ECHO
External Final Presentation of the CDF study

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22/07/2011

European Space Agency

Study goals

1. Assess the technical feasibility of the ECHO proposal
2. Design an example mission compatible with achieving the science goals
    a. Mission analysis
    b. System level and instrument design
    c. System resources analysis
    d. Technology development needs
    e. Preliminary programmatic assessment

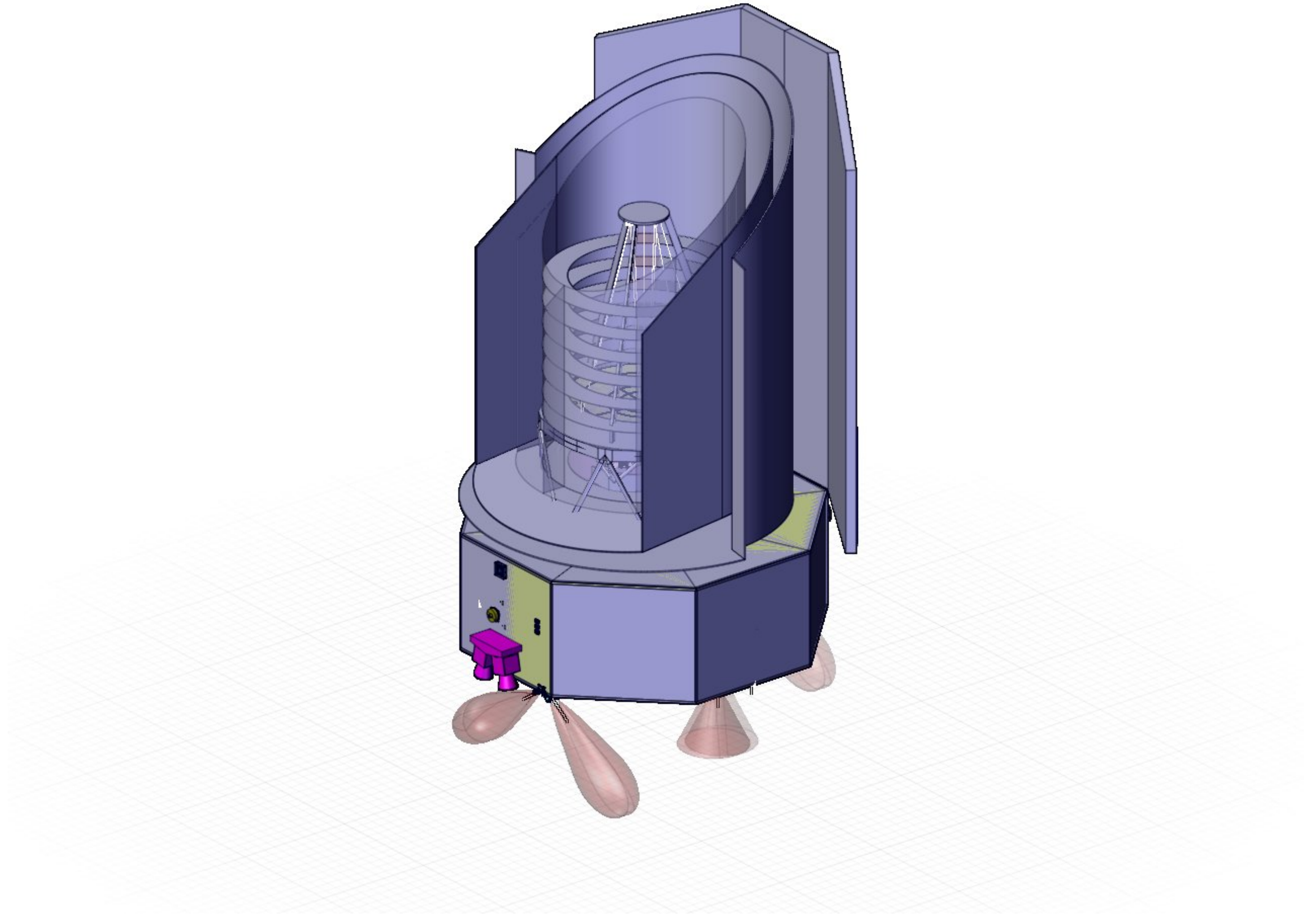
Specific study tasks

1. Provide a baseline missions analysis scenario: LV performance, injection strategy, operational orbit, operations plan
2. Provide a reference instrument optical design
3. Assess detector options
4. Identify technology developments needed (instrument + S/C)
5. Perform a system level analysis of the photometric stability and the photon noise limit requirements
6. Impact of mechanisms and mechanically vibrating units (AOCS actuators, active cryocooler etc.)
7. Cryogenic and fine pointing design
8. Observation efficiency analysis
9. Preliminary cost and risk analysis
10. Preliminary development plan compatible with M3 constraints

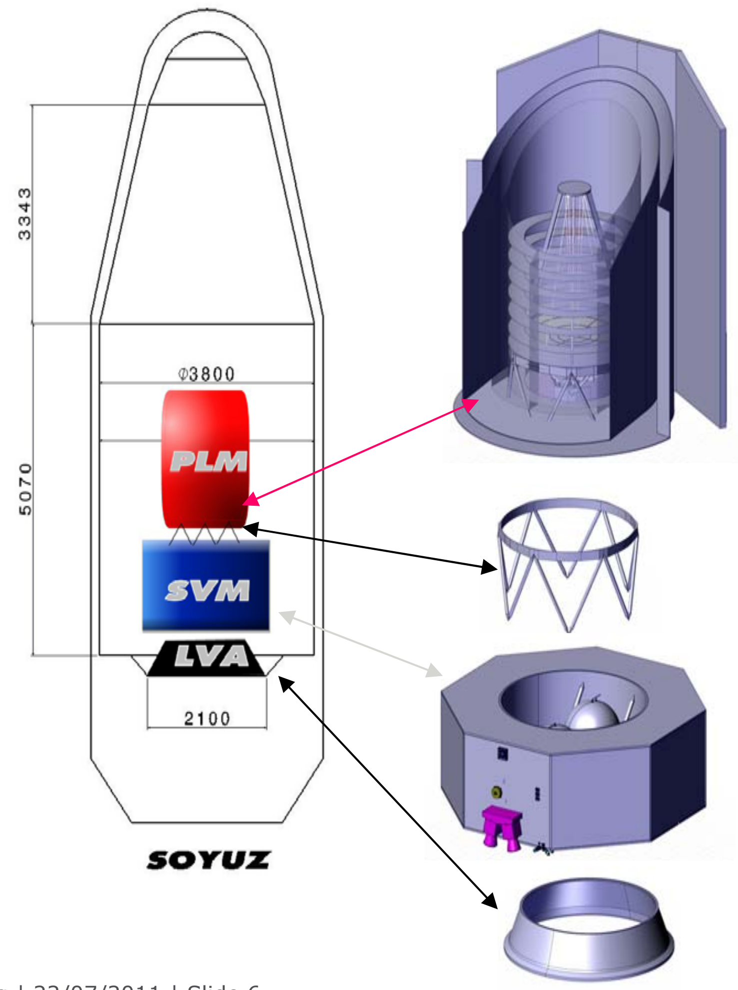
Constraints

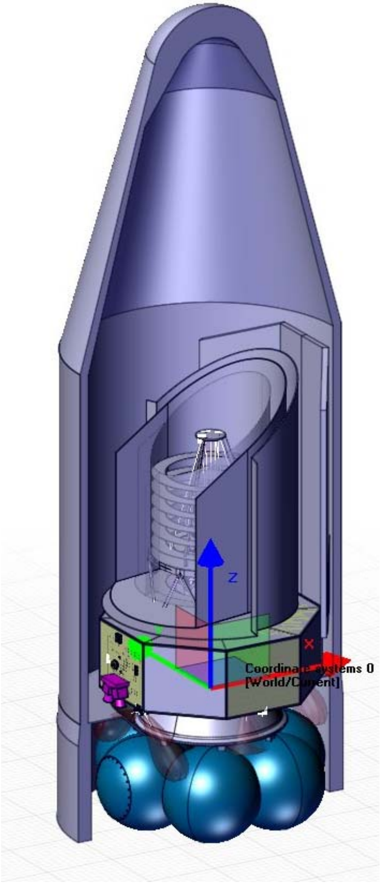
1. Soyuz launch from Kourou
2. Between 2020 and 2022
3. Technology Readiness Level (TRL) 5 by end of definition phase (expected around end 2014)
4. Low development risk for future phases
5. ESA CaC < 470 MEur (2010)

Space segment overview



Configuration





Payload

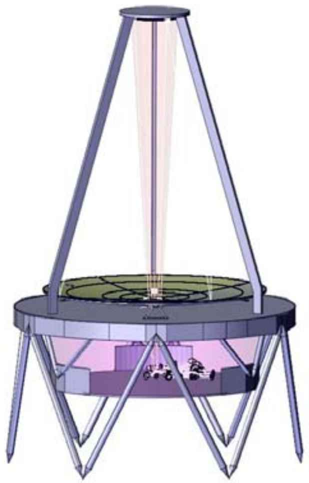
Instruments

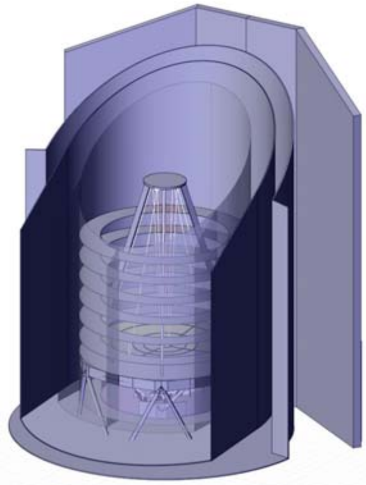
1. 1.26 m Ø Cassegrain telescope, 20''x20'' FoV diffraction limited in Vis
2. 2 instruments:
   a. Science instrument (spectrometer):
      – 0.4 to 5 microns, R=300
      – 5 to 16 microns, R=30
   b. Fine Guidance Sensor (FGS, non scientific-instrument)
      – No more than 50% of Vis light

Channel	Vis		IR 1	IR 2	IR 3	IR 4	IR 5	IR 6 (goal)
λ	0.4 – 0.8 [micron]		0.8 – 1.5 [micron]	1.5 – 2.5 [micron]	2.5 – 5 [micron]	5 – 8.5 [micron]	8.5 – 11 [micron]	11 – 16 [micron]
	FGS	Science Vis						
Slit width [arcsec]	NA	2.1	2.6	3.3	5.2	7.7	9.5	13.2
η (tel + inst)	0.148	0.191	0.284	0.278	0.378	0.418	0.418	0.326

