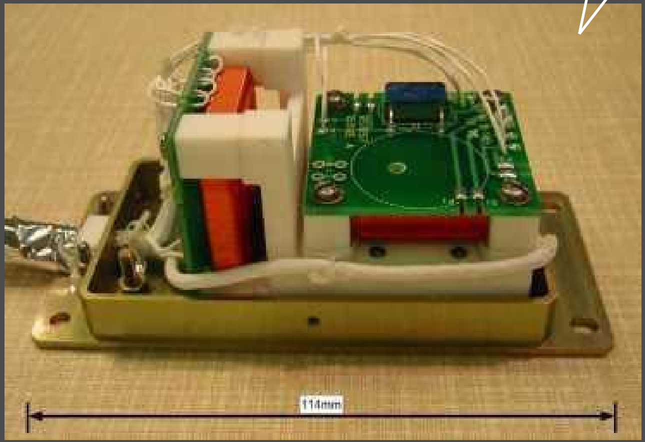




In-situ instruments: (II)

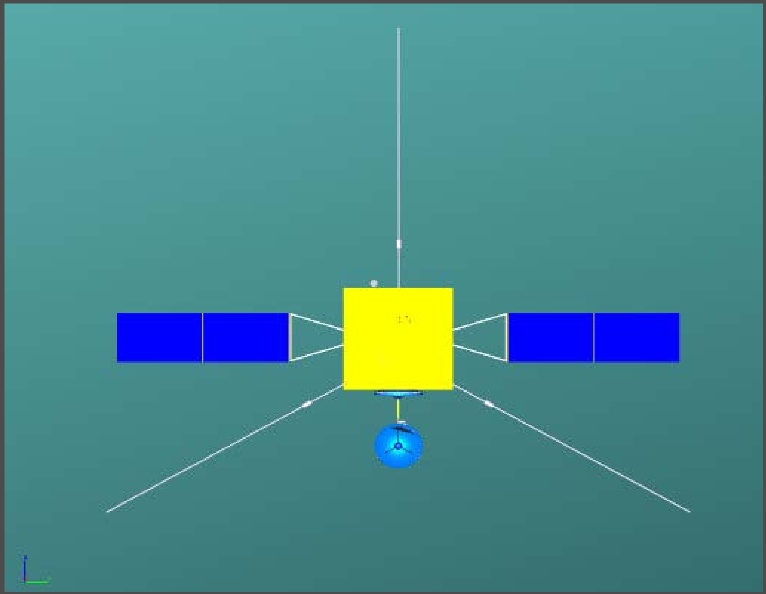


SWA **Solar Wind Analyser**

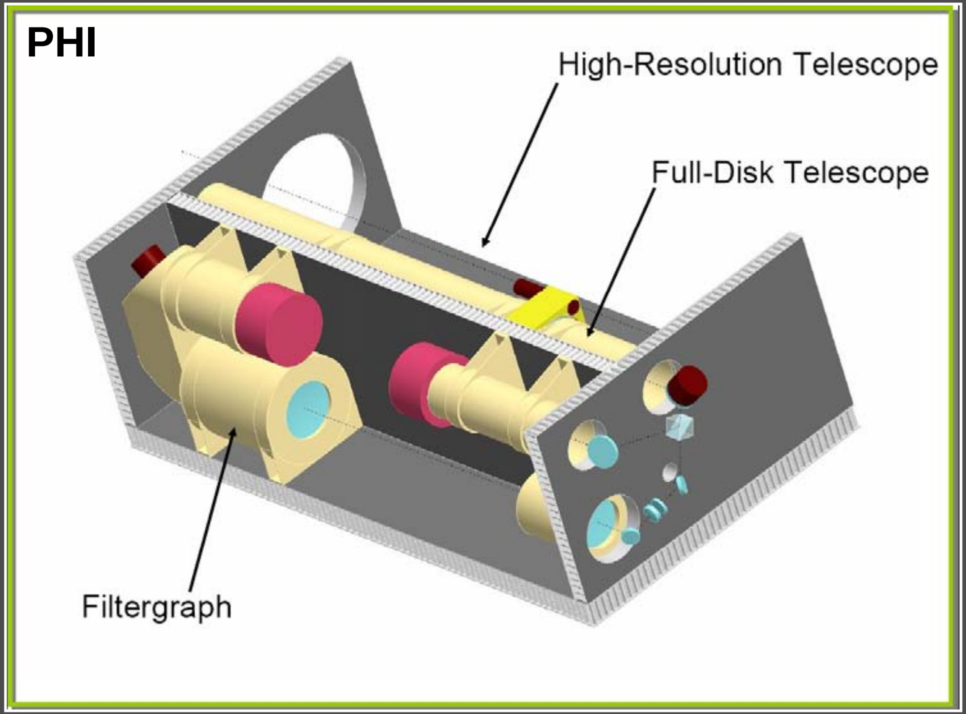


MAG
Magnetometer

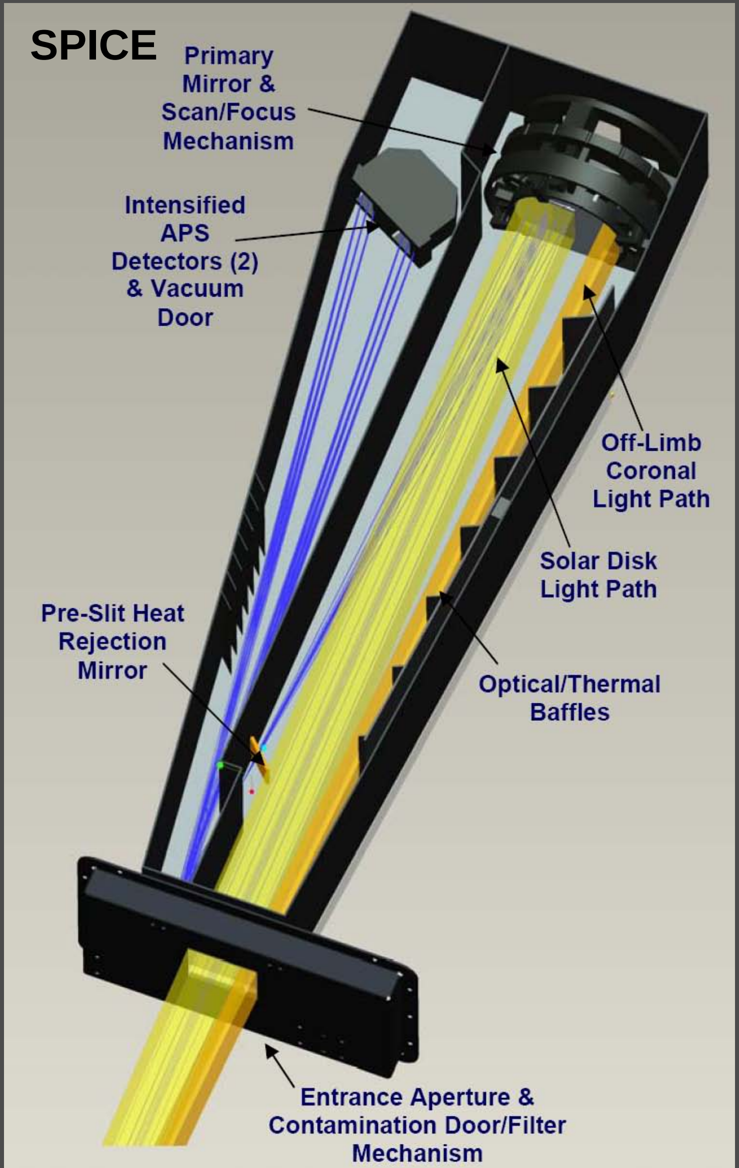
RPW Radio and Plasma Waves



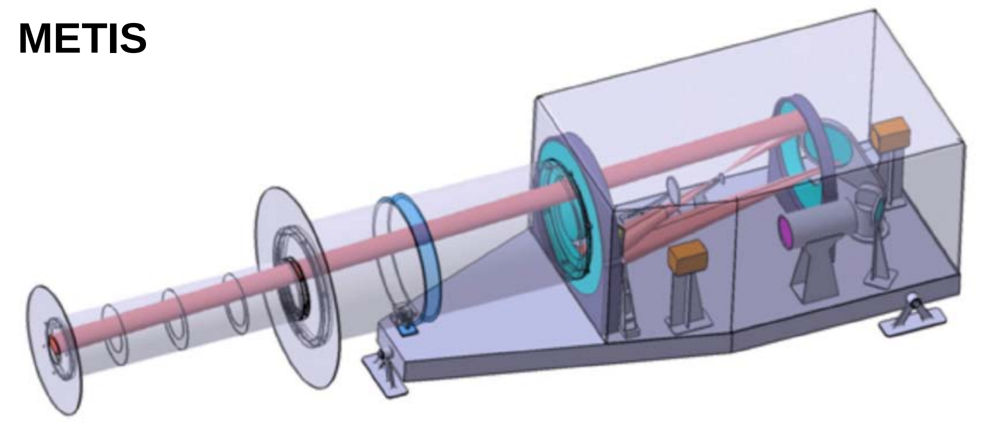
Remote-sensing instruments (I)



PHI

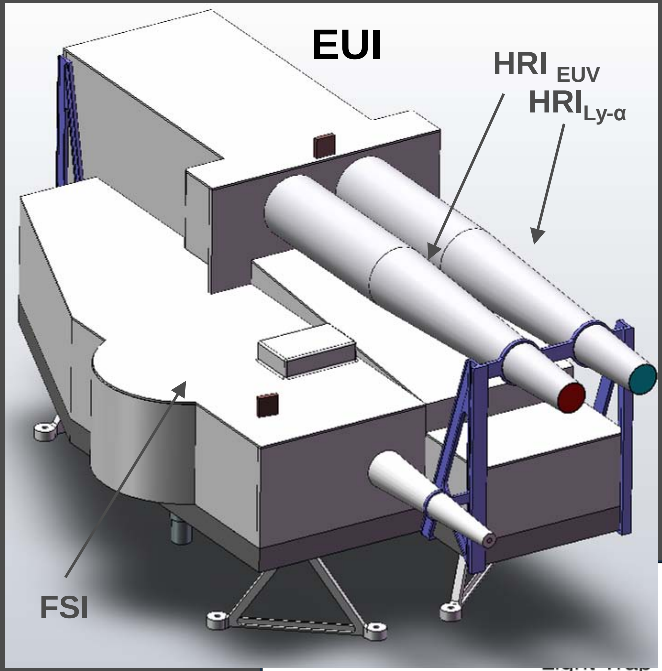


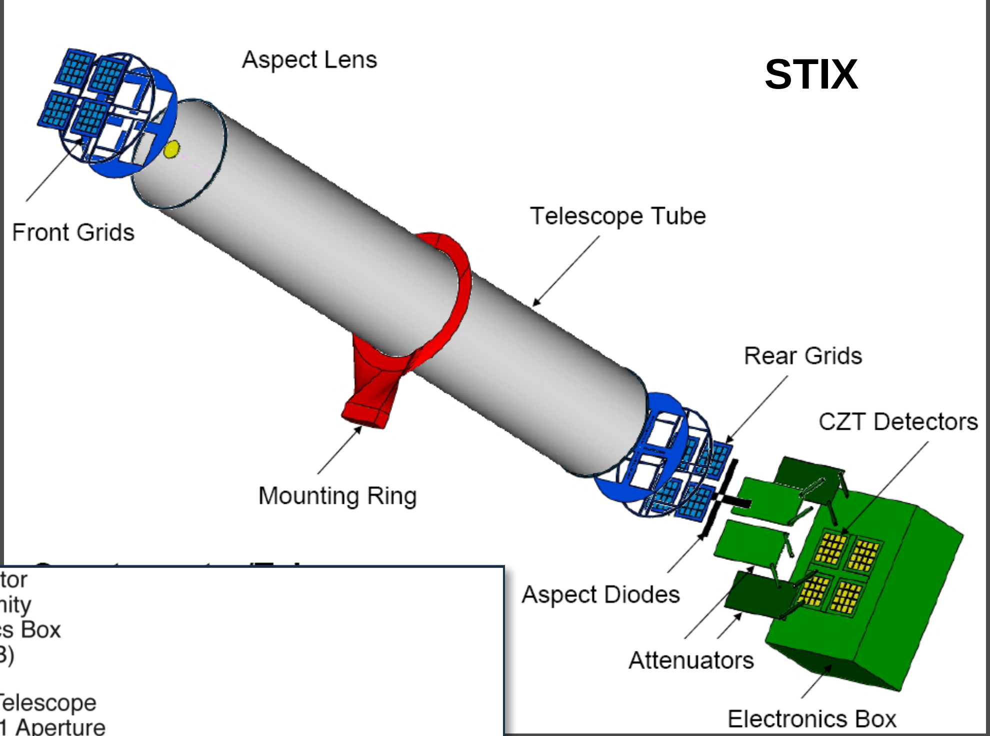
SPICE

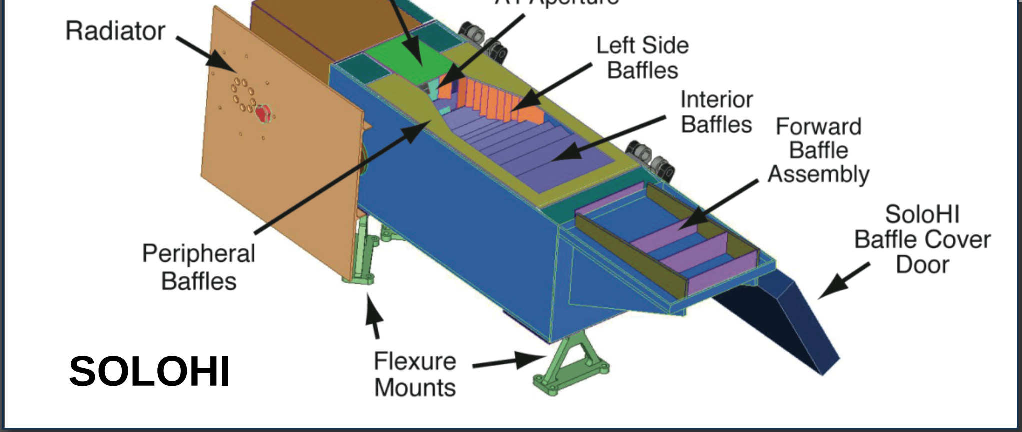


METIS

Remote-sensing instruments (II)







