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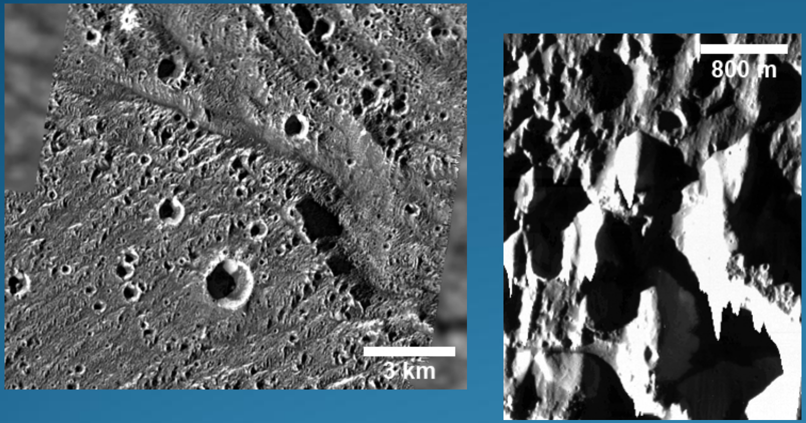
Update on the study for a High Resolution Camera (HRC) onboard the Jupiter Ganymede Orbiter (JGO)

Proposing Institutions: INAF/DLR

L. Colangeli[1], R. Jaumann[2], F. Capaccioni[3], A. J. Coates[4], G. Cremonese[5], S. Debei[6],V. Della Corte[1], T. Denk[7], K. Eichentopf[2], P. Eng[8], F. Esposito[1], G. Galuba[7], R. Greeley[9], A. D. Griffiths[4], O. Hartmann[7], H. Hiesinger[10], H. Hoffmann[2], Y. Langevin[11], G. Marra[1], E. Mazzotta Epifani[1], H. Michaelis[2], C. Molfese[1], S. Mottola[2], J.-P. Muller[4], G. Neukum[7], J. Oberst[2], P. Palumbo[12], C. Popa[1], T. Roatsch[2], P. Schipani[1], N. Schmedemann[7], N. Schmitz[2], H. Sierks[13], K. Stephan[2], R. Wagner[2], S. van Gasselt[7], M. Zusi[1]

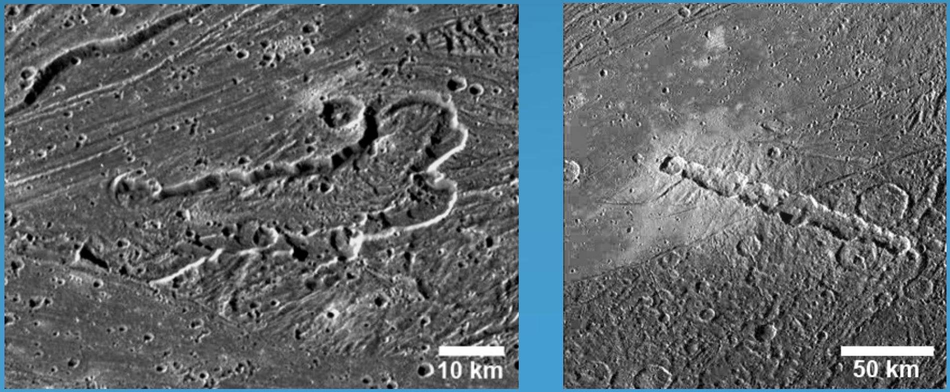
[1] INAF – Osservatorio Astronomico di Capodimonte, Napoli (Italy)
[2] German Aerospace Center, DLR, Institute of Planetary Research, Berlin (Germany)
[3] INAF – IASF, Rome (Italy)
[4] Mullard Space Science Laboratory – University College London, Holmbury St. Mary, Dorking, Surrey (UK)
[5] INAF – Osservatorio Astronomico di Padova (Italy)
[6] CISAS - Università di Padova (Italy)
[7] Freie Universität, Institut für Geologische Wissenschaften, Berlin (Germany)
[8] Institut d'Astrophysique Spatiale – Orsay (France)
[9] School of Earth and Space Exploration, Arizona State University, Tempe, Arizona (USA)
[10] Institut für Planetologie, Westfälische Wilhelms-Universität, Münster (Germany)
[11] Institut d'Astrophysique Spatiale - CNRS / Univ. Paris Sud XI, Orsay (France)
[12] Università Parthenope – Napoli (Italy)
[13] MPI für Sonnensystemforschung, Katlenburg-Lindau (Germany)

Major scientific goals

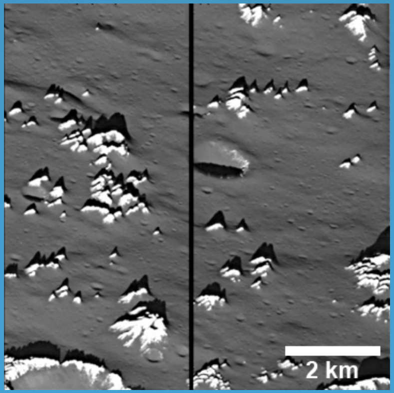


Highest-resolution images of Ganymede acquired during the Galileo mission with 15 m/pxl (SSI observation 28GSSMOOTH01) (left) and 11 m/pxl (SSI observation G1GSSULCUS01) (right).

1. Investigation of Ganymede's and Callisto's geology
2. Monitoring of Io's geologic activity and investigation of the surface of Europa
3. Studying the physical and chemical properties of Jupiter's rings as well as the inner and outer irregular satellites including the discovery of new ones and the detailed structure of Jupiter's atmosphere.



Possible volcanic activity on Ganymede (left) and Impact features on Ganymede



Highest-resolution images of Callisto acquired during the Galileo mission acquired with 10 m/pxl (Galileo image PICNO 30C004).

Performance Requirements

Performances required at Ganymede are considered design drivers:

- Derive imaging swaths at highest resolution (swath width: ~ 1000 m, ~1 m/pix @ 200 km)
- Allow for stereo coverage by repeated passes over areas of interest with camera tilt
- High signal-to-noise ratio
- Lifetime: 2 years in Ganymede orbit

Other requirements are related to other mission phases (Jupiter Orbit, satellites fly-bys):

- Allow for astrometric measurements (high sensitivity and dynamics)
- Derive high-resolution snapshots of distant targets
- Multispectral imaging capability with different colours
- Allow for geometric and radiometric calibration

Operation Requirements

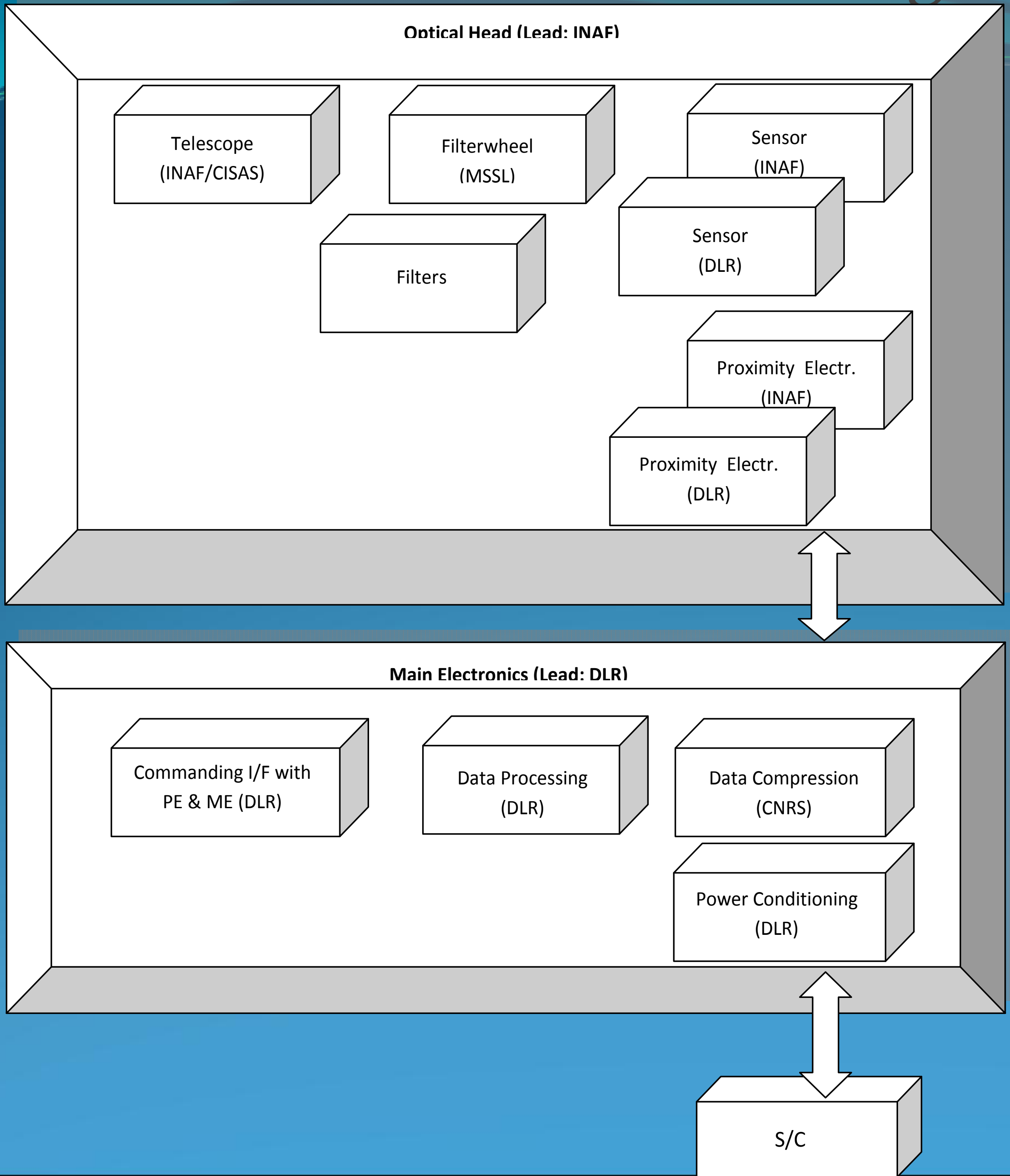
Operation requirements include:

