WE LOOK AFTER THE EARTH BEAT

Avionic Architectures for Entry Descent and Landing missions on MARS, MOON and ASTEROIDS

A.Tramutola

A.Martelli

24 October 2013

Noordwijk ADCSS

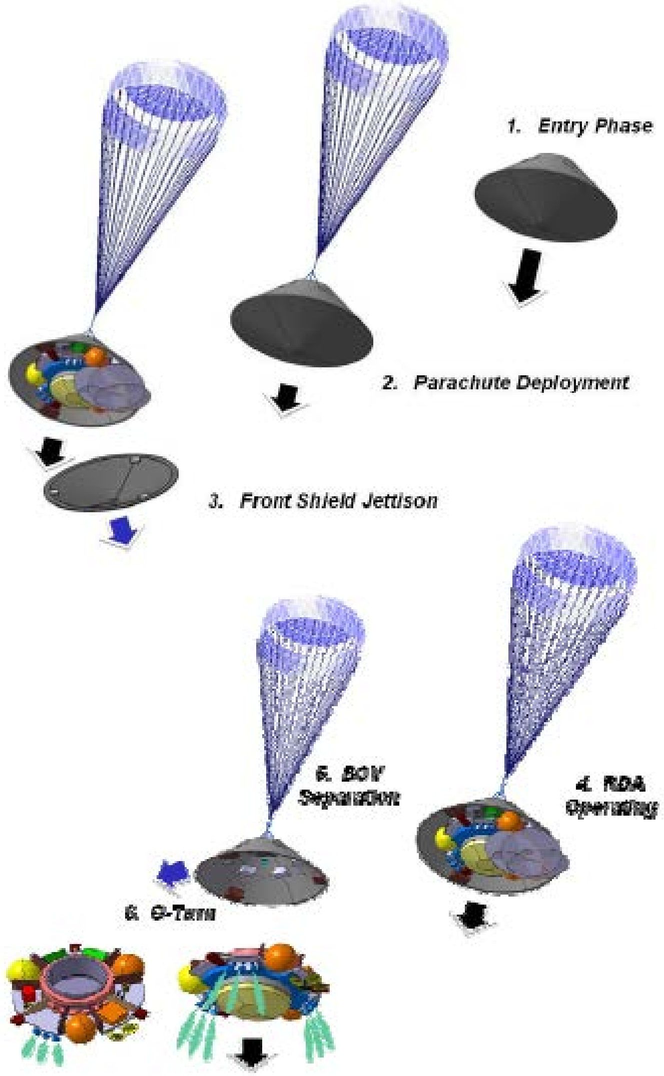
Content

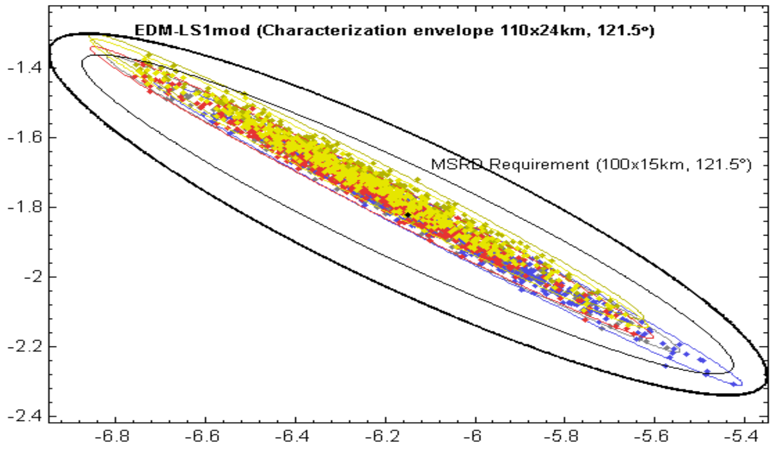
- LANDING ON MARS: Atmospheric landing avionic platforms
  - EXOMARS: Current exploration mission (launch in 2016) (next 2018)
  - INSPIRE : future mission (2024 - 2026)
- LANDING ON ASTEROID: Non atmospheric landing, low gravity
  - PhootPrint : Landing/sampling on PHOBOS
  - Marco Polo R : Touchdown/sampling on NEA 2008 EV5
- Evolution towards high performance platforms for GNC (SAGE)
  - Mars landing
  - Moon landing
- Evolution towards Image Processing Unit (IPU) for IP based EDL Navigation (VISNAV)
- Conclusions

