GG – GALILEO GALILEI

PAYLOAD

ARCHITECTURES and TRADE-OFF REPORT

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CHANGE RECORDS

ISSUE	DATE	§ CHANGE RECORDS	AUTHOR
1	Jan. '09	First issue of the doc.	J.M. Poulsen
2	Feb. '09	Second issue of the doc for I.R. Review Titel changed according to definition in the Contract. The previous titel was"Payload – Assessment Study Report". General update including: a) Comments by TAS-Torino, 22 Jan. 2009. b) Para. 3.1 LOOCKING MECHANIMS is new c) Ch.5: T.M. CAPACITORS and MEASUREMENT BRIDGE has more details.	J.M. Poulsen
3	June '09	Third issue of the doc for PRR (Final Review) General update of Product Trees New paragraph: Preliminary assessment of test mass materials New chapter: Payload EGSE	J.M. Poulsen

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1. GENERAL

1.1 SCOPE OF THE DOCUMENT

This report is written in the framework of the GG Phase A2 study.
The GG - Galileo Galilei project is an ASI (the Italian Space Agency) study assigned to Thales Alenia Space Italia.
In particular this technical note is an "output" of the work package: Payload Architecture (WP ref: 1B1-AD). The relevant contract/purchase order is n. PE-BA 48590.

1.2 APPLICABLE DOCUMENTS

[AD1] TAS contract/purchase order n. PE-BA 48590

[AD2] GG- Galileo Galilei WP n. 1B1-AD “Payload Architecture” in SGS-TASI-PRO-0063.

1.3 REFERENCE DOCUMENTS

[RD1] Proposta Tecnico – Gestionale, Galileo Galilei (GG) Fase A2, SGS-TASI-PRO-0063, vol. 1, TAS-Torino, Dec.2007.

[RD2] “Proposed noncryogenic, nondrag-free test of equivalence principle in space” A.M. Nobili et al, in New Astronomy 3, 175-218 (1998).

[RD3] Analog Dialogue vol. 39 n.2 (2005) in http://www.analog.com/analogdialogue

[RD4] GG – Payload Development & Verification Plan, TL25314-1, TAS-Milano, 2009

1.4 ACRONYMS

ASI	The Italian Space Agency
COG	Centre of Gravity
CPE	Control & Processing Electronics (unit)
CE	Conducted Emission)
ECE	Experiment Control Electronics
EGSE	Electronic Ground Support Equipment
EMC	Electro-Magnetic Compatibility
EP	Equivalence Principle
FEE	Front End Electronic
FPGA	Field Programmable Gate Array
GGG	GG on-Ground (experiment)
GSE	Ground Support Equipment
HK	House Keeping data
HV	High Voltage
HW	Hardware
I/F	Interface
MGSE	Mechanical Ground Support Equipment
MOI	Moment of Inertia
PA	Product Assurance
PCB	Printed Circuit Board
PGB	Pico Gravity Box
PI	Principal Investigator
PSU	Power Supply Unit
S/C	Spacecraft
SW	Software
TAS	Thales Alenia Space
TBC	To Be Confirmed
TBD	To Be Defined
TC	Telecommand
TE	Test Equipment
TM	Test Mass

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2. PAYLOAD DEFINITION

2.1 MISSION OVERVIEW

The GG spacecraft and payload is a small and compact satellite. It will fly in an almost circular and equatorial orbit at 520 km altitude around the Earth. The basic shape of the satellite is a cylinder 1m in diameter and 1.3m high. The satellite will rotate like a “spinning top” around its symmetry axis with a nominal rotation rate of 2 Hz. The rotation also provides attitude stabilization. The symmetry/rotation axis is almost perpendicular to the orbit/equatorial plane. The total mass at launch is about 250 kg.

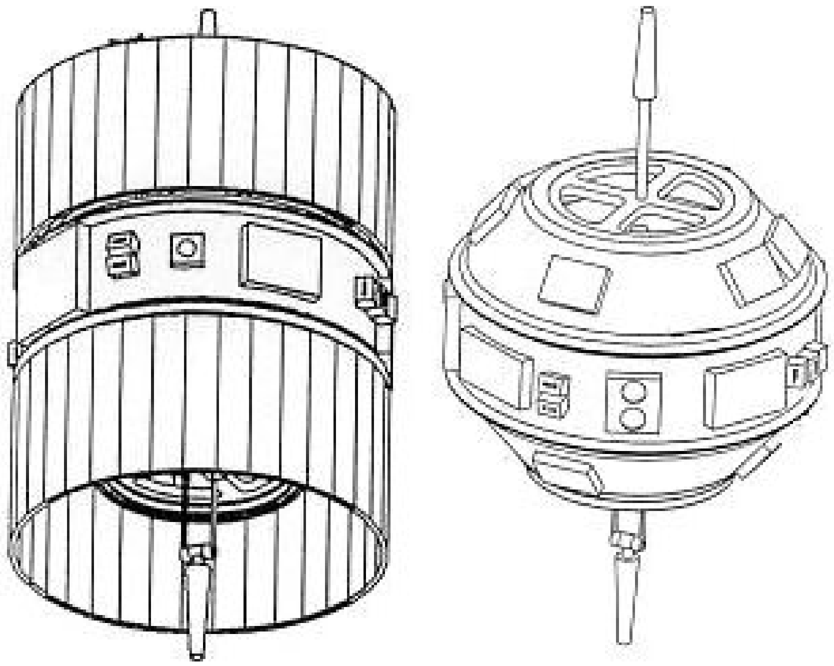


Fig. 2.1-1: The GG spacecraft with (left) and without (right) solar panels.
It is a “spinning top” with a rotation period of ½ sec.

A differential accelerometer for testing the Universality of Free Fall (UFF) is placed inside the “spinning top”. Actually, the accelerometer is mounted inside the so called Pico Gravity Box (PGB) which in turn is suspended inside the satellite, as shown on fig. 2.1-2.

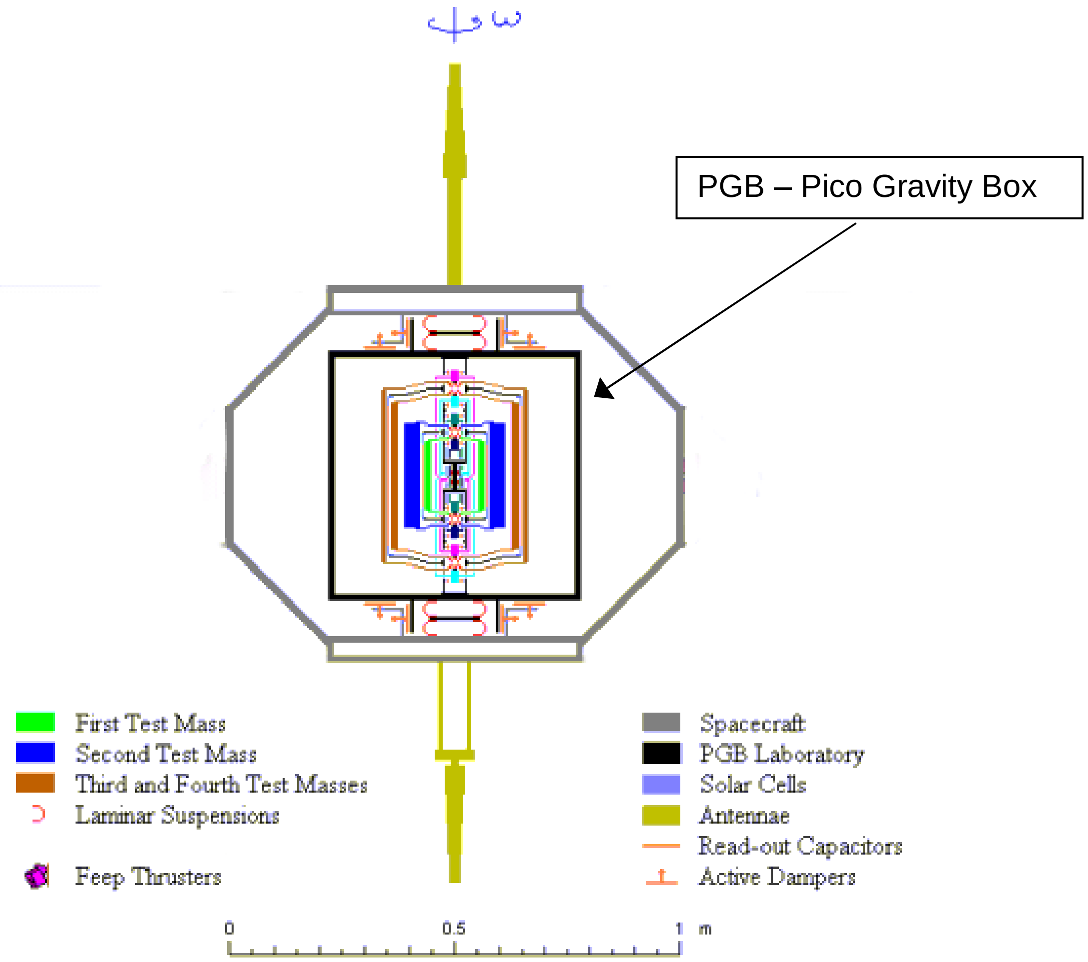


Fig. 2.1-2 Section through the spin axis of the GG satellite, a "spinning top". The accelerometer (green and blue test masses) is mounted inside the Pico Gravity Box (PGB) which in turn is suspended inside the satellite.

2.2 ACCELEROMETR KEY FEATURES

The accelerometer also has cylindrical symmetry about the rotation axis and is sensitive to differential accelerations in the plane perpendicular to the symmetry/rotation axis (see fig. 2.1-2). It will therefore sense an acceleration resulting from a breakdown of UFF in the gravitational field of the Earth, and thus test the Equivalence Principle (EP).

The challenging task of the GG mission is to reduce the level of differential disturbances between the test masses to 10^{-17} of the Earth gravitational acceleration at the satellite location.

This will be a tremendous improvement for the detection of an EP violation signal, and GG sets out to do it with a single, but symmetrical accelerometer.