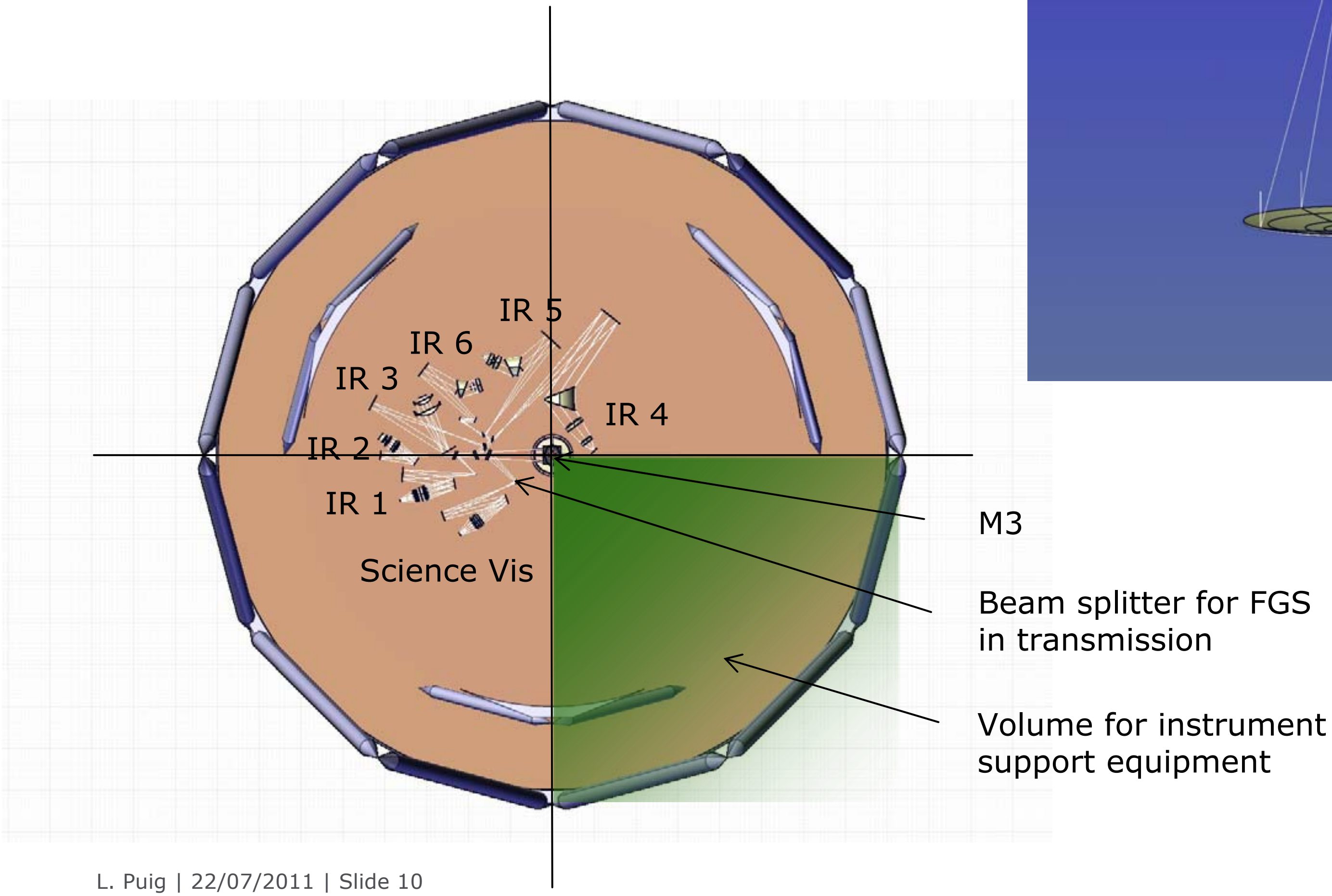
Instrument accommodation constraints

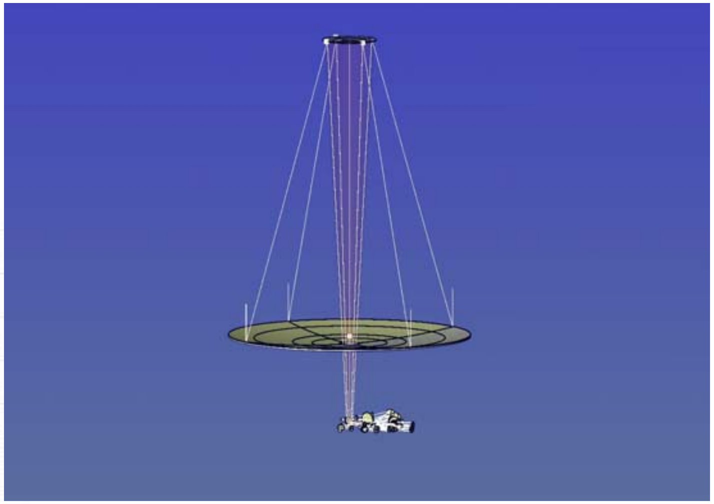
1. Volume allocated is defined by a cylinder under M1:
    a. No wider than M1
    b. Instrument Optical Bench (IOB) located ≤ 0.6 m deep under M1, “hanging down” from Telescope Optical Bench
    c. M3 (with eventual fine steering mirror) in the centre of the IOB (1 DoF rotation around telescope axis)
    d. Instrument box(es) on IOB
2. ¾ of volume is instrument volume, with optics and detectors (science instrument + FGS + eventual calibration system)
3. ¼ of volume is instrument support equipment volume, for Front End Electronics, cryogenic equipment, SVM computer Remote Terminal Unit etc.
4. Telescope + instrument volume to be passively cooled at 45 K
5. Dedicated coolers / heaters where necessary





Instrument optics





Instrument detectors

1. Requirement for photon noise limited system => only solution currently available is:
    a. Vis: European Si CCD (or CMOS) at 150 K or HyViSi detector at 45 K
    b. 0.8 to 5 microns: Teledyne H2RG HgCdTe at 45 K
    c. 5 to 16 microns: Raytheon Si:As at 7 K

	Vis	IR 1	IR 2	IR 3	IR 4	IR 5	IR 6
	0.4 - 0.8	**0.8 - 1.5**	**1.5 - 2.5**	**2.5 - 5.0**	**5.0 - 8.5**	**8.5 - 11.0**	**11.0 - 16.0**
Dark current required	< 690 e-/s/p	< 2250 e-/s/p	< 1180 e-/s/p	< 530 e-/s/p	< 6840 e-/s/p	< 4360 e-/s/p	< 760 e-/s/p
RON required (TBC)	< √(0.9*FW/3)	< √(0.9*FW/3)	< √(0.9*FW/3)	< √(0.9*FW/3)	< √(0.9*FW/3)	< √(0.9*FW/3)	< √(0.9*FW/3)
Si CCD or CMOS							
Assume pixel size (um)	18						
Assume FWC (e)	200000						
Hence... RON required	244.9489743						
Reference Temperature	153 K						
T stability required	of order 5K						
Nominal power consumption	100 mW						
Typical Dark Current (e-/s/p)	cannot measure						
Typical RON (e-)	less than 10						
TRL	very high						
Values sourced from	many sources						
Mission (e.g.)	many missions						
MCT (US p on n)							
Assume pixel size (um)	18	18	18	18	18		
Assume FWC (e)	65000	65000	65000	65000	65000		
Hence... RON required	140	140	140	140	140		
Reference Temperature	?	50 K	50 K	50 K	50 K		
Theoretical T stability required*				3.7 K (at 50K)			0.27mK (at 30K)
Theoretical T stability goal*				0.37 K (at 50K)			0.027mK (at 30K)
Nominal power consumption**	1 mW	1 mW	1 mW	1 mW	1 mW		
Typical Dark Current (e-/s/p)	less than 1	less than 1	less than 1	less than 1	10		
Typical RON (e-)	30 (TBC)	30	18	15	?		
TRL	?	high	high	high	?		
Values sourced from	Teledyne	Teledyne	Teledyne	Teledyne	Teledyne		
Mission (e.g.)	?	several	several	several	?		

Instrument detectors

	Vis	IR 1	IR 2	IR 3	IR 4	IR 5	IR 6
	0.4 - 0.8	0.8 - 1.5	1.5 - 2.5	2.5 - 5.0	5.0 - 8.5	8.5 - 11.0	11.0 - 16.0
Dark current required	< 690 e-/s/p	< 2250 e-/s/p	< 1180 e-/s/p	< 530 e-/s/p	< 6840 e-/s/p	< 4360 e-/s/p	< 760 e-/s/p
RON required (TBC)	< √(0.9*FW/3)	< √(0.9*FW/3)	< √(0.9*FW/3)	< √(0.9*FW/3)	< √(0.9*FW/3)	< √(0.9*FW/3)	< √(0.9*FW/3)
MCT (Euro n on p)							
Assume pixel size (um)			30	30	30	30	
Assume FWC (e)			2500000	2500000	2500000	2500000	
Hence... RON required			866	866	866	866	
Reference Temperature			180 K	110 K	60 K	55 K	
Theoretical T stability required*				3.7 K (at 50K)			0.27mK (at 30K)
Theoretical T stability goal*				0.37 K (at 50K)			0.027mK (at 30K)
Nominal power consumption**			1 mW	1 mW	1 mW	1 mW	
Typical Dark Current (e-/s/p)			**300000**	**30 million**	**60 million**	**350 million**	
Typical RON (e-)			**350**	**350**	**350**	**350**	
TRL			**medium**	**medium**	**medium**	**medium**	
Values sourced from			**SofradIR**	**SofradIR**	**SofradIR**	**SofradIR**	
Mission (e.g.)			**MTG**	**MTG**	**MTG**	**MTG**	
SiAs (US)							
Assume pixel size (um)					25	25	25
Assume FWC (e)					200000	200000	200000
Hence... RON required					245	245	245
Reference Temperature					7.1 K	7.1 K	7.1 K
Theoretical T stability required*							38mK (at 7K)
Theoretical T stability goal*							3.8mK (at 7K)
Nominal power consumption**					0.5 mW	0.5 mW	0.5 mW
Typical Dark Current (e-/s/p)					**0.1**	**0.1**	**0.1**
Typical RON (e-)					**12**	**12**	**12**
TRL					**high**	**high**	**high**
Values sourced from					**Raytheon**	**Raytheon**	**Raytheon**
Mission (e.g.)					**MIRI**	**MIRI**	**MIRI**

System budgets

Mass budget

Payload Module

Dry mass contributions	Without Margin	Margin %	Margin kg	Total kg	% of Dry module
Structure	365.98 kg	20.00	73.20	439.17	53.09
Power	13.20 kg	5.00	0.66	13.86	1.68
Instruments	43.01 kg	20.00	8.60	51.61	6.24
Cryogenics	273.00 kg	18.13	49.50	322.50	38.99
FGS	0.04 kg	10.00	0.00	0.04	0.01
Total Dry	-			827.18	kg
System margin		20 %		165.44	kg
Total Dry with margin				992.62	kg

Service Module

Dry mass contributions	Without Margin	Margin %	Margin kg	Total kg	% of Dry module
Structure	168.33 kg	17.60	29.63	197.96	43.60
Thermal Control	14.76 kg	17.53	2.59	17.35	3.82
Communications	25.80 kg	5.39	1.39	27.19	5.99
Data Handling	20.40 kg	20.00	4.08	24.48	5.39
ACCS	53.40 kg	5.00	2.67	56.07	12.35
Propulsion	27.72 kg	7.77	2.15	29.87	6.58
Power	17.80 kg	5.00	0.89	18.69	4.12
Harness	66.67 kg	20.00	13.33	80.00	17.62
FGS	2.00 kg	20.00	0.40	2.40	0.53
Total Dry	-			454.01	kg
System margin		20 %		90.80	kg
Total Dry with margin				544.81	kg

CAUTION, incomplete, and total mass close to limit!

- Preliminary estimates in Phase 0 always tend to increase in future study phases
- Optimistic estimate of telescope mass assuming SiC
- Mass of instrument box missing
- Mass of FGS missing
- Mass of Calibration system missing
- Assumed typical RWs, although potentially non-compliant with pointing requirements

Dry Mass PLM incl. 20% Margin	992.62 kg
Dry Mass SVM incl. 20% Margin	544.81 kg
Dry Mass PLM/SVM composite	1537.43 kg
Mass Adapter	90.00 kg
Mass Propellant	87.00 kg
Total s/c Wet Mass incl. Adapter and Margin	1714.43 kg
Maximum Launch Mass (including launch margin)	2066.00 kg
Below Maximum Launch Mass	351.57 kg

Mission ΔV

	Nominal + Extension [yr]	Direct Injection Δv including margin [m/s]								
		Date of Injection correction Manoeuver [days]								
		1	2	3	4	5	6	7	8	9
Inj. Corr. Δv		8.00	47.00	60.00	71.00	79.00	91.00	104.00	118.00	133.00
L2 SK	5 + 1	36								
	5 + 2	42								
	5 + 3	48								
	5 + 4	54								
	5 + 5	60								
TOTAL	5 + 1	44	83	96	107	115	127	140	154	169
	5 + 2	50	89	102	113	121	133	146	160	175
	5 + 3	56	95	108	119	127	139	152	166	181
	5 + 4	62	101	114	125	133	145	158	172	187
	5 + 5	68	107	120	131	139	151	164	178	193

=> For a direct injection, all "Green" options are feasible with the current S/C design in terms of propellant (excluding propellant for slews by using RWs), e.g. correction manoeuvre at day 4 and 6 years mission or at day 2 and 10 years mission.