Payload resources summary

Investigation	Mass (kg)	Power (W)	Telemetry (kbps)
Solar Wind Analyzer (SWA)	15.9	14.2	14
Energetic Particle Detector (EPD)	13.8	16.1	3.1
Magnetometer (MAG)	2.1	1.9	0.9 (normal) 6.8 (burst mode)
Radio & Plasma Waves (RPW)	13.6	11.5	5
Polarimetric and Helioseismic Imager (PHI)	29.1	31.0	20
EUV Imager (EUI)	18.1	24	20
Spectral Imaging of Coronal Environment (SPICE)	18.4	28.8	17
X-ray Spectrometer Telescope (STIX)	4.4	4.4	0.2
Coronagraph (METIS/COR)	20.6	26.0	10
Heliospheric Imager (SolOHI)	11.2	10.0	20
Total	**147**	**168**	**110**

Solar Orbiter Instruments with MPS contributions

- PHI: Polarimetric and Helioseismic Imager (PI instrument of MPS)
- EUI: Extreme Ultraviolet Imager (co-PI contribution of MPS)
- SPICE: Extreme Ultraviolet imaging Spectrograph (EUS)
- METIS/ICOR: Imaging and Spectroscopy of the Corona

Instruments PI & CoI

	PI	**Co-I**
PHI	S. Solanki, MPS	Woch, Gandorfer, Gizon, Hirzberger, Lagg, Schühle
EUI	P. Rochus, CSL, Liege, B	Schühle, Büchner, Curdt, Marsch, Solanki, Teriaca
METIS	E. Antonucci, Univ. of Turin, I	Solanki, Teriaca, Schühle
SPICE	D. Hassler, SwRI, Boulder, USA	Curdt, Marsch, Peter, Schühle

Solar Orbiter Instruments
PHI

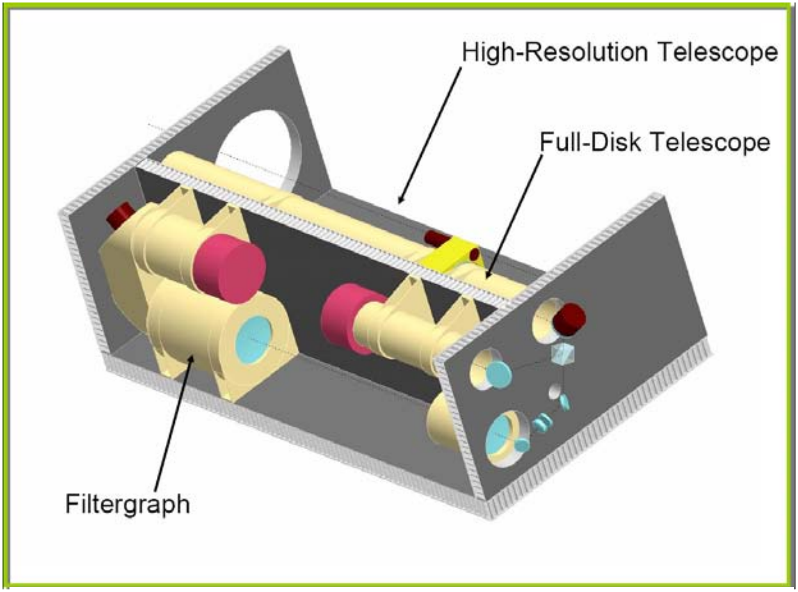
PHI – Polarimetric and Helioseismic Imager

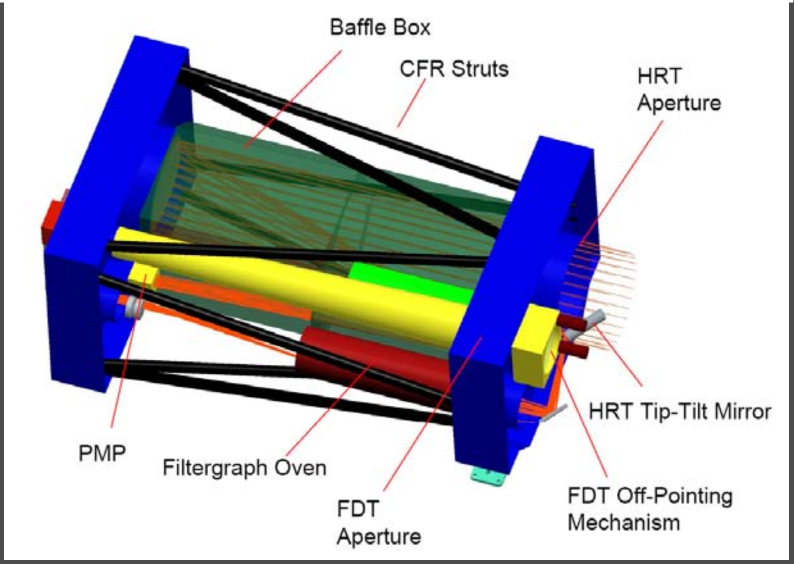
PHI will be composed of two telescopes and a filtergraph.

(1.) The off-axis Ritchey-Chrétien High Resolution Telescope (HRT) will image a fraction of the solar disk at a resolution reaching 150 km at perihelion (the same resolution as the Extreme Ultraviolet Imager's high resolution channels will have).

(2.) The refractor Full Disk Telescope (FDT) will be able to image the full solar disk at all phases of the orbit. It incorporates an off-pointing capability. Each telescope will have its own Polarization Modulation Package (PMP) located early in the optical path in order to minimize polarisation cross-talk effects. Polarimetry at a signal to noise level of 10^3 is baselined for PHI.

(3.) The HRT and the FDT will sequentially send light to a Fabry-Pérot filtergraph system (~ 100 mÅ spectral resolution) and on to a 2048 × 2048 pixel CMOS sensor. PHI will have its own Image Stabilization System (ISS) that will compensate spacecraft jitter or other disturbances.





Institutions with key H/W contributions:

Max-Planck-Institut für Sonnensystemforschung, Katlenburg-Lindau, D

Kiepenheuer-Institut für Sonnenphysik, Freiburg, D

Institute of Computer and Communication Engineering, Braunschweig, D

Instituto Nacional de Técnica Aeroespacial, Madrid, E

Instituto de Astrofísica de Canarias, La Laguna, E

Instituto de Astrofísica de Andalucía, Granada, E

ETSI Aeronáuticos, Madrid, E

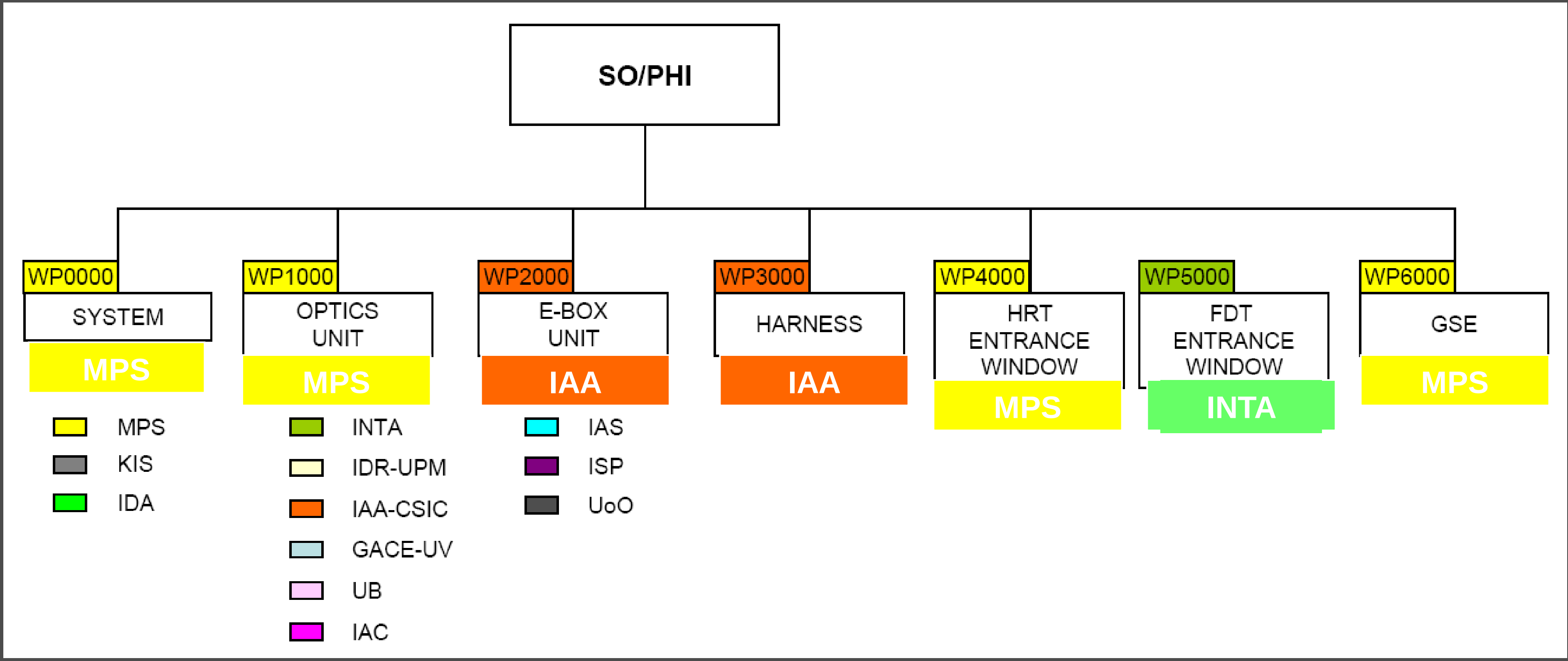
Dep. d’Electrònica Facultat de Física, Uni. de Barcelona, E

Grupo de Astronomía y Ciencias del Espacio, Valencia, E

Institut d’Astrophysique Spatiale, Paris, F

Institute for Solar Physics, Stockholm, S

PHI - Top Level Work Breakdown Structure

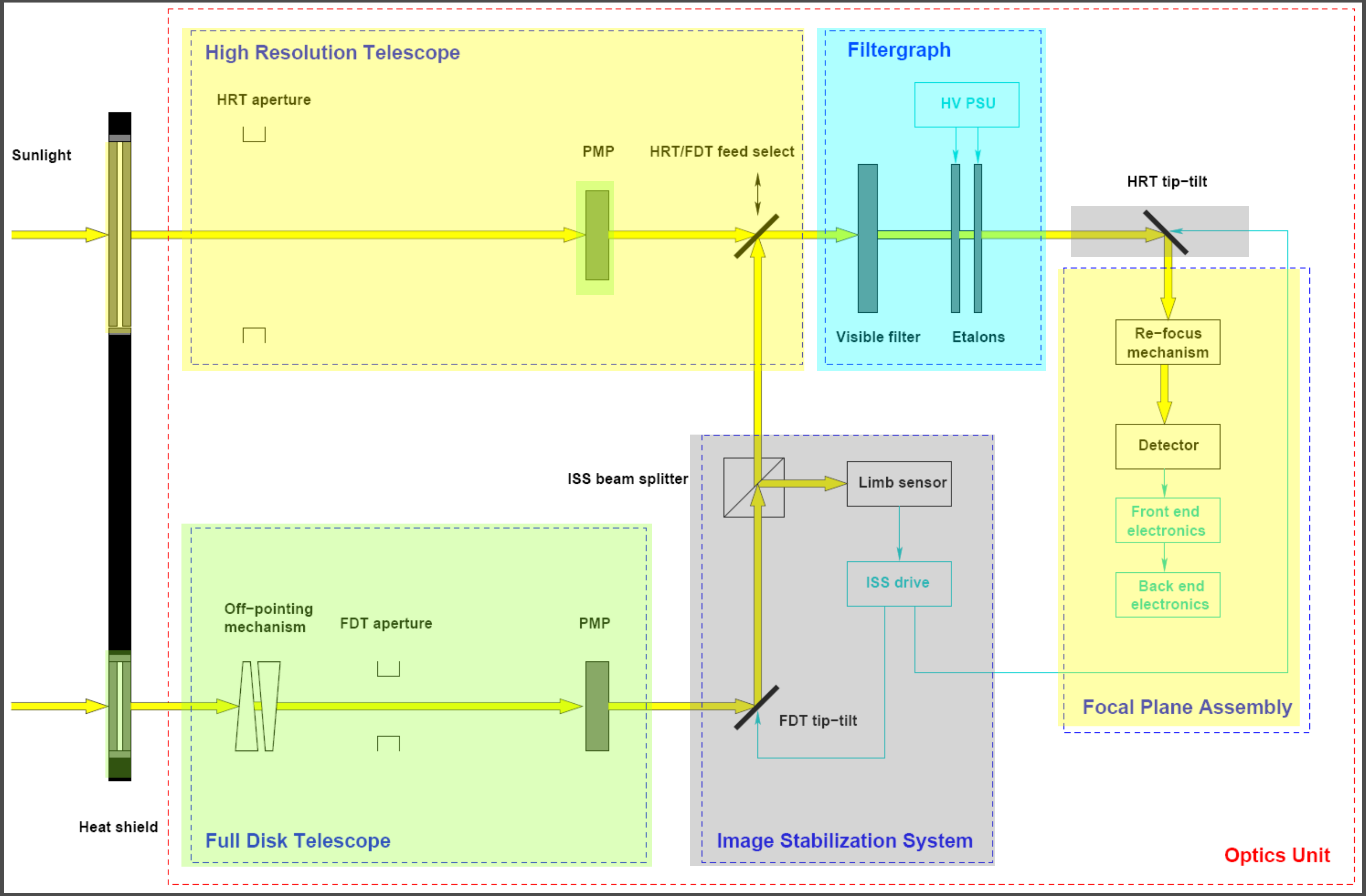


SO/PHI

- WP0000 SYSTEM – **MPS**
- WP1000 OPTICS UNIT – **MPS**
- WP2000 E-BOX UNIT – **IAA**
- WP3000 HARNESS – **IAA**
- WP4000 HRT ENTRANCE WINDOW – **MPS**
- WP5000 FDT ENTRANCE WINDOW – **INTA**
- WP6000 GSE – **MPS**