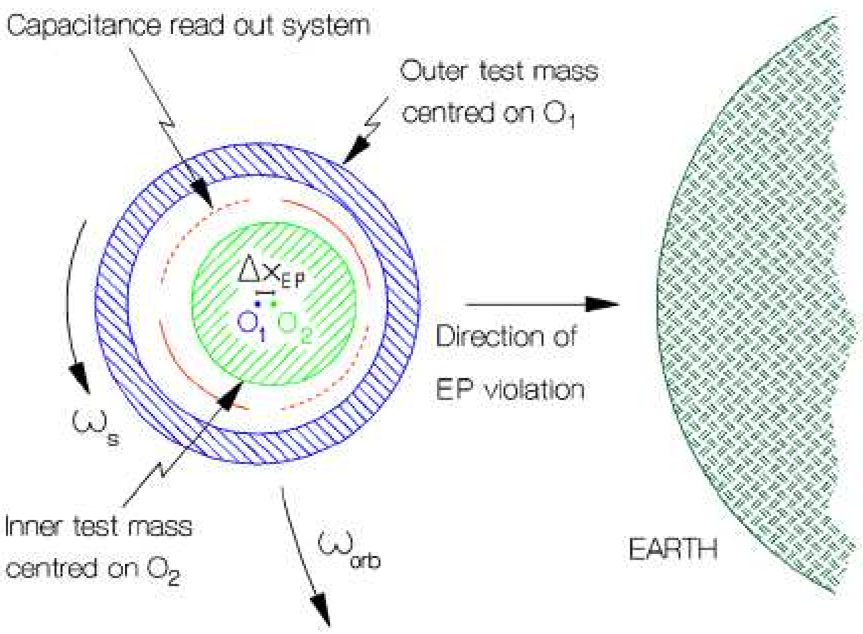


Fig. 2.2-1 Diagram of GG principle for detection of EP (Equivalence Principle) violation.

Here follows a summary of the accelerometer key features.

1. High spacecraft spin provides:
   - o Higher Q for the mechanical suspension
   - o Low electronic noise in the narrow bandwidth of the signal
   - o Negligible radial radiometric effect
2. The PGB provides:
   - o Passive attenuation of micro-vibrations (s/c vibrations, DFAC thruster noise, etc.) above its natural frequency
   - o Mechanical/Thermal shield for the test masses
3. Suspension balance as accelerometer provides:
   - o Self-centering suspended test masses
   - o High CMRR (Common Mode Rejection Ratio) ≈ 10^5
   - o Long differential motion period (≈ 500 s)

The only draw back of the GG accelerometer is the whirl motion, which is due to dissipation in its suspensions. The whirl motion happens at the natural frequency of the suspended test masses, a period of about 113 sec. However the whirl motion can be damped through active control by applying electrostatic forces on the two test masses.

2.3 PAYLOAD PRODUCT TREES

The overall product tree of the Payload is given in the figure below. For each colored box a detailed product tree is given on the following pages.

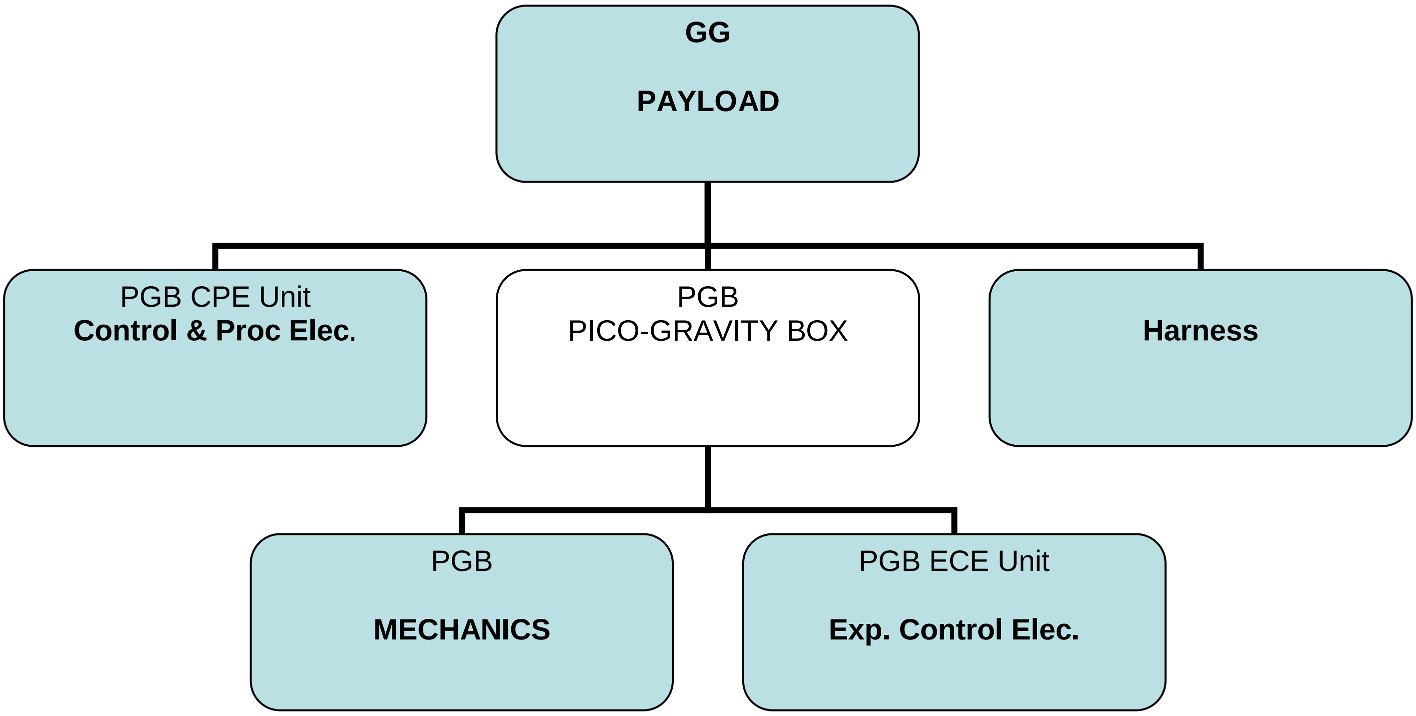


Fig. 2.3-1 Product tree of the GG payload

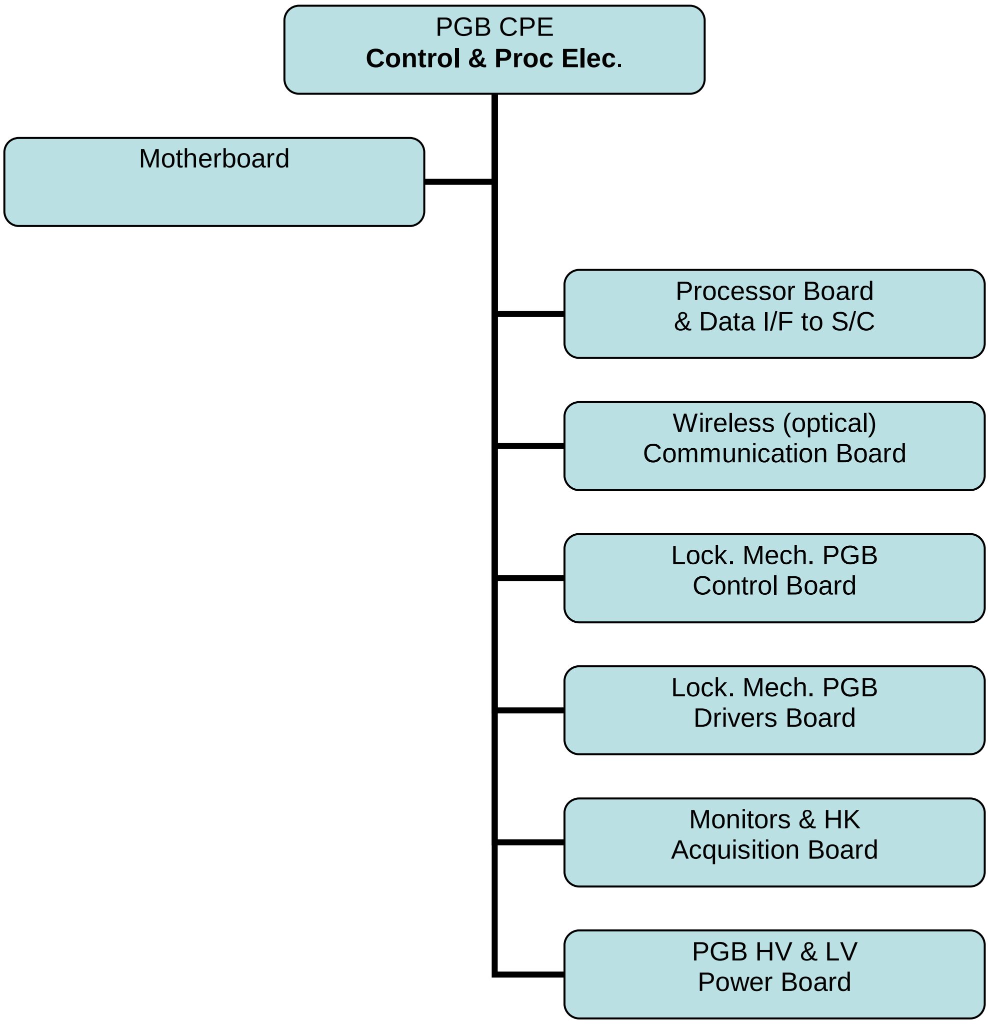


Fig. 2.3-2 Product tree of the C P E electronic unit. It is external to the PG-Box.