LANDING ON MARS - EXOMARS : Landing requirements

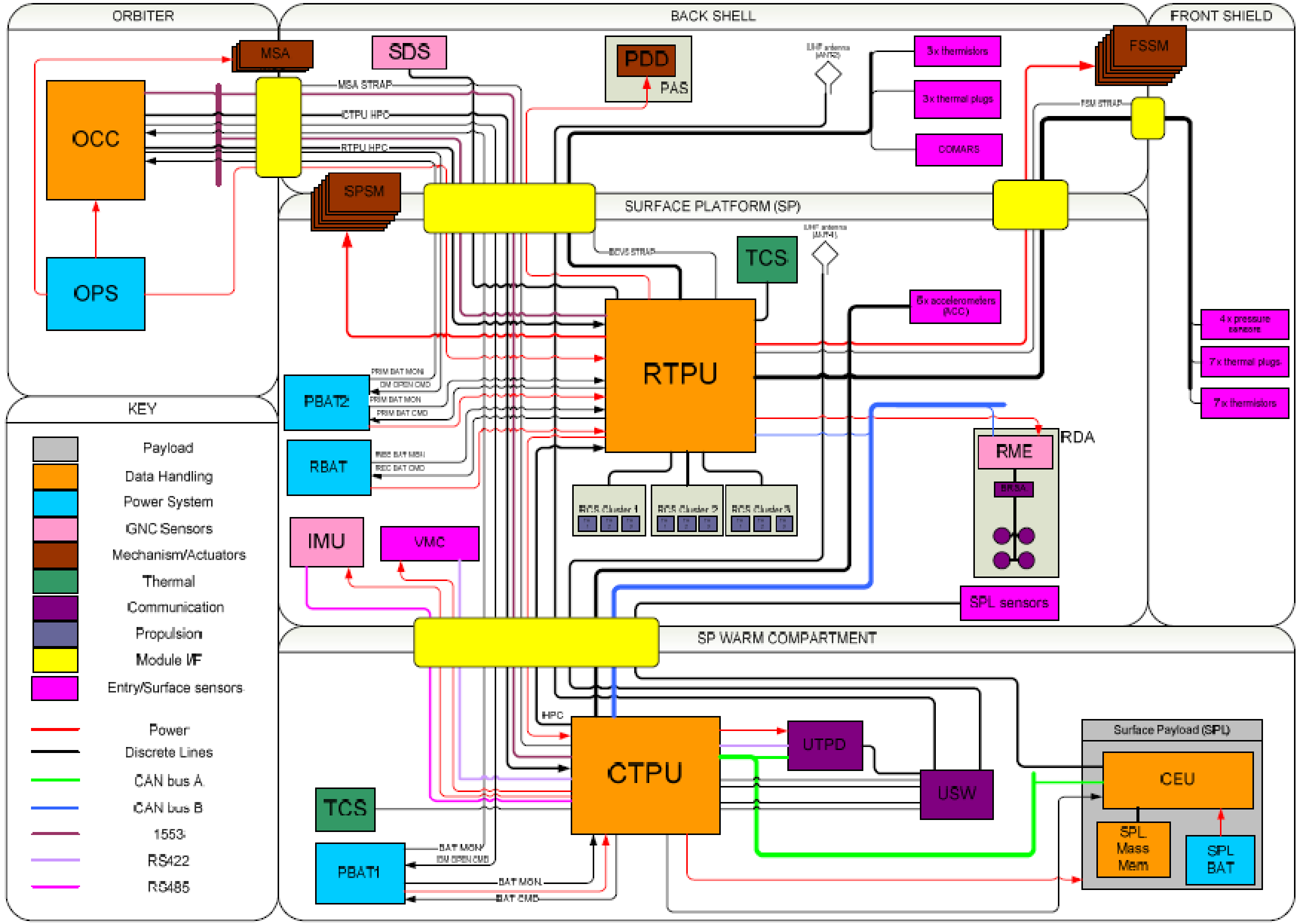
EXOMARS: Atmospheric landing

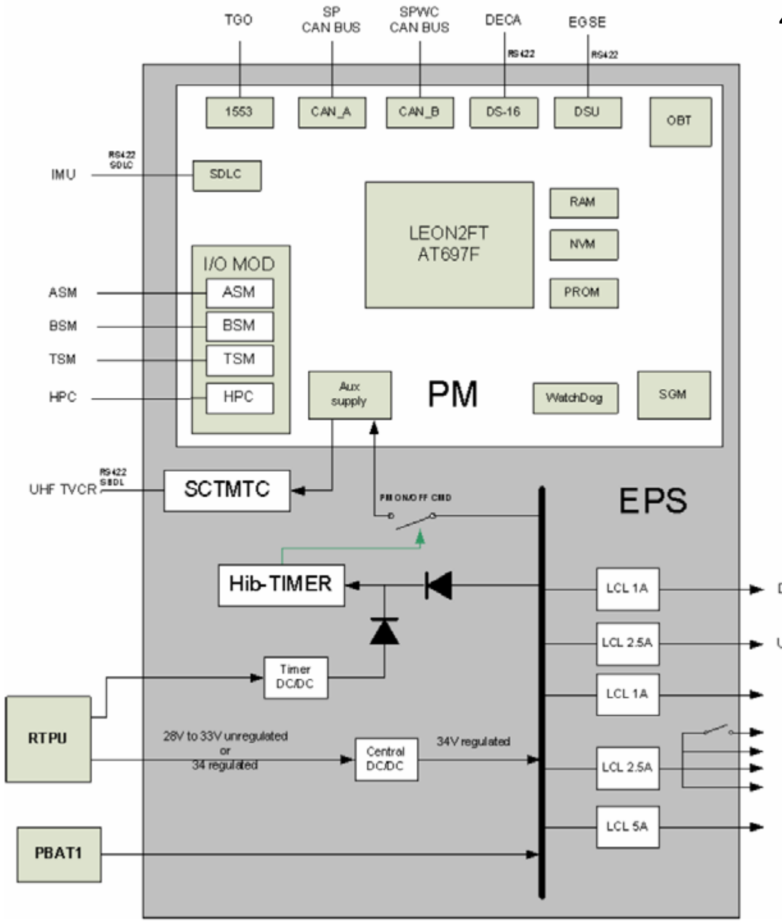
  - environment requests thermal shielding => delayed RAD activation
  - braking effect of the atmosphere reduces propellant consumption
  - parachute reduces velocity but is subject to lateral disturbances
- Achievable landing accuracy is low => requirement is semi-axes 50Km x 7.5Km [3σ]





EXOMARS : SCC Avionic architecture and CTPU architecture

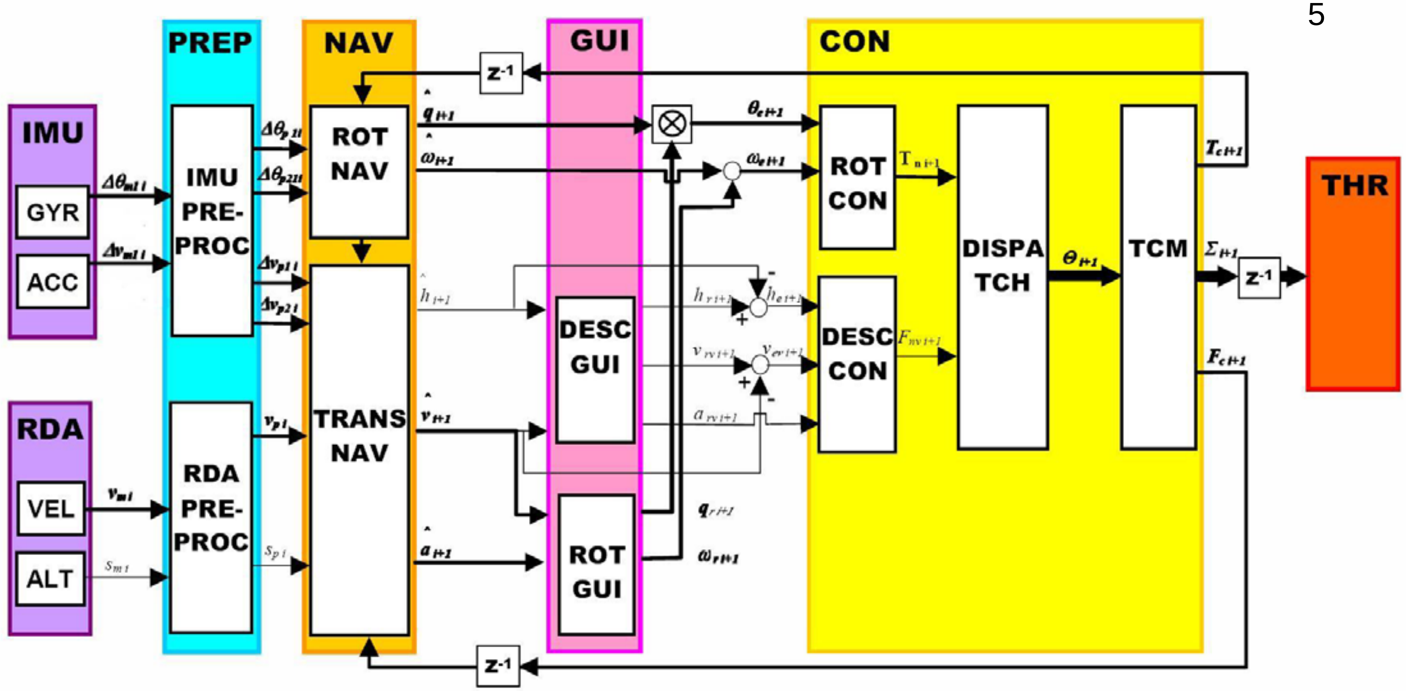




- EDM Data Handling subsystem consists of CTPU and RTPU
- CTPU architecture is based on
  - AT697F @64MHz (LEON-2 processor)
    - 55MIPS, 13 Mflops, 64kB PROM, 8MB SRAM, 32Gbits Flash Mass Memory

EXOMARS : GNC architecture and computing performance

- GNC cycle @ 10Hz
- In all GNC modes the CPU performance are compatible with AT697F performance leaving more than 75% of the 100ms slot time to other SW tasks
- GNC SW size is well within volatile and non volatile available memory
- **EXOMARS mission can be accomplished with available computing platform**



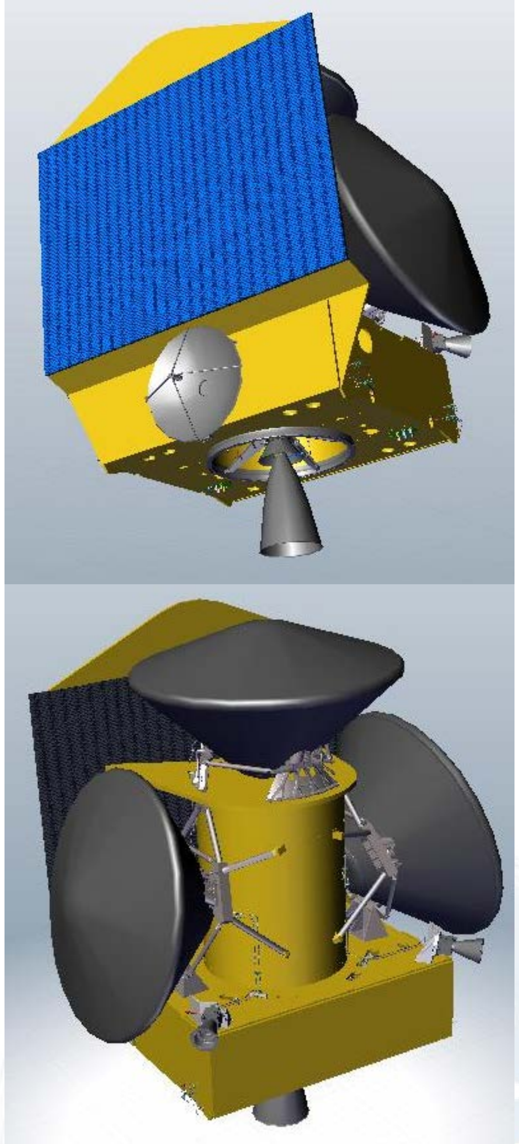
Size in Kb			
Data	Code	Total	Package
22,63	13,27	35,88	Data Package
0	22,86	22,86	Basic Package
36,61	128,49	165,05	Functional + Events
10,81	63,67	74,45	GNC SMS Interfaces
70	228,25	298,25	(TOTALS)