Observation efficiency estimate

	Action	Duration details (Reference)	fixed antenna		with pointing mechanism	
	One year in hours		8765.8	h/yr	8765.8	h/yr
COMMS	High data rate and Doppler navigation	1,5 h twice per week (G/S & Ops, Comms)	156.5	h/yr	0	h/yr
	Medium rate communication, ranging, and Doppler	0,5 h twice per week (G/S & Ops, Comms)	52.2	h/yr	0	h/yr
OPS/Maint	Orbit Maintenance + larger checks	8h every 28 days (G/S & Ops expert)	104.4	h/yr	104.4	h/yr
Slews not related to observation, AOCS	Slews for comms pointing	(1 before + 1 after) * 2 per week, each 180°	106.2	hr/yr	0	hr/yr
	Slews for thruster pointing for orbit maintenance manoeuvres	inlcuded in Orbit Maintenance above	0	hr/yr	0	hr/yr
	Momentum dumping	inlcuded in Orbit Maintenance above	0	hr/yr	0	hr/yr
	Safe mode	2 per year, each 4 days (MRD)	192.0	h/yr	192.0	h/yr
	Calibration	once per week for approx. 1 h (ESM Study)	52.2	h/yr	52	h/yr
	Time available for observations and science target acquisitions		8102.34	h/yr	8417.28	h/yr
	Fraction of a year available for observations and science target acquisitions		92.4	%	96.0	%
	Available time divided by observation and slewing time	i.e. number of observations / yr	1508.91	-	1567.56	-
	Observation time	number of observations * avg observ time	7544.54	h/yr	7837.80	h/yr
	Observation efficiency		86.1	%	89.4	%

→ No Antenna Pointing Mech. needed

Photometric stability

1. Photometric stability requirement of 10^{-4} (P≥99.73%, Goal: 10^{-5}) relatively to the expected faintest star signal
2. This will allow making differential measurement of in- and out- of transit measurements with stable (i.e. comparable) signals
3. Preliminary budget included the following contributors to photometric variations:
   a. Stellar variability (50% RSS)
   b. Pointing errors (12.5% RSS)
   c. Thermal background variations (12.5% RSS)
   d. Dark current variations (12.5% RSS)
   e. Margin (12.5% RSS)
4. All values to be met over 10h
5. Non–compliant with thermal background stability at 16 microns

	Relative Weight	Budget Required	Translation			Com-pliance
				Required	Goal	
Total		1.00E-04		N/A	N/A	N/A
├ Science	1	7.07E-05		N/A	N/A	N/A
└ Engineering	1	7.07E-05		N/A	N/A	TBD
├ pointing	1	3.54E-05		0.070″	0.045″	G
├ thermal	1	3.54E-05	16µm:	±0.8mK@45K	-	N
│			11µm:	0K to 47.5K	44.3K to 45.5K	G
├ detector/readout	1	3.54E-05	different for each channel			TBD
└ calibration(TBC)/margin	1	3.54E-05				

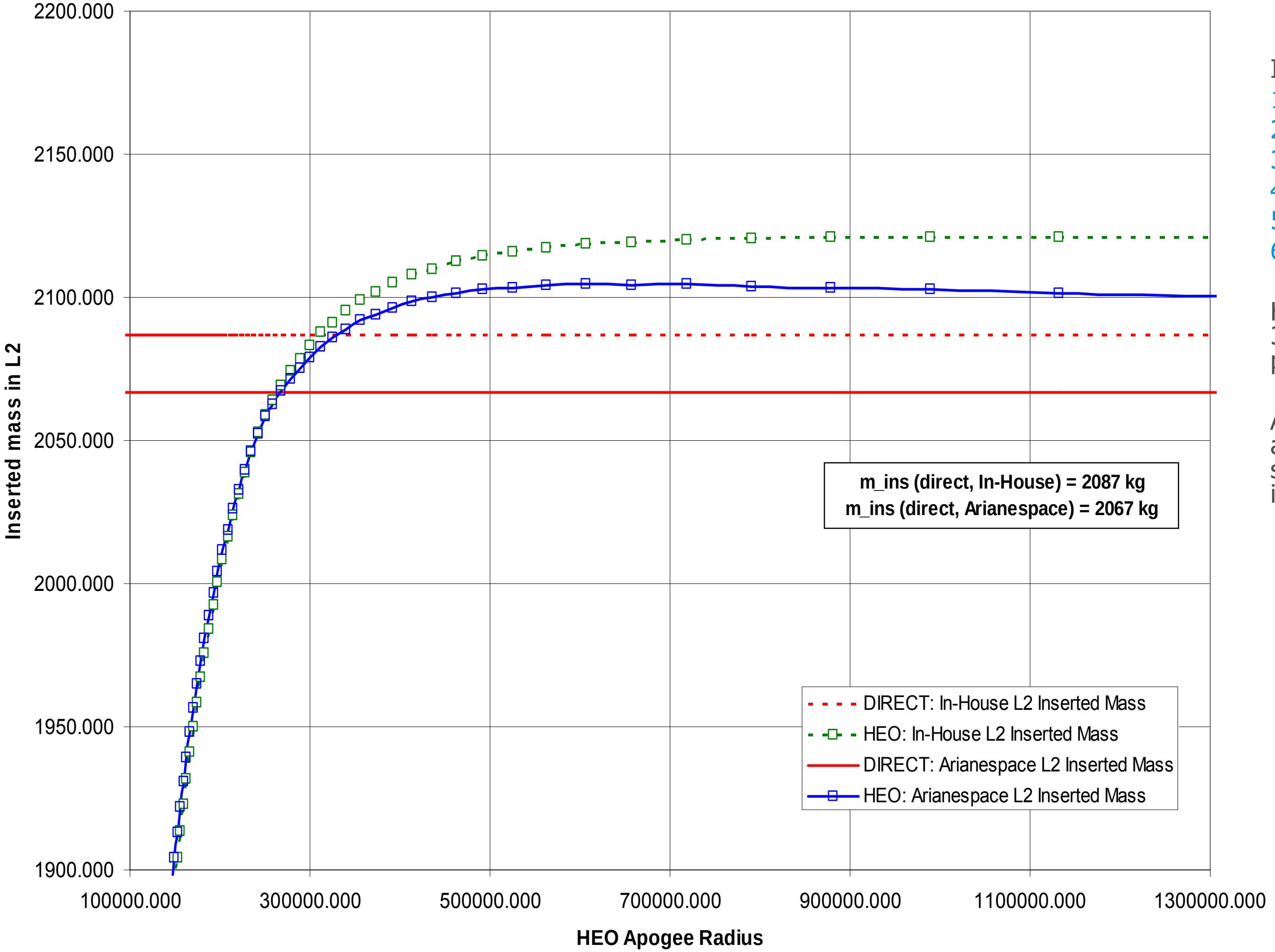
Mission analysis, ground segment and operations

Direct Insertion vs HEO

	Large Amplitude	Small Amplitude
Parking Orbit	$\Delta V\_ins = 0$ May need antenna repointing Engine Calibration possible Relaxes Launcher Dispersion manoeuvre May need mirror cover/shutter	High insertion ΔV No antenna repointing Engine Calibration possible Relaxes Launcher Dispersion manoeuvre May need mirror cover/shutter
Direct Insertion	$\Delta V\_ins = 0$ May need antenna repointing Tight Schedule for launcher dispersion manoeuvre	High insertion ΔV No antenna repointing Tight Schedule for launcher dispersion manoeuvre

=> If criticality of launcher dispersion manoeuvre can be removed, direct insertion is preferred.

Direct Insertion vs HEO



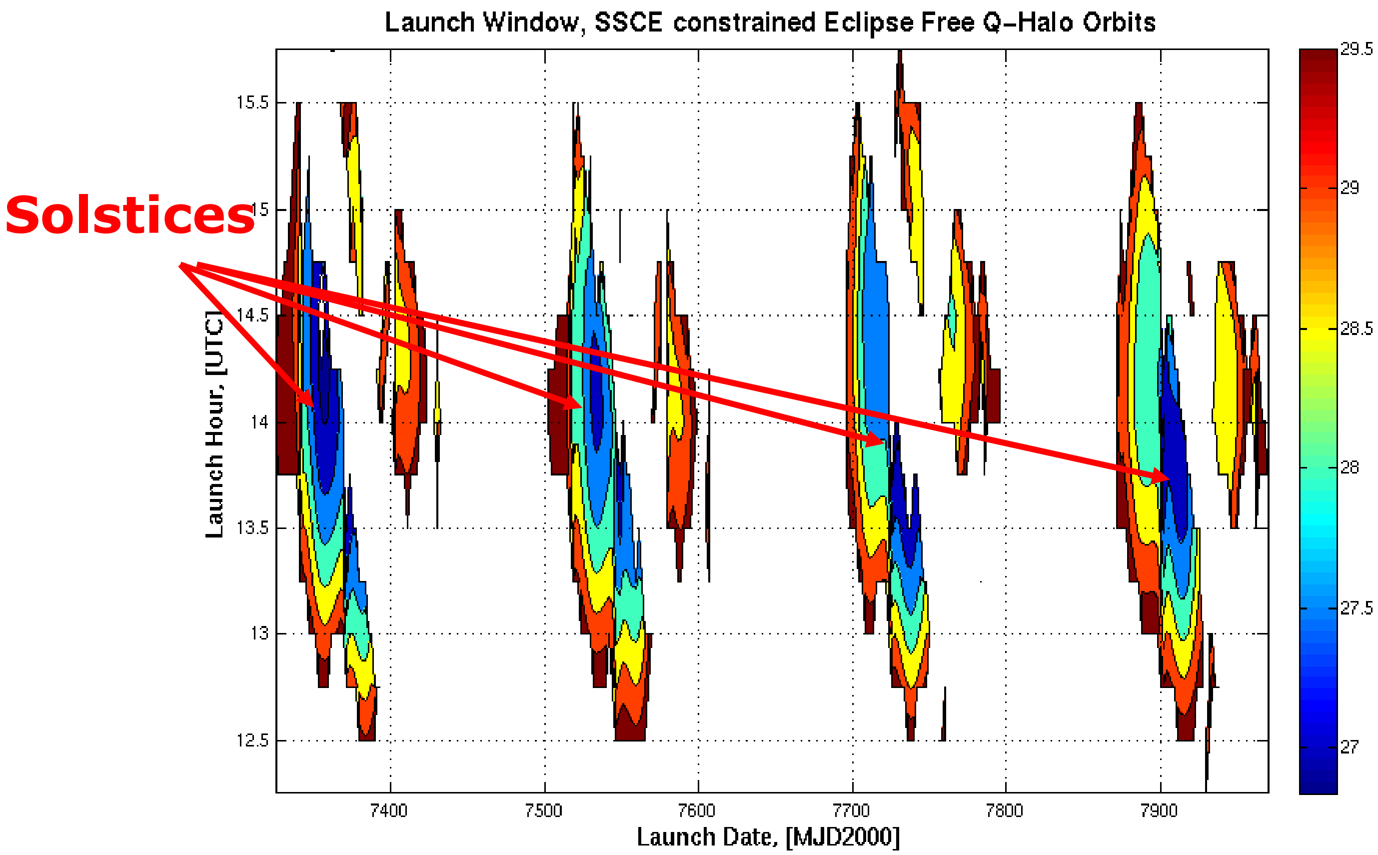
Included:

1. Launcher performance
2. Disposal
3. Gravity loss
4. Margins
5. Launcher dispersion @D2
6. Injection vel. Corr. @D2

HEO orbit with apogee under 300000 km does not provide higher performance.