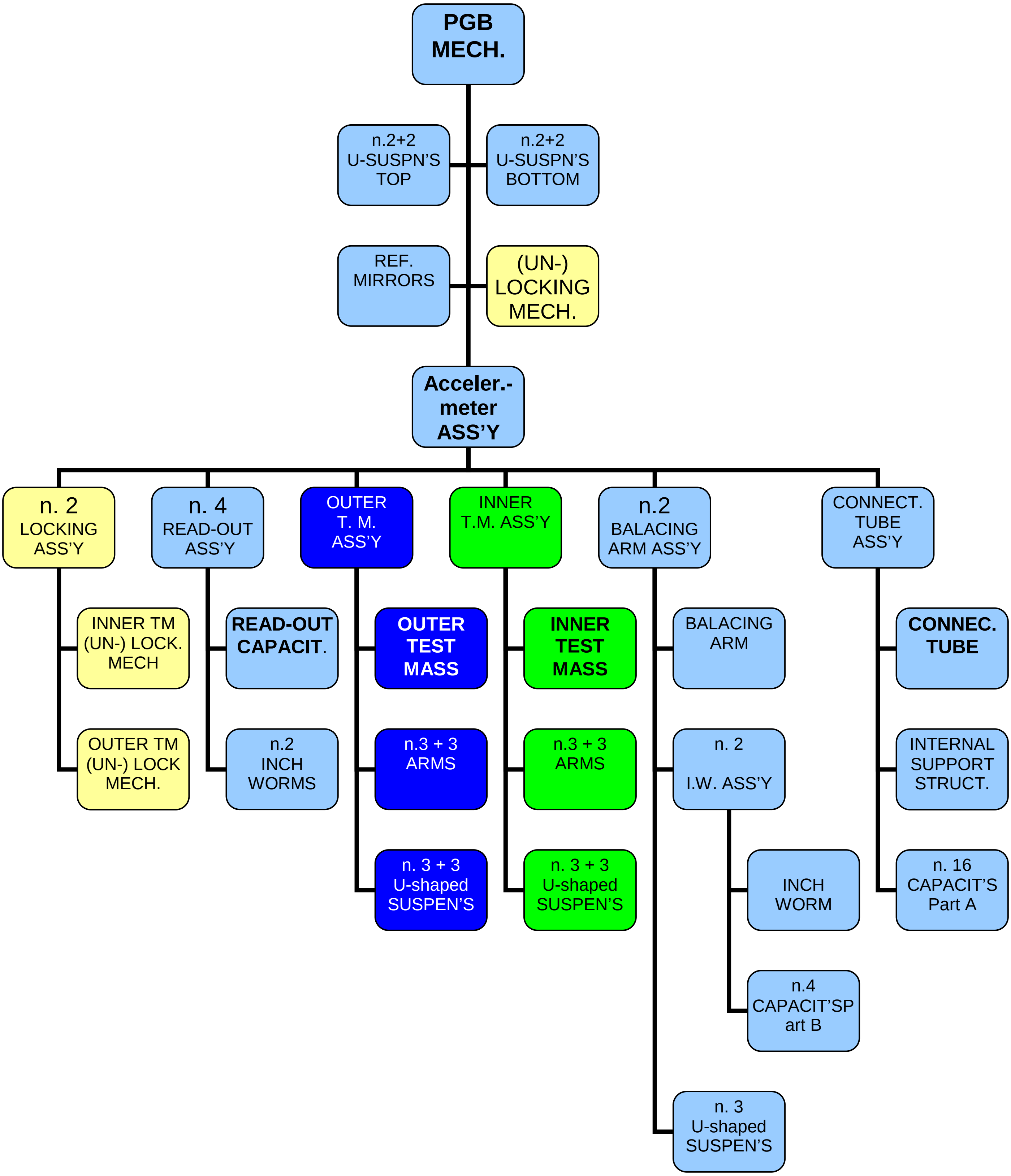


Fig. 2.3-3 Product tree of the PGB mechanics

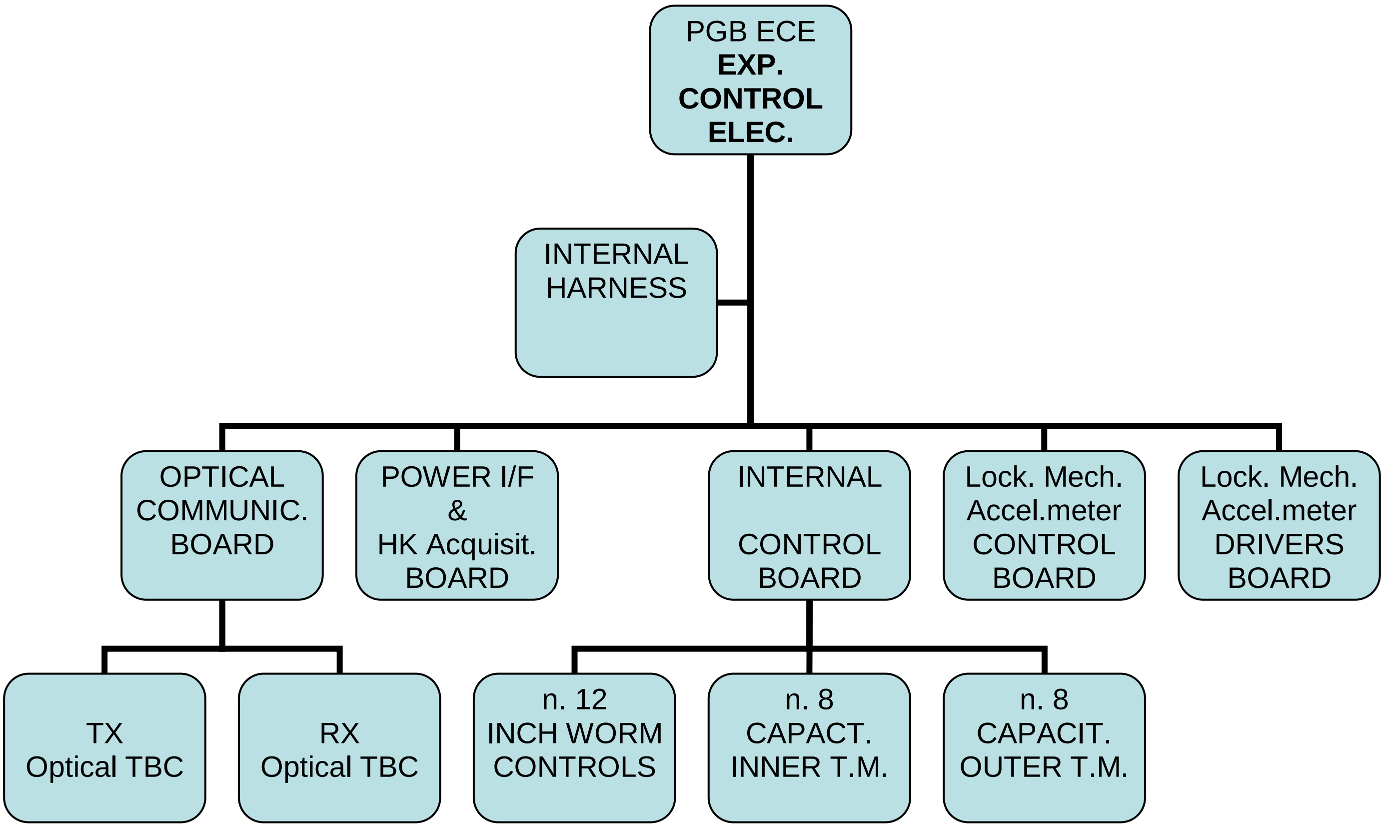


Fig. 2.3-4 Product tree of the PGB electronics, named Experiment Control Electronics (ECE). This is inside the PGB.

2.4 ACCELEROMETER FUNCTIONAL REQUIREMENTS

The Equivalence Principle testing instrument is shown schematically on Fig. 2.4-1. It is made of a differential accelerometer for EP violation test, co-axial and rotating with the spacecraft. The accelerometer is a (peculiar) beam balance with concentric test masses, with its beam along the symmetry/spin axis, sensitive to differential accelerations in the plane perpendicular to the axis (stiff along axis)

Her are listed the main functional requirements of the accelerometer:

1. Composed of two cylindrical shells (i.e. hollow cylinders), each weighing 10 kg.
2. Differential capacitance read-out for displacement measurements
3. Rotating around its symmetry axis in supercritical regime(≡ spin rate larger than the natural frequencies of the system). The rotation frequency is 2 Hz.
4. The two test masses and the related mechanics form a beam balance that is suspended by several very weak blades to a central tube-like structure. This is feasible thanks to the near zero gravity condition in space (see also fig. 2.4-1).
5. The accelerometer is centered on the CoM of the S/C.
6. Control of whirl motion of the TM by several small disc electrodes (capacitors), acting as electrostatic dampers for stabilization.
7. Passive electrical discharging.
8. Functional tests of the accelerometer can be performed on-ground in an proper custom-made facility or test bed (like GGG at INFN, Pisa). Full performance (EP sensitivity of eta = 10^-17) cannot be verified due to a very low signal to noise ratio on the Earth. In fact this is the reason to do the GG experiment on a satellite in-orbit.

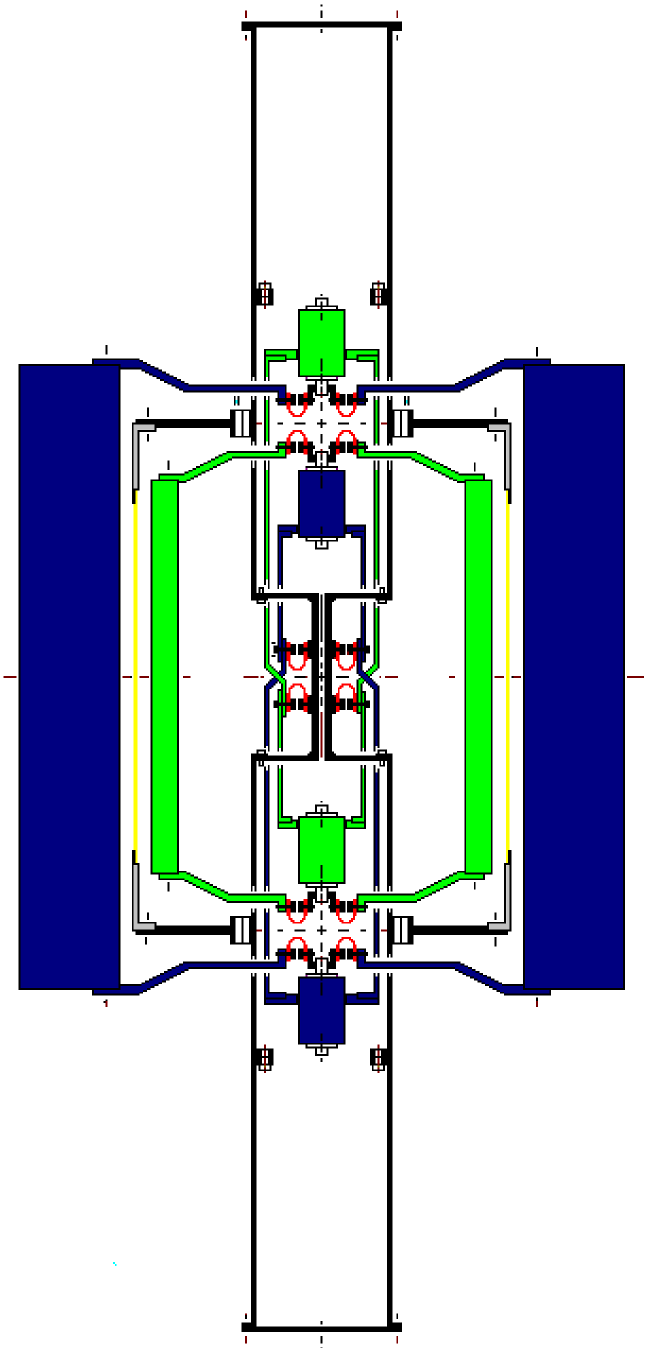


Fig. 2.4-1 Drawing of Test Mass Assembly which is basically a differential accelerometer with two test masses (T.M.: Outer T.M is dark blue and the inner T.M. is light green.
The central, long tube is the Connection Tube the only mechanical part fixed to the PGB.
Locking/un-locking mechanisms are not shown.