🟨 MPS
⬛ KIS
🟩 IDA
🟩 INTA
🟨 IDR-UPM
🟧 IAA-CSIC
🟦 GACE-UV
🟪 UB
🟪 IAC
🟦 IAS
🟪 ISP
⬛ UoO

PHI - Optics Unit Work Division



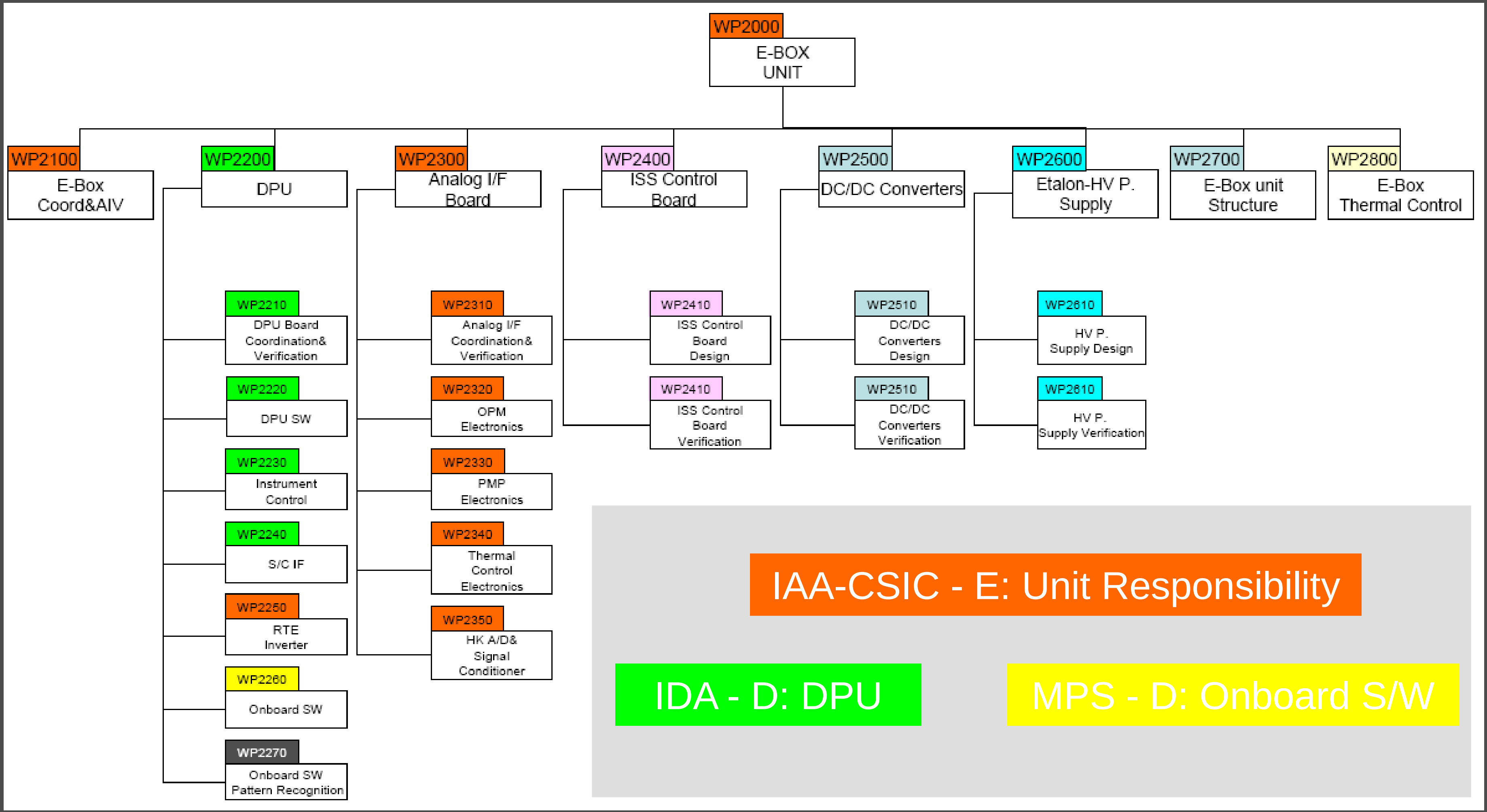
MPS - D

INTA - E

IAS - F

KIS - D

PHI - EBOX Work Breakdown Structure



WP2000 E-BOX UNIT

- WP2100 E-Box Coord&AIV
- WP2200 DPU
  - WP2210 DPU Board Coordination& Verification
  - WP2220 DPU SW
  - WP2230 Instrument Control
  - WP2240 S/C IF
  - WP2250 RTE Inverter
  - WP2260 Onboard SW
  - WP2270 Onboard SW Pattern Recognition
- WP2300 Analog I/F Board
  - WP2310 Analog I/F Coordination& Verification
  - WP2320 OPM Electronics
  - WP2330 PMP Electronics
  - WP2340 Thermal Control Electronics
  - WP2350 HK A/D& Signal Conditioner
- WP2400 ISS Control Board
  - WP2410 ISS Control Board Design
  - WP2410 ISS Control Board Verification
- WP2500 DC/DC Converters
  - WP2510 DC/DC Converters Design
  - WP2510 DC/DC Converters Verification
- WP2600 Etalon-HV P. Supply
  - WP2610 HV P. Supply Design
  - WP2610 HV P. Supply Verification
- WP2700 E-Box unit Structure
- WP2800 E-Box Thermal Control

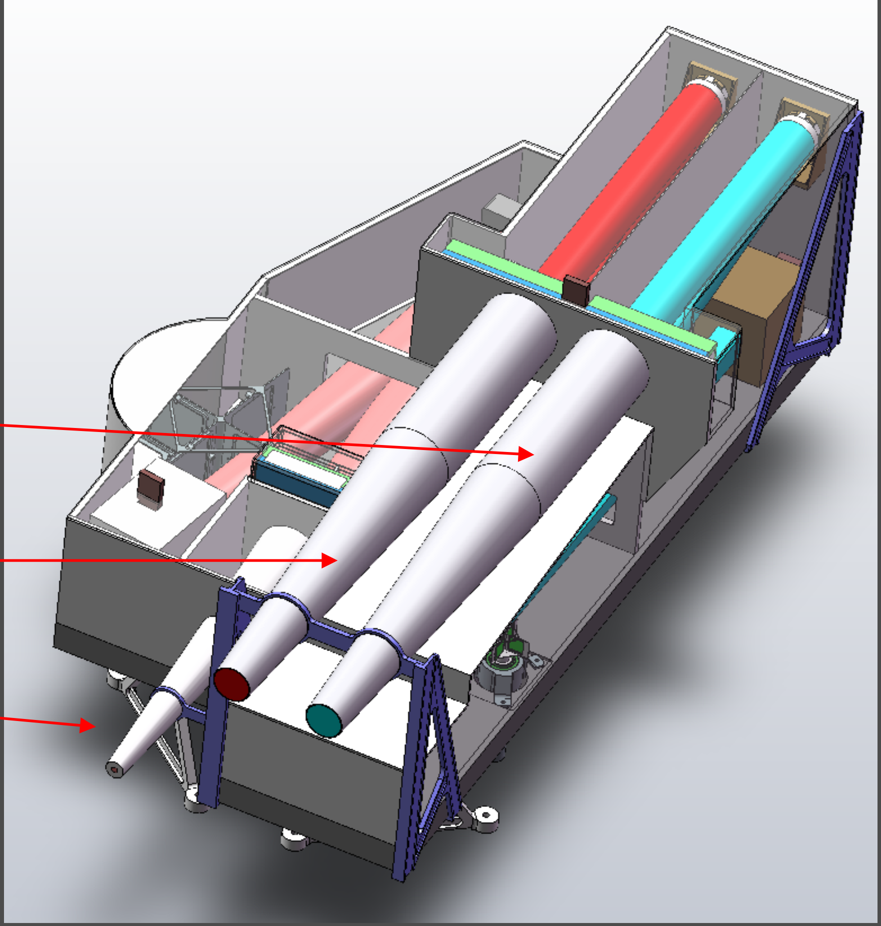
🟧 IAA-CSIC - E: Unit Responsibility

🟩 IDA - D: DPU

🟨 MPS - D: Onboard S/W

EUI telescope design

EUI: suite of 3 telescopes



HRI Lyman-α channel 121.6 nm

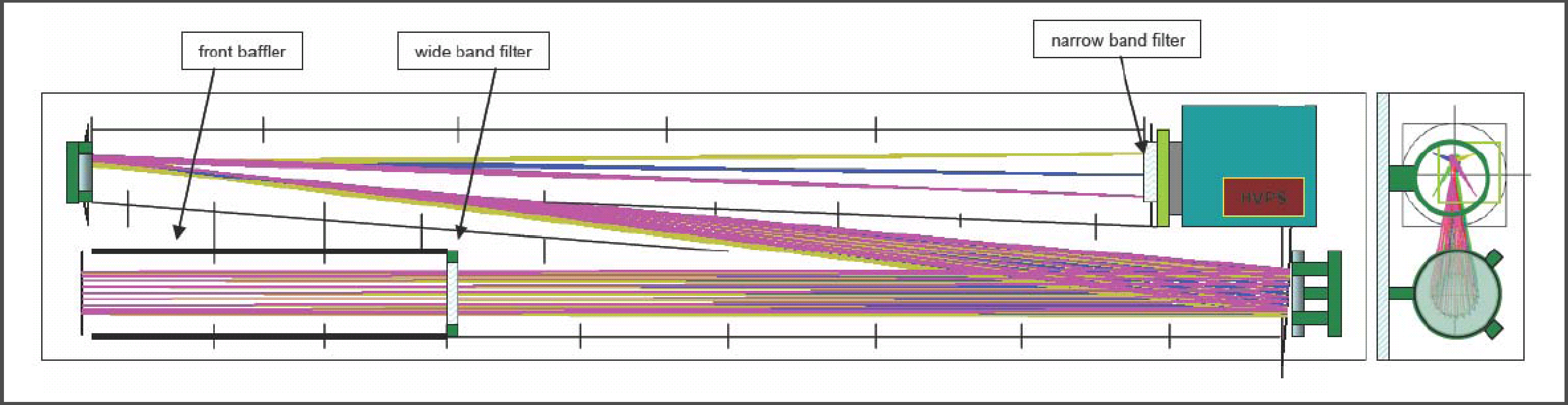
HRI EUV channel 17.4 nm

FSI dual EUV channel
17.4 nm and 30.4 nm

Ly-α channel components

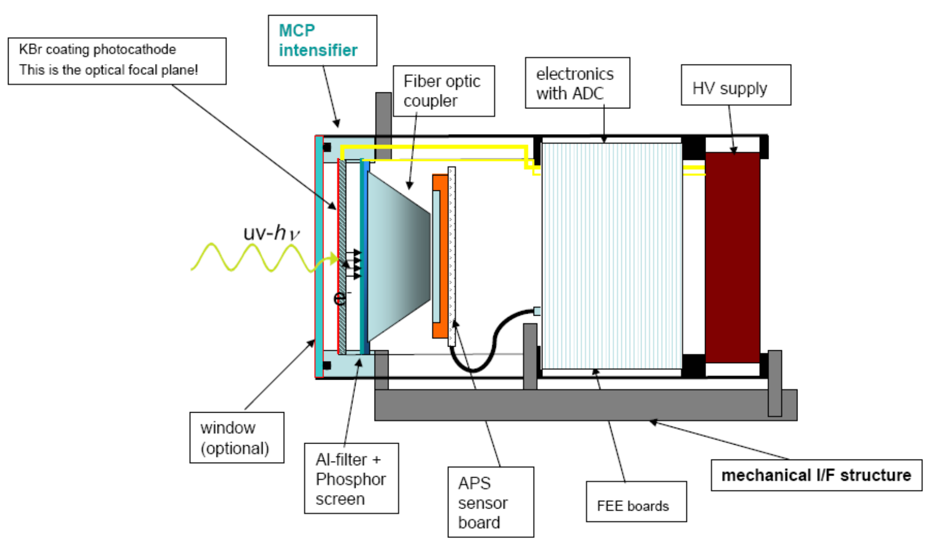
- Telescope entrance baffle door mechanism
- Solar-blind Lyman-α detector
- Optics:
  - Lyman-α narrow band filter (121.6 nm) by Acton Research C. inc.
  - off-axis primary mirror 30 mm diameter with special coating for 121.6 nm
  - off-axis secondary mirror with special coating

EUI Lyman- channel detector

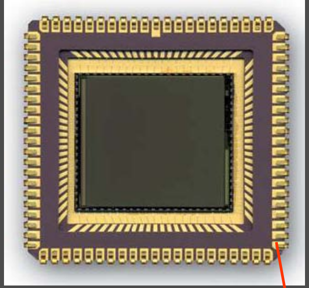


The Lyman-α detector:

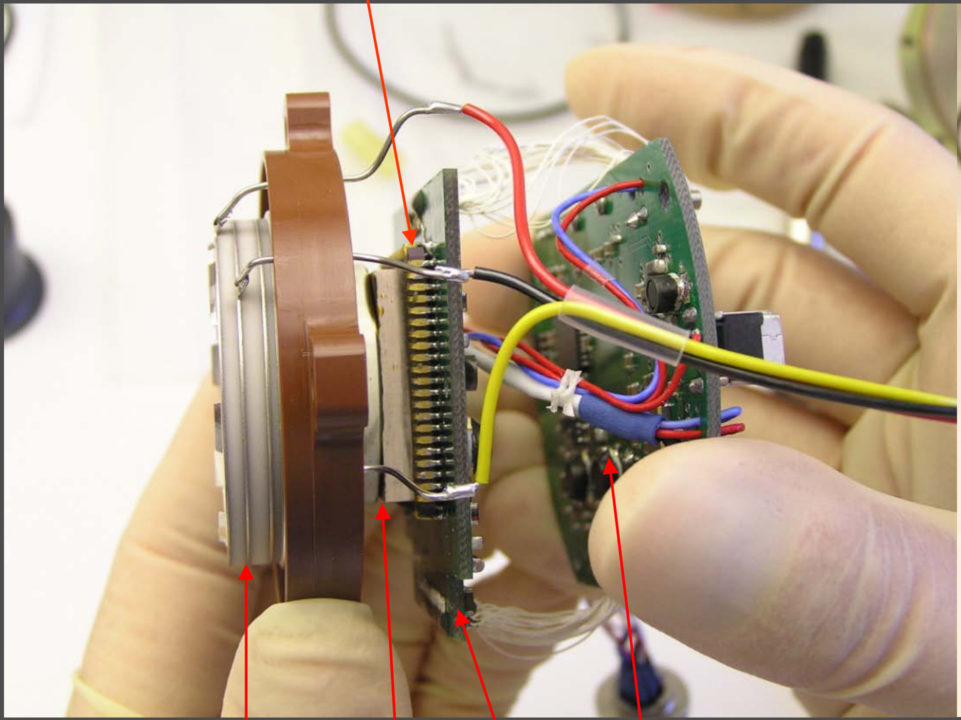
a solar-blind intensified CMOS/APS camera