- The instrument will operate during the Satellite tour as well as during the spacecraft orbit phase
- The pointing prediction shall be sufficiently accurate to successfully point the camera at distant targets. The pointing shall be stable within the size of a fraction of an image pixel during the typical exposure time
- The camera shall maintain nadir-pointing along orbit. *The direction of the velocity vector with respect to the spacecraft must be stable along the orbit to allow for the needed motion compensation during image acquisition*
- The instrument operation schedule should allow for geometric and radiometric calibration, instrument alignment cross-calibration and performance tests.

To be noted that:

- Yaw steering is foreseen on JGO
- AME: 125 µrad of absolute accuracy for co-location with low resolution images; 5 µrad to allow Ganymede rotational status measurements (e.g.: libration, polar wandering)
- RPE: It shall be 0.5 µrad/ms (1/10 pixel-2 σ) in pitch and roll and 97.7 µrad/ms in yaw at ms scale. RPE (s scale) shall be 5 µrad/s in pitch and roll and 488.3 µrad/s in yaw
- Requirements on Ganymede elliptical orbit to be discussed

Instrument block-diagram



Optical Head (Lead: INAF)

Telescope (INAF/CISAS)

Filterwheel (MSSL)

Sensor (INAF)

Sensor (DLR)

Filters

Proximity Electr. (INAF)

Proximity Electr. (DLR)

Main Electronics (Lead: DLR)

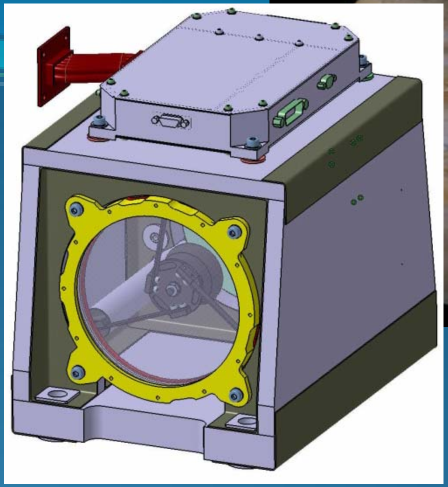
Commanding I/F with PE & ME (DLR)

Data Processing (DLR)

Data Compression (CNRS)

Power Conditioning (DLR)

S/C



HRIC SIMBIO-SYS for BepiColombo

Dawn Framing Camera, credit: MPS/DLR

Instrument Design Issues

Compromise between mission design, performances and operation requirements is challenging:

- ➢ high SNR vs. low flux, short integration time
- ➢ need of TDI or motion compensation vs. yaw steering
- ➢ different requirements for different mission phases (e.g., panchromatic vs. multi-filter observations)

Careful trade-off analysis needed

➢ **signal improvement**

- optical solution: f/3.3 => dia 600/700 => not feasible with available resources
- mechanism: various solutions with secondary or plane mirror tilting or FPA linear motion
- electronics: TDI, pseudo-TDI (frame or few lines)

➢ **yaw steering compensation**

- de-rotator optical mechanism
- motion compensation on two axis (but .... mosaic geometry not good)

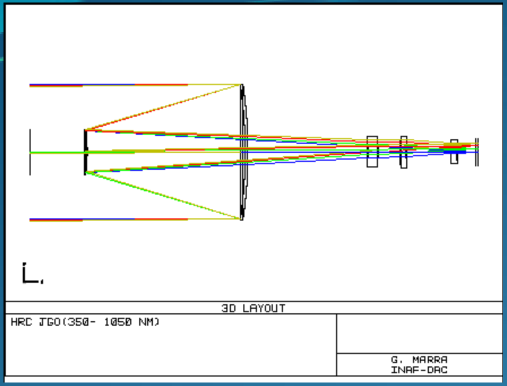
➢ **filters**

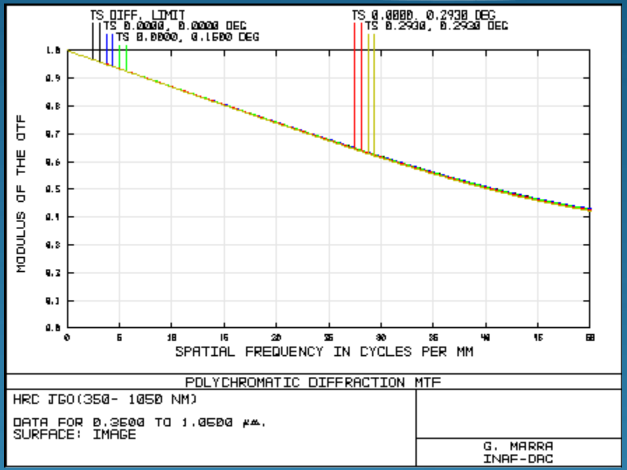
- filters wheel
- filters wheel plus one strip filter
- strip filters on detector

Instrument Concept

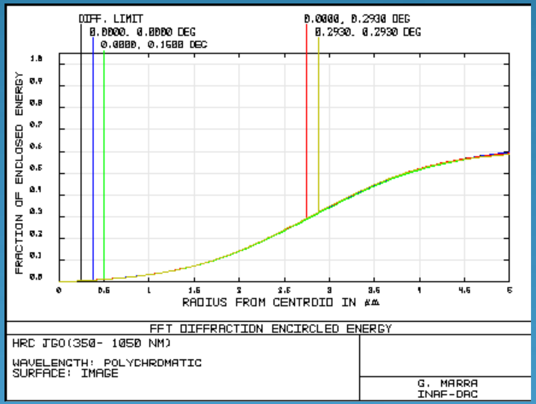
Approach	Pro’s	Con’s
No signal improvement	➢no devices MC ➢compatible with yaw steering	➢very low SNR due to short integration time
TDI on CCD	➢simple configuration for MC (customized detector) ➢better SNR	➢need of de-rotator device for YS compensation ➢used of CCD mandatory? Probably not: to be checked with CMOS provider ➢MTF degradation
pseudo-TDI	➢better SNR ➢compatible with yaw steering	➢high download rate and complex memory management inside PE (resources) ➢lower performances wrt TDI (to be evaluated)
mirror @ entrance pupil	➢much better SNR	➢resources for mirror and mechanism (large mirror!): probably not feasible ➢2 DoF to correct for yaw steering
FPA motion	➢much better SNR (up to 10 ms int.?) ➢compatible with yaw steering (with 2 DoF motion implemented)	➢ “new” mechanism for space application ➢2 DoF (2 linear or 1 linear + 1 rotation) ➢feasibility vs. optical tolerances to be demonstrated
secondary mirror tilting (1 or 2 DoF)	➢much better SNR (up to 10 ms int.?) ➢compatible with yaw steering (with 2 DoF motion implemented)	➢resource for mechanism ➢aberrations ➢challenging tolerances and position control ➢2 DoF to correct for yaw steering
small mirror tilting (1 or 2 DoF)	➢much better SNR (up to 10 ms int.?) ➢compatible with yaw steering (with 2 DoF motion implemented) ➢no aberrations introduced	➢resource for mechanism ➢challenging tolerances and position control ➢2 DoF to correct for yaw steering

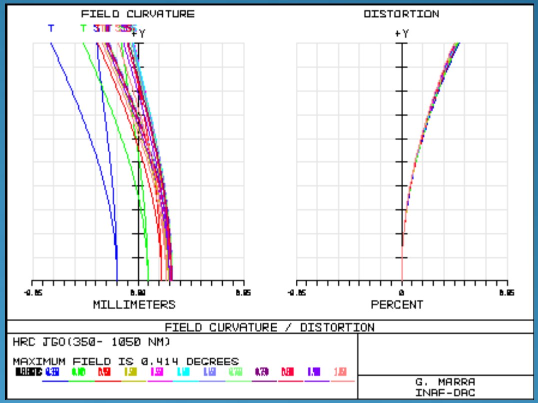
Optical design: F/10 centred configuration



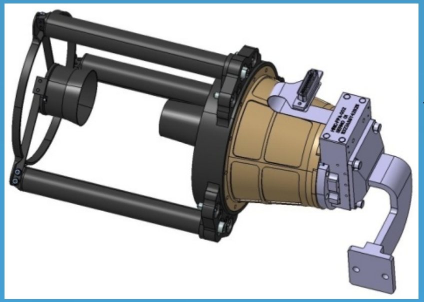


- In the centred configuration the obscuration factor can be minimized (40%) including mechanics and internal baffles in order to have good MTF and EE. Pixel scale: 1m from 200 km.
- The image plane is flat and distortion is very low: useful for pushbroom image acquisition and image motion correction. Image quality is good for all observation geometries.