3. PGB MECHANICS

3.1 ACCELEROMETER MECHANICS

The figure shows the mechanical assembly of the accelerometer.

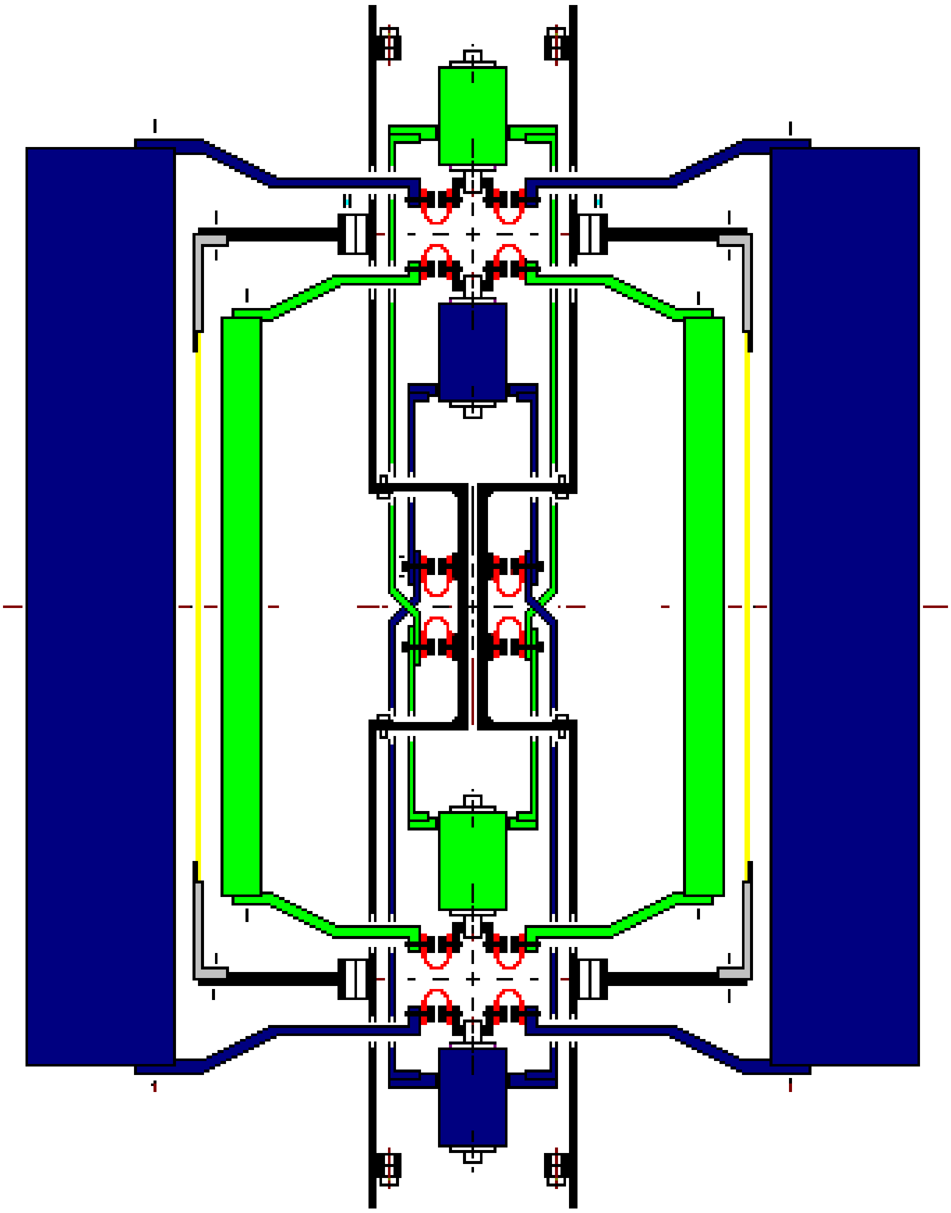


Fig. 3-1 Drawing of the accelerometer mechanics.
The green items are parts of the Inner T.M., while the dark blue items are part of the Outer T.M.
The yellow "line" in between are the measurement capacitors.
The capacitors for whirl control are not shown.

3.1.1 *Preliminary Assessment of Test Mass Materials*

In order to choose the materials suitable for the two Test Masses several characteristics and related parameters must be taken into account.

A scientific discussion of the atomic and nuclear properties of materials is given the GG Phase A-2 Study Report (para. 5.4). The paragraph concludes that the preferred materials are HDPE (high-density polyethylene) and tungsten for respectively the outer and the inner TMs. Major drawbacks for HDPE are 1) significant outgassing and 2) a high thermal expansion (CTE, see the table).

In this paragraph we consider a selected number of materials, and we list several macroscopic parameters as well as some engineering/manufacturing characteristics related to potentially useful Test Masses for GG.

The summary is in the following two tables, one for the outer and one for the inner test mass. In the tables the most promising or preferred parameters are colored blue while critical or undesired parameters are shown in with yellow.

The final selection of the Test Mass materials requires some in depth analysis, but one you can already make some conclusions, leading to a restricted number of material candidates.

Finally we note that both test masses must be coated with gold in order to have a good electrical conductivity on their surfaces and thus reduce preferential and unwanted charge patches.

OUTER "LIGHT" TEST MASS ¶

The potential materials considered for the Outer Test Mass are

HD-Polyethylene, Vespel, Beryllium, Silicon, Alumina, Silicon carbide (Al), Silicon carbide (C) and Aluminium.

1) PLASTIC materials and resins (epoxy) have a high outgassing of water vapour.
This phenomena is reversible - after vacuum and/or heating vapour in the environment can be absorbed.

Furthermore, the plastics have the highest CTE (thermal expansion).

2) BERYLLIUM has significant problems in processing as Be dust is toxic. In addition, the value A / Z = 2.25 is high.

3) CERAMIC materials seem promising. In particular, some composites of SiC (Silicon carbide) - see tables.

4) SILICON crystals seems a good candidate from this analysis. In particular it has a very low CTE. Also the ratio A / Z is low 2,01.

INNER "HEAVY" TEST MASS ¶

The potential materials considered for the Inner Test Mass are

Titanium, Copper, Bronze, Tantalum, and Tungsten

1) TUNGSTEN especially some “powder alloys” seems suitable. Although tungsten does have some difficulty for machining (for example, one cannot make threads in tungsten).

2) As an alternative (option) could be considered BRONZE (Cu alloy with Sn).

LEGEND: PREFERRED PARAMETER | VERY CRITICAL PARAMETER

MATERIAL	Type	Symbol	Atomic number Z avg	Atomic weight A avg	A/Z	Density (g/cm3)	CTE (ppm/°C)	Machine-able	Notes
HD-Polyethylene	plastic	C-H2	8	14	1,75	0,95	52	Yes	Soft, TML high
Vespel	plastic	CnHm	tbd	tbd	1,9x	(1,6)	tbd	Yes	TML ??
Beryllium	metal	Be	4	9,0	2,25	1,85	tbd	(No)	
Silicon	crystal	Si	14	28,08	2,01	2,33	3	Yes	
Alumina	ceramic	Al_2O_3	tbd	tbd	tbd	tbd	tbd	No ?	Only small pieces
Silicon carbide (Al)	ceramic	Al-SiC	10	20,04	2,1	2,96	9,8	Yes	
Silicon carbide (C)	ceramic	C-SiC	10	20,04	2,0	2,65	2,6	Yes	
Aluminium	metal	Al	13	27,0	2,07	2,75	22	Yes	

TABLE Material characteristics for potential outer ("light") Test Mass

LEGEND: PREFERRED PARAMETER | VERY CRITICAL PARAMETER

MATERIAL	Type	Symbol	Atomic number Z avg	Atomic weight A avg	A/Z	Density (g/cm3)	CTE (ppm/°C)	Machine-able	Notes
Titanium	metal	Ti	22	47,9	2,18	4,5	9	Yes	Ti-Grade 5
Copper	metal	Cu	29	63,5	2,19	8,9	17	Yes	
Bronze	metal	Cu-Sn	32	71,8	2,24	8	18	Yes	
Tantalum	metal	Ta	73	180.9	2,48	16.6	tbd	Yes ?	
Tungsten	metal	W	74	183.8	2,49	19.3	14 (x)	Yes (x)	(X) only for “powder” alloys

TABLE Material characteristics for potential inner (“heavy”) Test Mass

3.2 LOCKING MECHANISMS

The Test Mass Accelerometer is a very delicate instrument with several moving parts that cannot undergo the strong vibrations experienced during satellite launch. Therefore the moving parts must be secured by proper devices, locking mechanisms. These mechanisms will be activated, un-locked to release the moving parts in the accelerometer once the satellite is in-orbit. From that moment the accelerometer can start its operative phase.

The main parameters to consider for the choice of the mechanisms are:

1. Available envelope vs. size of the actuator devices
2. Required force to fix / lock the instrument items
3. Required/available power
4. Operational conditions
5. Reliability of the mechanism
6. Complexity of the mechanism

The time available for actuator operation/activation seems no problem. Also activation periods of several minutes is acceptable. On the other hand (quasi) instantaneous release of the test masses would be dangerous. For this reason pyro-based devices are excluded.