Above that apogee, uncertainties about de-orbiting the Fregat upper-stage, which is now a requirement in French law.

Launch Window Analysis



2 yr launch window: 2020-2021

For every launch date/hour, bifurcations to enter WSB and approach L2

Eclipse free 5+1yr:

1. Transfer
2. Operational orbit
3. Moon not modeled, but minor influence

Maximum Amplitude (scan): 1.5e6 km

Assume maximum SSCE: 30 deg

Color shows maximum SSCE reached

Mission analysis conclusions

1. Direct Insertion is sizing case with 2066 kg insertion mass. This includes the Day 2 TCM.
2. Overall DV Budget as function of TCM timing and lifetime extension was provided.
3. Feasible trajectories around L2 with limited SSCE exist.
4. There are 2 major launch windows per year that allow reaching the baselined operational orbits:
   a. Around the solstices
   b. Daily LW up to 3hrs.
5. 5+1 yrs Eclipse free guaranteed (w/o Moon).
6. Forbidden Attitude not violated.

Data Volume

Daily Data Volume		
	[Mbit]	Comment
ECHO Science best estimate	140	Very low
ECHO Science worst case estimate	1000	Still very low

Daily Data Volume		
	[Mbit]	Comment
Herschel HKTM Data SVM	778	9 kb/s (No need to reduce)
Herschel HKTM Data PLM	691	8 kb/s (No need to reduce)
Rosetta Cruise HKTM	69	0.8 kb/s minimum configuration
ECHO Estimate for System + Payload	1296	15 kb/s assumed (could even be reduced if needed)

Downlink Data Rate

ECHO Required Data Rate [Mbit/s]				
	daily pass 1h	2 passes /week 2h	2 passes /week 1h	weekly pass 1h
Compressed HKTM + Science best estimate	0.23	0.26	0.78	1.56
Compressed HKTM + Science worst case	0.70	0.82	2.45	4.90
HKTM + Science best estimate	0.81	0.95	2.81	5.60
HKTM + Science worst case	1.29	1.50	4.48	8.94
* note: 1/2h of pass reserved for ranging + low data rate, data rate calculated only for high data rate portion of pass				

Operations characteristics and conclusions

1. L2 mission with wide amplitude orbit (Halo)
2. LEOP and transfer similar to Plato and Euclid
3. Pre-planned operations in observation phase with moderate number of repointings
4. Monthly orbit correction manoeuvre
5. Low science data volume allows to reduce coverage to 2 times per week

CONCLUSIONS:

1. **2h contact 2 times per week driven by operational concept convenience and compatible with data volume:**
    a. **1/2h with 150 kb/s + ranging**
    b. **1 ½ h 1.5 Mb/s without ranging (satisfies even worst case data volume)**

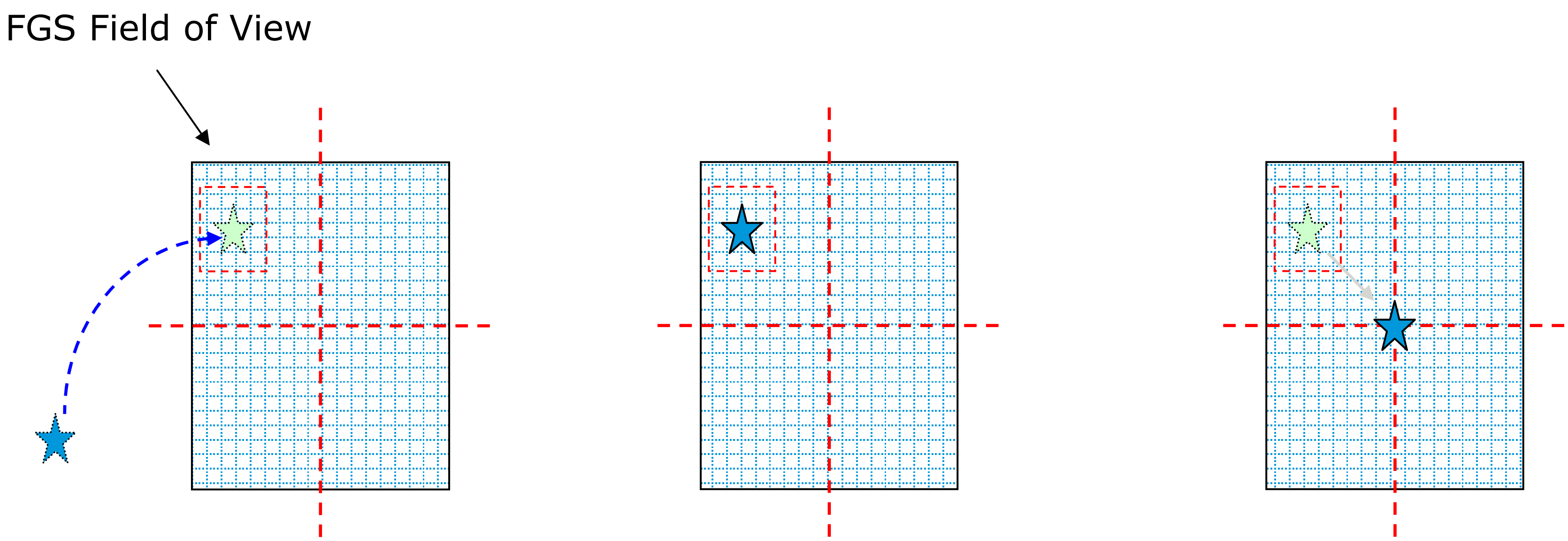
    => Few SPACON hours needed
2. **Moderate spacecraft autonomy requirements**
3. **Resulting data rates compatible with X-band and feasible with MGA on board, moderate RF power and 35m station on ground**

AOCS and FGS subsystems

Actuators trade-off

1. **Two solutions considered initially:**
    a. Reaction wheels vs micro-Thrusters (Cold Gas)
2. **Major downsides**
    a. RW: torque noise in the same order of the ctrl torques; source of micro-vibrations
    b. CG: not suitable for a long mission (>5years) because of lifetime and overall S/C mass
3. **Baseline: Reaction wheels**
    a. Existing off-the-shelf unit considered
    b. Use of dampers to reduce micro-vibrations
    c. In case of not compliance wrt. RPE requirement, a tip-tilt mirror mechanism can be used in addition
        – *Slight change in pointing strategy and controller to be implemented*
4. **Micro thruster solution to be "kept in the pocket" just in case…**
5. **Other solutions are also possible (to investigate in future phases):**
    a. Magnetic Bearing Reaction Wheels
    b. Micro-RIT (electric propulsion)

Target Pointing Strategy



1 Slew

From any attitude to the target (direct or Sun safe trajectory).

AOCS Ctrl loop based on STR and GYRO.

Ctrl B/W away from the tank sloshing frequency.

Settling 1-2min max.

2 Acquisition/Tracking

Acquisition of the star in the FGS FoV; the FGS is ON, but not in the loop.

Pointing stability (RPE) better than 0.01”over 100ms

Same AOCS Ctrl loop, but with different gains.

3 Locking

Bring the star to the centre of the FGS.

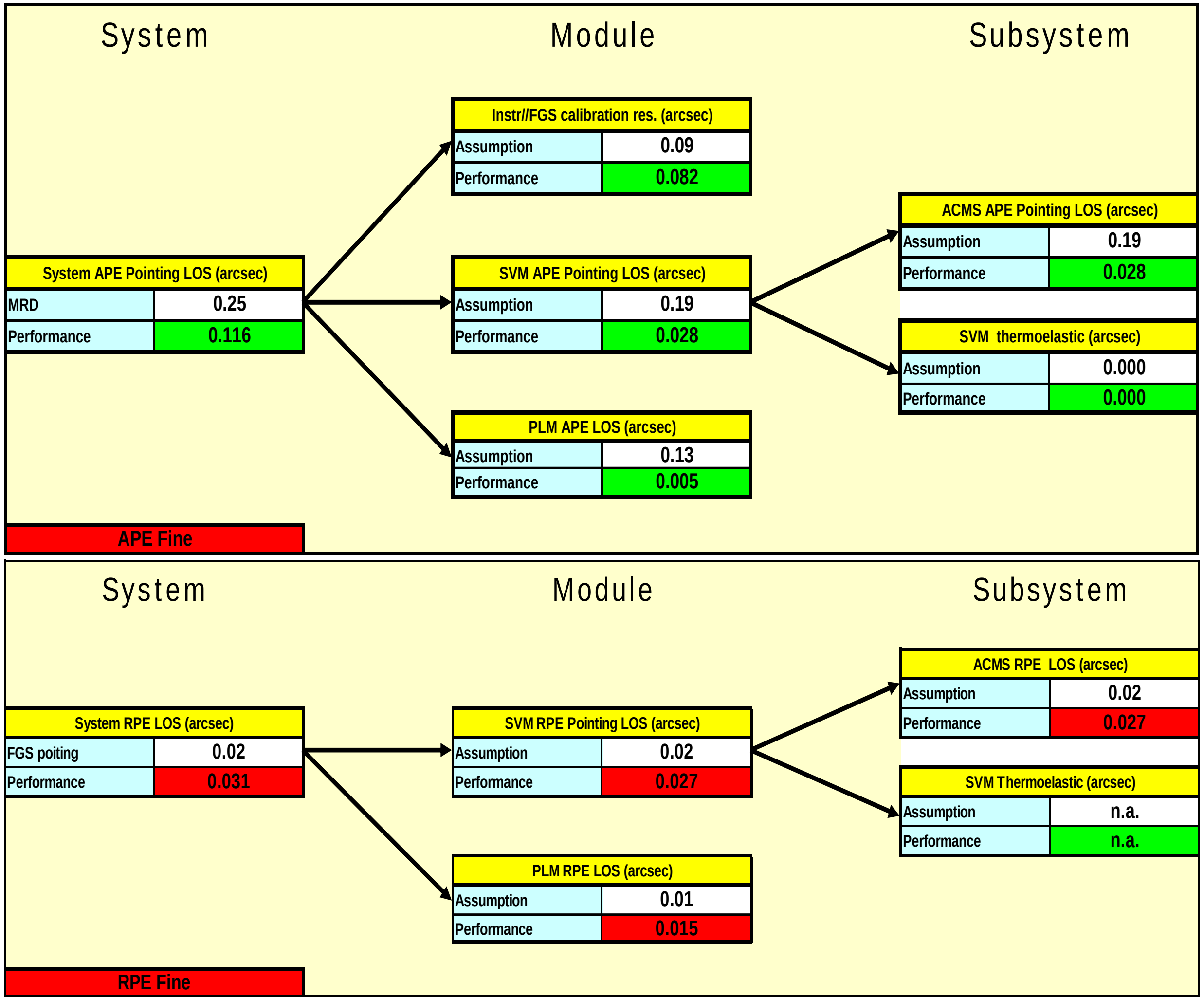
Two AOCS ctrl loop

- Z slow (1Hz) using STR and GYRO

-X/Y fast (10Hz) using FGS and GYRO

Optionally a tip-tilt mirror mechanism could be used to achieve stable pointing

Fine APE and RPE Allocation vs Performance



All values are half angle, 1 sigma, to be "RSSed".

Note: The FGS, as part of the AOCS subsystem, is considered as part of the "SVM" although included in the instrument volume.