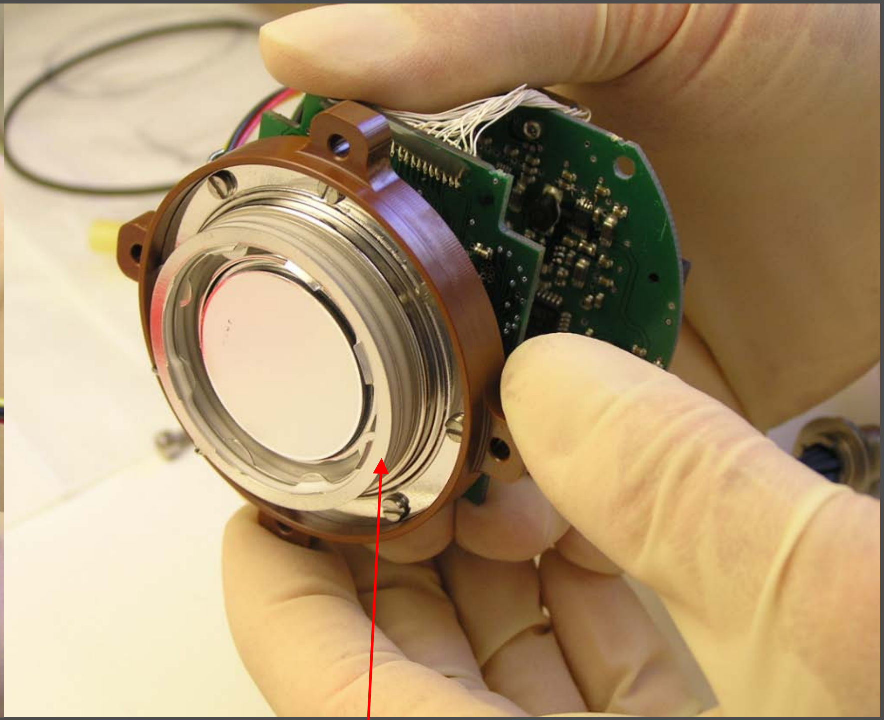
Coupling MCP intensifier with APS image sensor



STAR 1000
visible CMOS-APS sensor



MCP stack
fiber optic blocks
APS sensor board
FEE board



MCP housing

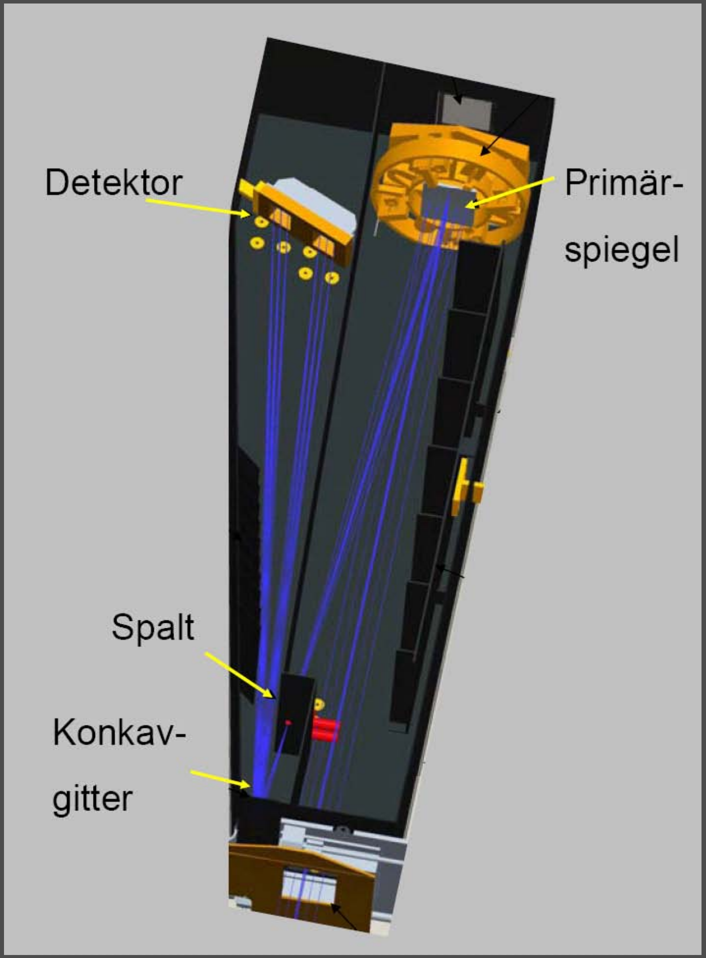
Solar Orbiter Instruments

SPICE

SPICE – Extreme-Ultraviolet Spektrograph:

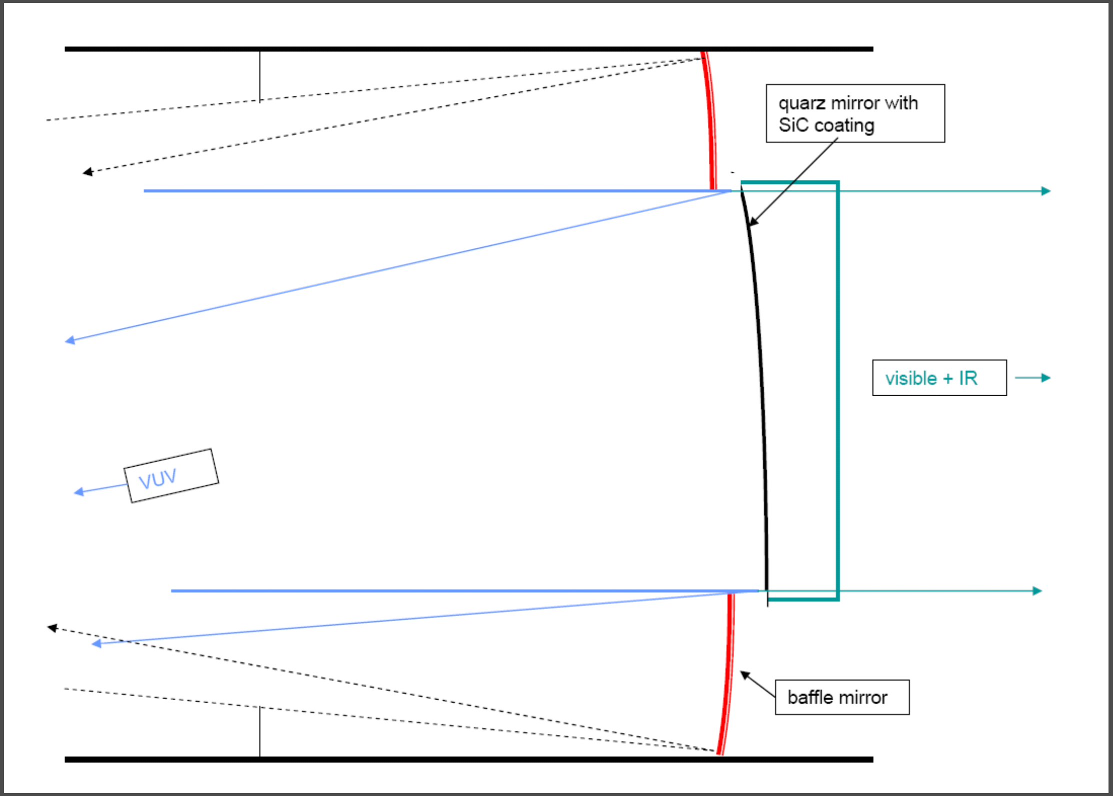
The SPICE instrument is a high-resolution imaging spectrograph with a movable occulter to observe the solar corona both on the solar disk and off limb out to 3 solar radii. For outer coronal observations the occulter is used to reduce stray light by fully occulting the solar disk.

To optimize throughput, the instrument consists of only two optical elements: a single off-axis parabolic telescope mirror and a toroidal variable line-spaced grating which re-images the spectrally dispersed radiation onto two array detectors. Two spectral passbands are recorded simultaneously with two intensified active pixel sensor (IAPS) detectors. The spectrograph will cover the extreme ultraviolet wavelength bands from 70.2 nm to 79.2 nm and from 97.0 nm to 105.0 nm (and 48.5 nm to 52.5 nm in 2nd order).



Developments for Solar Orbiter SPICE

Study of a dichroic telescope mirror

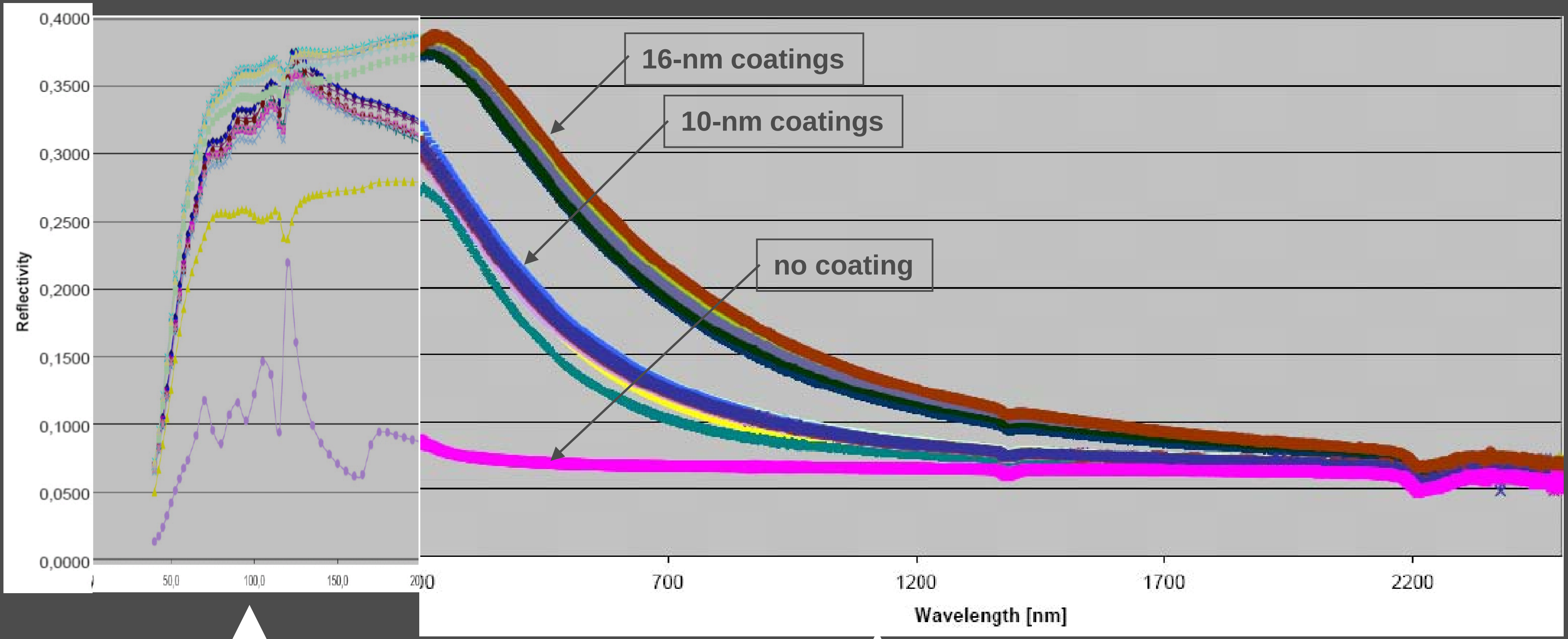


==> heat will be transmitted towards a radiator

Space qualification of mirror coatings

- Space radiation simulation: irradiation with 10 - 60 MeV protons
- Solar wind simulation: irradiation with 1 keV protons (mission equivalent dose)
- Solar UV simulation: irradiation with UV (20 solar constants)

Reflectance of B$_4$C coatings



EUV reflectance

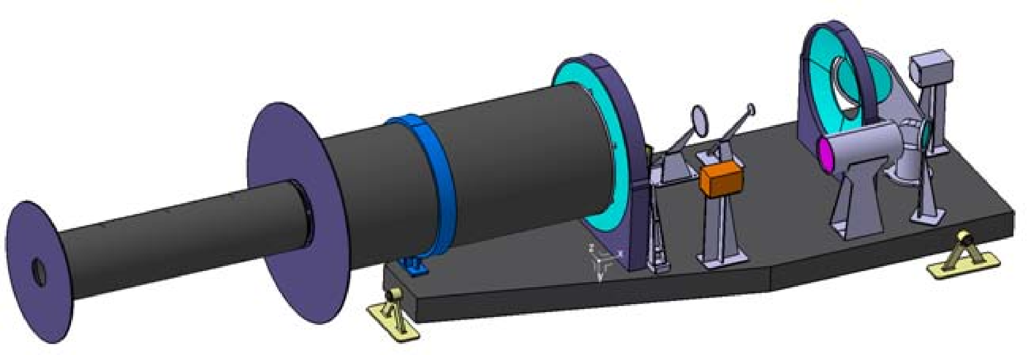
vis-IR relectance

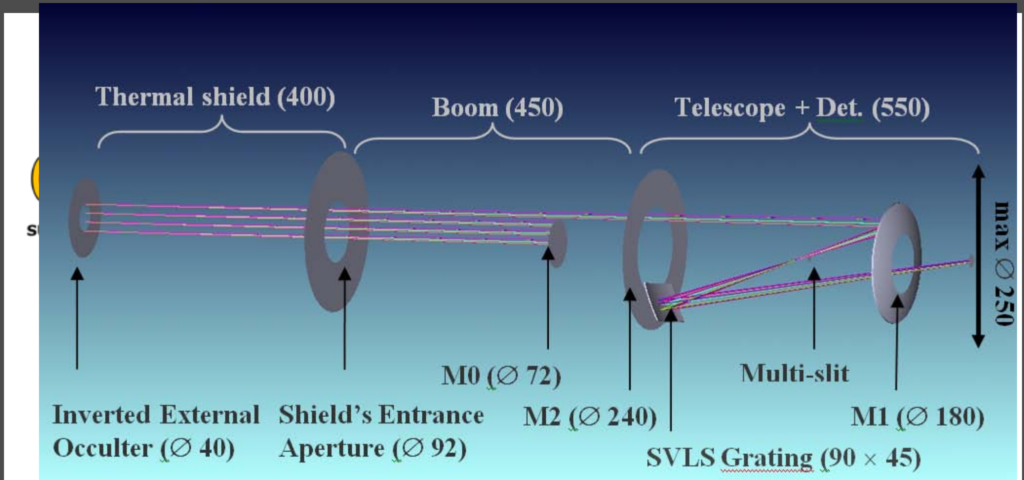
Solar Orbiter Instruments
METIS

METIS - The Multi Element Telescope for Imaging and Spectroscopy:

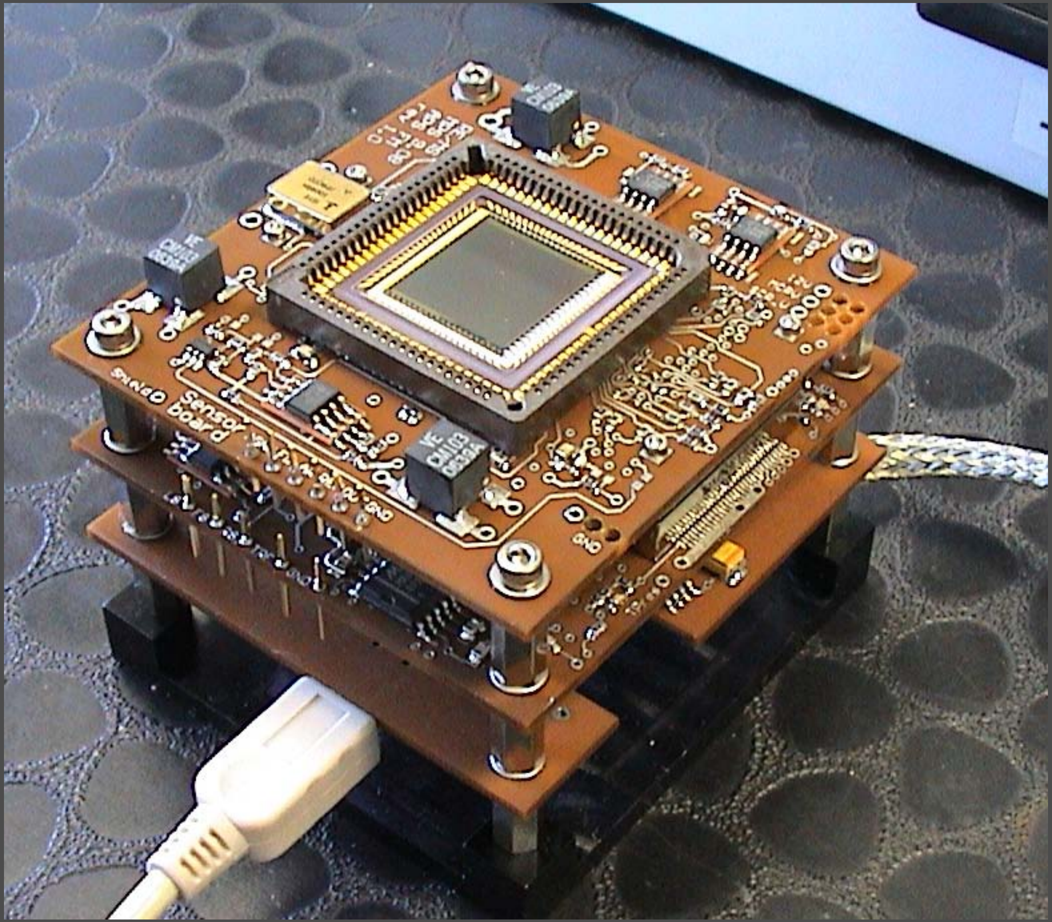
The METIS instrument is an inverted-occultation coronagraph that will image the solar corona in three different wavelengths (visible light between 450 and 650 nm, and the two Lyman-α lines of hydrogen and helium, H I 121.6 nm and He II 30.4 nm) by a combination of multilayer coatings and spectral bandpass filters. The visible channel also includes a polarimeter assembly to observe the linearly polarized component of the K corona.

Inclusion of spectroscopic capabilities allowing to record spectra of the H I and He II Lyman-α lines simultaneously at three different heights (accomplished by a multiple slit) in a 32° sector of the corona is under design study.





Space-qualifiable camera with the Star-1000 APS sensor



For the METIS UV camera this detector will be coupled with an open MCP intensifier (not MPS responsibility)

Performance characterization

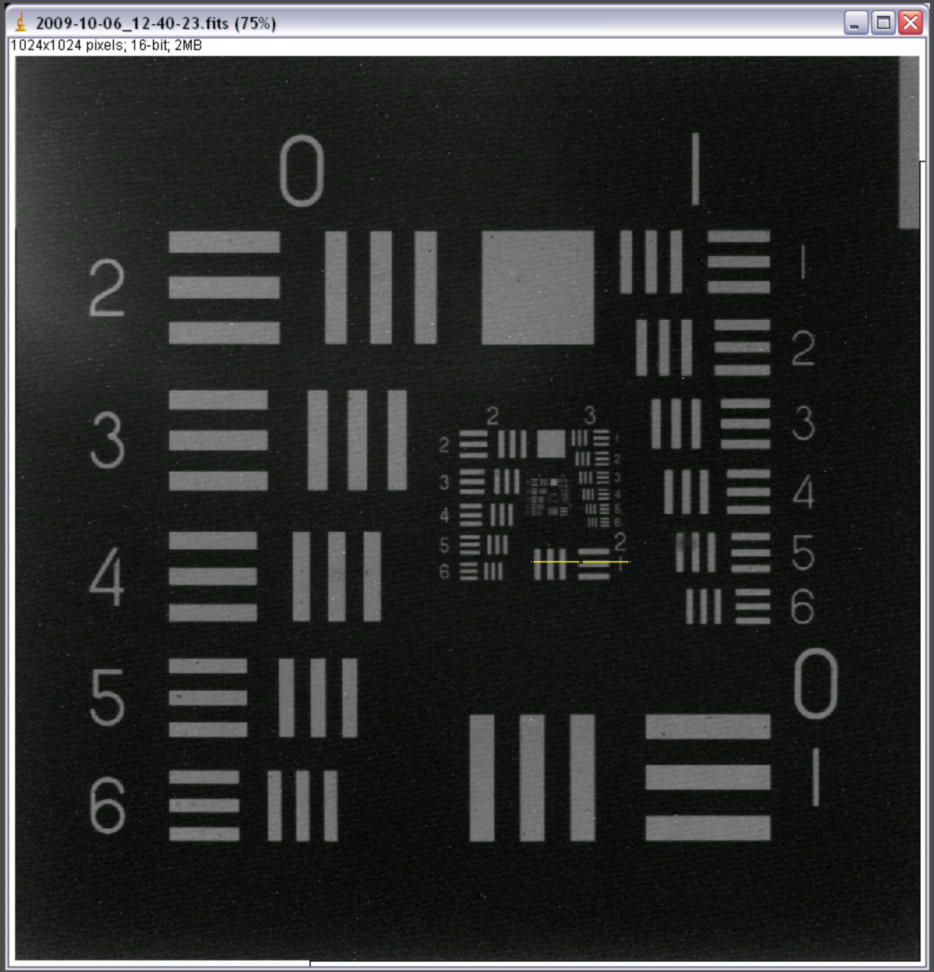
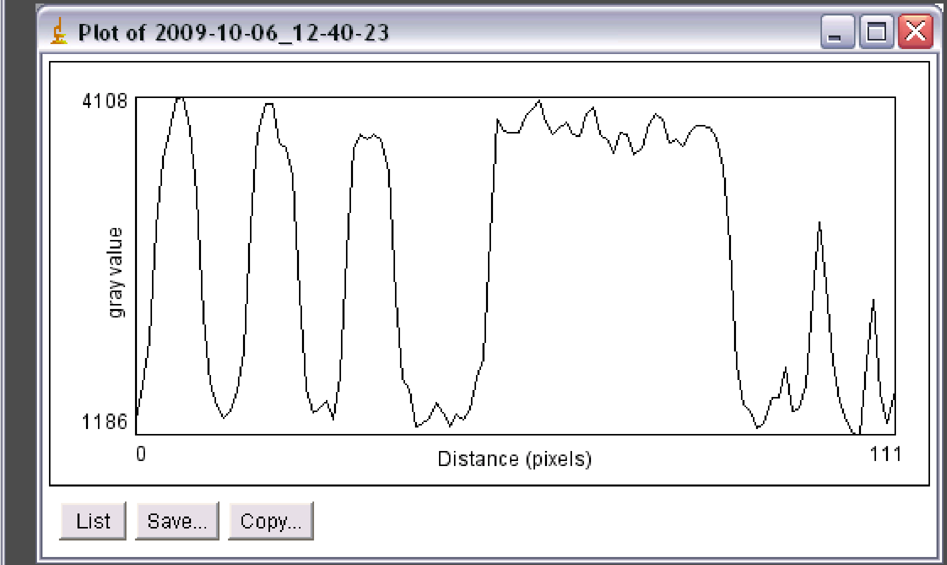


Image of a target. The yellow line is the location of the profile shown below



Instruments and Teams

Investigation	Principal Investigator	Collaborating countries
Solar Wind Analyzer (SWA)	C. Owen, MSSL, UK	UK, I, F, Japan, D, CH, USA
Energetic Particle Detector (EPD)	J. Rodríguez-Pacheco, Univ. Alcala, E	E, D, FI, GR, CH, F, SL, USA,Korea
Magnetometer (MAG)	T. Horbury, ICSTM, London, UK	UK, A, I, H, D, F, E, DK, USA
Radio & Plasma Waves (RPW)	M. Maksimovic, Obs. Meudon, Paris, F	F, SE, CZ, NO, UK, A, D, GR, AU, I, H, FI, Rus, USA
Polarimetric and Helioseismic Imager (PHI)	S. Solanki, MPS, Katlenburg-Lindau, D	D, E, F, S, NO, CH, AU, USA
EUV Imager (EUI)	P. Rochus, CSL, Liege, B	B, UK, F, D
Spectral Imaging of the Coronal Environment (SPICE)	D. Hassler, SwRI, Boulder, USA	USA, UK, D, F, N
X-ray Spectrometer Telescope (STIX)	A. Benz, ETH Zurich, CH	CH, PL, D, CZ, IRE, A, UK, F, USA
Coronagraph (METIS/COR)	E. Antonucci, Univ. of Turin, I	I, UK, F, D, GR, USA
Heliospheric Imager (SolOHI)	R. Howard, NRL, Washington DC,USA	USA

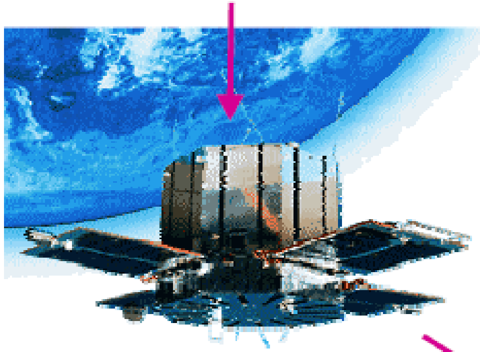
Solar-C:
the next Japanese Solar Mission

Material provided by S. Tsuneta, T. Shimizu, H. Hara

Historical background

Solar physics from space in Japan

Tansei
(Path finder mission)

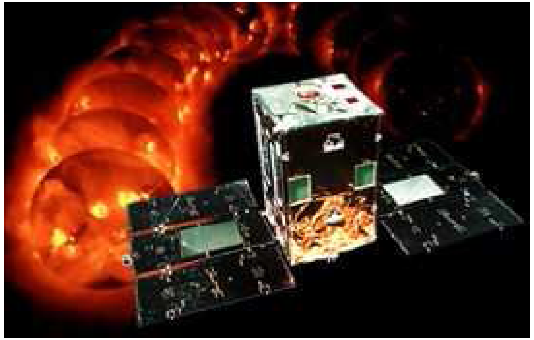


Hinotori (ASTRO-A)
188 kg, 1981

Non-thermal acceleration

- Hard-Xray imaging with rotation modulation collimator 10 arcsec
- Bragg crystal spectrometer
- SXS, HXS

With NASA, UK



Yohkoh (SOLAR-A)
390 kg, 1991

Non-thermal acceleration and plasma heating

- HXR Fourier telescope (J)
  7 arcsec
- Soft X-ray telescope (J/US)
  5arcsec
- Bragg spectrometer
  (J, US, UK)
- WBS

With NASA, UK

Hinode (SOLAR-B)
~ 900kg, 2006

Magnetic fields with corona

- SOT (Japan, US)
  0.2 arcsec
- XRT (US, Japan)
  2arcsec
- EIS (UK, US, Japan)
  2arcsec

New mission after Hinode: **Two *SOLAR-C* mission concepts**

- ***Plan A***: *Magnetic field, helioseismic and X-ray observations* from an out-of-ecliptic orbit to explore the polar region, internal structure and **solar activity cycle origin** (dynamo).

  <<Toward understanding the solar magnetic activity cycle>>

- ***Plan B*** *:*High spatial resolution, *high throughput, high cadence* spectroscopic and polarimetric observations *seamlessly from photosphere to corona* to investigate magnetism of the Sun and its role in heating and dynamism of solar atmosphere.

  <<Toward understanding the magnetic field dissipation processes and energy transfer in the atmosphere>>

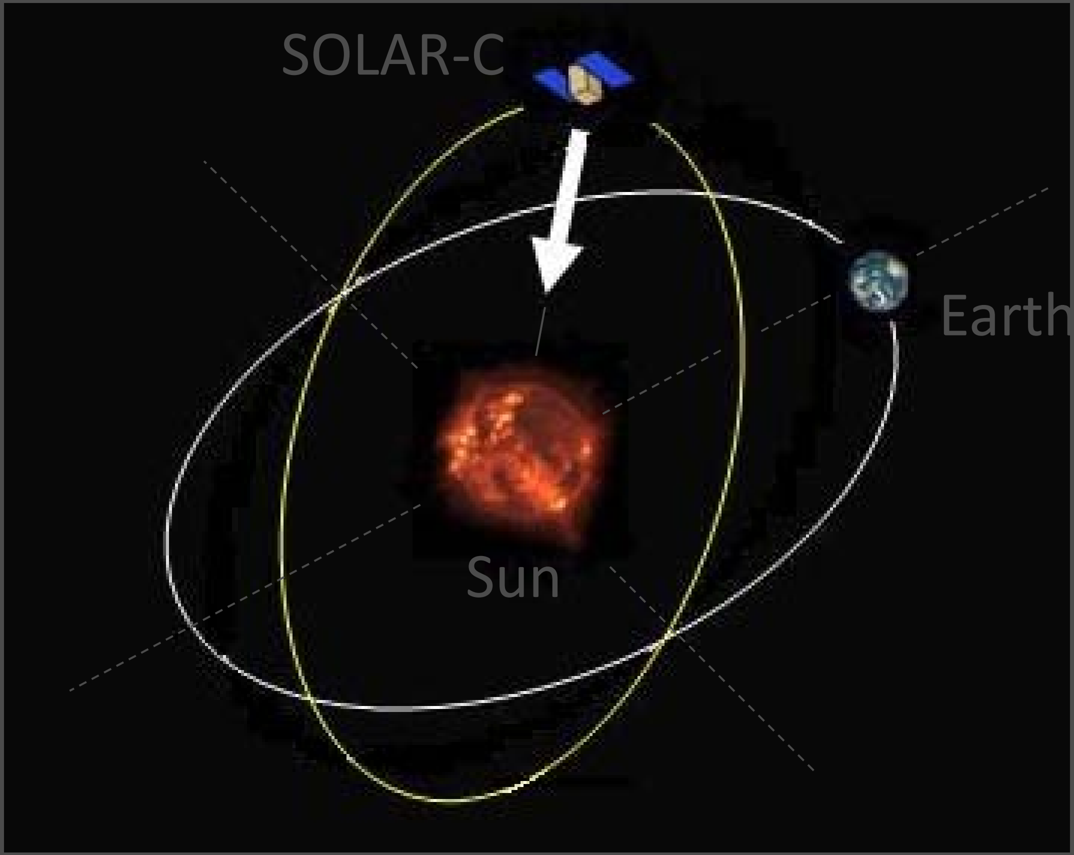
Latest study status

- The Solar-C WG was organized in JAXA in December 2008.
- "***International SOLAR-C Science Definition Meeting***" was held twice at ISAS/JAXA with participation of many scientists from European countries and US.
  - 18-21 November, 2008
  - 9-12 March, 2011
- Since March 2009, 4 sub WGs have been working to polish up sciences and payload concepts.
- The proposal will be submitted when the AO of the next JAXA mission comes out in 2011.