Heritage: HRIC-SIMBIO-SYS BC

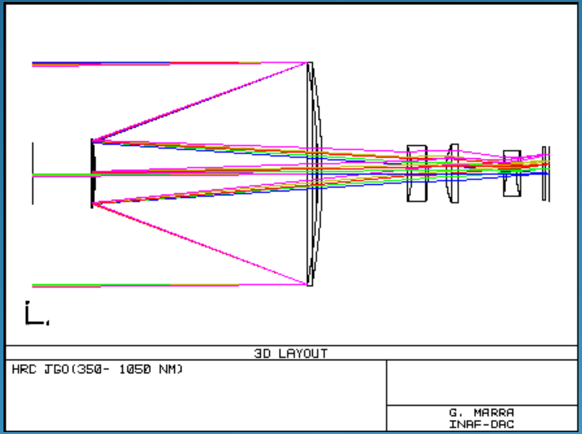


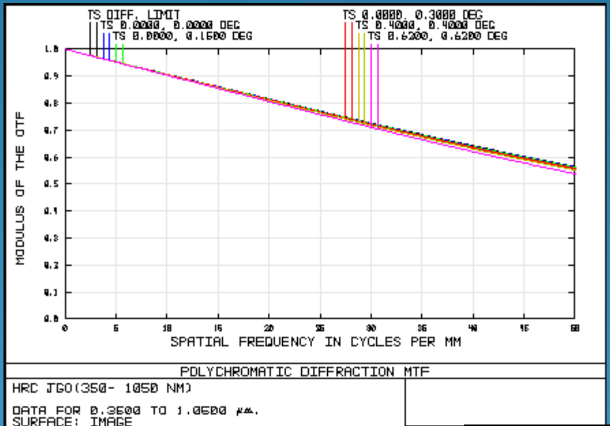
Areas of Technology Development:

- **Coatings**
- **Lenses (materials, manufacturing)**
- **Mirrors (materials, manufacturing)**

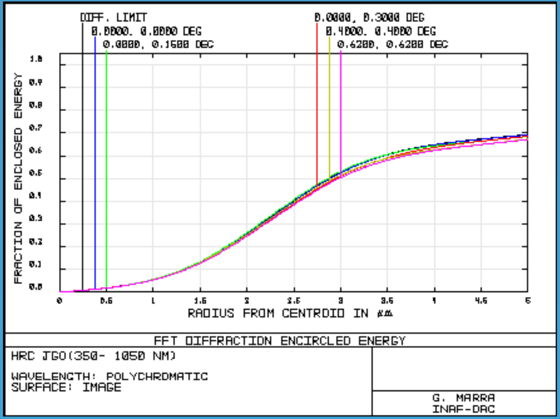
Optical design: F/8 centred configuration

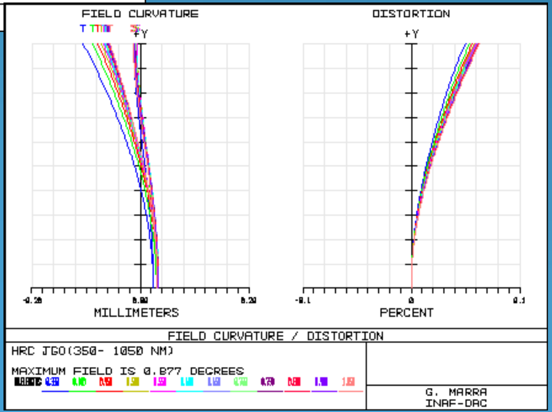
Approach	Pro’s	Con’s
IFOV increasing	➢No (or reduced) need for MC ➢compatible with yaw steering ➢quite high SNR ➢ volume and mass reduction	➢Lower space resolution



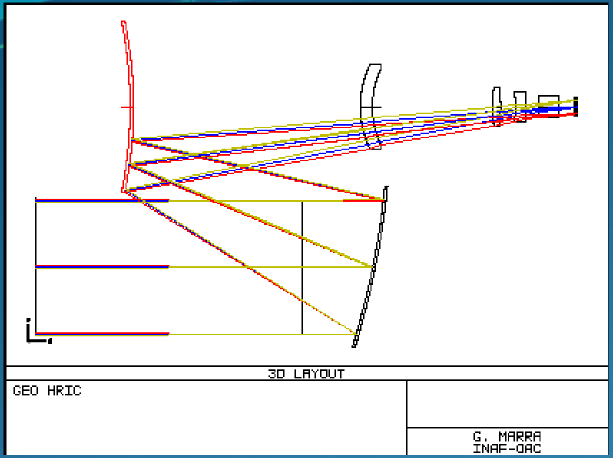


- F/8 centred configuration, 3 m pixel scale, 82 mm aperture diameter.
- SNR increases
- The image plane is flat and distortion is very low: useful for pushbroom image acquisition and image motion correction.





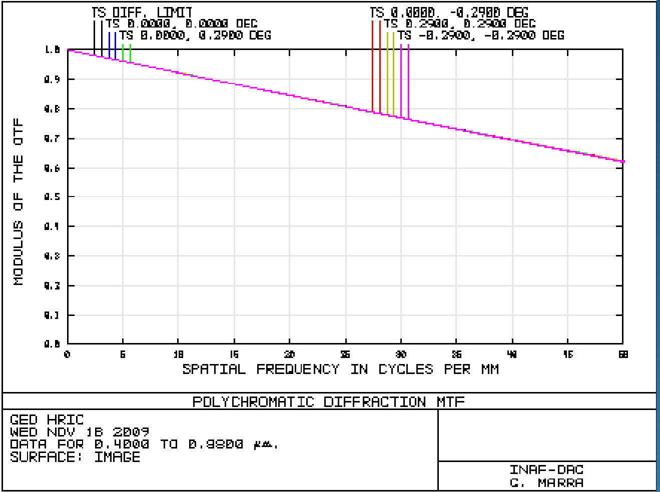
Optical design: F/10 off-axis configuration



3D LAYOUT

GEO HRIC

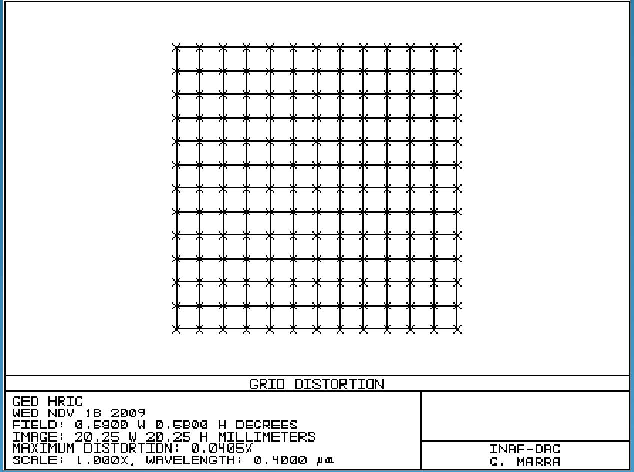
G. MARRA
INAF-OAC



POLYCHROMATIC DIFFRACTION MTF

GEO HRIC
WED NOV 18 2009
DATA FOR 0.4000 TO 0.9800 µm.
SURFACE: IMAGE

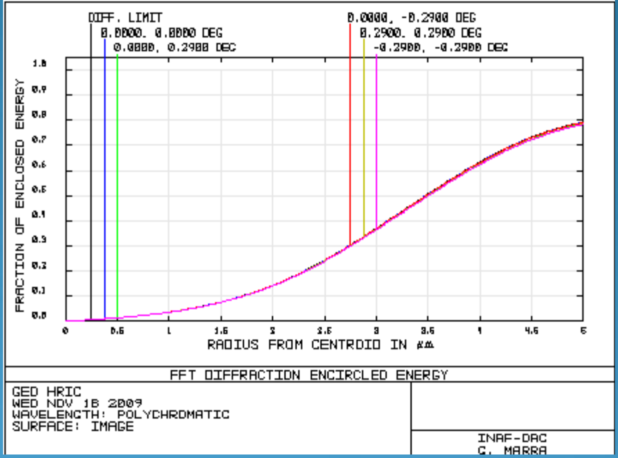
INAF-OAC
G. MARRA



GRID DISTORTION

GEO HRIC
WED NOV 18 2009
FIELD: 0.5800 W 0.5800 H DEGREES
IMAGE: 20.25 W 20.25 H MILLIMETERS
MAXIMUM DISTORTION: 0.0405%
SCALE: 1.000X, WAVELENGTH: 0.4000 µm