Mode	Task_Init	100Hz Task	20Hz Task		CPU 50MHz	CPU 66MHz
	Time	Time	20 Hz	10 Hz	%	%
Preseparation	2043	153		1171	4,74%	3,59%
Coasting 1	155	1547		1527	17,15%	12,99%
Coasting-3	93	847		467	9,03%	6,84%
Coasting 4	102	1248		3999	16,58%	12,56%
Coasting 5	74	1689		90	17,05%	12,92%
Coasting-6	37	2189		178	22,11%	16,75%
Entry	1472	2625		544	28,27%	21,41%
I. Descent	1472	2185		115	23,44%	17,76%
Int. Descent	1533	2105	2781		28,15%	21,32%
T. Descent	1454	1767	3709		26,54%	20,11%
Landing1	169	1794	4119		26,35%	19,96%
Landing2	1734	1774	3694	4102	30,96%	23,46%
Landing3	67	1792	1042	3127	23,20%	17,57%
Drop	4	1764	1096		19,84%	15,03%

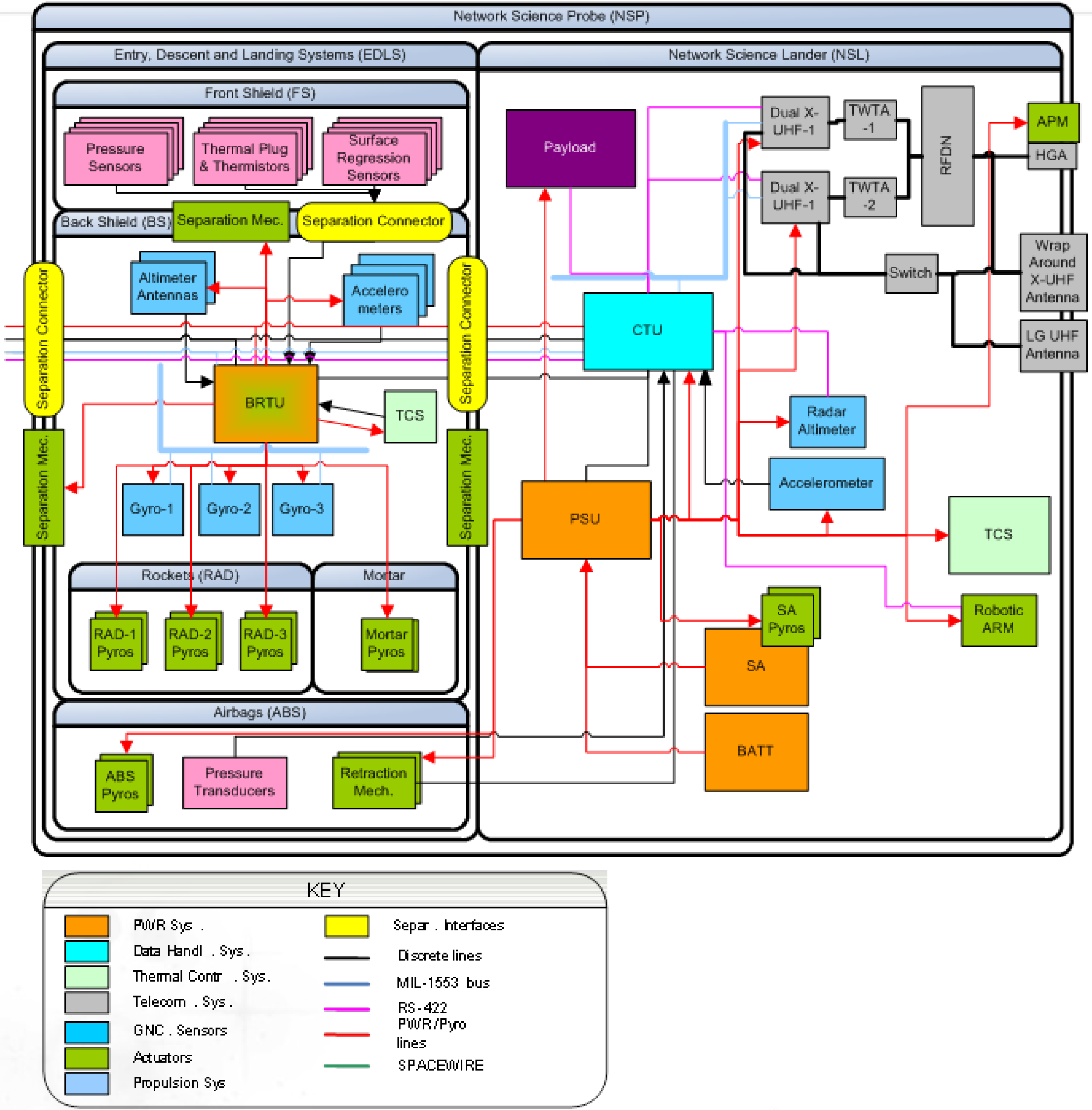
LANDING ON MARS - INSPIRE: Landing requirements

INSPIRE : landing of three Network Science Probes (NSP) on Mars

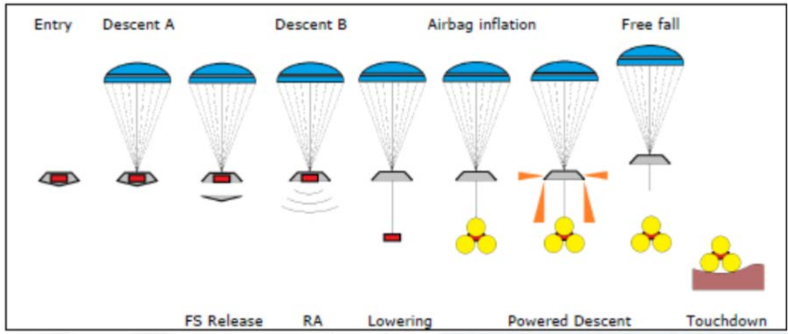
- Probes release operations starts 12 days before the Mars arrival
    - trajectory will be targeted to the landing site of the first lander
- Second probe is separated 6 days after the first
    - Re-targeting maneuver is followed by orbit determination including Delta DOR to improve delivery accuracy
- Third probe is separated several hours before entering the Mars atmosphere
    - Re-targeting also in this case is followed by orbit determination including Delta DOR to improve delivery accuracy
- Parachute will reduce rapidly the velocity and front shield jettisoning allows the RDA to measure the altitude
- Airbags are inflated and retrorockets are ignited 7 seconds before landing.
- At 20 m altitude (3 seconds before landing) back-shield with parachute is released and Lander perform a free fall bouncing on Mars



INSPIRE: NSP Avionic architecture



- Main tasks are payloads operation and telemetry/science data acquisition and storage
- CTU based on Leon3 SoC (SCOC, EPICA-Next, COLE) seems to be adequate
- Mass Memory is needed to store 40 SOL telemetry
- GNC algorithms have very limited control capability
- Vision Based Navigation could be used to reduce horizontal velocity due to strong winds