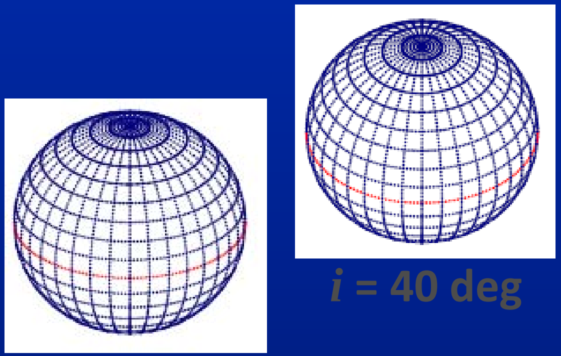
Plan A Candidate orbit

- Two different orbits are examined for the out-of-ecliptic mission for the Sun.
  - Short-period orbits near the earth by the cruise with Solar Electric Propulsion (SEP) like ion engines (+earth swing-by); SEP option
  - Long-period orbits by Jupiter swing-by; Jupiter Option

Plan-A: Target Final Orbit



Polar view from the out-of-ecliptic orbit



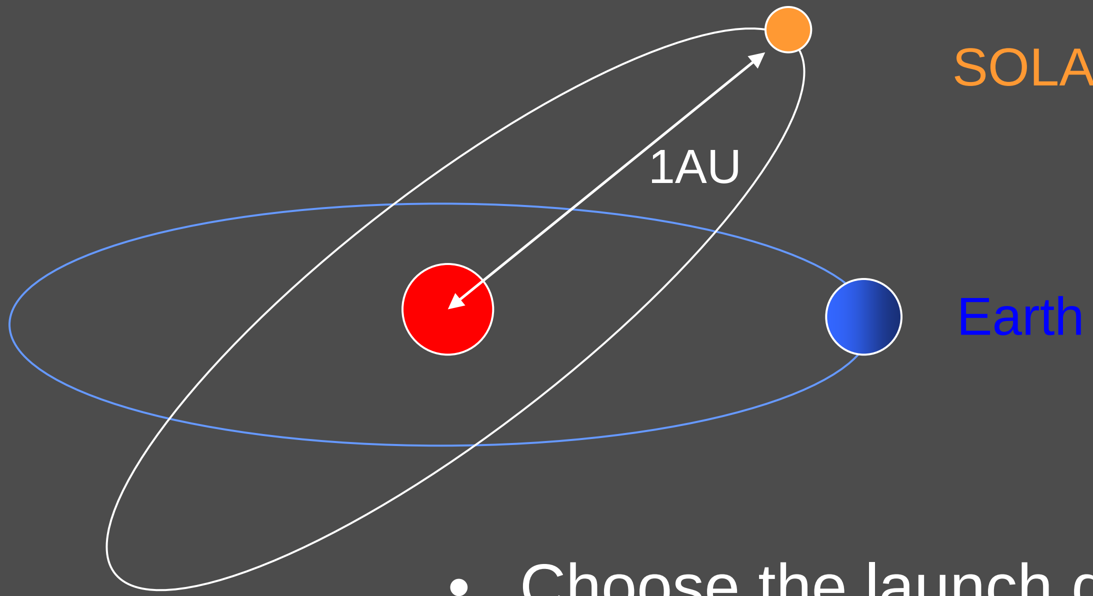
i = 40 deg

i = 30 deg

- The final orbit's inclination is ~40° from the equatorial plane

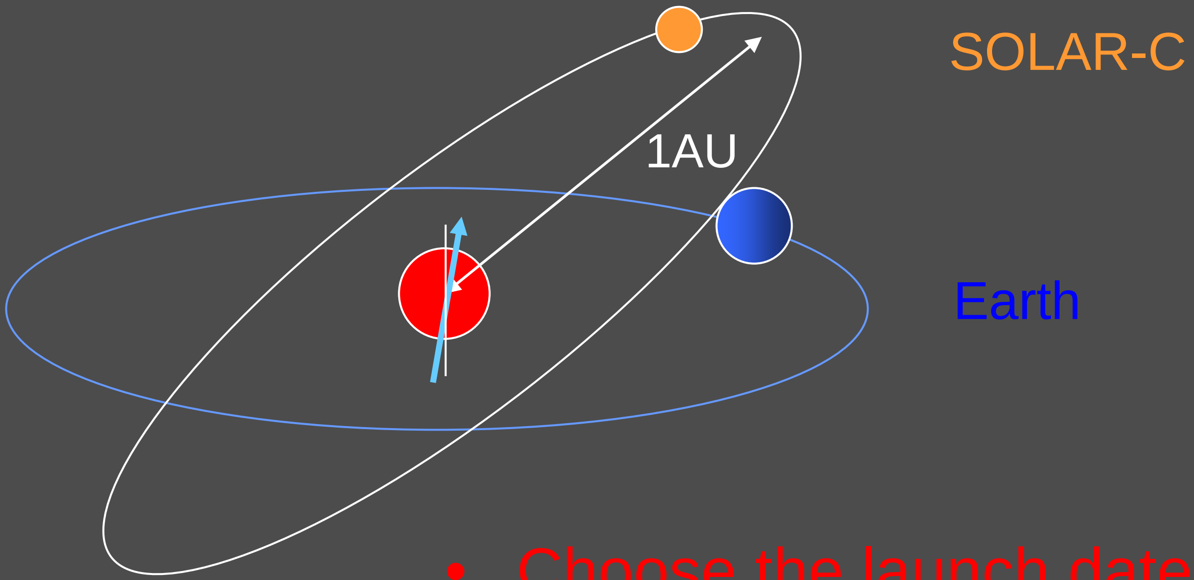
- The final orbit is at ~1 AU, orbital period of 1 y, synchronized with Earth orbit
- Cruise period ~5 years

Plan A: Final orbit to be achieved



- Choose the launch date to use the tilt angle of the Sun (7.25deg) to the ecliptic plane
- Rotate around the Sun in synchronization with the Earth. The Sun-spacecraft distance ~ 1.0 AU for a good telemetry condition
- Stable thermal conditions
- A moderate radiation environment

Plan A: Final orbit to be achieved



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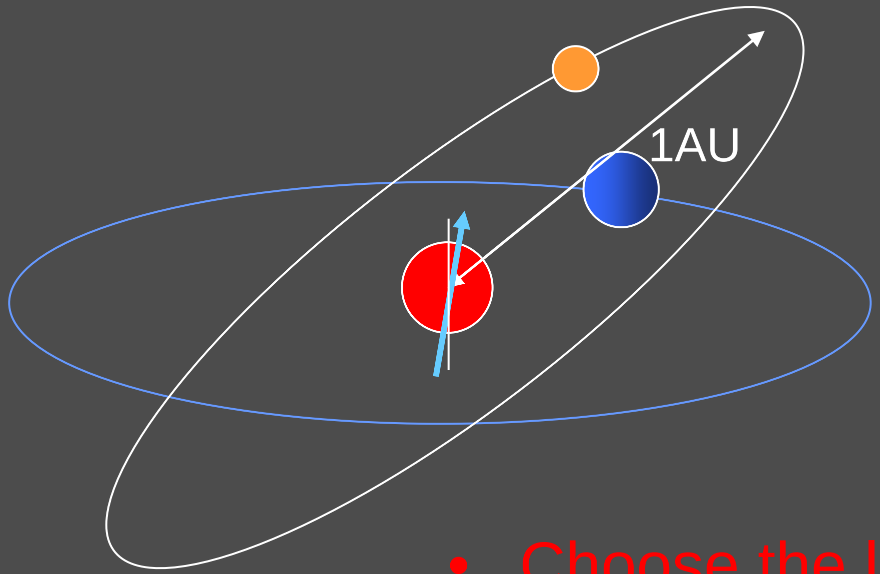

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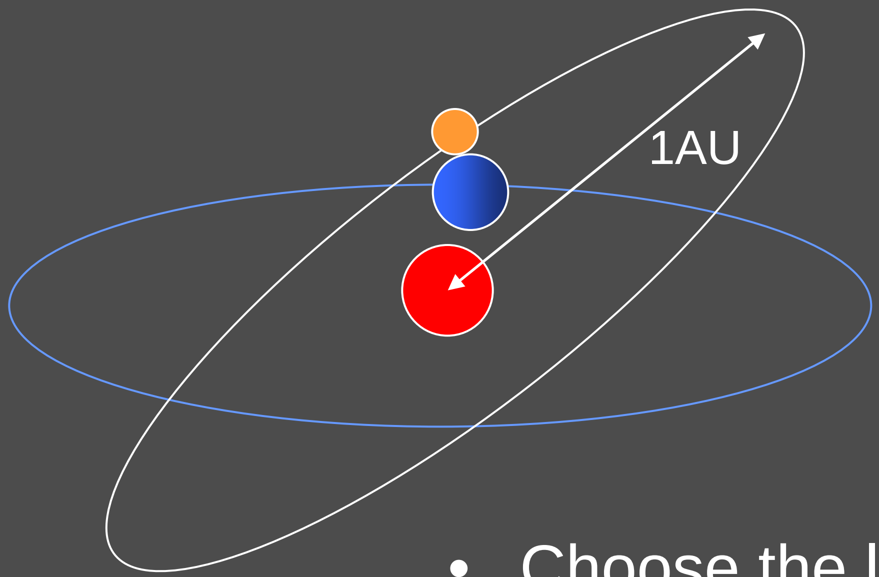

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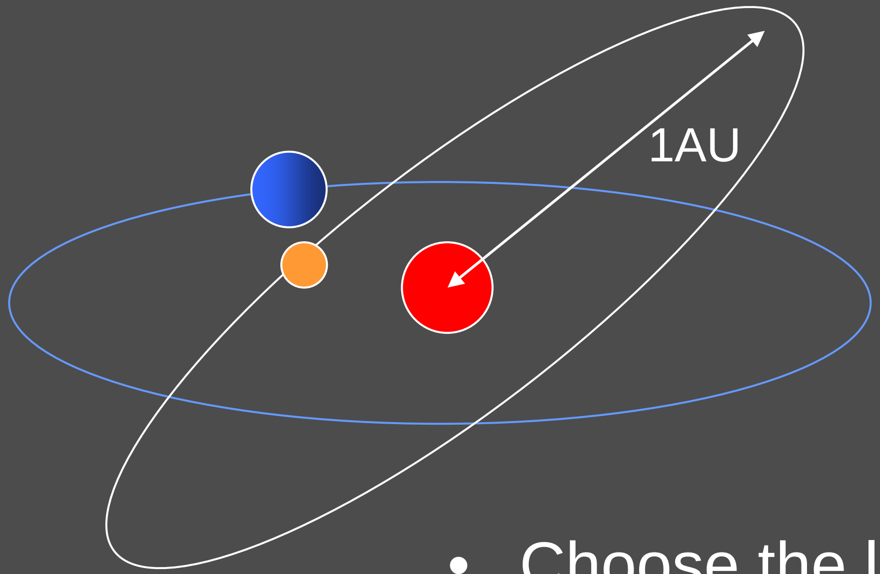

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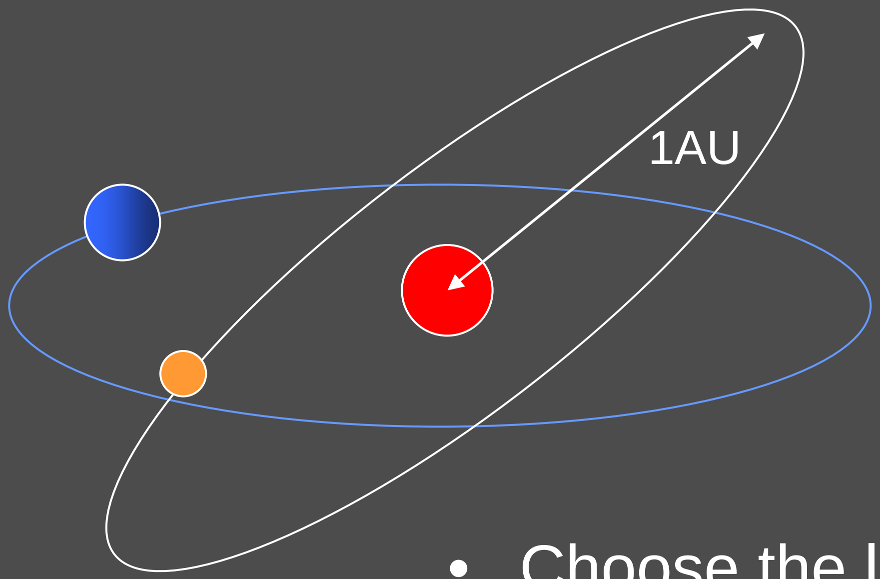

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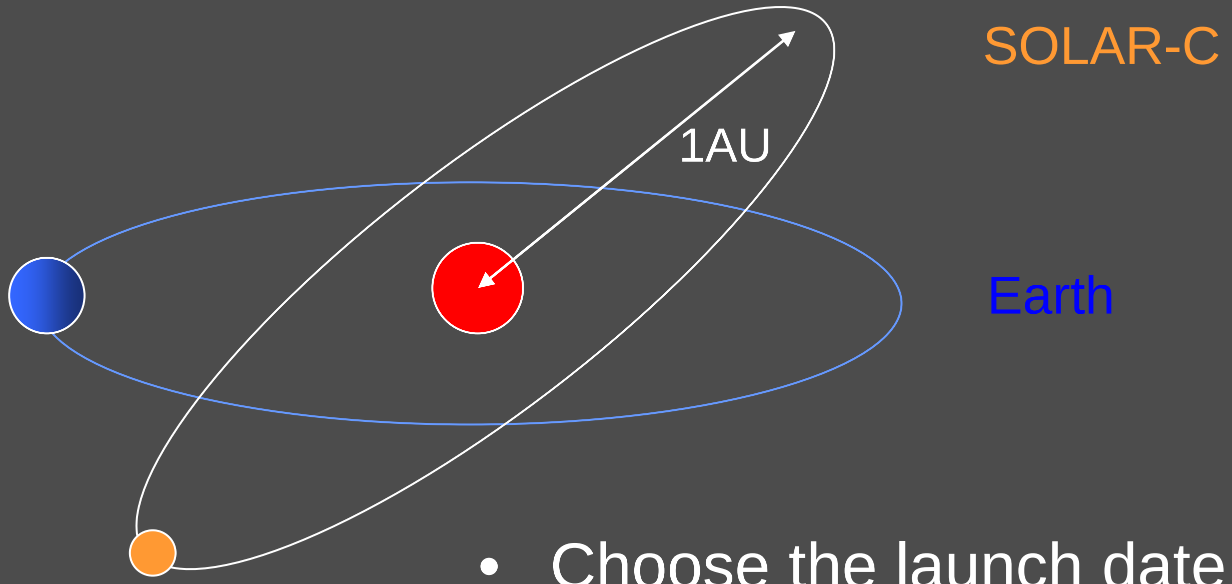