INAF-OAC
G. MARRA



FFT DIFFRACTION ENCIRCLED ENERGY

GEO HRIC
WED NOV 18 2009
WAVELENGTH: POLYCHROMATIC
SURFACE: IMAGE

INAF-OAC
G. MARRA

Comparing with the centred configuration:

- Un-obscured => optical performances in terms of MTF and EE better than for the centred config.
- Lenses and mirror manufacturing is more complex than for the centred configuration
- Larger volume and mass with respect to the centred configuration
- Less sensitive to stray-light

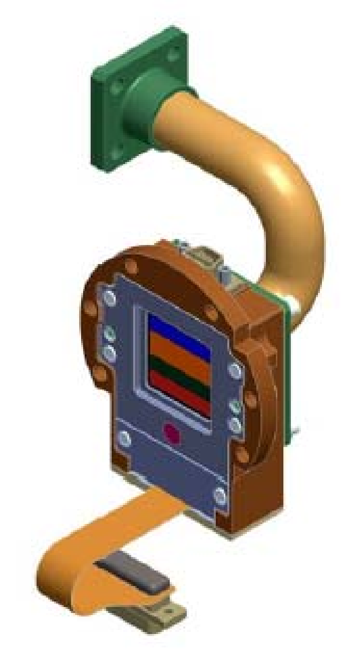
Detector 1/2

TECHNOLOGY: hybrid Si-PIN CMOS

- SIMBIO-SYS heritage: 2048x2048 array, 10 μm pixel, high Quantum Efficiency (QE), low power, high radiation tolerance;
- in hybrid Si-PIN CMOS, Noise and Responsivity are not affected up to several hundreds of krads of T.D. (<750krad). Dark Current increases for absorbed T.D. of few hundreds of krads (<300krad).

NEED FOR HIGH SNR: due to the low flux on detector, long integration time will be used. To achieve this goal avoiding image blurring, one of the following solutions could be implemented on detector:

- Piezoelectric actuators integrated in the focal plane package
- Summing several (re-synchronized) frames in an external memory buffer
- On-chip TDI (more details reported in the following slide)



DETECTOR BASELINE REQUIREMENTS

- Resolution: 2048x2048
- fill factor: 100%
- Pixel Dimension: 10 μm (TBC)
- Spectral response: 350 ÷ 1050 nm
- Detector Quantum Efficiency (QE): > 80% (TBC)
- Full well: >100 ke- (TBC)

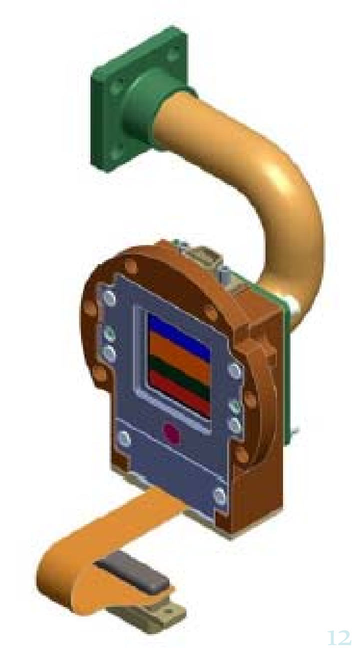
Detector 2/2

On-chip TDI

- TDI is implemented at charge level inside the detector ROIC by means of several additional capacitances and CMOS switches to store and sum the correspondent pixels acquired at different time. This approach, recently used for Hybrid detectors, could be the preferable one. It is being evaluated by the team, together with SG and RVS.

Requirements for on-chip TDI are:

- Total Exposition Time with TDI: settable between 0.1ms and 10ms (this total time is the sum of the integration time of each line + the time necessary to swap the charge);
- Total Exposition Time without TDI: up to 1s (TBC) (this exposition time is applicable for snapshot acquisition only, without TDI and, in this case, is equal to the integration time);
- TDI depth: settable between 0 and 100. It can be varied continuously, by command, according to the current operation mode;
- TDI time (max time to transfer the charge of each acquired line under TDI): $3.5\ 10^{-4}$.



Areas of Technology Development

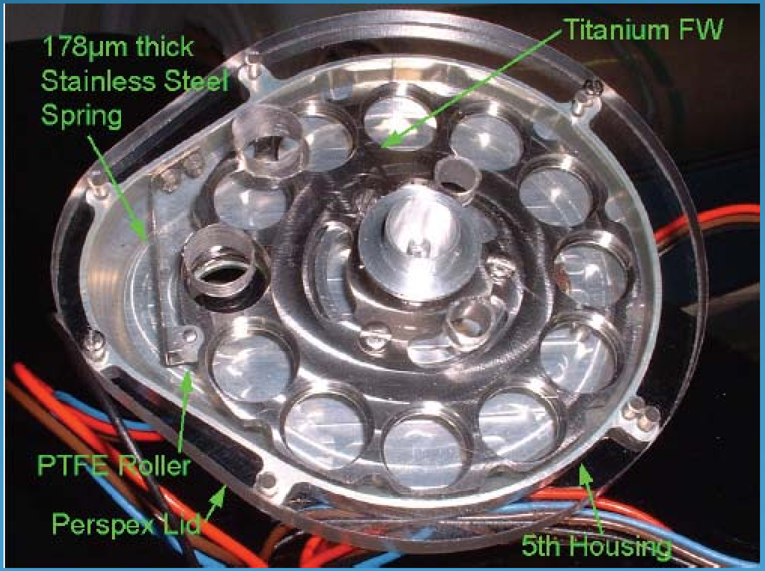
Parallel studies are foreseen, starting from heritage on:

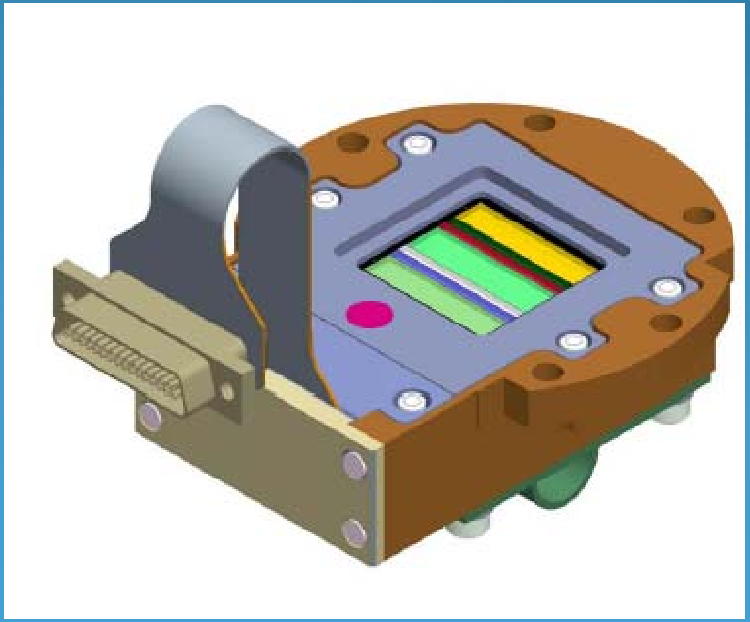
- Hybrid Si-PIN CMOS (SIMBIO-SYS)
- Star-1000, CMOS APS, total dose >250 krad (ExoMars PanCam)
- CCD (MEX) detectors

Filters

- **Filter Strip Assembly formed by parallel strips (in across-track direction) deposited onto the window of the detector package, close to focal plane => HRIC-SIM experiment. Parallel acquisition of multi-filter images during orbit or target scan.**
- **A number of filters (up to 10-12) covering the entire focal plane to be mounted on a filter wheel. Multi-filter images shall be acquired through follow-up observation during orbit or by keeping target pointing.**