Concerning point 2) one can assume a preliminary value for the quasi-static load during launch of 40-g. This leads to a pressure force of about 4000 Newton for one mechanism.

One operational condition of concern in case of two or more actuators acting on the same item is simultaneous or sequential activation. For example paraffin actuators has not a well defined actuation period, but rather a interval between a minimum and a maximum time of several tens of seconds.

3.2.1 Actuator Technology

Concerning the technical implementation of the locking mechanisms several technologies are available, although with very different characteristics and complexity. As a starting point we consider:

A. Electrical motors
B. Hydraulic actuators with piezo pumps
C. High Output Paraffin (HOP) actuators

Hydraulic actuators with piezo pumps

For a brief presentation we consider an example of a locking system with 4 actuators or “fingers” as shown in the fig. 3.1-1. The system is complex and is composed on the high pressure side of hydraulic actuators, piezo pump, piezo valve, and on the low pressure side of reservoir bellows, vacuum and fill connection ports.

The HYDRAULIC SYSTEM is required to satisfy the following main requirements:

- Apply a high pre-load to the TM during launch and AIV phase, varying from 300N (storage and test) to 3000N (launch), without damaging the TM surface
- Perform the release of the TM in orbit
- Have a low mass while occupying a small envelope
- Survive and maintain in position the TM under a quasi static load of 25g rms due to launch vibration, to be tested under vacuum.

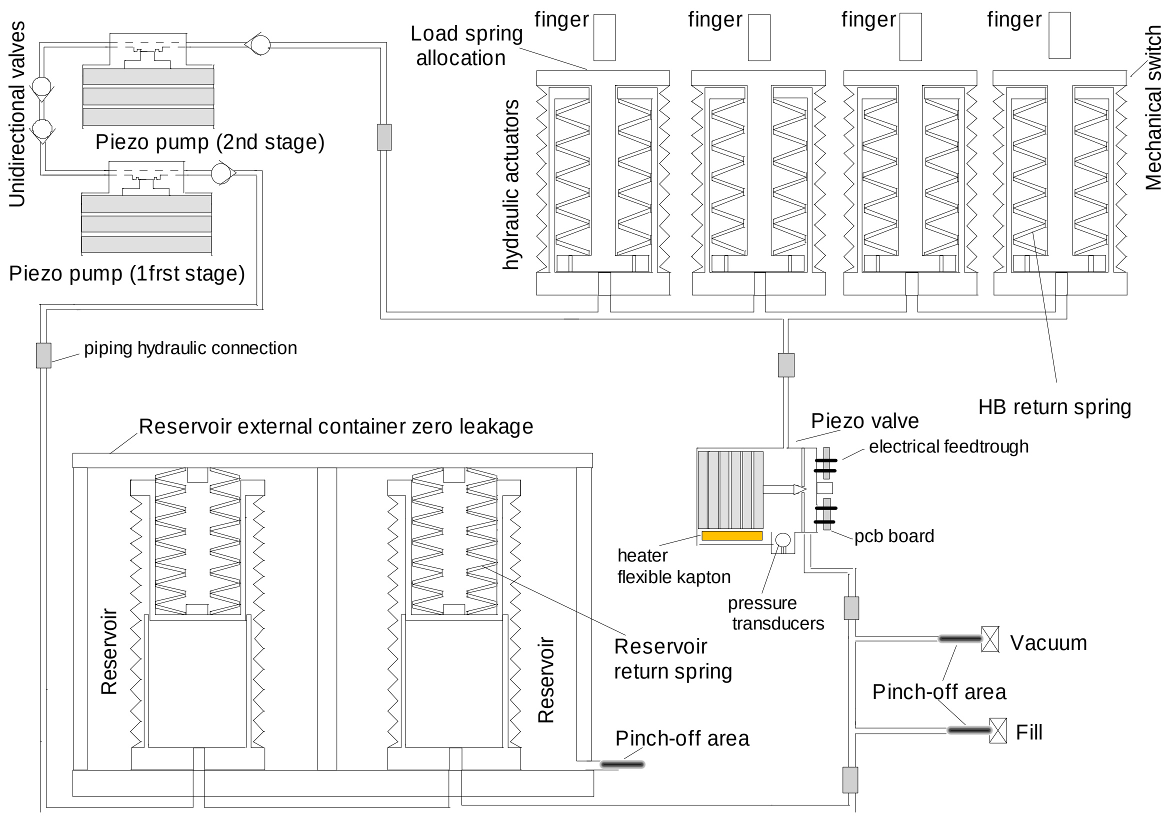


Fig. 3.1-1 Hydraulic actuators for locking mechanism with four actuators (fingers)

In the HYDRAULIC SYSTEM four fingers connected with an hydraulic actuator are pushed by the hydraulic fluid pressurized by the piezo pump that is the active actuator.
The piezo valve provides to regulate the liquid pressure transferring it from the actuator to the reservoir.
Two reservoirs are necessary to compensate the actuators elongations,
The unlocking of the TM is performed by release springs integrated into the bellows. A piezo-valve in series to the piezo-pump and normally closed, is able to decrease the pressure of the hydraulic liquid transferring it into suitable reservoirs based on metallic bellows as well.

High Output Paraffin (HOP) actuators

High Output Paraffin (HOP) actuator is a patented technology by STARSYS Inc. The HOP actuators provide mechanical work for mechanisms that are used for single-operation functions such as launch restraint, as well as multiple-operation functions such as aperture cover actuation.
The mechanisms are often an optimum solution due to the unique characteristics of HOP actuators:

- Exceptional reliability from simplicity of operation
- Capable of thousands of operations
- Gentle, no-shock operation
- Significant work is provided from a small component

Operation
The volumetric expansion of paraffin that occurs during the solid-to-liquid phase change provides the motive force for High Output Paraffin (HOP) actuators (linear motors). Significant hydrostatic pressure is generated by constraining the expansion within the actuator body. This pressure is transformed by the actuator to mechanical work in the form of linear shaft motion (see the fig.).

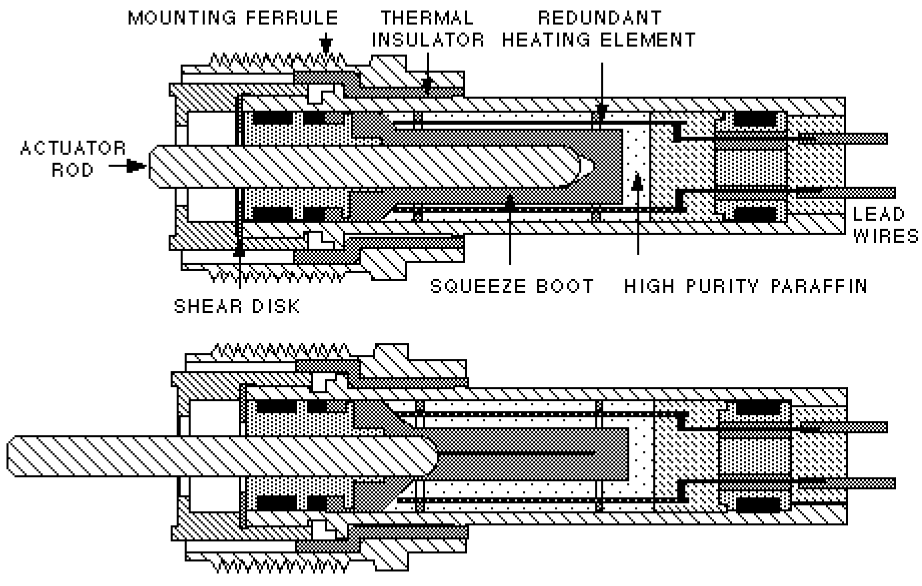


Fig. 3.1-2 Principle of High Output Paraffin (HOP) actuators.
Upper panel: Actuator at rest position without power.
Lower Panel: Actuator is energized and the rod moved.

3.2.2 Summary

A qualitative comparison between the three different technologies considered is given in the table. An assessment of the characteristics can be performed when preliminary envelope requirements are available.

PARAMETER	Electrical motors	Hydraulic actuators with piezo pumps	High Output Paraffin (HOP) actuators
Envelope	high	medium	medium
Force	Low - medium	high	a) high b) low
Power	medium	low - medium	medium
Complexity	Medium - high	High	a) high b) low
Reliability	high	low	medium

TABLE Preliminary comparison between different technologies of locking mechanisms.

4. PAYLOAD ELECTRONICS

The electronics is basically composed of an unit external to the PG Box named **CPE Control & Proc Electronics** and several boards accommodated inside the PG Box**.** These boards, which might be housed in a unit, are named **ECE – Experiment Control Electronics.**

The accommodation of this electronics is an open point. In view of a preliminary assessment we propose two different concepts. In both cases the ECE communicates with the CPE via an optical link. In concept A the electronics is "aligned" along the spin/symmetry axis (see fig. 4-1). While for concept B the electronics is placed in a the transverse direction i.e. in a plane orthogonal to the axis (see fig. 4-2).