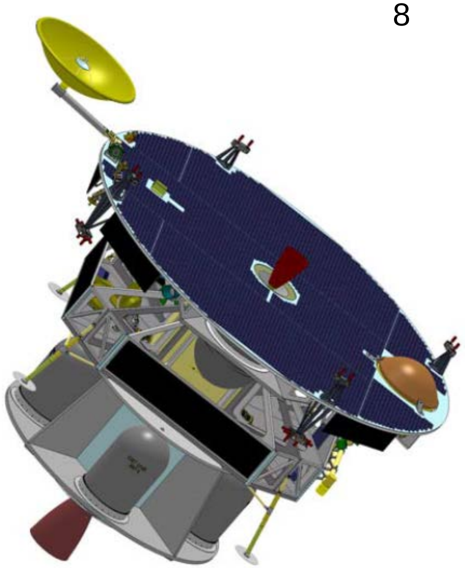


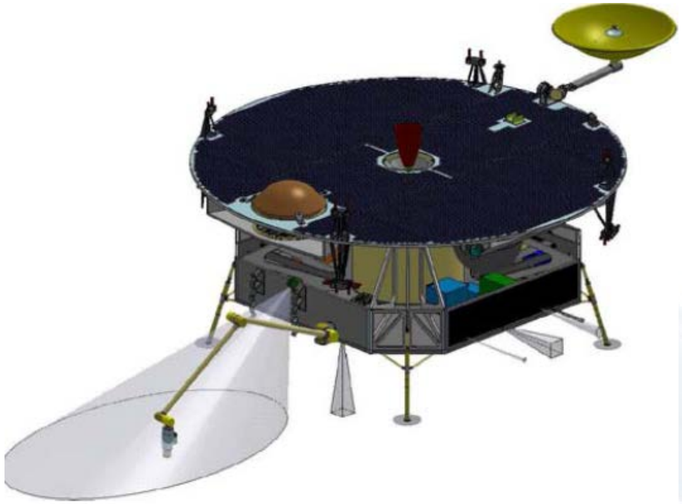
THALES ALENIA SPACE INTERNAL

LANDING ON ASTEROIDS - PHOOTPRINT: Landing requirements

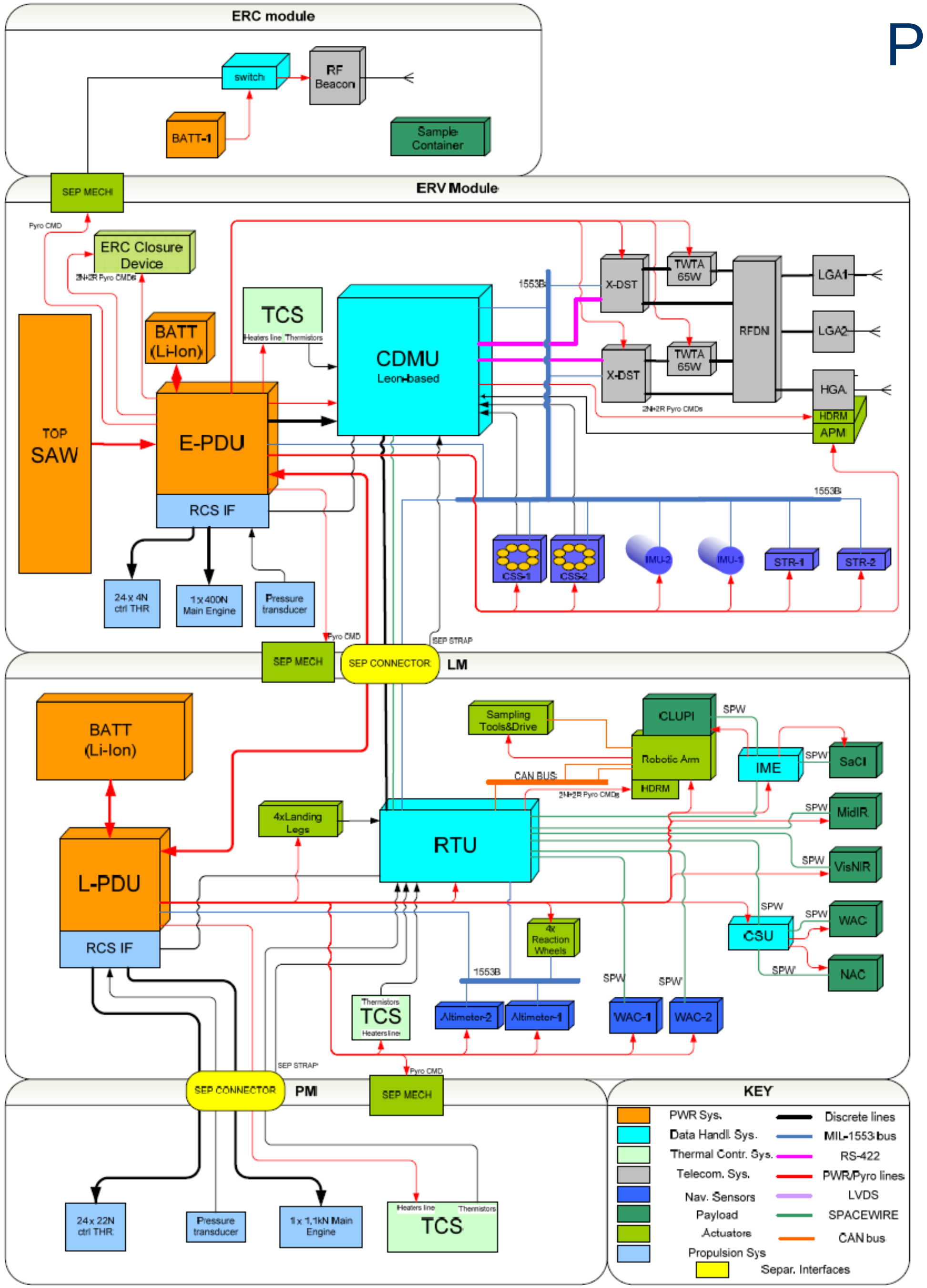
PHOBOS : non atmospheric landing in a very low gravity environment

- Objective of the PHOOTPRINT mission is to get and return to ground a 100g sample from the Mars moon Phobos and the scientific characterization of the Martian moon
- Landing site is identified by ground (MOC) based on the WAC and NAC observation
- Required landing accuracy around 100m
- Descent split in multiple segments to include way point for communication with ground to allow compliance with landing accuracy
- Relative measurements to Phobos surface are needed to cope with lateral and vertical velocity constraints
- Implement a proportional guidance based on altitude and rate measurement and on surface relative lateral velocity (feature tracking).





PHOOTPRINT: Avionic architecture



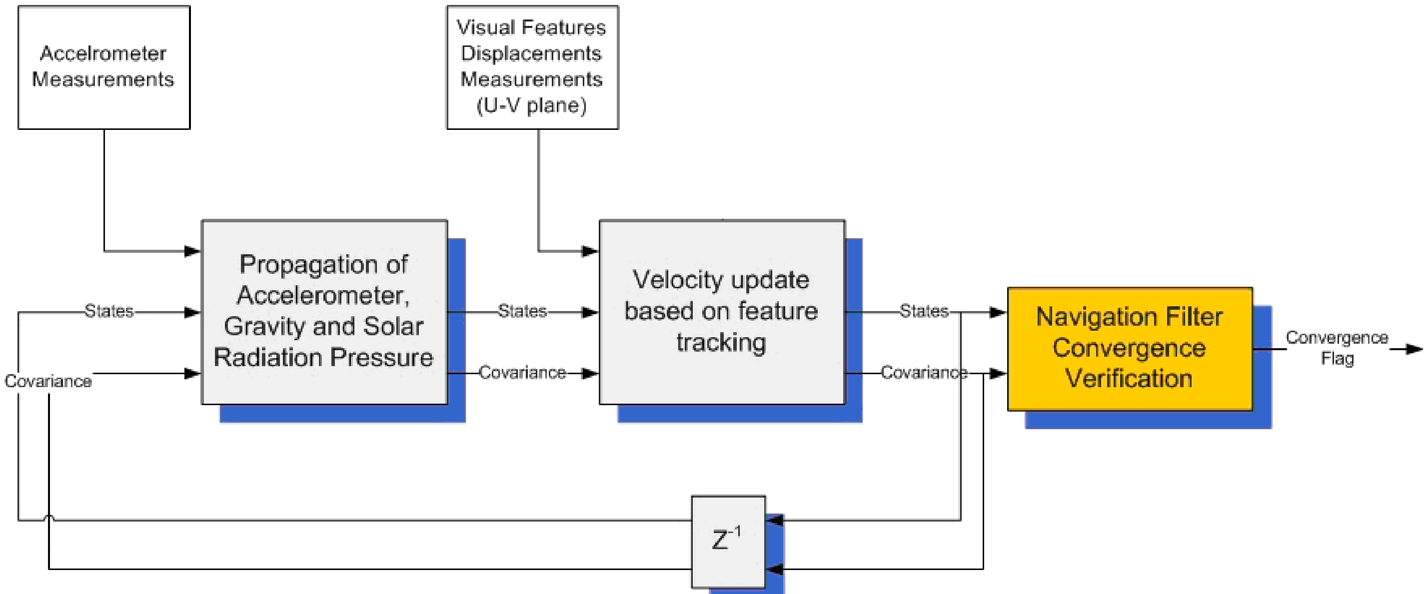
- Centralized architecture based on single computer (CDMU) in ERV based on SoC device (Leon)
- RTU is in the Lander Module and interfaces with the scientific instruments and other LM equipment (Pyro-actuation, robotic Arm, thermal control, landing lags). It is controlled and commanded by the CDMU.
- Mass Memory is needed to store all data collected by payloads and needed on ground to dirive the mission. Baseline is 24Gbit of redundant flash memory
- Navigation cameras WAC-1 and WAC-2 are also present in the LM

THALES ALENIA SPACE INTERNAL

PHOOTPRINT: preliminary GNC architecture

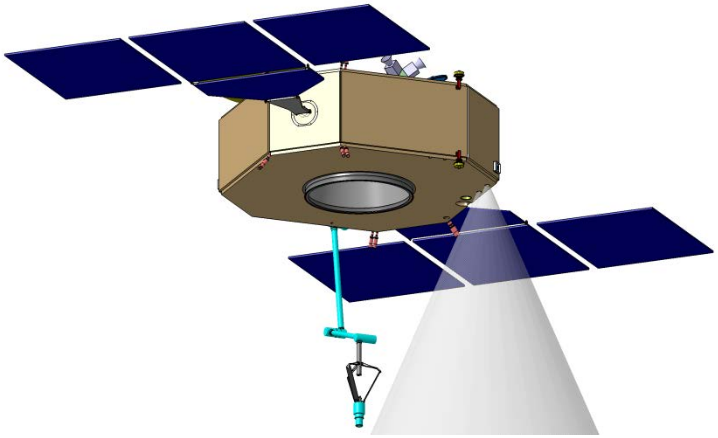
- GNC sensors for navigation are: Star Trackers, IMUs and Sun sensors
  - They are also used during Cruise phase so they are located in ERV
  - Two STRs and two IMUs are considered for redundancy
  - Sun sensors are used for FDIR
- GNC actuators are thrusters. They are located in ERV because used also during Cruise