➡ **Integration of both concept allows operational flexibility**

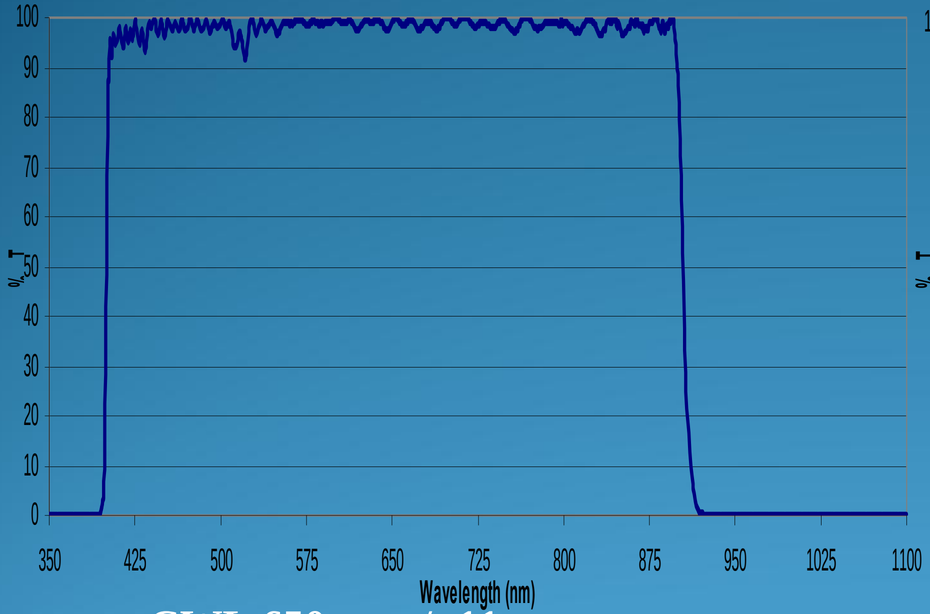




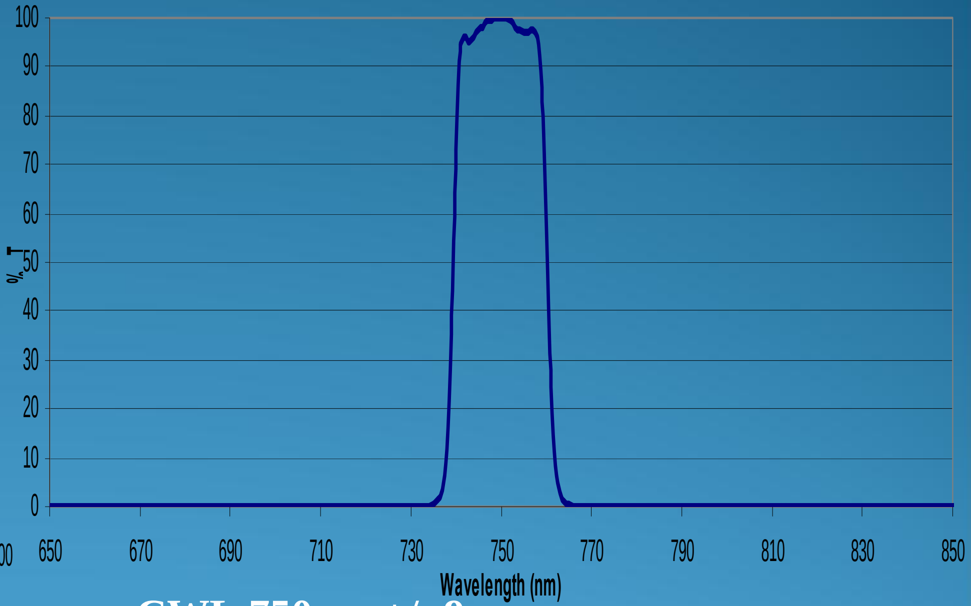
Areas of Technology Development:
•Filter coatings

Filters

- **Presently available technology is being considered for filter performances evaluation:**



CWL 650nm +/- 11nm
50% Cut-on - 400nm by design
50% Cut-off 900nm by design
FWHM 500nm +/- 5nm
Tout / Tin < 0.005%
Tpeak > 85%
Tout ave < 0.05%



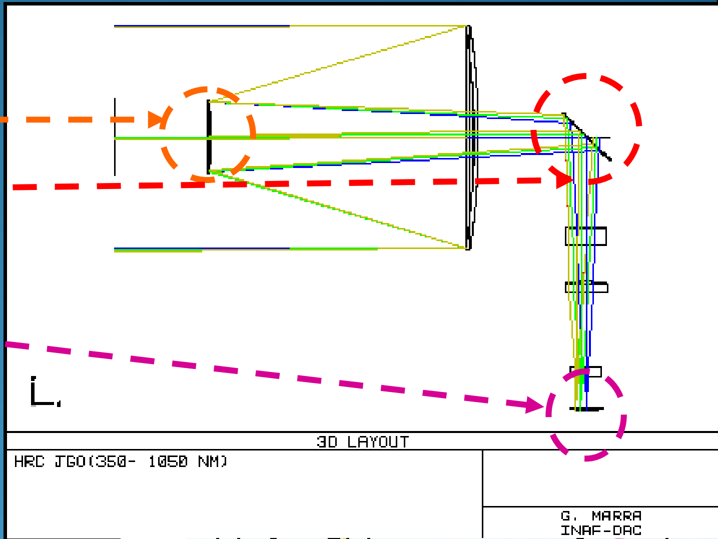
CWL 750nm +/- 9nm
50% Cut-on - 730nm by design
50% Cut-off 770nm by design
FWHM 20nm +/- 2nm
Tout / Tin < 0.01%
Tpeak > 80%
Tout ave < 0.05%

Mechanisms

1) MOTION COMPENSATION

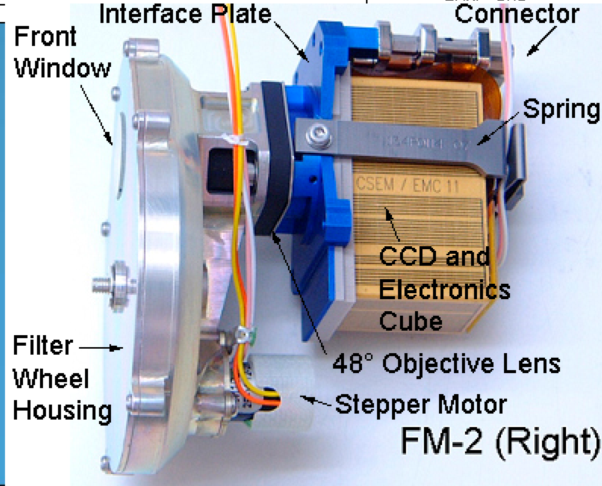
Requirement: to freeze the image on the detector for up to 10 ms

- Motion of an optical element
  - Tilt of secondary (off-axis design) : small aberration
  - Tilt of a pickup mirror
- Motion of focal plane



2) FILTER WHEEL

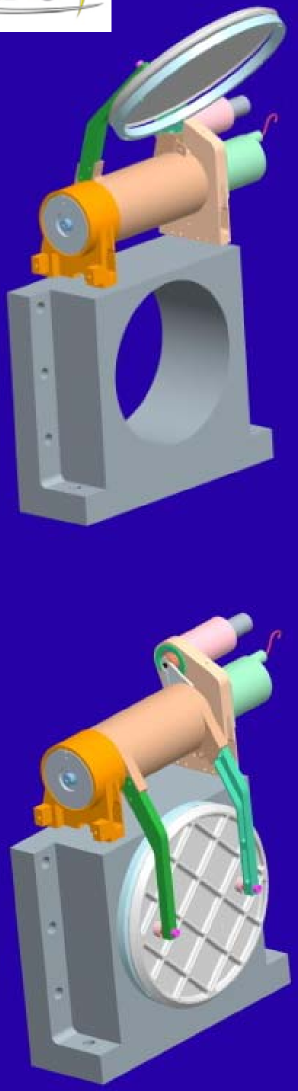
- Heritage: motorized 12-position titanium filter wheel => Panoramic Camera on Beagle2 (SCS) and ExoMars (PanCam).



3) YAW STEERING COMPENSATION

- Motion compensation solutions are likely applicable only on one axis => need of fixed velocity vector wrt focal plane
- Possible solution: optical derotation (moving part)
- Different opto-mechanical design under study

Mechanisms



4) FRONT DOOR AND DRIVER STAGE

Mechanical protection of the optical aperture is essential

- Micro-meteorites
- Contamination of the optical surfaces
- Accidental sun exposure
- Radiation shielding
- In-flight calibration “flat” surface

Flight heritage @MPS from recent missions

- SOHO and STEREO
- Framing Cameras (DAWN)

Prototype (demonstrator) will ensure the required maturity of the technology and the compliance with power and mass budgets