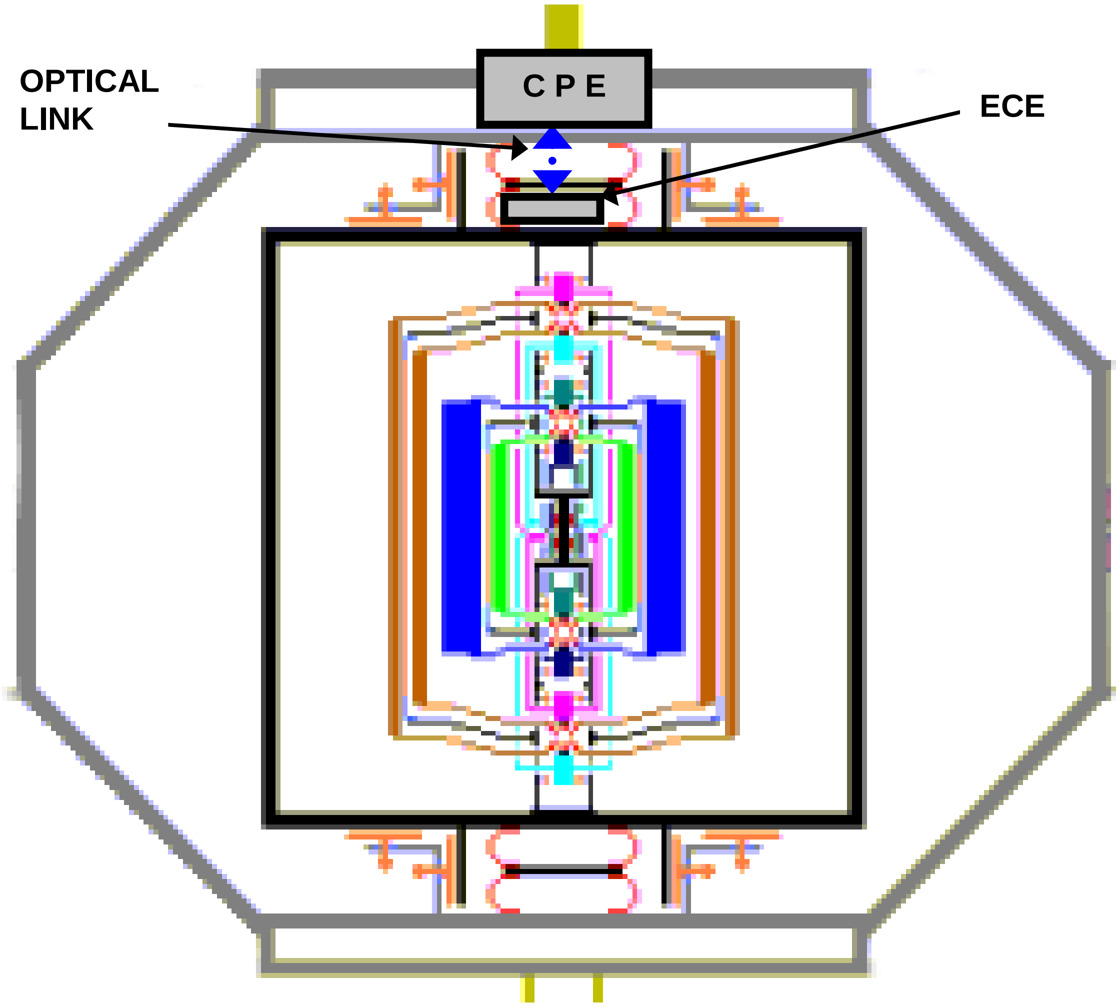


Fig. 4-1 ACCOMMODATION CONCEPT-A of the experiment electronics: The ECE is on the "top" of the PGB, and the CPE unit is placed above "on axis" of the S/C. There is an optical data link (indicated in blue) between the two units. This solution requires a free optical path along the axis, but no additional units as for Concept-B

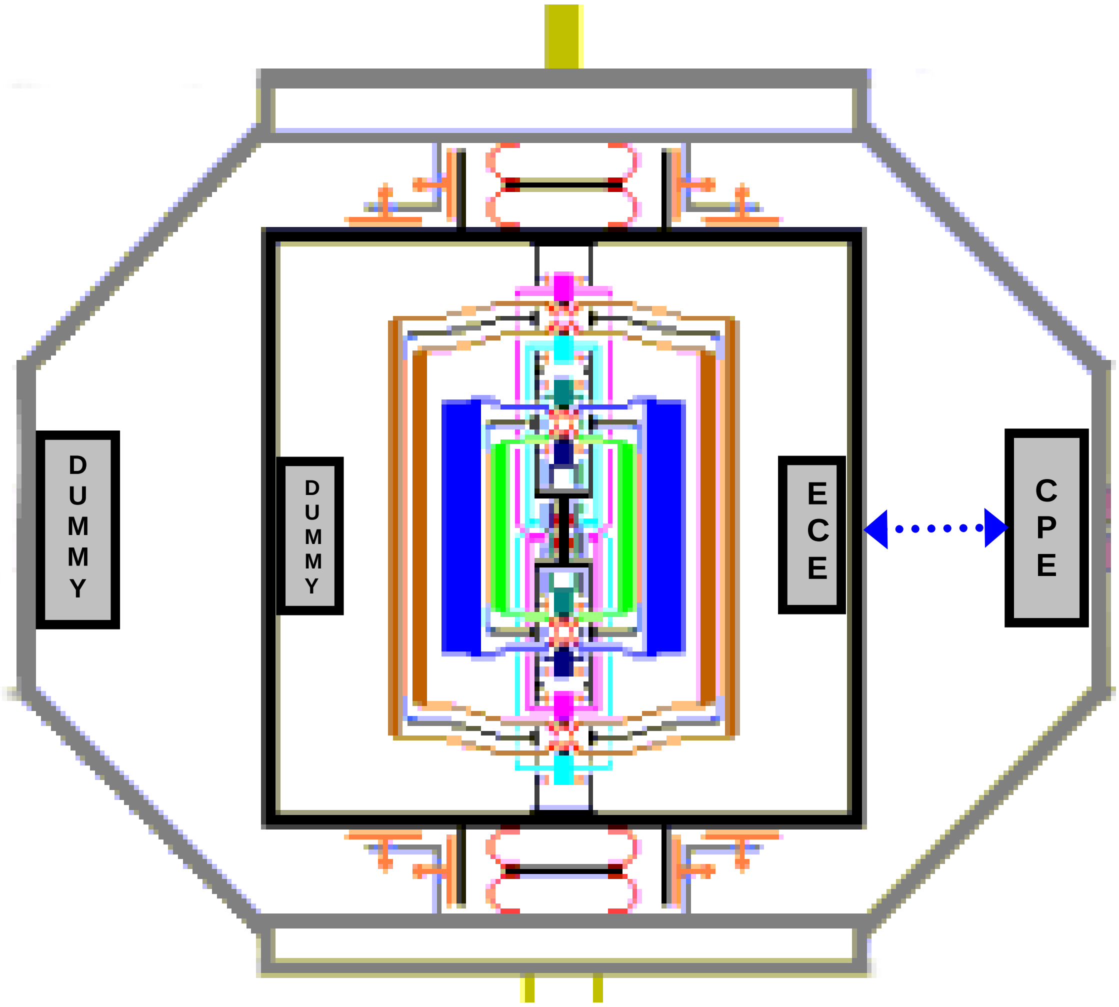


Fig. 4-2 ACCOMMODATION CONCEPT-B of the experiment electronics: The ECE is inside the PGB, while the CPE unit is on the S/C platform. There is an optical data link (indicated in blue) between the two units. Two dummy units provides rotational symmetry.

This solution seems <u>not to be feasible</u> because the wall of the PGB used to mount the ECE does not provide structural support being a thin thermal cover.

4.1 CPE – CONTROL & PROCESSOR ELECTRONICS

4.1.1 CPE Functions & Science Modes

<u>CPE functions</u>

The following functions of the CPE are foreseen/defined:

- o Wireless (probably optical) transmitter and receiver of data to/from the PGB
- o Circuit for handling of power transfer to the PGB (could be by induction)
- o Processing of science data (see below)
- o Reading and collection of HK data
- o Generation of science data packages
- o TC reception from spacecraft and command execution
- o Transmission of data (packages) to the S/C Data Handling.

<u>Processing of science data</u>

There are two different science modes of the GG.

A) EP measurement mode (science mode)
B) Active damping mode

Active damping control by sending proper command sequences to the ECE.
The actual active damping of the two test masses is performed by acting on the 8 + 8 small damping capacitors in the TMA.

4.1.2 CPE Unit Configuration

The unit is composed of 7 boards as follows:

1. Processor board & data I/F to SC
2. Wireless (optical) Communication Board
3. PGB LM control board (w. micro-ctrl 80C32 or FPGA)
4. LM drivers board
5. Monitors & HK Acquisition board
6. PGB Power Board (high and low voltages)
7. Motherboard

The dimensions of the mechanical housing (box) are defined in para. 6.1.

4.1.3 CPE Mass & Power

The CPE mass and power budgets are reported in the tables.

	Mass
Mechanics	1,6 Kg
Boards	4,6 Kg
TOTAL	6,2 Kg
TOTAL with 20% margin	7,4 Kg

	Secondary (+)	Primary
TOTAL	14,4 W	19,2 W
TOTAL with 20% margin	17,3 W	23,0 W

(+) DC/DC converter efficiency : 75%

4.2 ECE – EXPERIMENT CONTROL ELECTRONICS

4.2.1 ECE Functions

The ECE, experiment Control Electronics is placed inside the PG Box.

It will transmit/receive data to/from the CPE (on the platform) through a "wireless" (optical) link.

The PGB electronics is composed of the following main circuits / items:

1) MEASUREMENT BRIDGES FOR T.M. CAPACITORS
n. 2 EP measurement chains each chain is based on 2 X or 2 Y curved capacitor plates

2) INCH WORM DRIVERS
n. 8 inch worm drivers for adjustment of the EP capacitor plates in the X-Y plane (i.e. two inch worms, one upper and one lower for each capacitor plate).
n. 4 inch worm drivers for adjustment of the test masses along the Z-axis.

3) ACTIVE CAPACITIVE DAMPERS
n. 8 capacitive sensors and active dampers for control of the Inner Test Mass (4 dampers at the top and 4 dampers at the bottom of the ITM)
n. 8 capacitive sensors and active dampers for control of the Outer Test Mass (4 dampers at the top and 4 dampers at the bottom of the OTM)

4) "WIRELESS" OPTICAL COMMUNICATION CIRCUIT
This circuit will transmit (and receive) data from (to) the Test Mass Assembly to (from) outside the PGB.

5) POWER CIRCUIT
The power to the ECE, and the accelerometer in general, will be provided through metallic connections in the assembly. In particular the U-shaped suspensions will be exploited to provide connections.

An alterative power supply was considered early in this study. This system had a battery that is charged by a rectifier and control circuit based on a transformer. One inductor inside the PGB, and the other outside the PGB. However this option was discarded due to the potential interference effects of the alternating field in the transformer.