CAUTION:

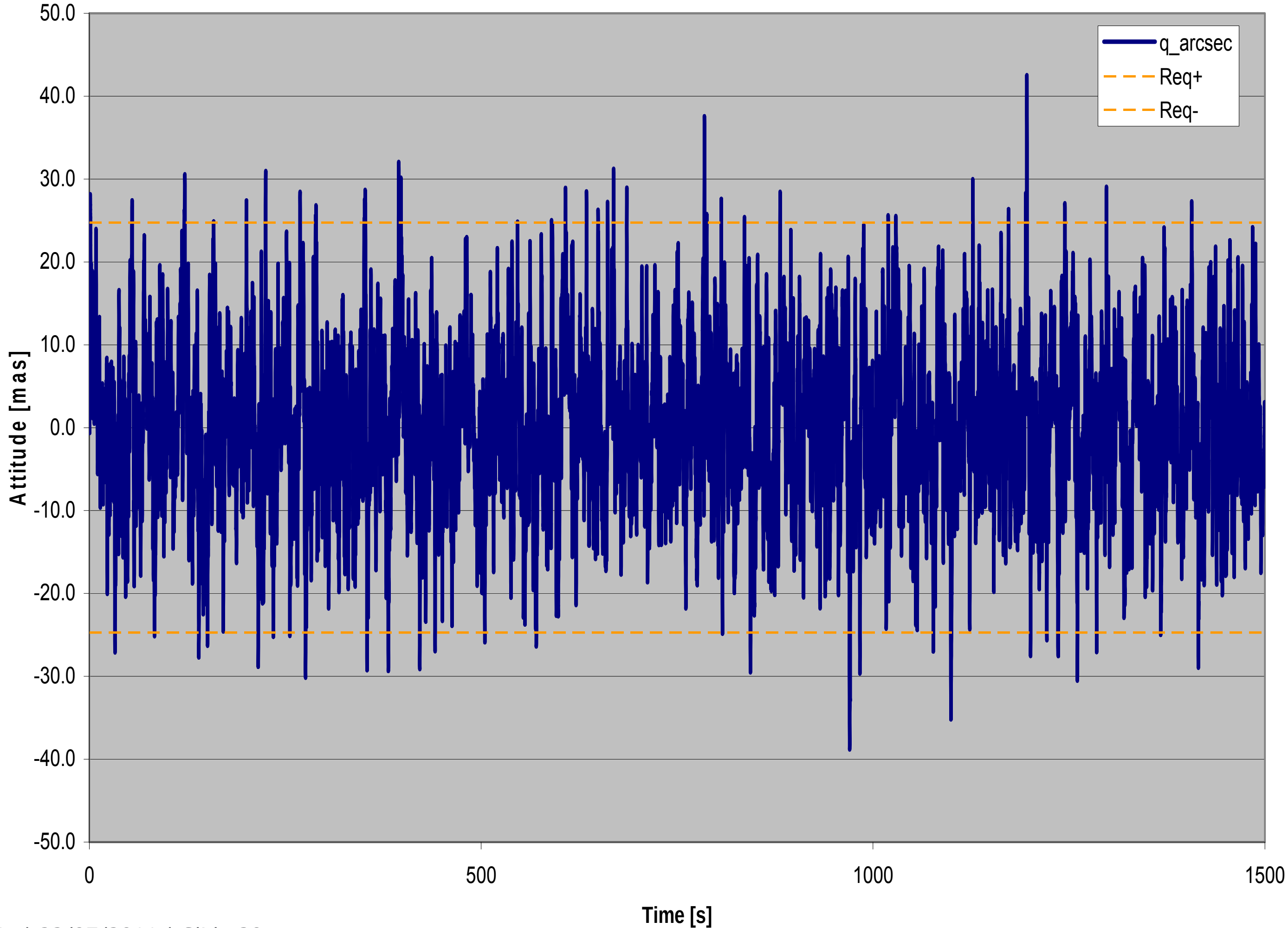
This is a preliminary pointing budget.

Actuators performance are pessimistic, in line with Phase 0 definition level.

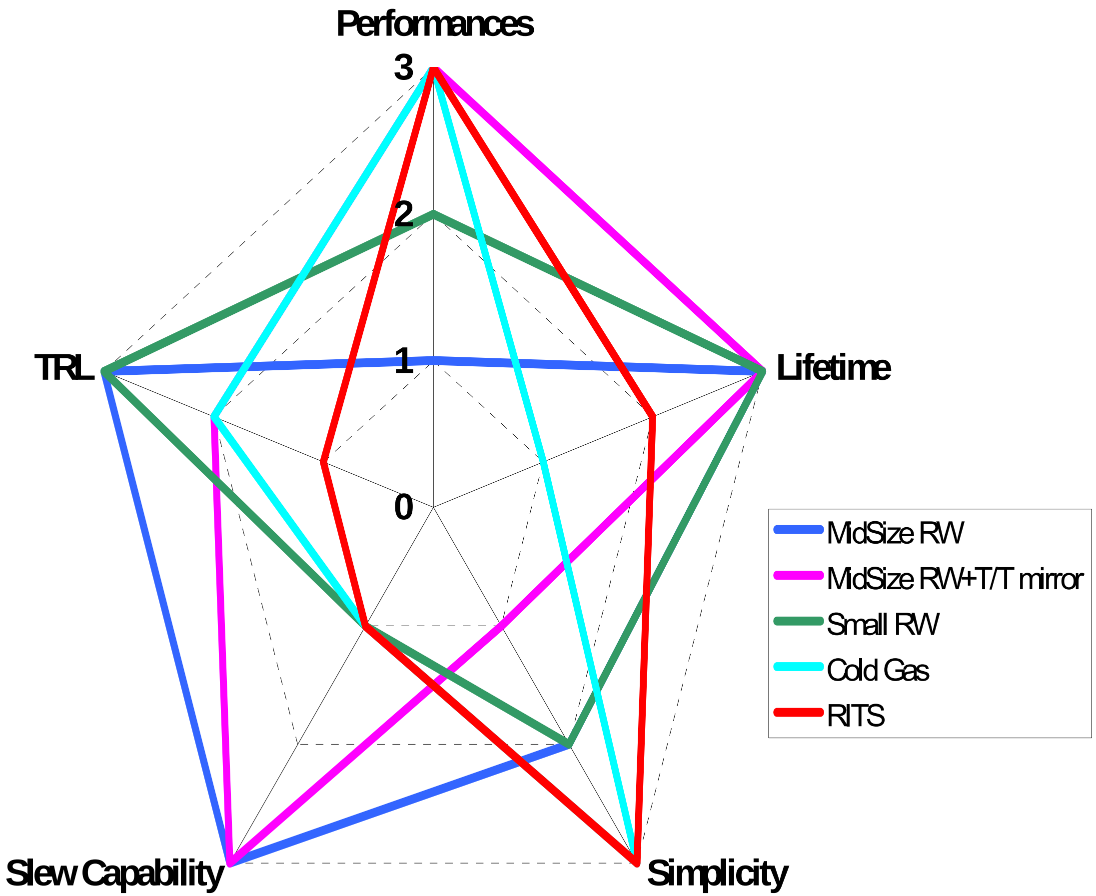
Assumptions within each term are numerous, and unverifiable at this stage without a detailed design.

This budget (allocation to each term and final numbers) is to be further iterated.

Relative Pointing Error
(Control torque delivered at 4Hz)



Quick look into options



AOCS conclusion

1. Feasibility of a control solution solely based on RW not confirmed at this stage. If worst case assumptions were confirmed, the tip-tilt mirror may recover the situation.
2. All other solutions (eg. Smaller RW or µThursters) could have an impact on the mission:
   a. Impacts on performance:
      - Need to relax pointing requirements
      - Forcing to shorter observations
   b. Shorter life time
   c. Additional complexity (sophisticated control logic)
   d. New Technology Development

FGS conclusion

1. In nominal operation, FGS can operate in cold redundancy
    a. Tracking Mode can be entered in a commanded way without passing through acquisition in case of failure of 1 FGS.

2. The baseline is :
    a. Teledyne HyVISI detector : 1024x1024 pixels
    b. Pixel resolution : 0.02 to 0.1 arcsec
    c. SideCar ASIC @ 12 bits
    d. Windowing mode (around 400 pixels per readout, 20x20 window)
    e. Custom equipment to be developed for centroiding computation or processing to be performed by central computer (preferred to avoid NRE)

3. Expected performances (optimistic):
    a. Bias : below 2 marcsec
    b. Noise : below 1 marcsec

4. Previously, the computed performances always took into account a static environment.
    a. In case wheels are used in fine pointing mode, then 50% of the light has to be allocated to the FGS
    b. In case a more “smooth control” is chosen, (cold gas or elecrical micropopulsion like Micro RITS), this can be relaxed to the original 10%

Thermal and cryogenic subsystems

Cryogenic architecture

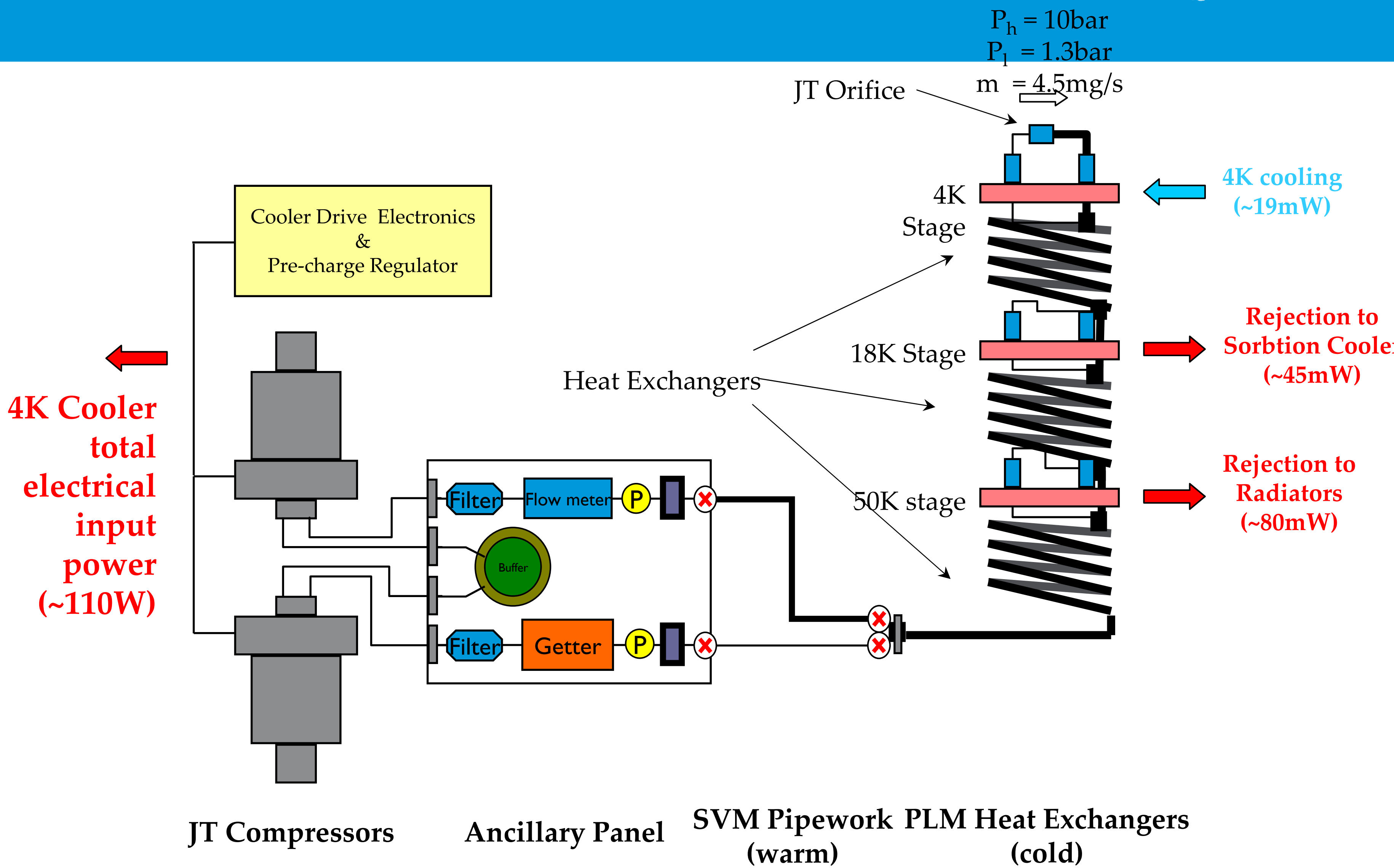
1. Photon noise limit requirement implies:
   a. Cooling of all elements in view of detectors (telescope + instrument box) to reduce the thermal background noise, more stringent the higher the wave length.
   b. Cooling detectors to reduce dark current noise.
2. Photometric stability requirement implies:
   a. Thermal background variations must be minimised
   b. Dark current variations must be minimised