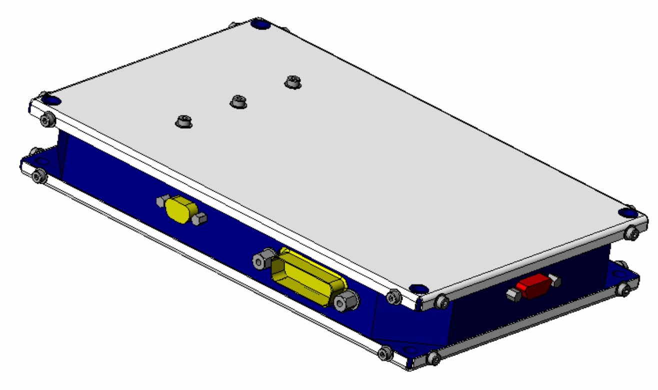
Proximity Electronics

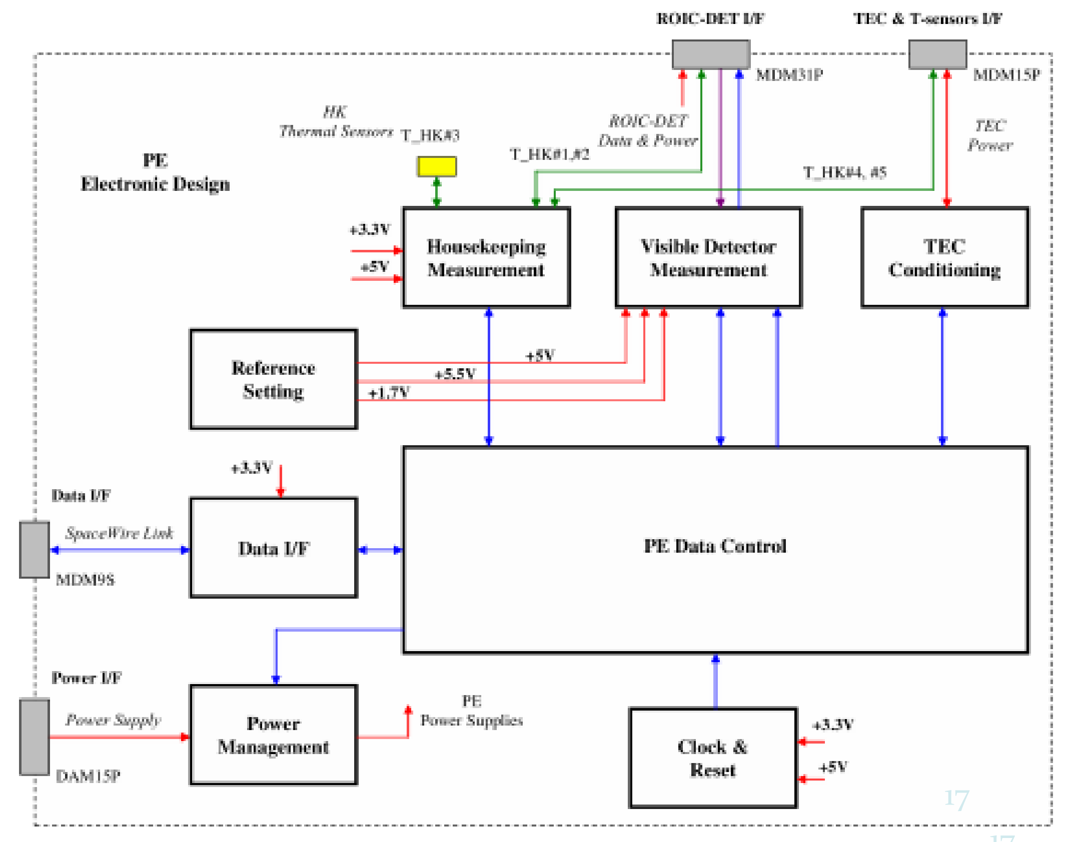
- 3D architecture to be evaluated
- Integration of most functions inside a FPGA
- Implementation of the SpaceWire communication I/F to/from ME

Past experience of the team on similar experiments, such as BepiColombo SIMBIO-SYS and BELA, MEX HRSC, Dawn FC and Venus Express Virtis.

MAIN FUNCTIONS
- Power supply regulation and filtering
- Visible Detector bias conditioning and filtering
- Visible Detector clocks generation
- Visible Detector Readout Sequencer
- Pixel video processing chain, including ADC
- Temperature and other housekeeping readout
- Data handling digital interface
- If needed, visible Detector temperature control via a thermo-electric cooler

Areas of Technology Development:
- •FPGA
- •ASIC



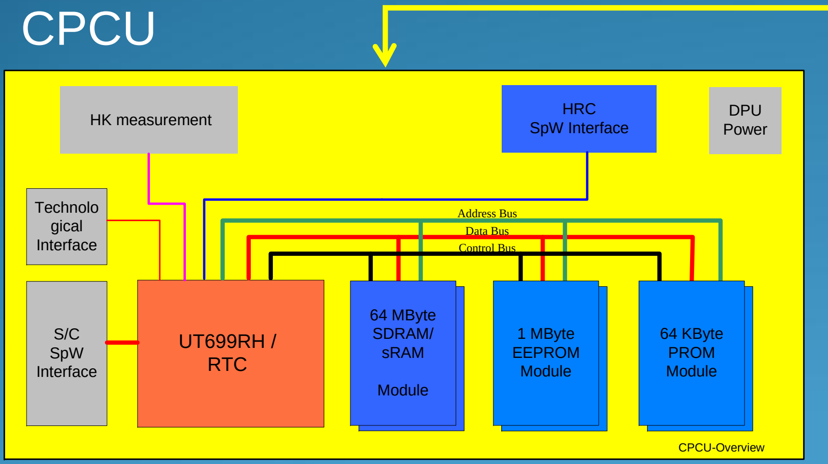


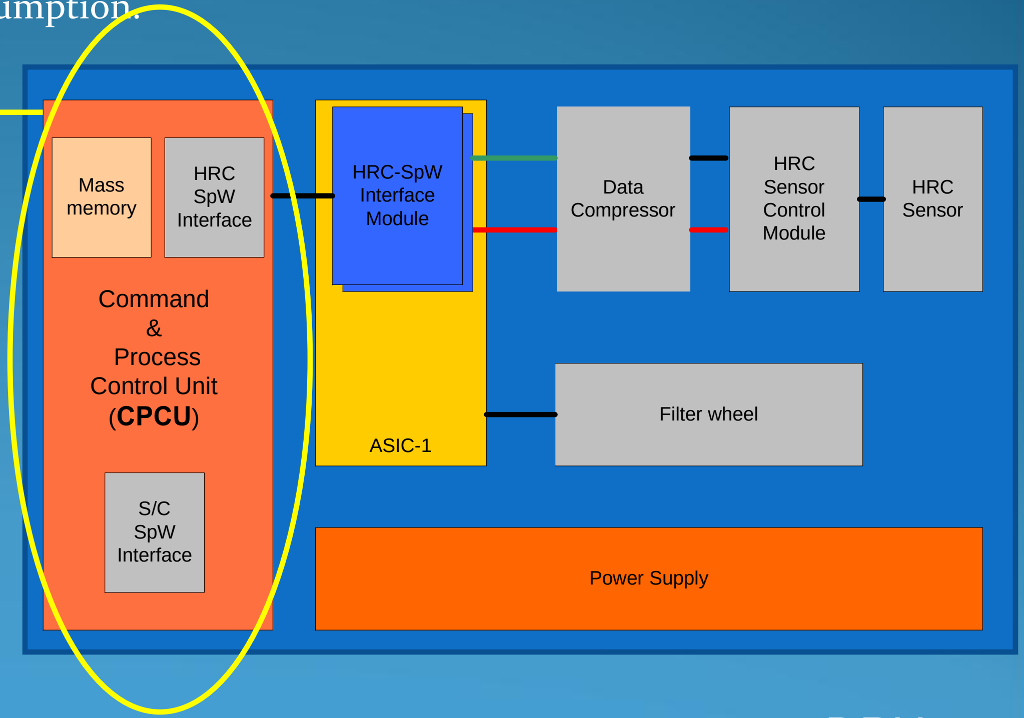
Main electronics

Key Functionalities:

- shall control the camera via high level commands to be sent to the detector and related PE through the SpaceWire communication link,
- perform scientific data compression,
- distribute power supply to the detector/PE,
- receive command and send scientific/housekeeping data through the SpaceWire communication link from/to the S/C.
- Integration of processor and data compression and mechanism control functionality into a radiation hard ASIC
- Implementation of a ME common to more than one instrument (i.e. camera system ME) shall be analyzed to further reduce mass and power consumption.

CPCU





Key units

- Microcontroller and memory
- FPGA support logic
- FPGA pixel processing
- Low voltage power supply and power switching
- Voltage and temperature monitors

DPU

Data compression

- Compression unit (CU) task is to handle the data flow from PE and to generate data packets.
- Each frame transmitted by PE is stored (or added to the previous frame if frame binning is requested by TC).
- CU compresses and formats the data in series of data fields of TM packets with three possible compression schemes: Bit-packing, Lossless compression, Lossy compression with an output in terms of bit/pixel which is defined by TC.
- A wavelet transform is first performed by the FPGA of the CU on sub-frames with dimensions along both axes of either 64 or 128 pixels, then a speed-optimized version of the Said-Pearlman tree-coding algorithm (Said and Pearlman, 1996; Langevin and Forni, 2000) is implemented by the LEON processor of the CU.
- CU is able to process a data flux of up to 2 Mpixels/s.