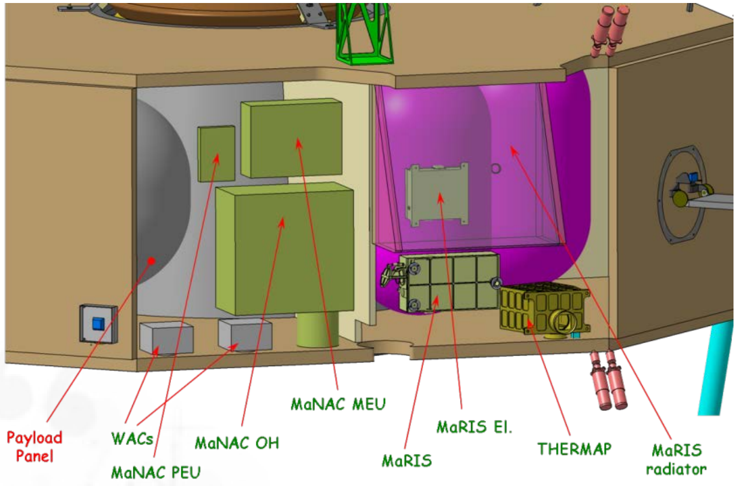
- GNC sensors for Phobos proximity maneuvers are : Wide Angle Camera , Radar-altimeter
  - They are located in the Lander together with RWLs
- Vision Based Navigation is needed to estimate horizontal velocity w.r.t Phobos surface



BLOCK DIAGRAM OF TRANSLATIONAL STATE ESTIMATOR

LANDING ON ASTEROIDS - MARCO POLO R: Landing requirements



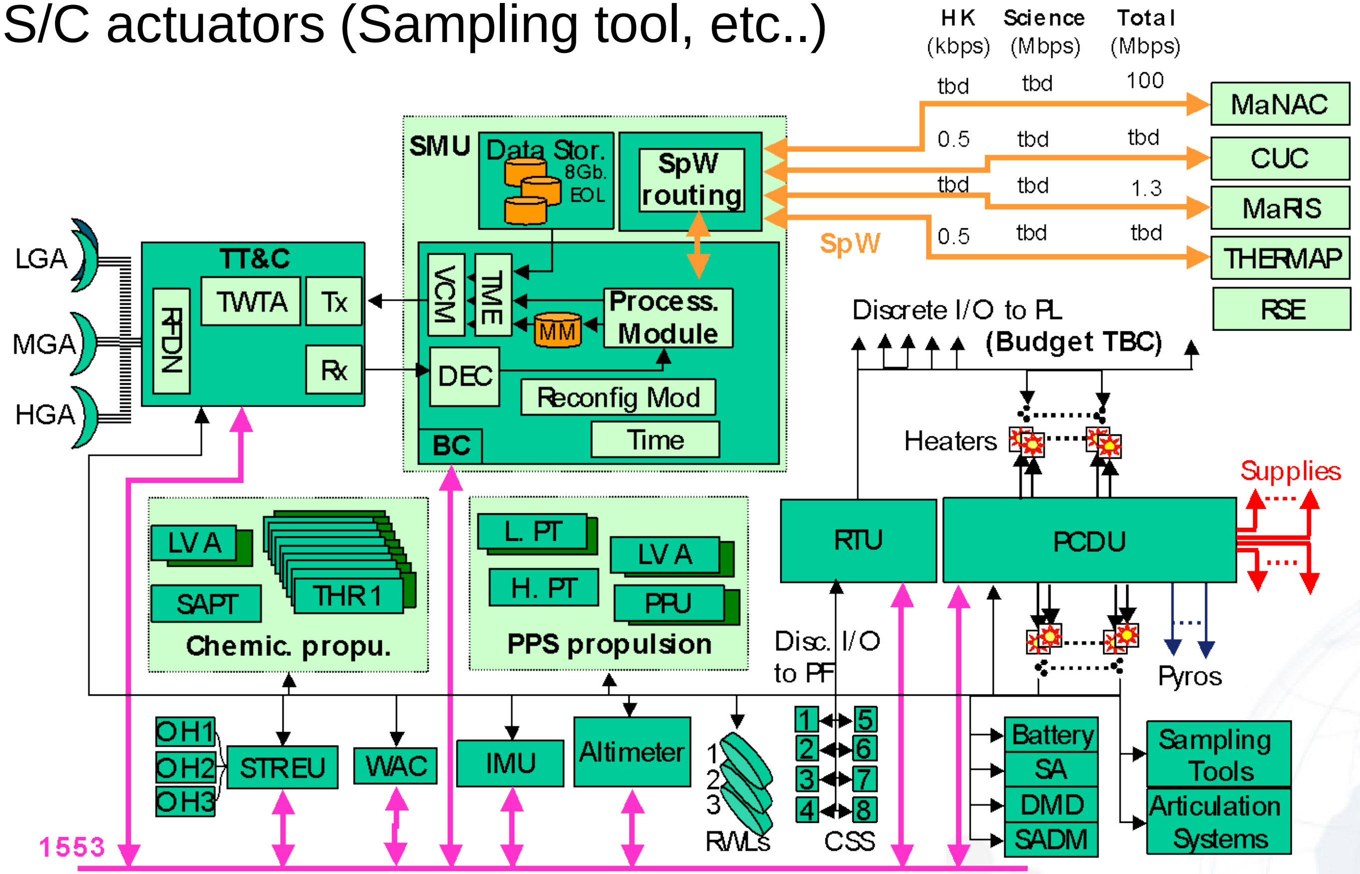


Marco Polo R : non atmospheric landing in a very low gravity environment

- Objective of the Marco Polo mission is to get and return to ground a terrain sample from the Near-Earth Asteroid (NEA) 2008 EV5
- Sampling strategy is based on a soft touchdown of the surface for 2-3 seconds and immediate takes-off
- Touchdown/sampling site is selected within 5 candidates sites characterized at 250m altitude, 3 sampling attempts are foreseen (position error 5m 1σ)
- Vision based GNC for proximity operation is required
- Estimation of ground-relative lateral velocity by feature extraction provides a means of propagating autonomously the spacecraft position.
- WAC and Altimeter are the relative navigation sensors

MARCO POLO R : Avionic architecture

- Centralized architecture with single computer (SMU) based on SoC device (EPICA-NEXT, Leon3) collecting data from payloads in a dedicated Mass Memory via SpaceWire Links and GNC measurements via MIL1553 bus
- RTU is a separate unit acquiring discrete and analogue signals and commanding GNC actuators and S/C actuators (Sampling tool, etc..)