=> Low T environment and high T stability

Strategy:

1. Passive cooling of telescope and optical bench to 40K (guarantee 45K including margins)
2. Active detector cooling for 5-16 µm down to 7K (RAL 4K JT & Twente H2 sorption 18K)
3. MCT and CCD detectors under 5 microns cooled passively via Optical bench

Planck 4K cooler



H2 Sorption cooler

1. Under development for Darwin cooler chain as a He JT pre-cooler
2. Mass ~6kg/unit
3. 2 units required for redundancy
4. High pressure stage can be accomodated on the 120K radiator
5. For 200 mW cooling power at 18K, dissipation is:
    a. 8.9W at 90K
    b. 9.6W at 120K

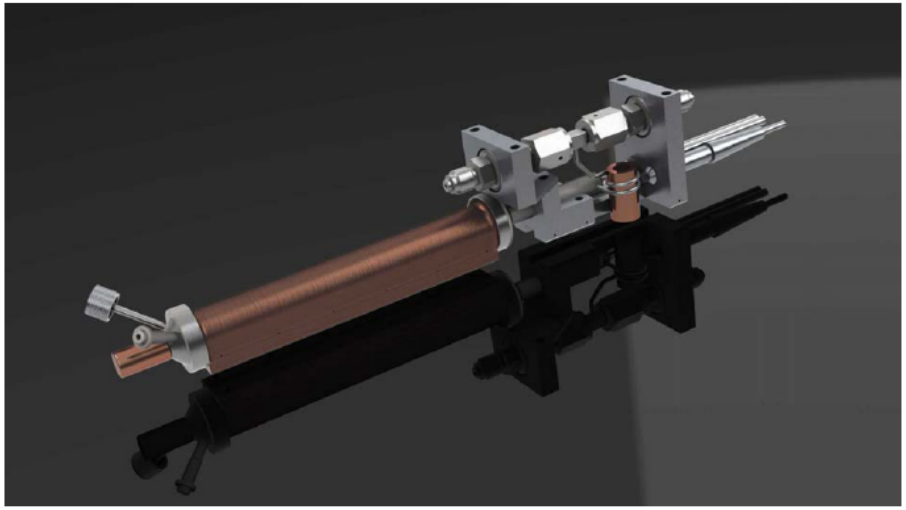
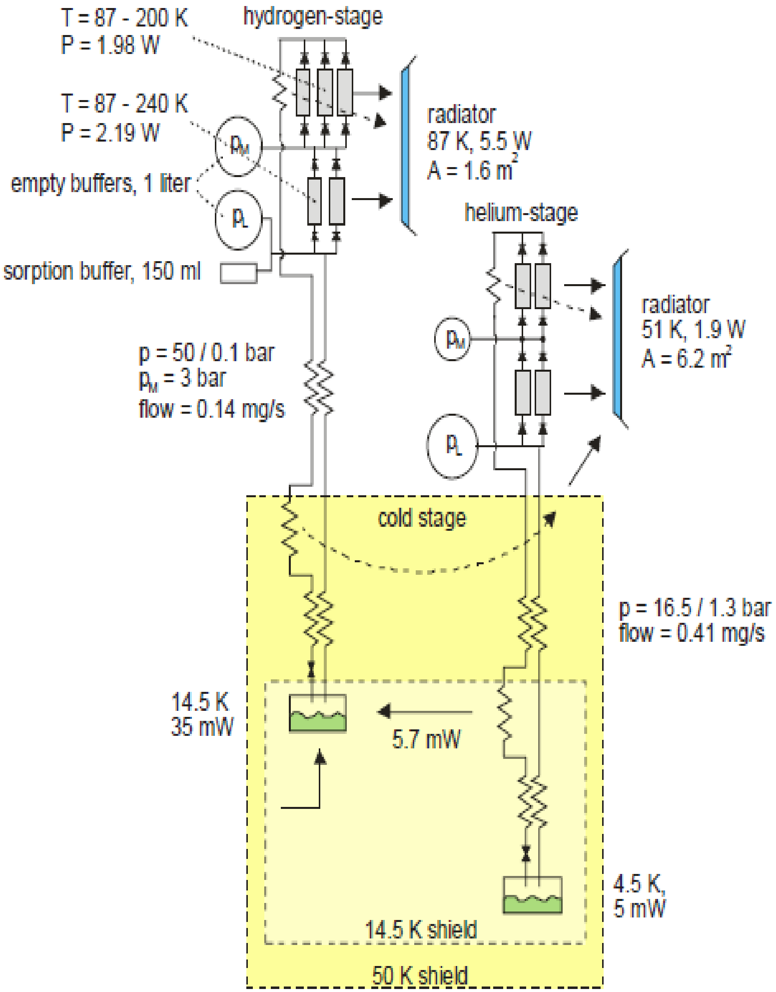
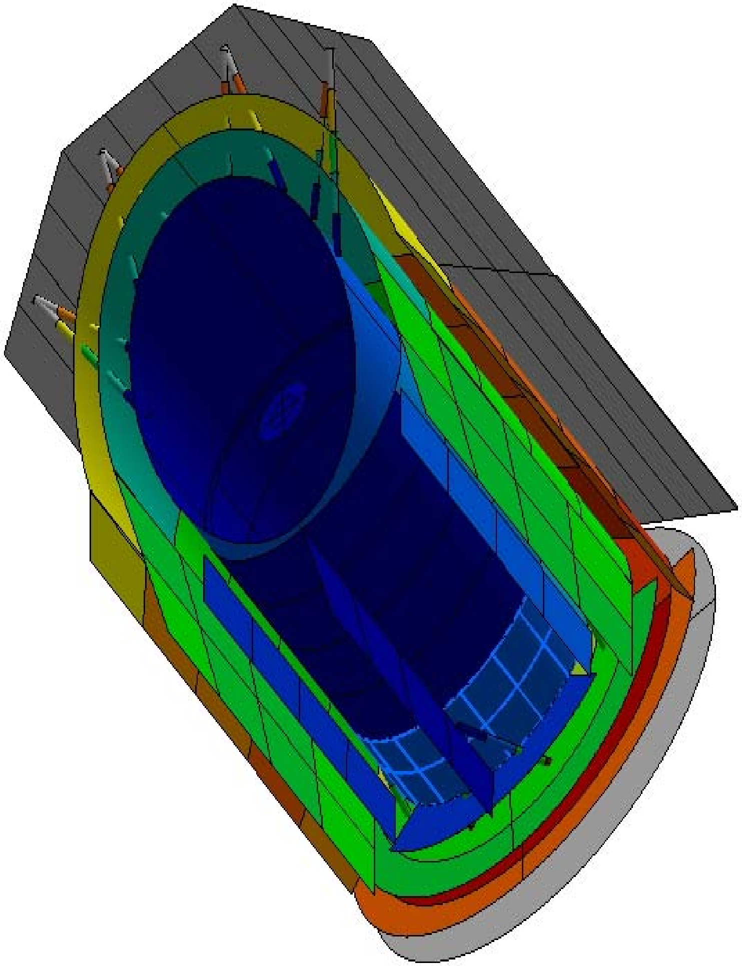


Figure 5.22 Hydrogen sorption compressor cell with integrated check valves on top of it.

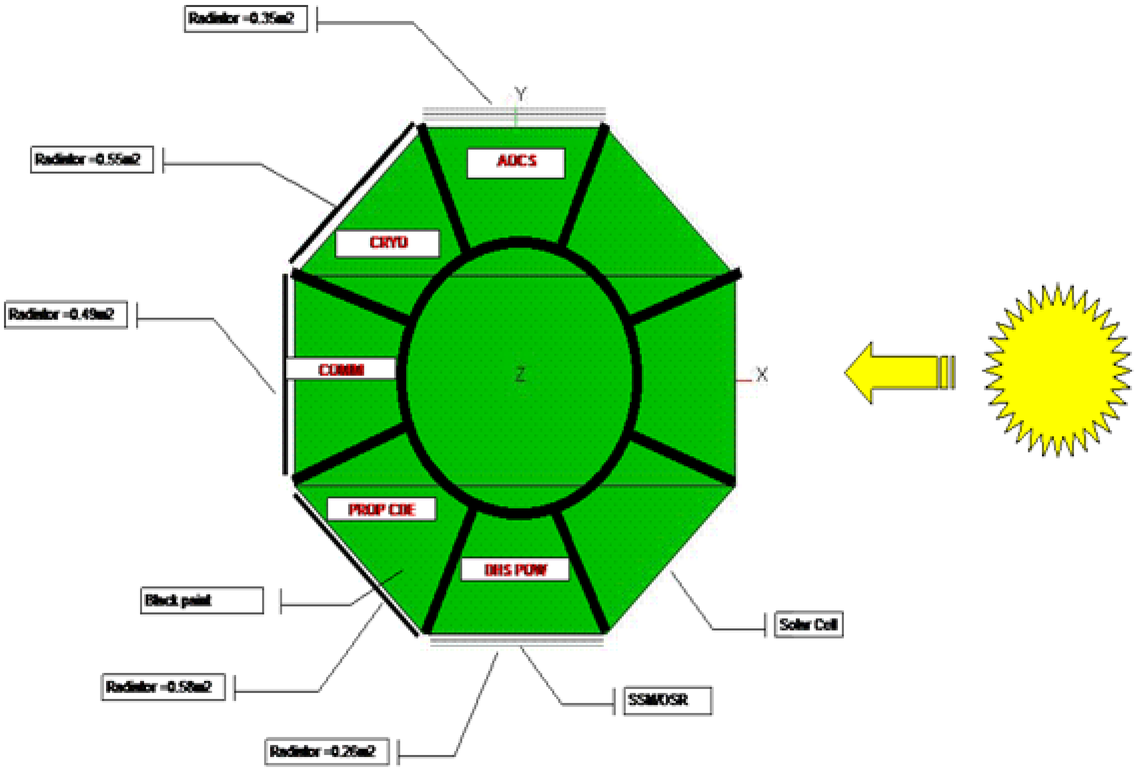


Passive design performance

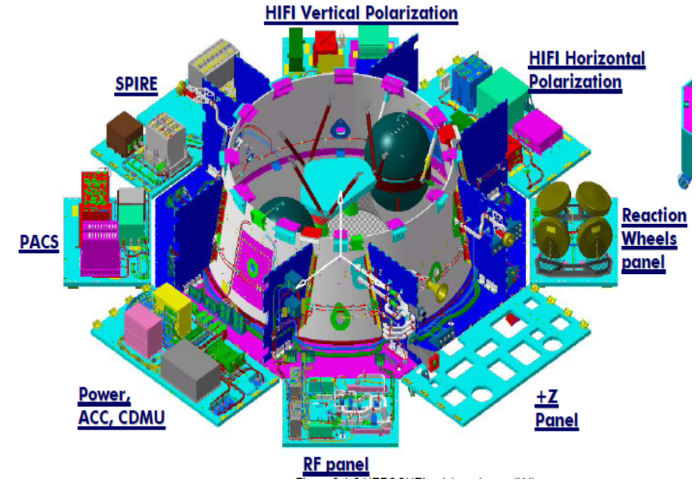
1. Telescope predicted ~38K
2. Sorption radiators OK:
   a. Thermal shield 1:90K
   b. Thermal shield 2: 125K
   c. Outer baffle 42K
3. Instrument Radiator 55K



Baseline SVM thermal design



Similarity with Herschel:



The SVM temperature was set to be at 0°C for all the enclosures.
Classical thermal control solutions are foreseen (MLI, radiators, Heaters).