4.2.2 ECE Boards

The ECE is composed of 5 boards as follows:

1. Wireless (optical) Communication Board
2. LM control board (w. micro-ctrl 80C32 or FPGA)
3. LM drivers board
4. Accelerometer Control Board for control/measurement of n. 2 pairs of T.M. capacitors, n. 12 Inch Worms & n. 16 “whirl” capacitors (micro 80C32 or FPGA)
5. Power distribution and HK Acquisition board

4.2.3 ECE Mass & Power

The ECE mass and power budgets are reported in the tables.

	Mass
Mechanics (*)	1,4 Kg
Boards	3,3 Kg
TOTAL	4,7 Kg
TOTAL with 20% margin	5,6 Kg

(*) assuming a configuration in a “standard” box.

	Secondary (+)	Primary
TOTAL	6,9 W	9,2 W
TOTAL with 20% margin	8,3 W	11,0 W

(+) DC/DC converter efficiency : 75%

4.2.4 *Internal Data Types and Rates*

In this paragraph we evaluate the digital data to be exchanged (transmitted/received) between the PGB and the (external) electronics CPE on the platform. These evaluations are based on the requirements reported in para. 5.2. First we analyze the nominal rate and then a worst case rate.

The main data to be transmitted to the CPE are output from the two measurement bridges and signal on damping capacitors. We assume that both are measured with an 24bit AD Converter, although the require accuracy is lower (20-21 bits see para. 5.2). The data for one measurement bridge is acquired 10 times for each rotation of the experiment/satellite, i.e. 20 samples per second.
The damping capacitors are measured less frequently, 1 sample per sec. In addition are considered some status words and engineering data (HK data).
A summary is given in the table.

Parameter	Size (bits)	Frequency (samp/sec)	Number of channels	Datarate (bits/sec)
Accel. Bridges	24	20,0	2	960
Accel. Bridge ID	2	1,0	1	2
Damping cap.	24	1,0	16	384
Damping cap. ID	16	1,0	1	16
Status Measurement	2	1,0	1	2
HK data	64	0,1	1	6,4
TOTAL OUTPUT				**1362**
Inch-worms	14	1,0	16	224
Inch-worm ID	16	1,0	1	16
Status setting	2	1,0	1	2
Bridge fine tuning	12	1,0	4	48
CMDs on-off	32	0,1	1	3,2
TOTAL INPUT				**293**

Summary of internal (digital) data between the ECE and the CPE.
The data rates are for the NOMINAL case.

This preliminary evaluation gives an output rate of about 1400 bits/sec (to the CPE) and the rate of commands data (input) of about 300 bits/sec.
This allow us to define the capacity (rate) of the optical link between the ECE and the CPE taking a reasonable margin into account.

NOMINAL Rate of data link to the CPE from the ECE (output) 2.500 bits/sec
NOMINAL Rate of data link to the ECE from the ECE (commands) 600 bits/sec

Parameter	Size (bits)	Frequency (samp/sec)	Number of channels	Datarate (bits/sec)
Accel. Bridges	24	50,0	2	2400
Accel. Bridge ID	2	1,0	1	2
Damping cap.	24	1,0	16	384
Damping cap. ID	16	1,0	1	16
Status Measurement	2	1,0	1	2
HK data	64	0,1	1	6,4
TOTAL OUTPUT				**2802**
Inch-worms	14	1,0	16	224
Inch-worm ID	16	1,0	1	16
Status setting	2	1,0	1	2
Bridge fine tuning	14	1,0	4	56
CMDs on-off	32	0,1	1	3,2
TOTAL INPUT				**301**

Summary of internal (digital) data between the ECE and the CPE.
The data rates are for the WORST CASE.

This preliminary evaluation gives a “worst case” output rate of about twice the nominal case (2800 bits/sec to the CPE) while the “worst case” rate of command data (input) is basically the same, about 300 bits/sec.
Taking some margin into account we define the capacity (rate) of the optical link between the ECE and the CPE for the worst case scenario as:

WORST CASE Rate of data link to the CPE from the ECE (output) 5.000 bits/sec
WORST CASE Rate of data link to the ECE from the ECE (commands) 600 bits/sec

4.2.5 Accelerometer Measurement Chains

The EP measurement chains must possess an extremely high sensitivity as indicated in the next chapter (the minimum displacements are about 0.6 pm (pico-meters)).
A well established laboratory technique for sub-nanometric displacement measurements is based on the use of balanced capacitive bridges (Jones R. *et al.*, 1973). The same approach has been chosen for the EP measurement in the GG mission. A block diagram of the foreseen EP measurement bridge is shown in the figure below, as it comes out from the GGG experiment.

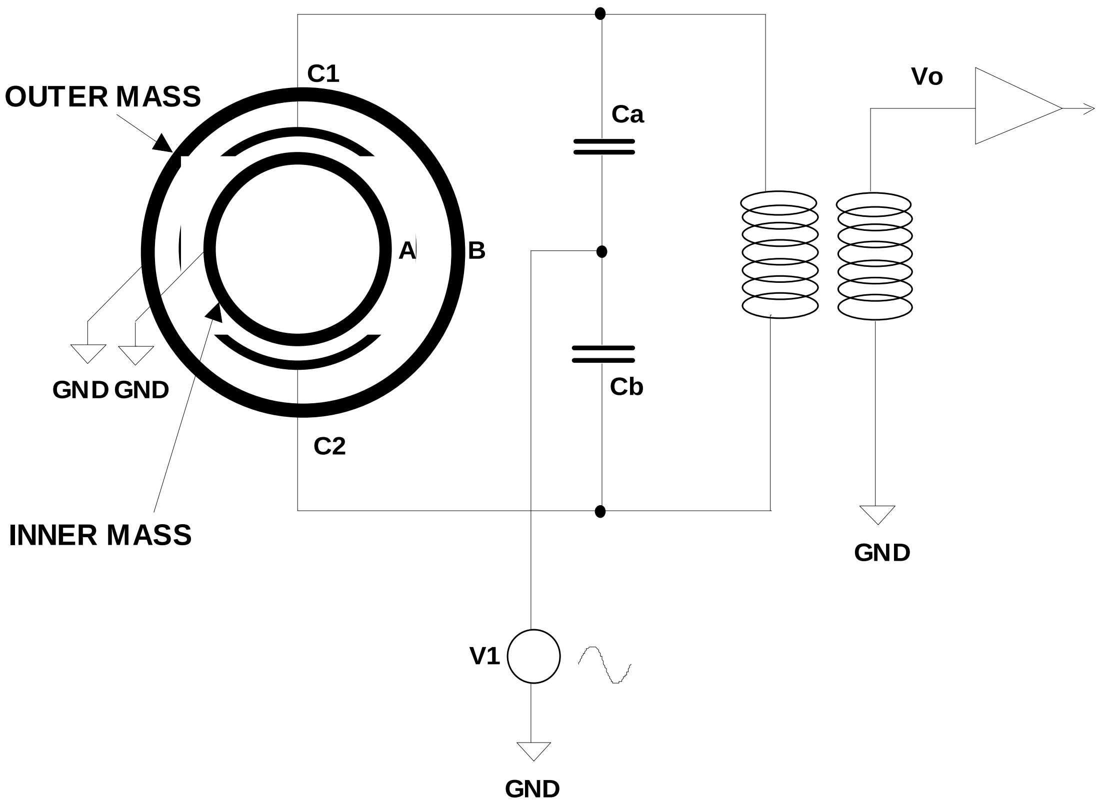


Fig. 5.1-2 Proposed concept of circuit bridge for measurement of capacitance variations along one axis (X or Y). The capacitors C1 and C2 are the two “left and right “sectors of a measurement pair. The input signal V1 will have a frequency of about 1MHz.

There will be two measurement chains on the Accelerometer Control Board one chain for the X-axis and one for the Y-axis.

The two test masses (*A* and *B* on the figure) are assumed to be at ground potential. The reference capacitors Ca and Cb have about the same values as the TM capacitors C1 and C2, and they are finely tuned for proper zero adjustment of the bridge output (electrical fine centering via compensating variable capacitors is also foreseen).

The *V1* signal is the output of a local oscillator running at an frequency of F_0 MHz. The value of this frequency is driven by a trade-off between various constraints: higher frequencies are preferred in order to reduce the *1/f* noise contribution and with the aim of having smaller coils, while lower frequencies are preferred in order to avoid speed constraints on the electronic circuit and its components. A suitable value of F_0 seems to be around 1 *MHz.*

Making some simplifying assumptions it can be shown that the output signal V_0 from the above circuit is given by the following expression:

$$Vo = \frac{C1 - C2}{2 \cdot Co} \cdot V1 \cdot K(C1o, C2o)$$

where K(C1o,C2o) is a fixed value depending on *C1o* and *C2o,* which are the "nominal" values of *C1* and *C2* when the system is perfectly centered (no differential displacement). The V_0 signal will be sinusoidal with the same frequency as the driving signal V_1, but its amplitude will be modulated by the (*C1-C2*) term.

If the capacitor plates C1 and C2 are fine adjusted to be placed just in the middle of the gap between the test masses (accuracy better than 0.4 nanom, see previous section), then the *(C1-C2)* term is dominated by the differential displacement between the plates, as required for high sensitivity measurements of EP violation.

In such a situation the EP-related modulating signal *(C1-C2)* as a function of time is a periodic signal with the frequency of the satellite spin *(2 Hz)* modulating the *Vin* carrier of frequency F_0.

For the current mechanical design the expected (minimum) differential displacement between the masses is estimated to produce a voltage V_0 with an amplitude of the order of 120 pico-*V.*

5. THE ACCELEROMETER and ITS REQUIREMENTS

5.1 DESCRIPTION

There are two EP measurement chains in the accelerometer. Each chain is based on 2 X or 2 Y curved capacitor plates as indicated in the fig.. The surfaces of the TMs are conducting and kept at ground potential (at least the ones facing the internal gap). The main dimensions are reported in the table 5.2-1.