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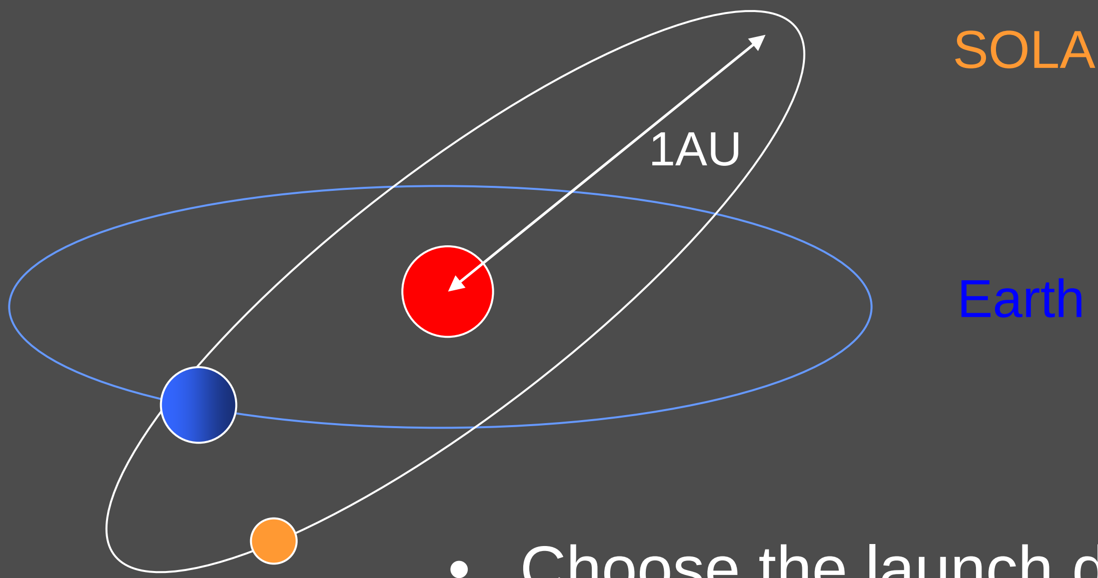

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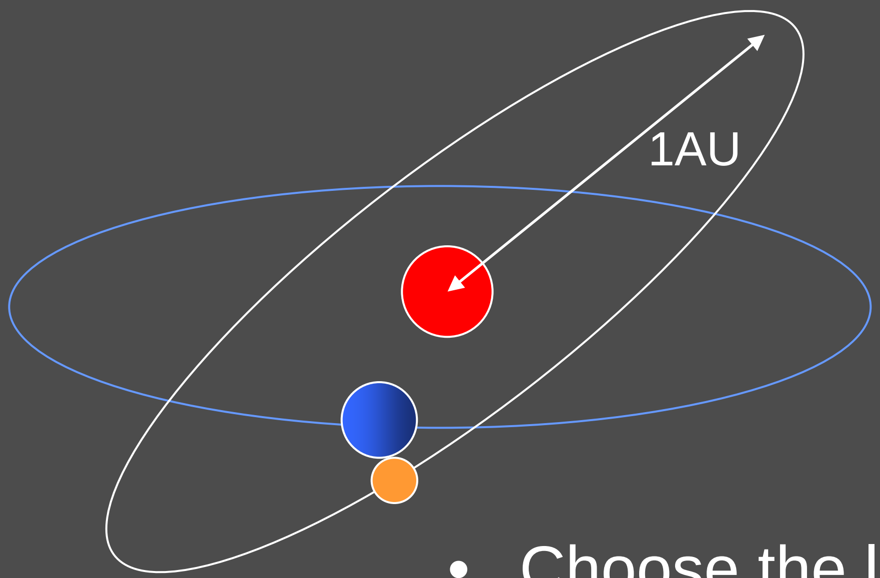

SOLAR-C

Earth

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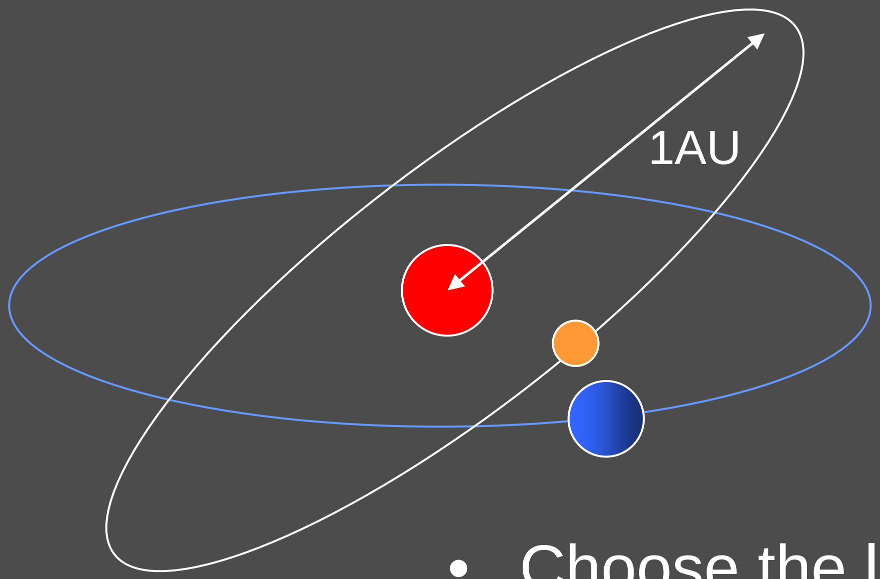
Plan A: Final orbit to be achieved



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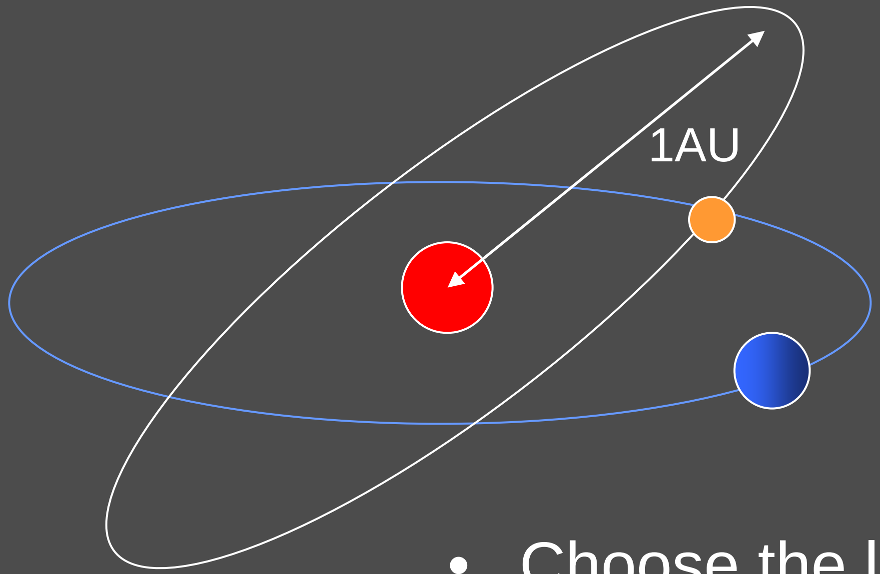
Plan A: Final orbit to be achieved



SOLAR-C

Earth

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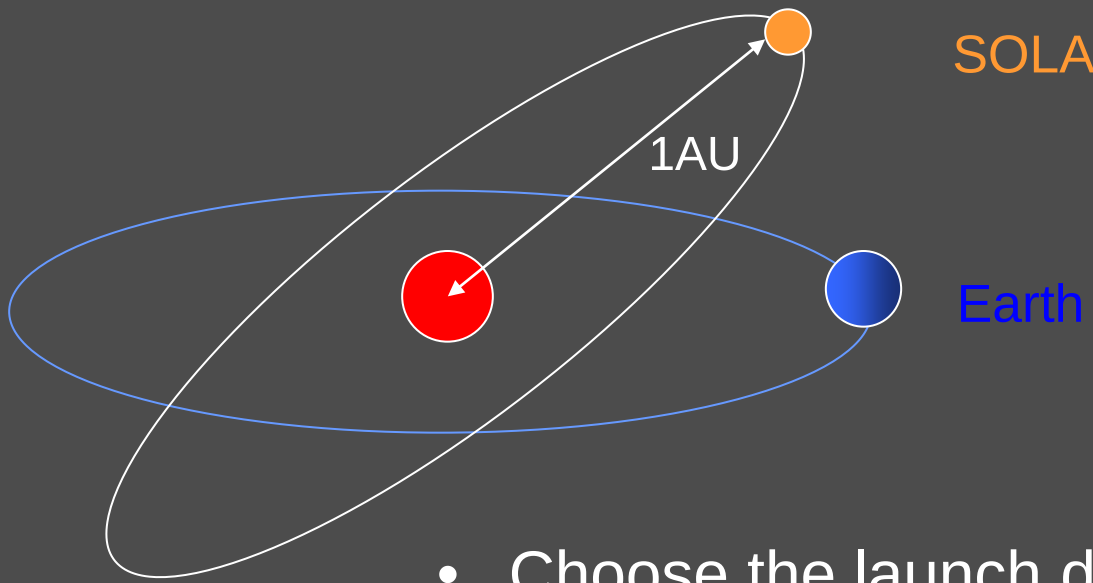
Plan A: Orbit to be achieved



Final inclination depends on the propulsion (SEP or ballistic) and trajectory characteristics.

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Plan-A :Model Payloads

Total mass **130 kg** (tentative allocation for design activity)
Data recording rate: **> 100 kbps on average**

Each has a space heritage (a slightly modified version) in the missions that have been already flown.

- **Visible-light Magnetic-field and Doppler imager**
  - full-disk observations
  - Internal flow structures, mag. fields, convection, .. in polar regions
- X-ray/EUV telescope
  - Coronal dynamics in polar regions, synergy with coronal imagers, observing the Sun around the Earth, in stereoscopic views
- EUV imaging spectrometer
  - Flow/wave structures in polar regions (plume, solar wind)
- Total irradiance monitor
  - Latitudinal distribution of surface irradiance
- Others (Options at present)
  - Heliospheric imager: CME imaging, solar wind/CIR shock structures
  - Zodiacal-light photometer: distribution of interplanetary dust
  - In-situ instruments (magnetometer, dust counter, …., etc.)

Plan-B: Spectroscopic & Polarimetric Observations

- *Mission*
  - *Quantitatively investigate fundamental physical processes in variety of solar plasma; roles of magnetic reconnection and MHD waves*
  - *How are fundamental processes linked to large-scale structures, dynamics, and heating?*

- New observational tools with ***SOLAR-C***
  - *From imaging to spectroscopy: Significantly enhance spectroscopic & polarimetric capabilities to UV and near-IR*
  - *High time resolution, high throughput spectrometer*
  - *Seamless observations from photosphere to corona*

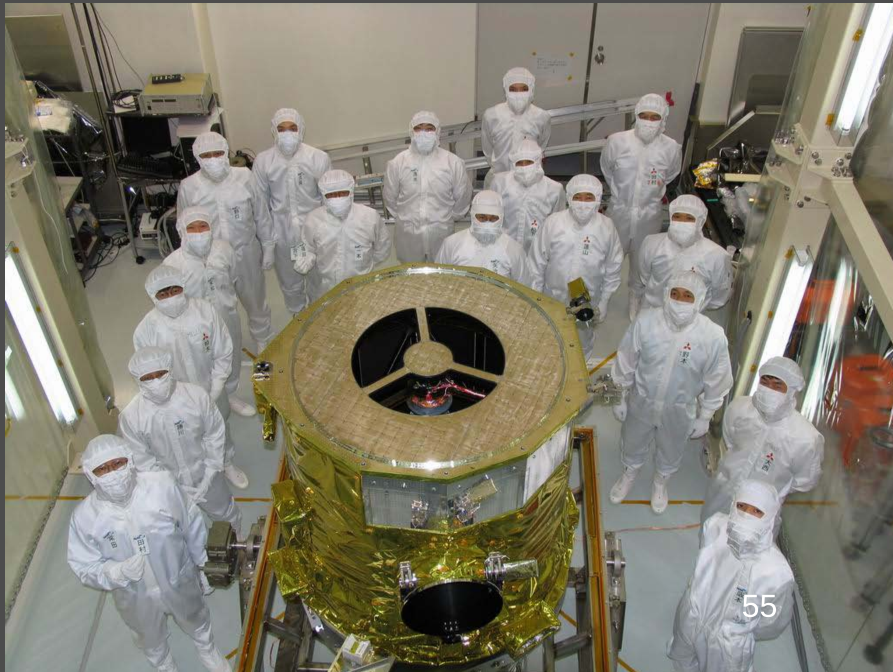
Plan-B: Concepts of mission instruments

- Advanced instruments to explore the solar magnetic atmosphere:
  - Precise spectroscopic & polarimetric observations for understanding nature of magnetic fields, especially in the chromosphere
  - High time resolution, high throughput spectroscopic observations for understanding nature of dynamics
  - Seamless observations over the entire atmosphere, i.e., from photosphere to corona, for understanding the entire pictures of heating and dynamics
  - High spatial resolution observations for resolving elementary physical processes

Plan B: model payloads (1)

- ***UV-Visible-Near IR telescope***
  - The aperture size under study is 1.5 meter in diameter, which can accumulate one order of magnitude larger number of photons in an exposure time than Hinode SOT.
  - Spectro-polarimetric and imaging measurements of magnetic field and dynamics with chromospheric spectral lines
    - He 1083nm and Ca II IR(854nm) with Zeeman + Hanle effect sensitivity
    - Mg II k/h (280nm) most suitable for dynamics.
  - Variety of spectral lines available for diagnosing the wide range of the lower atmosphere from photosphere to chromosphere.