Budgets

1. POWER BUDGET

Total Average Power	**< 15 W (tbc)**
Sensor (incl. PE)	2.7 W
CPCU	5 W
DPU (excl. CPCU)	7 W
Filter Wheel	1-2 W
Thermal Control	0.6 W

The power dissipation is mainly driven by pixel rate, data compression and the high-speed SpaceWire interface.

2. DATA RATE/VOLUME

- Characterize Ganymede as a planetary object
- Ganymede’s ice shell and ocean
- Ganymede’s geology and search for present and past activity

Optical configuration	**Frame swath [m]**	**Repetition time [s]**	**Data rate uncomp. [Mbps]**
F/10	2048	1	55

Performance Simulation

Given the demanding spatial resolution requirements vs. mission design (dwell time < 1 ms) three observation approaches are being considered:

1. Standard

Optical Conf.	**Ganymede pericentre**		**Ganymede apocentre**	
	SNR_{fr}	**SNR_{px}**	**SNR_{fr}**	**SNR_{px}**
F/10 on-axis	9	9	254	292
F/10 off-axis	10	10	261	292
F/8 on-axis	32	32	220	293
F/8 off-axis	35	35	231	293

2. TDI

Optical Conf.	**Exposure Time / TDI deep**	**Ganymede percentre**		**Ganymede apocentre**	
		SNR_{fr}	**SNR_{px}**	**SNR_{fr}**	**SNR_{px}**
F/10 on-axis	1 ms / 9	52	52	254	292
	3 ms / 26	105	107	254	292
	5 ms / 44	140	144	254	292
F/10 off-axis	1 ms / 9	56	56	261	292
	3 ms / 26	113	115	261	292
	5 ms / 44	150	154	261	292
F/8 on-axis	1 ms / 3	68	70	220	293
	3 ms / 9	127	137	220	293
	5 ms / 15	161	182	220	293
F/8 off-axis	1 ms / 3	74	75	231	293
	3 ms / 9	137	146	231	293
	5 ms / 15	174	194	231	293

3. Motion compensation

not yet simulated; opto-mechanical performances to be evaluated

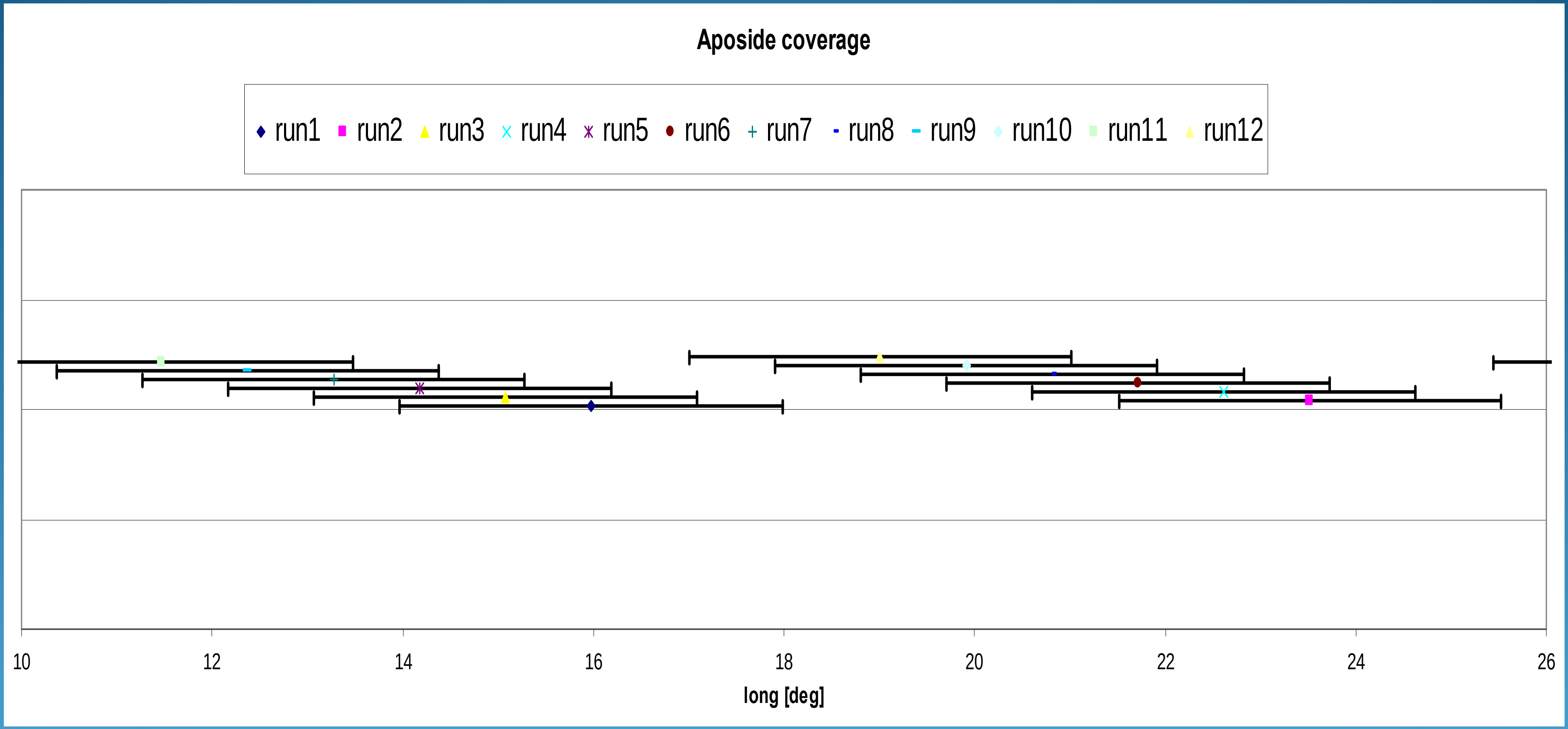
Note: Ganymede elliptical orbit

Coverage Simulation

Coverage capabilities

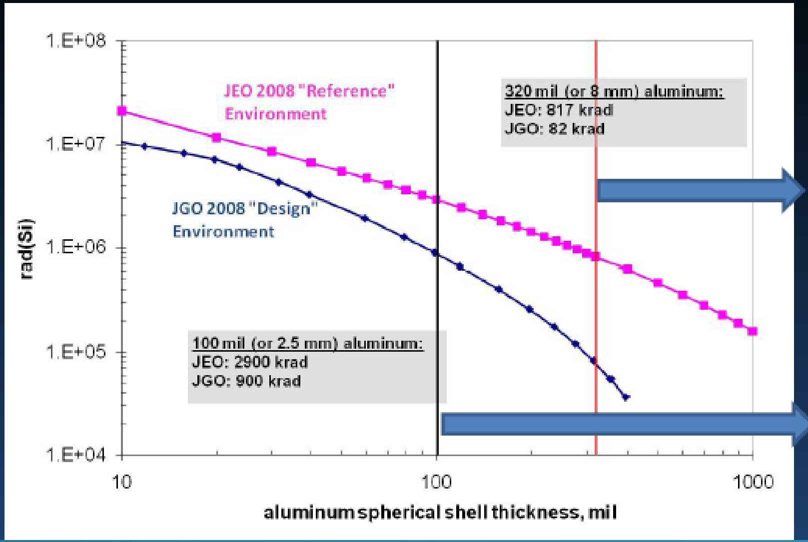
F/10 optical config

F/8 optical config



Radiation: JGO TID and Flux

Dose-depth curve for both JEO and JGO



Factor of ~10 difference at 8mm (320 mils)

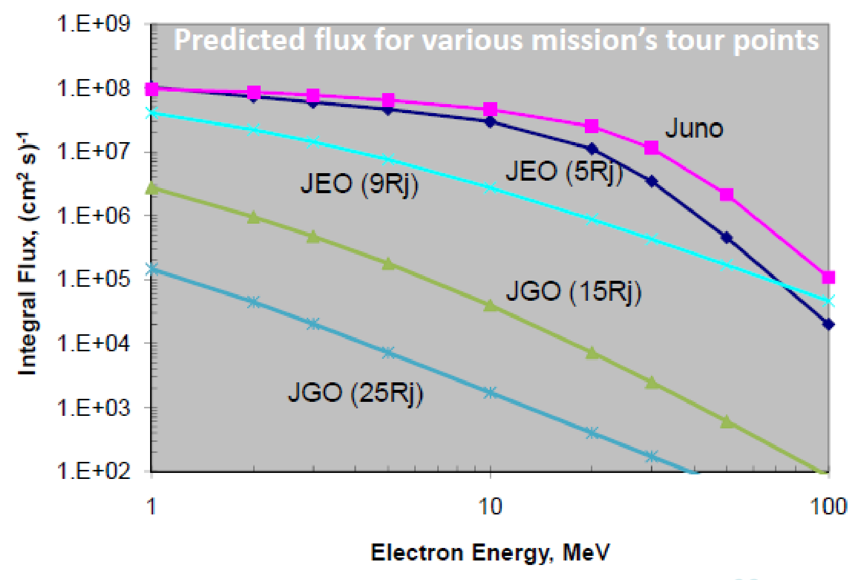
Factor of ~3 difference at 2.5 mm (100 mils)

TID:
Radiation can be a long term performance issue!