No criticalities envisaged.

Power subsystem

Power

Solar Array sizing:

1. Assuming failure of one string
2. Triple Junction 28 % 3J GaAs Cells
3. EOL power generation, assuming worst case illumination: 1.13kW
4. Body mounted:
    a. One centre panel 4.2m^2, and two side panels of 1.2m^2 each
    b. 2kg/m^2 → 8.4kg for the centre panel, and 2.4kg for each side panel

Battery sizing:

1. Assuming a power consumption of 350 Watt for contingency mode, for 90 minutes, and being able to cover peak demands for short duration (if necessary)
2. Capacity: 36Ah
3. 6 cells in series, 24 strings
4. 15V<Vbatt<25V
5. Li-Ion battery with approximate 110Wh/kg → 4.7kg (without including battery structure mass)
6. It is chosen to use a Herschel re-built (and qualified) battery, since it has the same capacity and configuration concerning the cells (6S24P). Mass → 7.3kg

Control, Command and Data Handling subsystem

Data System Summary

1. No particular processing capabilities are required for the On-Board Computer
2. A single on-board computer (1nom+1red) handles the tasks related to both the platform and the payload
3. Some acquisition tasks are handled by Remote Terminal Units which concentrate several I/Os
4. The CPU also handles some light AOCS tasks (e.g. star tracking)
5. On-board memory storage is small due to the relatively little amount of data produced by the payload
6. Compression will be performed for housekeeping data only, raw science data can be stored and downloaded as is.

Radiation environment:

1. At SE-L2 solar protons dominate the total radiation dose, thus dose may depend on the launch date vs actual solar cycle.
2. Preliminary SPENVIS analysis with the assumption of 1 'quiet' year and 2 'stormy' years shows that electronic behind shielding requires a tolerance of not more than 20 krad (Si).
3. With this inputs use of up-screened COTS devices for some non critical digital functions, with the aim of reducing budgets is achievable.
    a. Mass Memory
    b. (> 80K) Thermal control

Propulsion subsystem

Propulsion subsystem sizing

1. Dry mass = 1548 kg (with 1 tank)
2. Dry mass = 1567 kg (if 2 tanks)

3. Taking dry mass, ΔV and heritage into account, the following propulsion system was chosen:
   a. Monopropellant (Hydrazine)
   b. Isp = 220 s (low level assumed due to blow down operations)

4. Calculate propellant amount to provide required ΔV

5. Calculate additional / total ΔV when 1 or 2 tanks are topped off with propellant.

6. Additional constraints:
   a. Preferably European off the shelf component selection
   b. Single fault tolerant system design

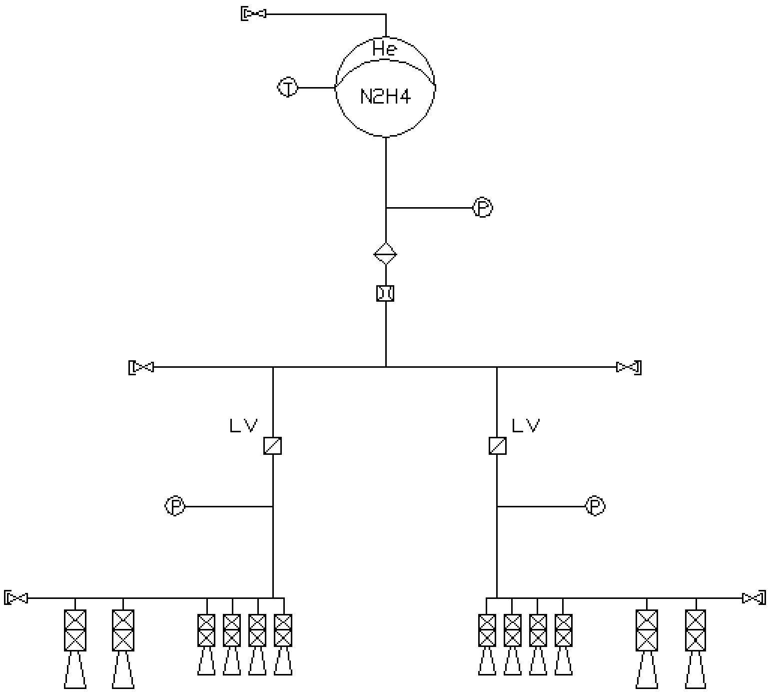
Velocity increments (incl. margins), propellant loads and tank sizing.

VELOCITY INCREMENTS INCLUDING MARGIN		
Launcher dispersion	38.22	[m/s]
Apogee raise	0	[m/s]
Station keeping	18.9	[m/s]
Reaction wheel offloading, safe mode, sun acquisition	9.46	[m/s]
AOCS manouvres	3.64	[m/s]
Direct transfer	0	[m/s]
Used velocity increment (Summed up)	70.2	[m/s]

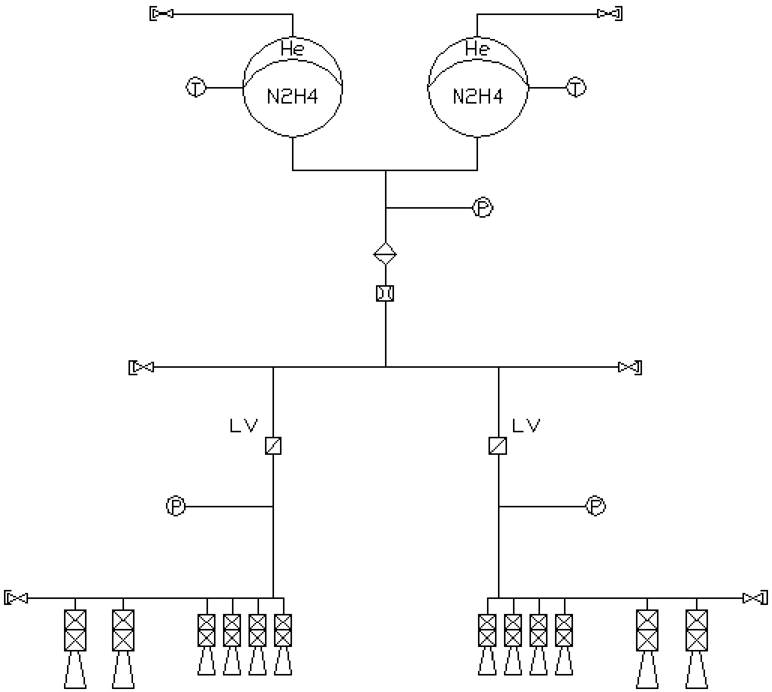
PROPELLANT CALCULATIONS		
Total propellant for all velocity increments (including margins excluding residuals)	51.2	[kg]
ECHO safe mode - recovery	8.0	[kg]
ECHO RSC reaction wheel offload	26.0	[kg]
Total propellant for alll velocity increments (including margins including residuals)	87	[kg]

TANK CALCULATION		
Number of tanks (Herschel)	1	[-]
Propellant mass per tank including margins and residuals	86.9	[kg]
Propellant volume	0.086	[m3]

Propulsion system architecture



1 tank architecture



2 tanks architecture

Communications subsystem

Requirements and design drivers

Design drivers:

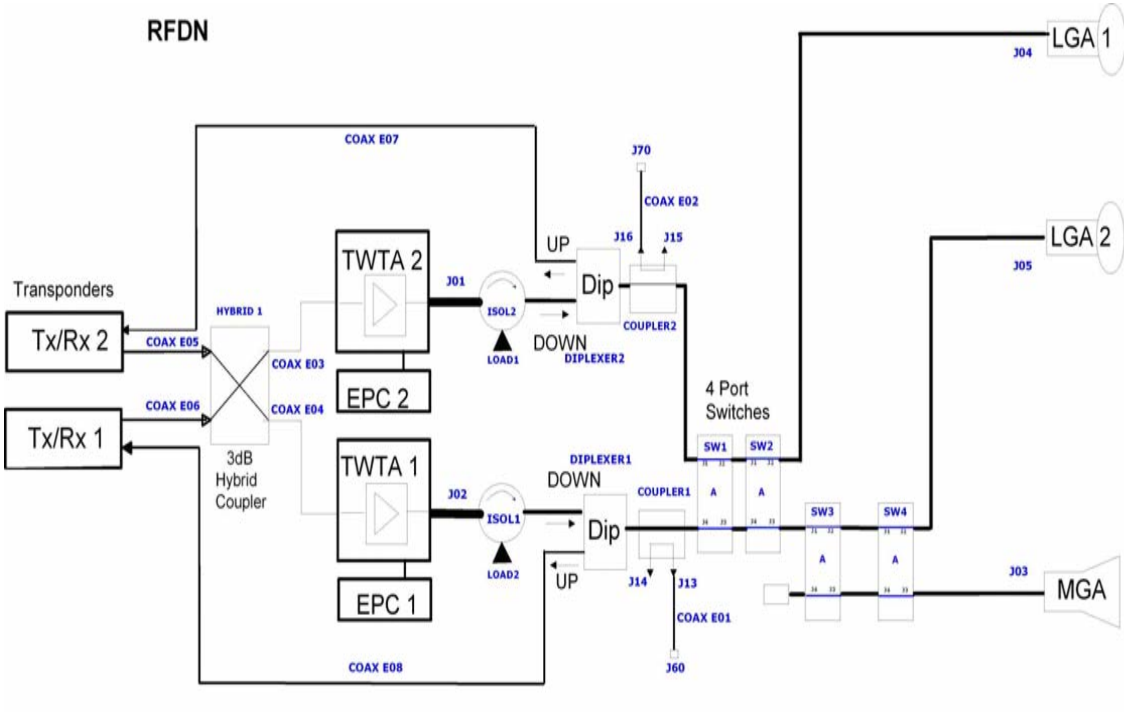
a. SE-L2 orbit. Maximum distance Earth-S/C = 1.8e6 km
b. 35 m X-band antenna, G/T=49.6 dBK
c. Two passes of 2 hours each per week (1/2h every contact for RNG+LRT and 1.5h at HRT)
d. Mechanism activation not allowed during Scientific Runs
e. Data Rate: as defined in Ground Segment presentation

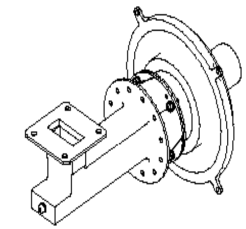
  - HRT: Assumed 1.5Mbps

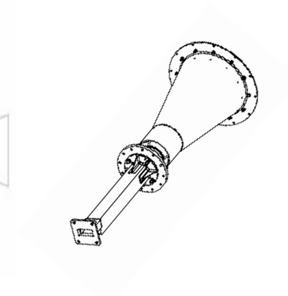
Communication architecture

The whole Herschel-Planck communications architecture could be reused:

- 2 x X-band transponders
- 2 x TWTA
- 1 x RDFN
- 2 x LGA
- 1 x MGA







Mechanically steerable MGA Option

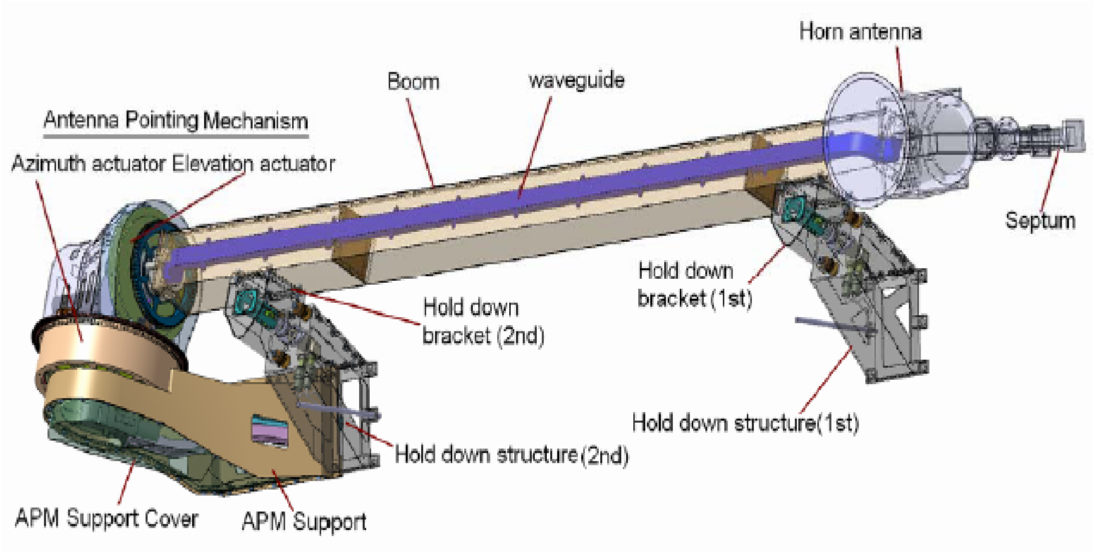


Figure 3-6: MGAMA without MLI.