Heritage: Completion of 50 cm diffraction-limited telescope for Hinode SOT @ NAOJ, Japan



Why we need a 1.5-m aperture

- S/N~10^4 for high precision spectro-polarimetry
  - He I 10830Å & Ca II 8542Å: 0.18"/pix, 10sec integration

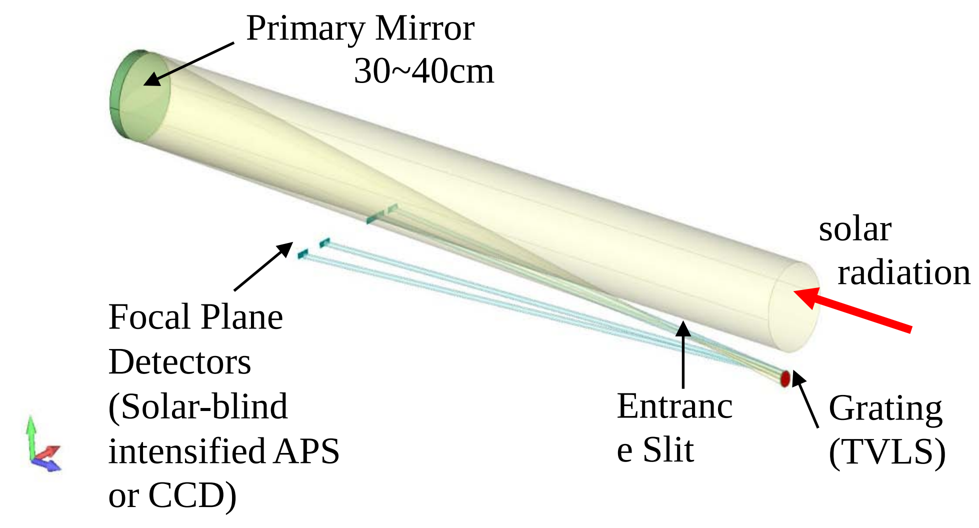
    We can temporally and spatially resolve dynamical phenomena in the chromosphere (spicules, jets, etc.) with magnetic field diagnostics.
- S/N~10^2 for high-speed spectroscopy
  - Mg II k 2796Å: 0.06"/pix, <0.5sec integration

    We can achieve the highest spatial and temporal resolution in spectroscopic diagnostics of the chromosphere.

Plan B: model payloads (2)

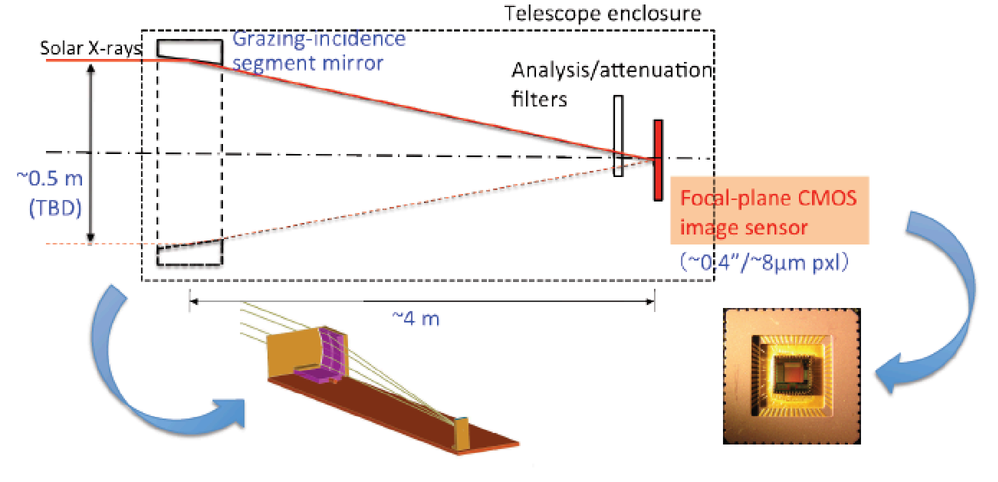
- ***UV/EUV high-throughput spectrometer***
  - High throughput to increase high temporal cadence
  - High spatial resolution better than 0.5 arcsec
  - The entire coverage of plasma temperature from the chromosphere, transition region to the corona and flare.

Strawman spectrometer



- ***X-ray imaging (spectroscopic) telescope***
  - Imaging emissions from >1MK coronal plasma
  - Option 1) Photon counting, i.e., spectroscopic capability for grazing incidence telescope with 0.5 arcsec
  - Option 2) Ultra-high spatial resolution (0.1arcsec) for normal incidence telescope

Photon-counting X-ray telescope



Tentative basic specifications of the three telescopes

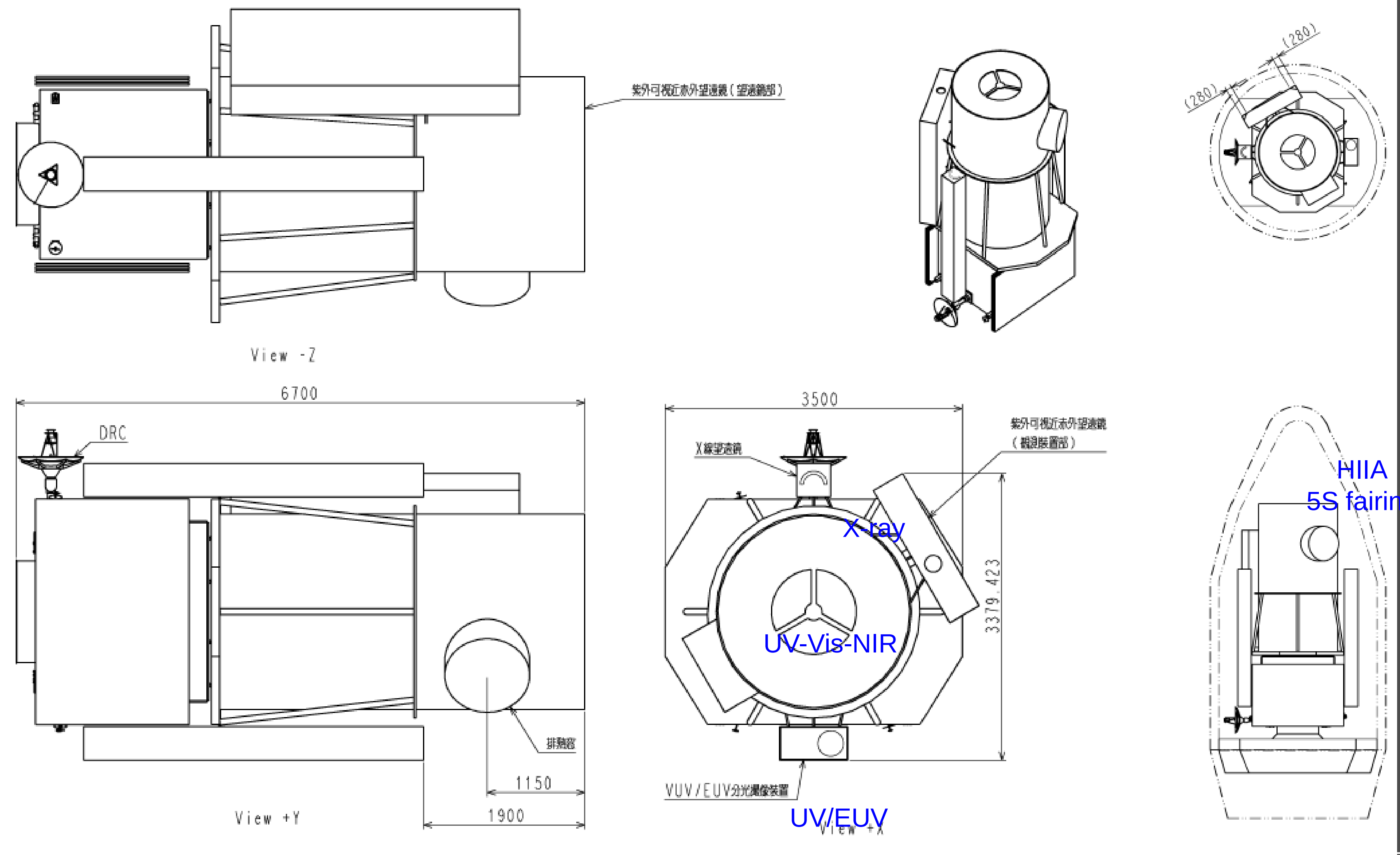
Pixel size and FOV

			FOV	Pixel size	Exposure	Note.
UV-Vis-NIR telescope		Broadband	164" x 164"	0.04"	< 1sec	• 2.5 pix sampling of **0.1"** res. • 4Kx4K detector
		Narrowband	246" x 246"	0.06"	< 1sec	• 2.5 pix sampling of **0.16"** res. • 4Kx4K detector
		Spectrometer	246" x 246"	0.06"	1sec (S/N~1600)	• 2.5 pix sampling of **0.16"** res. • 4K pix along slit
				0.12"	10sec (S/N~10^4)	
UV/EUV imaging spectrometer		Spectrometer	1024"x 1024"	0.5"	0.5sec (AR) 5sec(QS)	• **0.5"**pixel size • 2Kx2K MCP+CMOS detector
X-ray telescope	NI	Imaging	410"x410"	0.1"	1sec (AR) 10sec (QS)	• High res imaging with NI telescope • 4Kx4K detector
	GI	Imaging	1024"x1024"	0.5"	1sec	• Imaging spectroscopy with GI • 2Kx2K CMOS detector
		Photon count	1024"x1024"	2.0"	60sec	

Payload Size (used for spacecraft design)

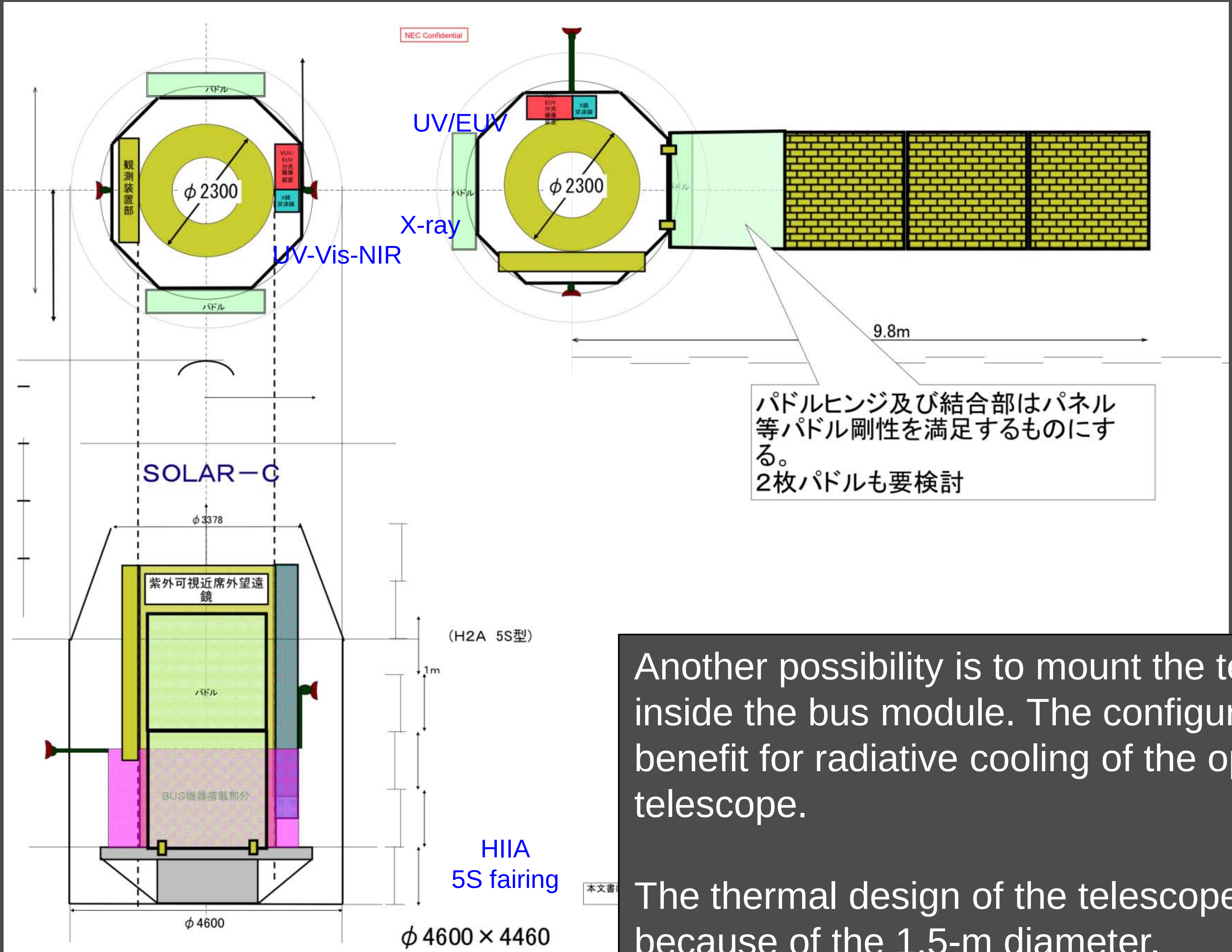
	Size (mm)	Weight (kg)
UV-Vis-NIR telescope (telescope)	ϕ2300x4300	500
UV-Vis-NIR telescope (focal plane instruments)	2500x400x3000	200
UV/EUV imaging spectrometer	400x800x4000	120
X-ray telescope	400x400x4000	100

Strawman configuration of the S/C (1)



Configuration similar to the design of HINODE (SOLAR-B). Telescopes are supported by an optical bench unit (OBU), which is a cylinder made up of composite material (Hinode heritage). Telescopes are kinematically mounted on OBU with six mounting legs constraining the degrees of freedom of the rigid body.

Strawman configuration of the S/C (2)



図＊＊－＊ H2A 搭載イメージ図

Another possibility is to mount the telescope inside the bus module. The configuration has benefit for radiative cooling of the optical telescope.

The thermal design of the telescope is critical because of the 1.5-m diameter.

Summary

- Two mission concepts have been studied for SOLAR-C.
- Both two mission concepts challenge important scientific questions of the Sun.
  - Plan A – the solar magnetic activity cycle.
  - Plan B – the magnetic field dissipation processes and energy transfer in the solar plasma.

  Both are important for solar physics and related fields.

- The JAXA SOLAR-C WG is now preparing an interim report.
  - The report is prepared for both mission concepts.
  - One of the missions will be submitted to JAXA in 2011, after reviewing them in the community.