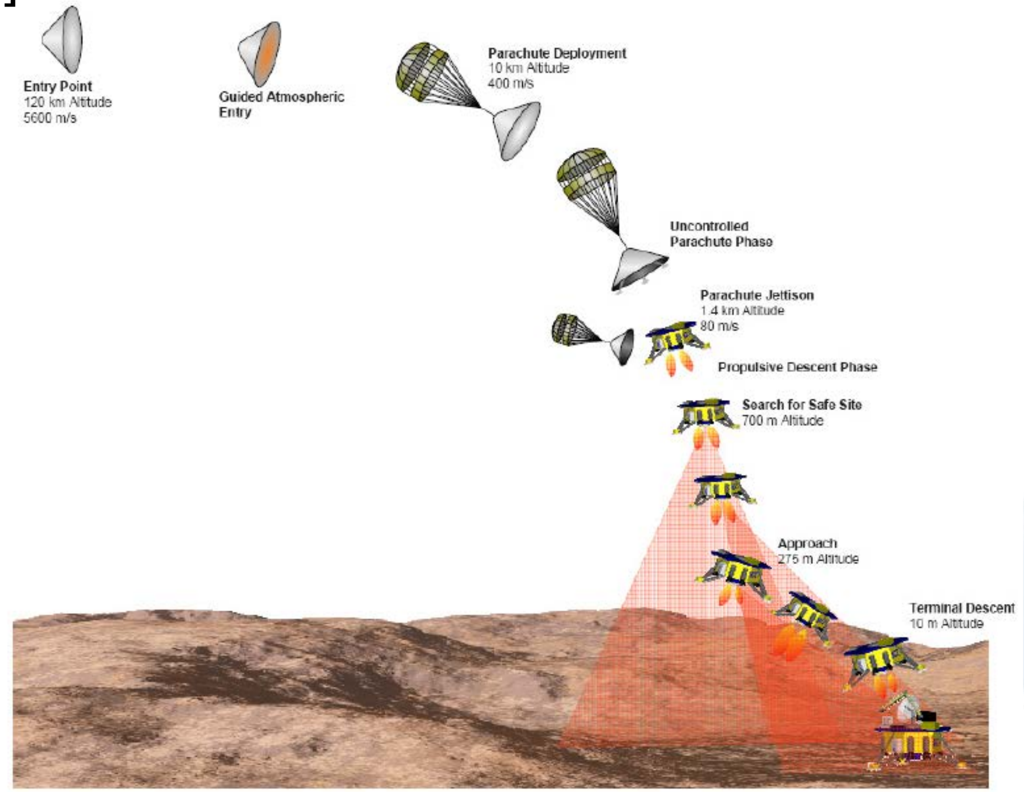
THALES ALENIA SPACE INTERNAL

High Performance Platform for GNC - SAGE: MARS Landing requirements

Mars scenario from Mars Sample Return mission. Requirements are:

- Safe landing within a landing circle of maximum diameter below 10Km [3σ]. Goal is 3Km [3σ]
- At landing instant vertical velocity below 2.5m/s, horizontal velocity below 2m/s
- At landing instant angular displacement w.r.t vertical axis less than 2 deg [1σ], angular rate relative to the surface less than 1deg/s [1σ]

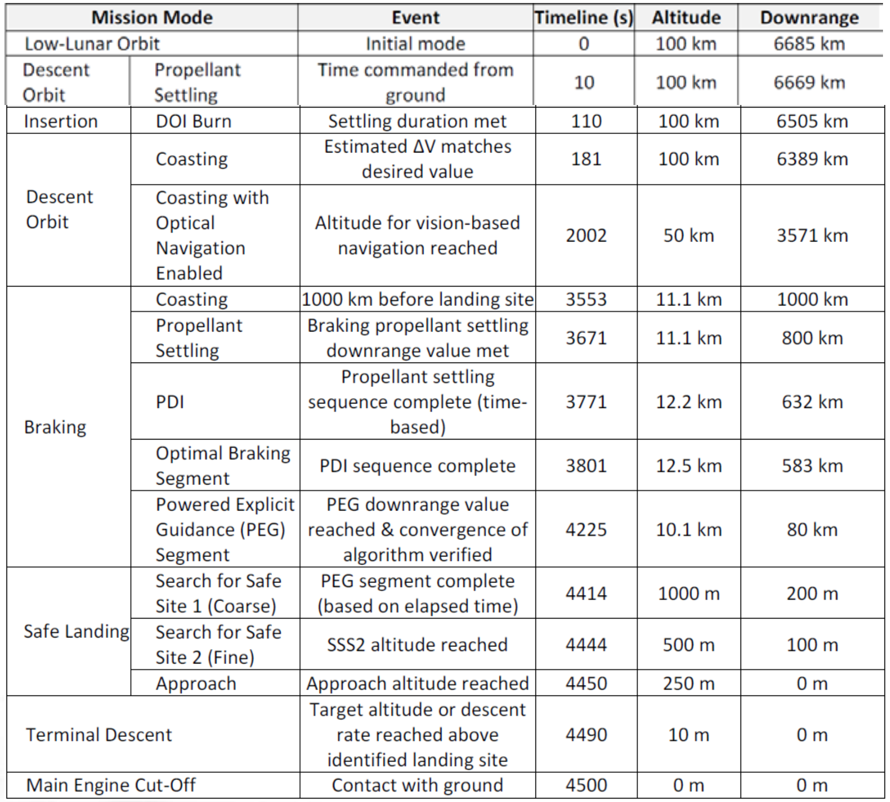
Mission Phase	EDL Mode	Event	Timeline	Altitude
CRUISE	0a: CRS	Last Ground Based Measurement	-14 h	N/A
CRUISE	0a: CRS	CM/DM separation	-10 min	N/A
COASTING	0b: CST	EIP detection	0	120 Km
Atmospheric Entry	1a: AE	Bank Angle Reversal Manoeuvres start	70 sec	40 Km
Guided Entry	1b: GE	Parachute Opening	140 sec	10 km
Parachute Phase	2: PAR	FS separation	180 sec	6 Km
DESCENT Phase	3: PD	Backshell Jettison	228 sec	1.65 Km
	4: SSS	Safe Site Identification Phase (100x100 m search Area)	238 sec	990 m
	5: APP	Safe Site Identified	272 sec	235 m
	6: TD	Altitude-based	302 sec	10 m
	7: MECO	Touchdown	312 sec	0 m



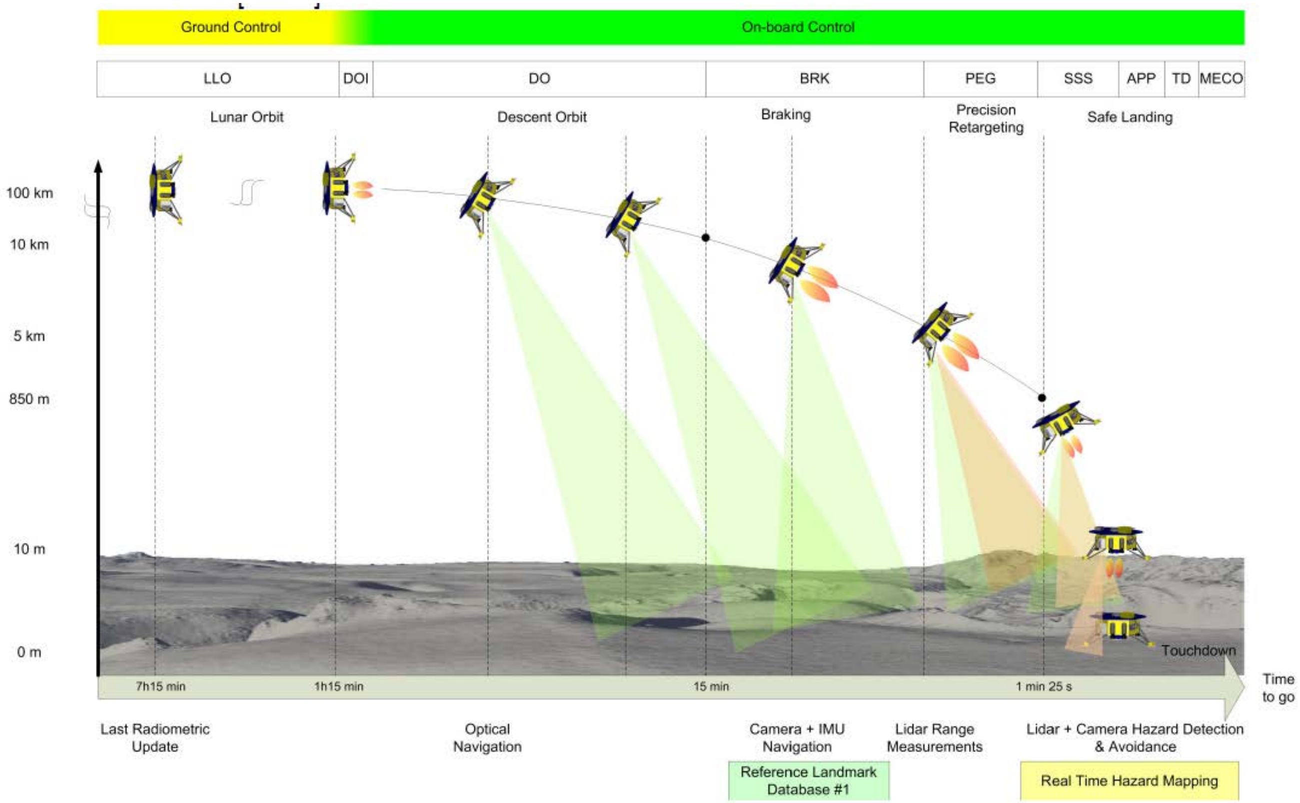
High Performance Platform for GNC - SAGE: MOON Landing requirements

Moon scenario from Next Lunar Lander mission. Requirements are:

- Safe landing within a landing ellipse semi-major axis 200m [3σ].
- At landing instant vertical velocity below 3 m/s [3σ], horizontal velocity below 0.5 m/s [3σ]
- At landing instant angular displacement w.r.t vertical axis less than 2 deg [3σ], angular rate relative to the surface below 0.25 deg/s [3σ]



Mission Mode		Event	Timeline (s)	Altitude	Downrange
Low-Lunar Orbit		Initial mode	0	100 km	6685 km
Descent Orbit	Propellant Settling	Time commanded from ground	10	100 km	6669 km
Insertion	DOI Burn	Settling duration met	110	100 km	6505 km
Descent Orbit	Coasting	Estimated ΔV matches desired value	181	100 km	6389 km
	Coasting with Optical Navigation Enabled	Altitude for vision-based navigation reached	2002	50 km	3571 km
Braking	Coasting	1000 km before landing site	3553	11.1 km	1000 km
	Propellant Settling	Braking propellant settling downrange value met	3671	11.1 km	800 km
	PDI	Propellant settling sequence complete (time-based)	3771	12.2 km	632 km
	Optimal Braking Segment	PDI sequence complete	3801	12.5 km	583 km
	Powered Explicit Guidance (PEG) Segment	PEG downrange value reached & convergence of algorithm verified	4225	10.1 km	80 km
Safe Landing	Search for Safe Site 1 (Coarse)	PEG segment complete (based on elapsed time)	4414	1000 m	200 m
	Search for Safe Site 2 (Fine)	SSS2 altitude reached	4444	500 m	100 m
	Approach	Approach altitude reached	4450	250 m	0 m
Terminal Descent		Target altitude or descent rate reached above identified landing site	4490	10 m	0 m
Main Engine Cut-Off		Contact with ground	4500	0 m	0 m



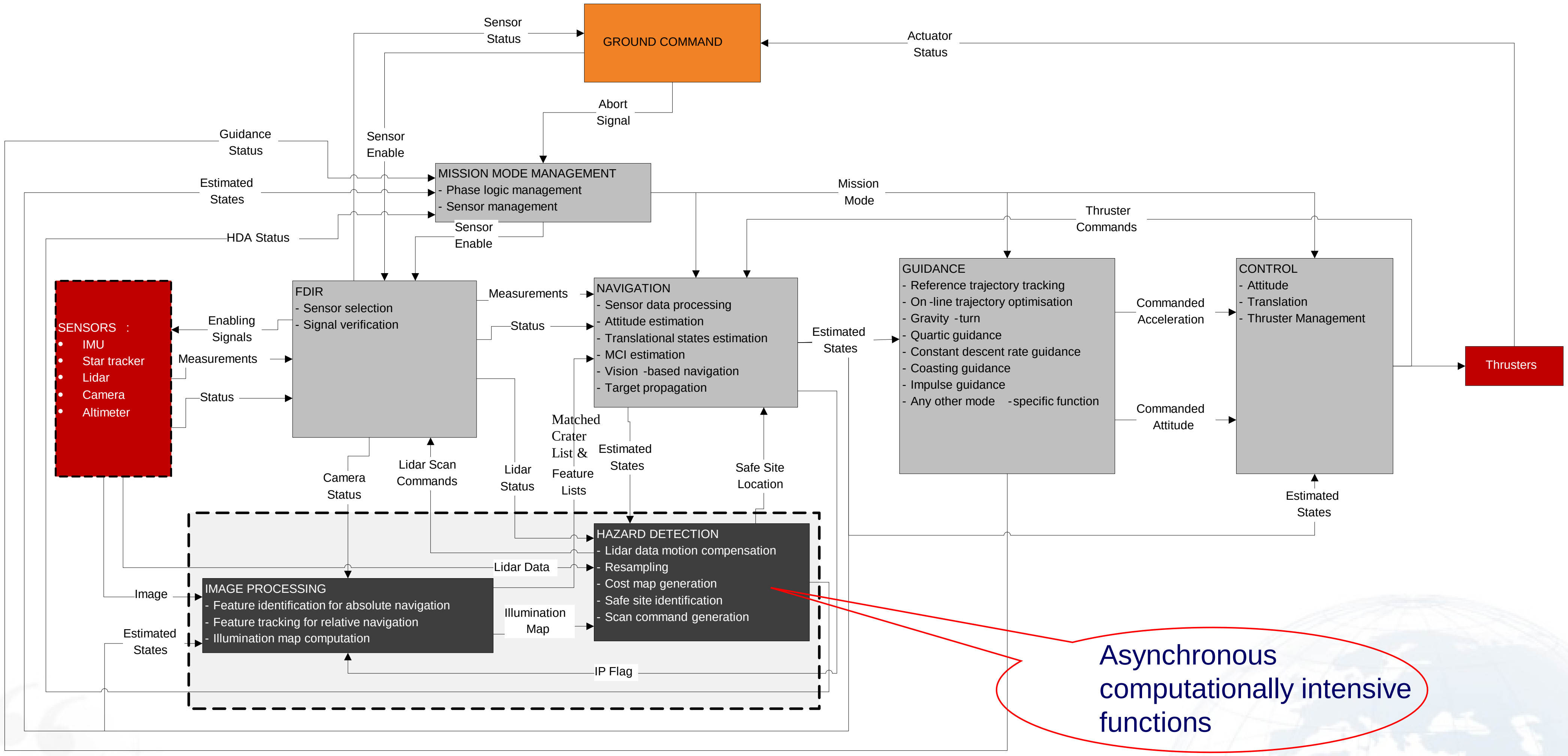
SAGE: GNC sensors

Altitude [km]	120			80	10 to 5	2	0,7	0,25	0,01
MARS	CRUISE	COASTING	ATMOSPHERIC ENTRY	GUIDED ENTRY	PARACHUTE PHASE	POWERED DESCENT	SAFE SISTE SEARCH	SAFETY RETARGETING	TERMINAL DESCENT
IMU	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
ALTIMETER					🟦	🟦	🟦	🟦	
HDA - LIDAR							🟩	🟩	
VBNAV - CAMERA						🟪	🟪	🟪	

Altitude [km]	100 TO 10			5	5 TO 1	0,9	0,25	0,01
MOON	LOW LUNAR ORBIT	DESCENT ORBIT INITIALIZATION	DESCENT ORBIT	BRAKE	POWERED ENTRY GUIDANCE	SAFE SISTE SEARCH	APPROACH	TERMINAL DESCENT
STAR TRACKER	🟧	🟧	🟧					
IMU	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
ABSOLUTE NAV			⬛	⬛	⬛			
ALTIMETER					🟦	🟦	🟦	
HDA - LIDAR						🟩	🟩	
VBNAV - CAMERA			🟪	🟪	🟪	🟪	🟪	

- In both scenarios LIDAR and Camera as terrain relative sensors are needed
  - Increase the accuracy in attitude and velocity measurement compensating IMU drift
  - Increase accuracy and robustness in searching safe site (illumination maps and redundant roughness map source)
  - Increase EDL robustness in case of Lidar Failure
  - Improve commonalties between the two scenarios

SAGE : GNC Functional architecture



GROUND COMMAND

MISSION MODE MANAGEMENT
- Phase logic management
- Sensor management

SENSORS :
- IMU
- Star tracker
- Lidar
- Camera
- Altimeter

FDIR
- Sensor selection
- Signal verification

NAVIGATION
- Sensor data processing
- Attitude estimation
- Translational states estimation
- MCI estimation
- Vision -based navigation
- Target propagation

GUIDANCE
- Reference trajectory tracking
- On -line trajectory optimisation
- Gravity -turn
- Quartic guidance
- Constant descent rate guidance
- Coasting guidance
- Impulse guidance
- Any other mode -specific function

CONTROL
- Attitude
- Translation
- Thruster Management

Thrusters

HAZARD DETECTION
- Lidar data motion compensation
- Resampling
- Cost map generation
- Safe site identification
- Scan command generation

IMAGE PROCESSING
- Feature identification for absolute navigation
- Feature tracking for relative navigation
- Illumination map computation

Asynchronous computationally intensive functions

THALES ALENIA SPACE INTERNAL

SAGE: Algorithms profiling

- Wheatstone benchmark has been used to compute a scaling factor between the performance of the platform used to develop the algorithms and the candidate flight microprocessors.