1. Mass Penalty extremely limited compared to fixed MGA
2. Power consumption negligible
3. No issues for accommodation
4. Antenna re-pointing can be done during slews to ensure antenna is Earth pointing while telescope is on the next science target
   ⇒ scientific outage for TM & TC goes to 0%
   ⇒ Observation efficiency gains ~3%

Risk, AIV, programmatics and cost

Risk severity

Severity	Schedule	Science	Technical (ECSS-Q-30 and ECSS-Q-40)	Cost
Catastrophic 5	Launch opportunity lost	Failure leading to the impossibility of fulfilling the mission's Scientific objectives	Safety : Loss of system, launcher or launch facilities. Loss of life, life-threatening or permanently disabling injury or occupational illness; Severe detrimental environmental effects.	Cost increase result in project cancellation
Critical 4	Launch delayed (TBD) months	Failure results in a major reduction (70-90%) of mission's Science return	Dependability: Loss of mission. Safety: Major damage to flight systems, major damage to ground facilities; Major damage to public or private property; Temporarily disabling but not life- threatening injury, or temporary occupational illness; Major detrimental environmental effects.	Critical increase in estimated cost
Major 3	Launch delayed (TBD) months	Failure results in an important reduction (30-70%) of the mission's Science return	Dependability: Major degradation of the system. Safety: Minor injury, minor disability, minor occupational illness. Minor system or environmental damage.	Major increase in estimated cost
Significant 2	Launch delayed (TBD) months	Failure results in a substantial reduction (<30%) of the mission's Science return	Dependability: Minor degradation of system (e.g.: system is still able to control the consequences) Safety: Impact less than minor	Significant increase in estimated cost
Minimum 1	No/ minimal consequences	No/ minimal consequences.	No/ minimal consequences.	No/ minimal consequences.

Risk likelihood

Score	Likelihood	Definition
E (5)	Maximum	Certain to occur, will occur once or more times per project.
D (4)	High	Will occur frequently, about 1 in 10 projects Pf=0.1 R=0.9
C (3)	Medium	Will occur sometimes, about 1 in 100 projects Pf=0.01 R=0.99
B (2)	Low	Will occur seldom, about 1 in 1000 projects Pf=0.001 R= 0.999
A (1)	Minimum	Will almost never occur, 1 in 10000 projects Pf=0.0001 R=0.9999

Risk index - total

Combination of Severity and Likelihood of occurrence

Severity					
5		1		1	
4		1	5	3	
3	1		3	6	
2		2		1	
1					
	A	B	C	D	E
					Likelihood

Risk criticalities

Results of the preliminary analysis (to be further refined):

1. Red:
   a. 5D is launcher failure (common to all programmes)
   b. 4D are:
      - Criticality of launcher dispersion correction manoeuvre at day 2
      - ITAR restrictions on US HgCdTe detectors
      - ITAR restrictions on US Si:As detectors
2. Yellow:
   a. Missing launch window or unavailability of LV
   b. Loss of science detector or cryogenic chain
   c. Telescope degradation (on-ground or in-orbit)
   d. Micro-vibrations, SEU on FGS detectors, stray light, cryo-chain development and procurement, loss of thermal, power or attitude control etc.

AIV model philosophy

1. Structural Thermal Model - STM / Cryogenic Qualification Model - CQM:

    a. STM
        - Mechanical verification: sine, acoustic, shock
        - Thermoelastic verification: videogrammetry measurement of structure and telescope in a TV chamber will be needed (PLM level)

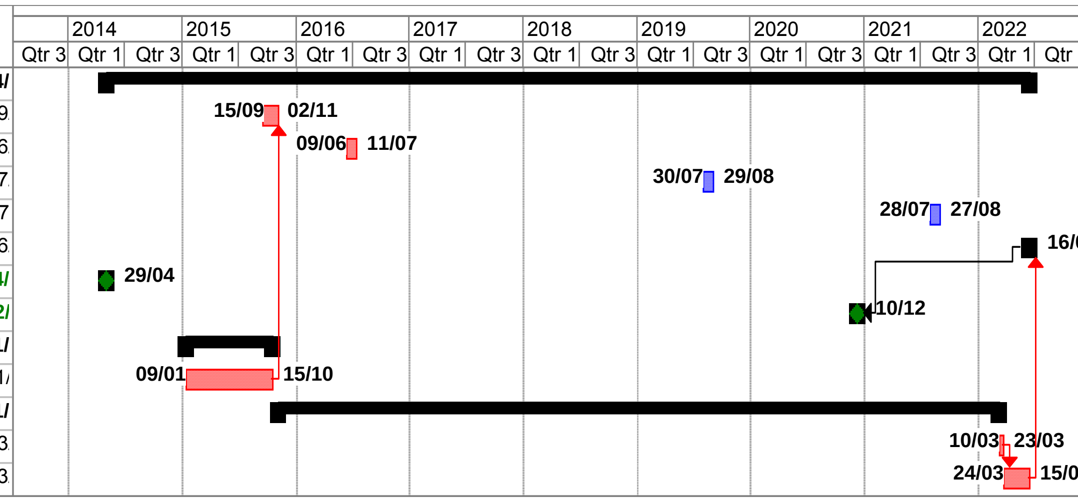
    b. CQM (as for Planck approach)
        - Thermal verification: thermal balance and TMM correlation
        - Thermal verification: cryogenic instrument test needed at integrated PLM level, many Instrument units on SVM though
        - Cryogenic chain verification, PLM only
        - Microvibration levels to be verified here. Sources from test set up to be identified and monitored

2. Avionics Verification Model
    a. Functional testing of the avionics including instruments

3. Proto-Flight Model
    a. Flight spacecraft joint qualification and acceptance (protoflight)

Schedule

ID		Task Name	Duration	Start
2		**ECHO**	**2122 day**	**Tue 29/04/**
3		SRR	35 day	Tue 15/09
4		PDR	23 day	Thu 09/06
5		CDR	23 day	Tue 30/07
6		FAR	23 day	Wed 28/07
7		Launch	0 day	Thu 16/06
8		Impl. Phase start with launch on Dec	0 day	Tue 29/04/
9		Launch December 2020	0 day	Thu 10/12/
10		**Definition Phase**	**200 day**	**Fri 09/01/**
11		Phase B1	200 day	Fri 09/01/
12		**Implementation Phase**	**1657 day**	**Tue 03/11/**
82		Transportation to Launch Site	10 day	Thu 10/03
83		Launch campaign	60 day	Thu 24/03



⇒ Launch in mid 2022 means implementation (Phase C) needs to start end 2015

⇒ Compatible with a B2/C/D duration of 6 yr, OK.

Preliminary cost assessment

Preliminary cost analysis on 3 options:

Option	Cost
1) Baseline mission: - US MCT up to 5 microns - US Si:As up to 16 microns	
2) Back-up solution: - European MCT	
3) Wave range cut at 5 microns, no active cryo-cooler	

Color code		
≤ 470 M€	≤ 470 M€ + 15%	> 470 M€ + 15%

No large difference between options 1 and 2: suppression of 7 K cryo-cooling stage is compensated by larger contingencies due to risk on MCT developments.

Option 3 is the only one close to M3 cost constraint: fewer channels, smaller instrument, relaxed cryogenic needs.

=> All efforts should be drawn towards simplifying the mission as close as possible towards option 3, to reduce the risk of not being down-selected against other M3 candidates!

Conclusion

Requirements review

1. Photon noise limited system is achievable at the expense of US ITAR detectors and deep cryo-cooling needs.
2. Target distribution and observation efficiency is OK.
3. Preliminary photometric stability budget:
    a. AOCS and FGS solution needs re-visiting, compliance with RPE requirement is uncertain with current baseline.
    b. If fine pointing achieved, compliance to photometric stability goal up to 11 microns seems feasible, but uncertain due to thermal background variations at 16 microns.
4. Other subsystems are fine: communications, propulsion (if no propellant for slews), CCDH, thermal, structures, configuration etc.
5. Compliance with Soyuz requirements is OK.
6. Schedule feasibility is OK.
7. Preliminary cost analysis shows mission needs simplifying!

Open trades

1. Need for a tip-tilt mechanism depends on consolidation of fine pointing performance with standard RWs.
2. Need for a re-focussing mechanism to be analysed.
3. Need for an internal calibration (photometric and spectroscopic) system.
4. Need for redundant cryogenic chains (risk to be analysed).
5. Final choice of M1 size:
    a. Volume inside fairing does not allow an increase in M1 with current accommodation (on-axis).
    b. Re-design and larger structures, thermal shields etc. will add an extra increase in SVM cost and complexity.
    c. Cost analysis shows this should not be the way forward.

Way forward

1. Instrument design needs further consolidation.
2. Noise contributors need detail assessment for compliance with photon noise limit (e.g. instrument thermal background was not estimated, only the telescope thermal background).
3. AOCS actuators selection needs re-visiting.
4. Photometric stability budget needs a deeper analysis, to account for possible contributors left-out in the frame of the CDF (e.g. instrument box thermal background variations, inter- and intra- pixel response variations, micro-vibrations impact, instrument power input variations and induced offsets and gain shifts etc.).
5. Possibilities of down-scaling the mission to remain within budget need to be discussed – IMPORTANT.

Actions for Study Science Team

1. Preliminary estimates in Phase 0 always tend to increase in future phases.
2. Requirements need re-visiting, to bring the mission as close as possible to cost option 3 to remain competitive in down-selection:
    a. Is cut at 5 microns acceptable in terms of science?
    b. Otherwise provide a cut half-way between 5 and 16 microns (e.g. 8.5 or 11 microns).
    c. Deleting the science Vis channel will relieve criticality of FGS performance (more light for FGS) and relax the RPE to an achievable point with typical AOCS actuators (RWs only).

    => Mission might not get back within M3 envelope, but any efforts towards it will only help its case.
3. MRD needs updating as soon as possible (by September/October 2011):
    a. Contractors for S/C study need to know what to design for.
4. Report on calibration strategy is needed to define calibration requirements.
5. Report on operations and exoplanets visits planning is needed, with results from radiometric model indicating how many revisits per target are necessary to achieve required SNR, and to validate the proposed mission lifetime (5+1 year).

This study is based on the ESA CDF Integrated Design Model (IDM), which is copyright.