Flux-induced transient effects vary depending on point in tour

Unshielded Flux levels for Juno, JEO at Io and Europa and JGO at Ganymede and Callisto

JGO reduces the instantaneous flux requirement by staying away from Io and Europa's orbits



From: K.B. Clark, Comparison Of Key JEO and JGO Requirements, EJSM Instrument Workshop, July 15-17, 2009

Radiation mitigation and shielding

JGO requirements:

- JGO Design Point: 85 kRad after 8mm Al
- Formal Radiation Design Factor (RDF) of 2 required => parts shielded with 8mm Al should be radiation-hardened to ~170 kRad

Preliminary Concept (under study):

Combination of radiation hardened components and vault/spot shielding:

- Protection of HRC image sensor (and filter wheel, tbc) from **TID, DDD and transient effects**: trade-off between

  A) packaging of sensor + PE in miniaturized housing

  B) radiation spot shielding of detector with TBD mm of Al (depends mainly on detector selection, detector study is ongoing...)
- Protection of Main Electronics: use parts tolerant to > 170 krad, accommodation in central spacecraft vault (shielded) and integration of sensitive electronics (e.g. SpW I/F module, compression module) into radiation hard ASICs.
- **Mitigation of background radiation noise: under study.**
  - as-far-as possible reduction of exposure times (trade-off between longer exposure times and increased transient radiation noise)
  - Find optimal sensor ops temperature
  - Annealing (e.g. by detector anneal heater, tbc)

Planetary Protection

- PP Control methods:
  - In case DHMR is required (it should not be the case for JGO, classified as class II), a stringent selection of allowable materials and processes is necessary. Several components (as detectors) cannot be subjected to temperature in the typical DHMR 110-130°C.
  - DHMR can be applied to all parts able to withstand it, followed by AIV activities in the appropriate level of cleanroom (e.g. integration in class 10000B; bioburden lower than 300 spores/m^2).
  - Use of laminar flow hooks
  - Design phase will take into account the PP requirements (IPA cleaning of external sources, swabbing with pure water for microbiological assay)
  - Possibility to enclose parts in airtight boxes with a HEPA filter on the venting hole, minimizing the bioburden requirements
  - In case of S/C crash some cleaning process shall be envisaged; IPA or ultra-cleaning techniques (under development for EXOMARS)

Planetary Protection

- PP Control summary:
  - The method(s) shall be specified very early
  - Sterilization, biocleaning, microbiological controls impact on integration process and planning
  - Sterilization impacts on design and material choice (cleanability, compatibility)
  - Critical materials (items) shall be tested (validation) – Phase B
  - Sterilization shall be included in the equipment qualification program (with margin)
  - Sterility / biodecontamination level shall be controlled
  - Sterility shall be ensured and kept after sterilization: double packaging system, implementation of I/F connectors for tests, foresee problems with customs, ..etc

Planetary Protection

- Industrial know-how on PP in Italy (at SELEX Galileo)
  - ➢ It is worth mentioning that the approach for PP issues benefits of the heritage coming from the participation of SELEX Galileo to the PP Tiger Team established by ESA for the EXOMARS Programme in the frame of the development of three Instruments (Ma_Miss, MIMA, MEDUSA) and the key Drill System.
  - ➢ Presently JGO requirements are more comfortable than EXOMARS mission that is classified IVb and the specific requirements for the various part reached the need for DHMR for some part of Drill and Ma_Miss.
  - ➢ Key personnel (Engineering, Production, AIV) has already participated to level 1 and 2 courses; additional participation is planned in the next months, thus assuring the industrial capability to manage the Planetary Protection aspects.

Summary of Technology Developments

Optical Head

- System configuration
- Optical design
- Mirrors - Lenses
- Mountings
- Detector
- Proximity electronics mountings/components
- Filter mounting - Filters

Main Electronics

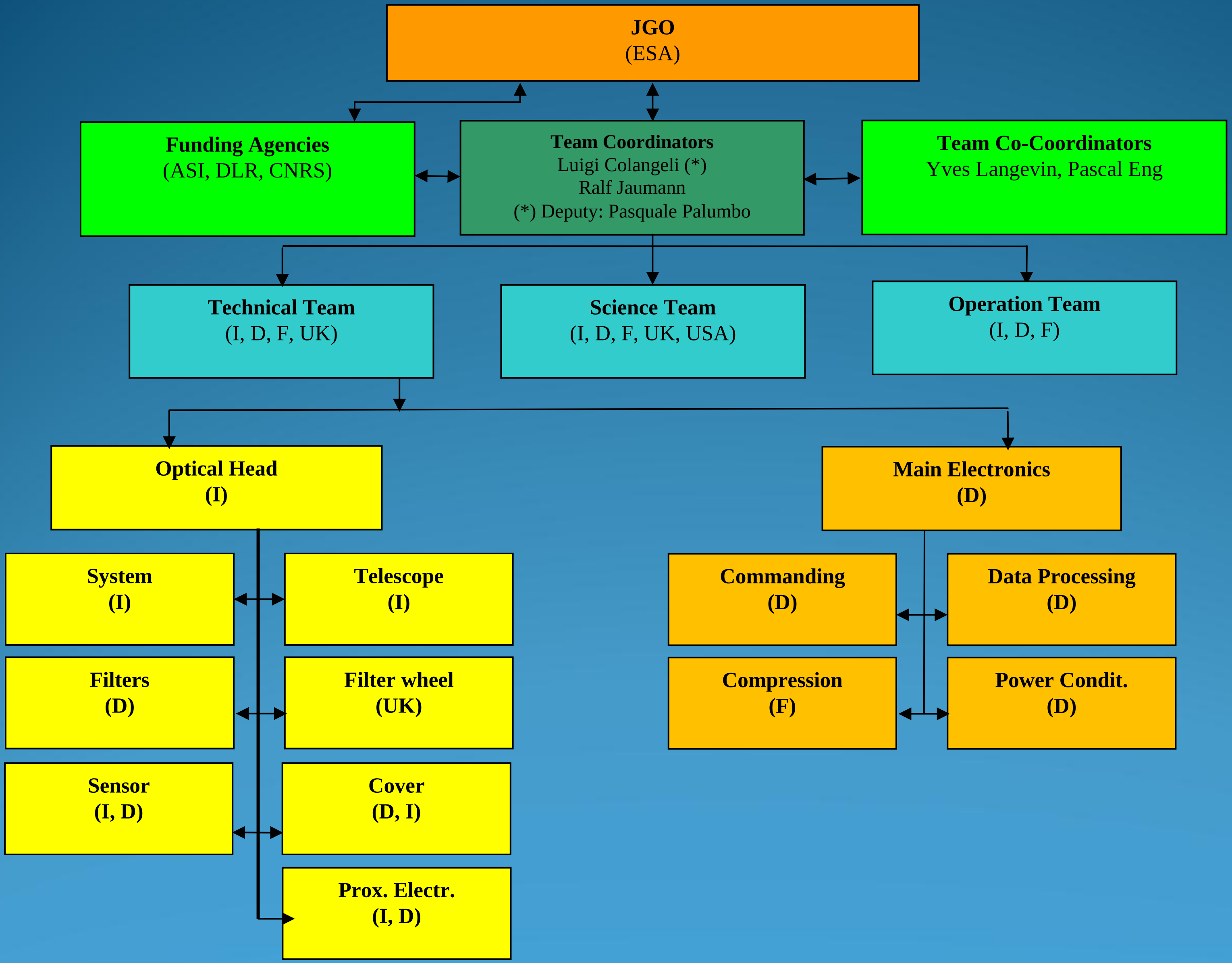
- System configuration
- Electronic design
- FPGA/ASIC
- Main electronics components

Miniaturizing and mass saving techniques

Main electronics: integration of processor, filter wheel and data compression functionality into a single FPGA or into a radiation hard ASIC, i.e. reduction of required resources in terms of mass and power.

Implementation of a common ME for the JGO P/L should be analyzed at S/C system level to reduce mass and power consumption.

Team Organisation



JGO
(ESA)

Funding Agencies
(ASI, DLR, CNRS)

Team Coordinators
Luigi Colangeli (*)
Ralf Jaumann
(*) Deputy: Pasquale Palumbo

Team Co-Coordinators
Yves Langevin, Pascal Eng

Technical Team
(I, D, F, UK)

Science Team
(I, D, F, UK, USA)

Operation Team
(I, D, F)

Optical Head
(I)

System
(I)

Telescope
(I)

Filters
(D)

Filter wheel
(UK)

Sensor
(I, D)

Cover
(D, I)

Prox. Electr.
(I, D)

Main Electronics
(D)

Commanding
(D)

Data Processing
(D)

Compression
(F)

Power Condit.
(D)