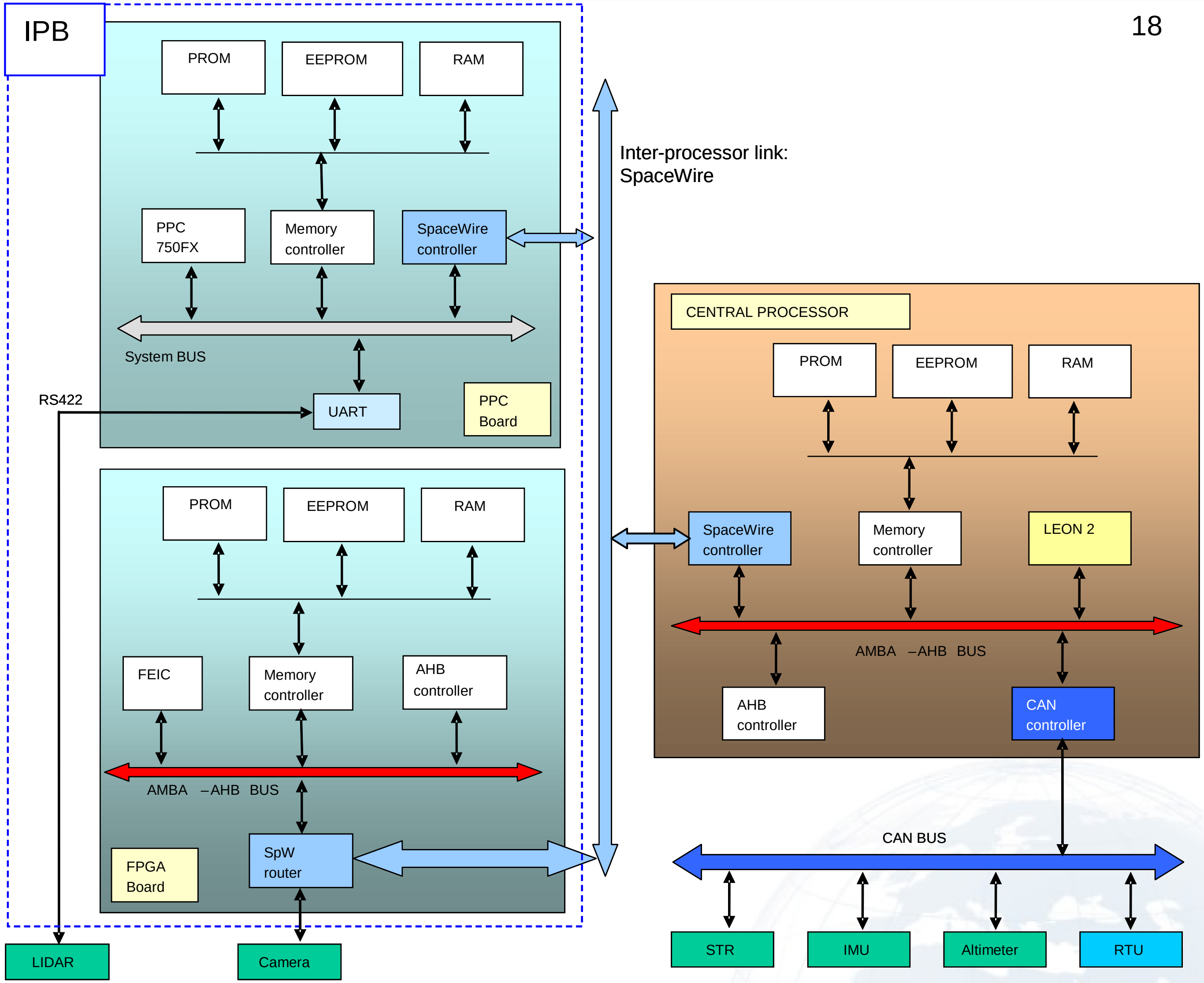
- Selected microprocessor are AT697F and PowerPC750 which can be considered flight representative platforms

SAGE SW functions	Function Frequency [Hz]	Test Platform perf. MWIPS	execution time (worst case) [ms]	AT697 time [ms]	PPC time [ms]	Leon2 perf. MWIPS	PPC Perf. MWIPS
						28,676	496,474
NAVIGATION	10	11,873	13,70	5,67	0,33		
GUIDANCE (GDC)	10	3074	0,05	5,36	0,31		
CONTROL	10	3074	0,05	5,36	0,31		
IMAGE PROCESSING							
Feature identification for absolute navigation	0,07	3229	1220	137375,51	7934,72		
Feature identification and tracking for relative navigation	10					already available in FPGA	
Illumination map computation	0,07	8287	0,12	34,68	2,00		
Hazard map		8287	150	43348,10	2503,76		
HAZARD DETECTION		3099	249	26909,30	1554,26		

THALES ALENIA SPACE INTERNAL

SAGE : GNC HW concept architecture

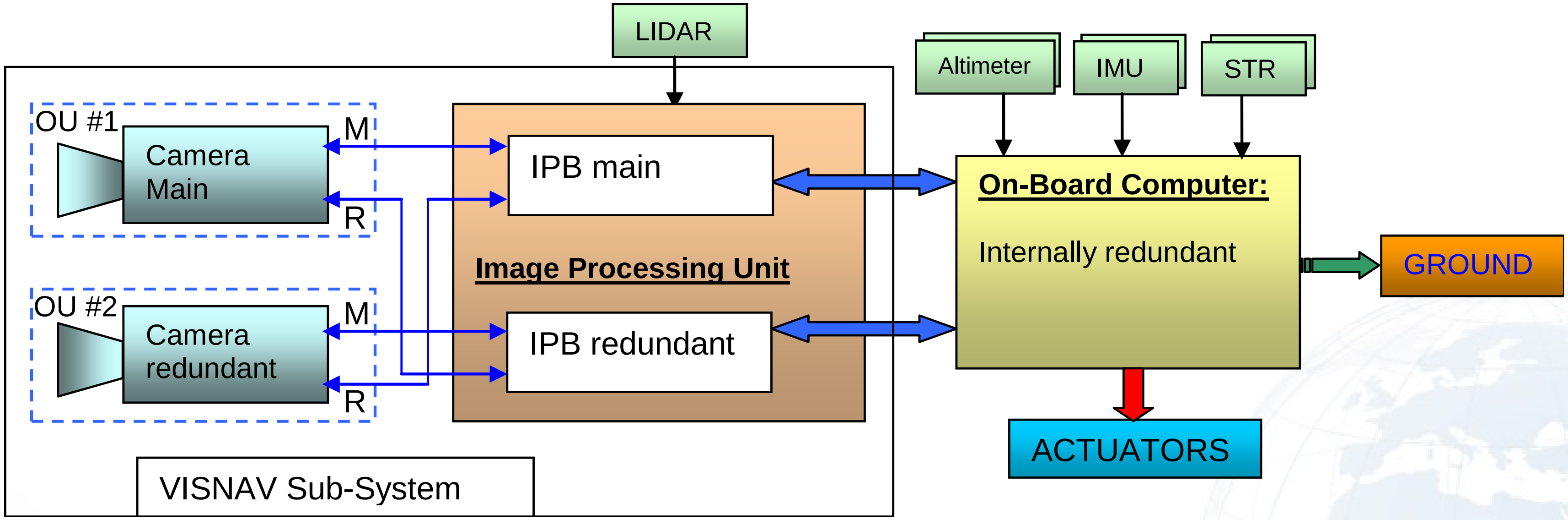
- CDMU configuration:
  - Processor – IPB
  - IPB: FPGA+PPC750FX
  - SpaceWire is the inter-processors link
  - SpaceWire router in FPGA allows full communication among OBC, FPGA, PPC
- Direct interface between FPGA and Camera
  - SpaceWire router channel
- Direct interface between PowerPC and LIDAR
  - RS422 link
- Memory mapping can be used to access all memory with minimum processor intervention



THALES ALENIA SPACE INTERNAL

VISNAV: HW concept architecture

- Extension of the SAGE architecture can be found in the VISNAV EM-1 ESA study
- The IPB of SAGE becomes the Image Processing Unit of VISNAV
- The IPB is based on HW section (FPGA Based) and SW section (PPC7448 based)
- FPGA embeds Image Processing algorithms used for relative navigation (10 Hz tasks)
- Microprocessor PPC7448 (3000 MIPS (Drystone 2.1) at 1.3GHz (2.3MIPS/MHz)) execute Image Processing algorithms for the Absolute navigation and Hazard detection



CONCLUSIONS

- Several mission scenarios have been presented:
  - Atmospheric landing with significant gravity
  - Non Atmospheric landing with low gravity
- Landing with low accuracy requirement can be obtained with current space qualified computing platform (LEON2, LEON3)
- Landing accuracy can be improved if Vision Based Navigation algorithms are implemented in the GNC
- Vision Based Navigation algorithms require high performance space qualified computing platform (more than 2000MIPS) which are not available
- Possible solution based on current technologies can be obtained assuming a processor-coprocessor configuration with IP algorithms embedded in FPGA
- New more powerful computer platforms could save power and mass