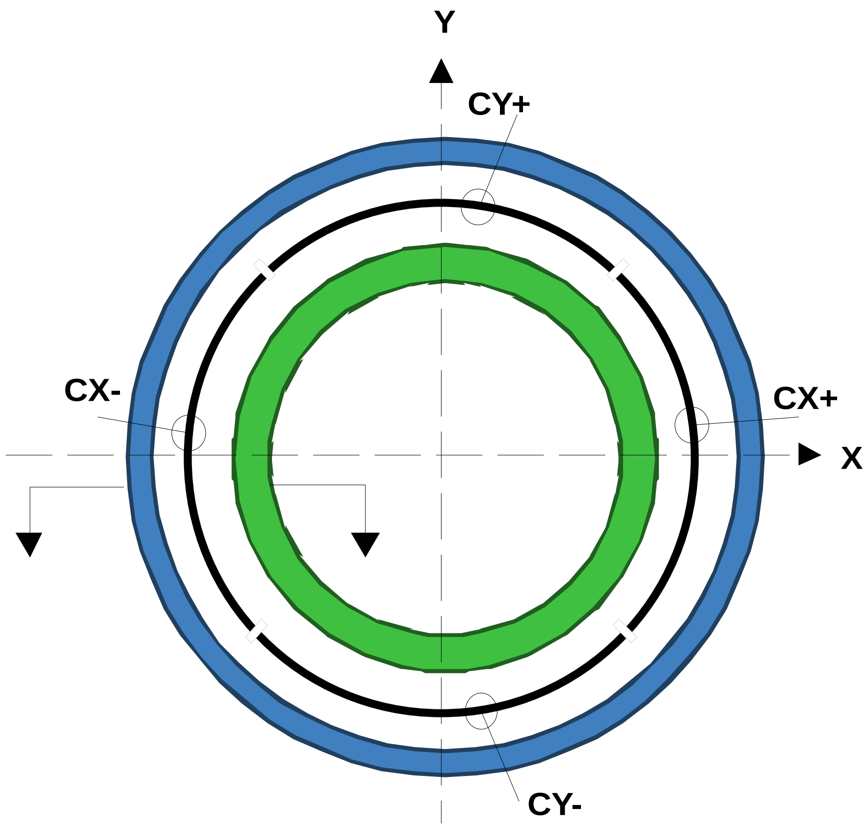


Fig. 5.1-1 Schematics of Test Masses (blue and green) as well as the four measurement capacitors for displacement measurements (black).

The expected differential displacement of the two test masses related to an EP violation of one part on 10^{17} is about *0.6 pm* (pico-meters), an extremely small value (see para. 5.2). The accelerometer and therefore the capacitor bridge will measure relative displacements of the two test masses and not absolute positions.
In fact, one can show (see RD-2) that the variation of the capacitance of a pair of capacitors, C1–C2 (= CX+ - CX or CY+ - CY-), is composed of two independent contributions: one variation due to common mode displacement ΔXcm and one due to differential mode displacement ΔXdm of the TM.

Common mode displacement:

$$(C1 – C2) / 2C0 = \Delta Xcm (a – b) / a^2 \quad (1)$$

Differential mode displacement

$$(C1 – C2) / 2C0 = – \Delta Xdm / a \quad (2)$$

Total variation

$$(C1 – C2) / 2C0 = \Delta Xcm (a – b)/a^2 – \Delta Xdm / a \quad (3)$$

Where a and b are the distances from a capacitor plate to respectively the inner and the outer test mass.

If the two arms are exactly equal (a = b) there will be non effect due to common mode displacement, and we will measure directly the differential displacement, like the effect of an EP violation. It is clear that:

<u>In order to measure an EP (violation) signal the differential signal (2) must be significantly higher than the common mode signal (1).</u>
Therefore we must have that

$$\Delta Xcm \times |a – b| << \Delta Xdm \times a \quad (4)$$

Assuming the values reported in table 5.2-1 (a = 3 mm and $\Delta Xdm = 6 \times 10^{-10}$ mm) we have

$$\Delta Xcm \times |a – b| << 1.8 \times 10^{-9} \text{ mm}^2 \quad (5)$$

This is a general mechanical constraint on the accelerometer, in particular for the adjustment of the balancing arms.

Equalization of balancing arms
The radial positions of the two TM must be well controlled and adjusted to obtain an almost equal distance on either side of the capacitors (i.e. distance a ~ b). For example if the common mode displacement (mainly due to air drag effect) amounts to 5 microns ($\Delta Xcm = 5 \times 10^{-3}$ mm) or less, then the radial positions of the TMs must be equal within 0.4×10^{-6} mm.

<u>Adjustment accuracy of TM positions should be better than 0.4 nanom (nm).</u> TBC

Maximum acceleration in common mode
The maximum displacement, ΔXcm due to common mode is due to a small acceleration Acom in a time which is similar to the rotation period T, and is given by $\Delta Xcm = ½ A T^2$ so the acceleration is $A = 2 \Delta Xcm / T^2$. In order guarantee that the common mode acceleration is insignificant we (arbitrarily) set A-max = 5% of the previous value A, and therefore the maximum acceleration is

$$A\text{-max} = 0.1 \Delta Xcm / T^2$$

For $\Delta Xcm = 5 \times 10^{-3}$ mm and T = 0.5 sec one finds

$$A\text{-}max = 2\ 10^{-6}\ m/s^2 \text{ or about } 0.2 \text{ micro-g}$$

5.2 REQUIREMENTS

This chapter gives the preliminary characteristics of the test mass capacitors and the two associated (and identical) measurement bridges. The table is a summary of the main requirements, while most of the parameters are discussed in the text here below.

	Parameter	Value	Notes
1.	Radial displacement resolution	0.6 pico-m = 6×10^{-10} mm	For measurement with one pair of capacitors
2.	Max. radial displacement (a)	1 micron	For science mode (after whirl / fine position adjustment)
3.	Size of gap between T.M. s	6 mm	Distance between TM1 and TM2
4.	Radius of capacitor	TBD mm	
5.	Capacitance variation sensitivity	TBD	Minimum capacitance variation to be measured
6.	Range of capacitance variation	TBC pF	Maximum capacitance variation to be measured
7.	Capacitance of one plate	150 picoF TBC	Assuming gap as defined below
8.	Max. Stray capacitance	< TBD picoF	For one pair of capacitors / bridge
9.	Sampling frequency	20 Hz	For a satellite rotation of 2 Hz
10.	Duration of continuous measurements	1 – 7 days	
11.	Frequency of measurement bridge	1 MHz	Sinus wave
12.	AD Converter digits	> 20 bits	See discussion of ADCs

(a) range of measurement

Table 5.2-1 Requirements of test mass capacitors and their measurement bridge(s).

5.2.1 Displacement resolution and range

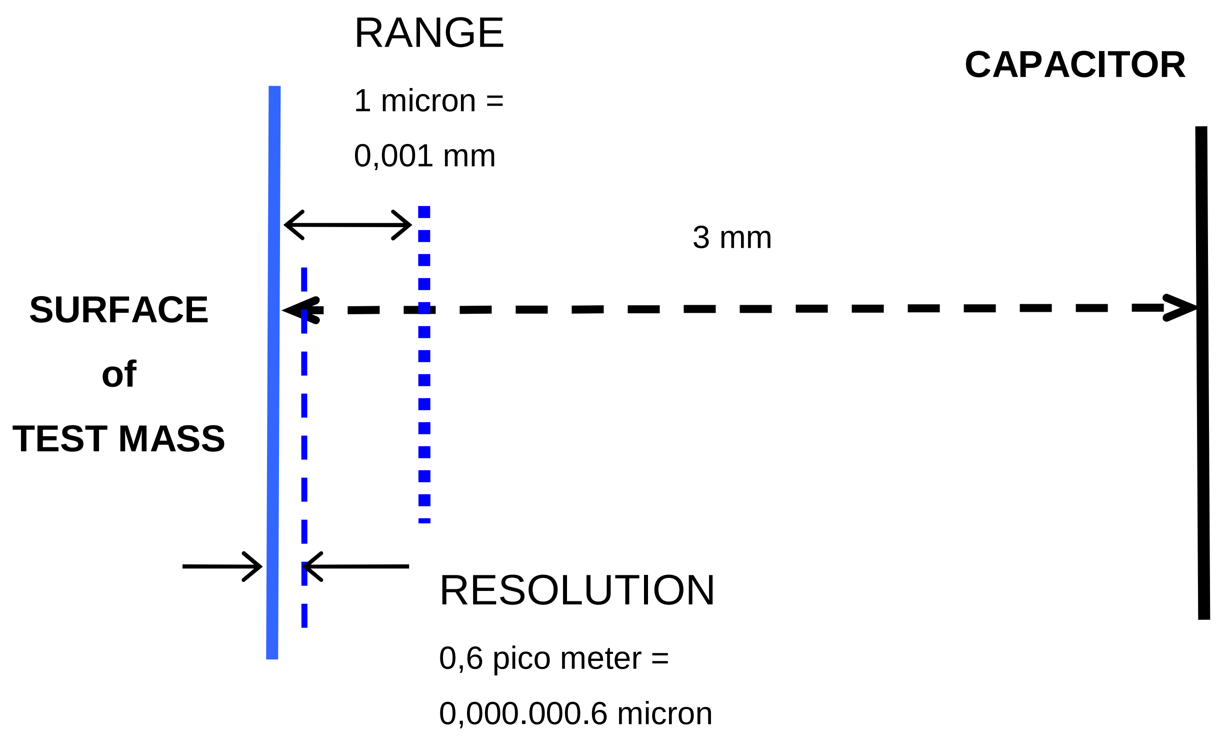


Fig. 5.2-2 Illustration of displacement resolution and range in the accelerometer.

With the values for the resolution and the range of displacement for the Test Masses shown on the figure and reported above we have that the ratio

$$\frac{\text{RANGE}}{\text{RESOLUTION}} = \frac{\text{1 micron}}{\text{0.6 pico meter}} = 1{,}6 \times 10^{6}$$

We note that the “binary power” 2^21 = 2,1 x 10^6.

<u>This implies that 21 bits are required to determine the expected variations.</u>

5.2.2 *Summary of mechanical ranges*

Following the above discussion the table gives the ranges (in the radial direction) for the accelerometer items

Distance / Range	Value
T.M. surface – science capacitor	3 mm = 3000 micron
Control (whirl) capacitor	100 micron
EP (science) measurement	1 micron

5.2.3 *Sampling frequency*

The sampling frequency is specified to be 20 Hz, which is in line with the satellite rotation, and in particular provides sufficient resolution of the AD converter (see below). The satellite will rotate 2 times in a second a therefore the number of samples for one rotation is 10. This means that <u>10 (digital) values will be generated each second</u> for each pair of “science” capacitors.
We note that the sampling frequency is also related to the demodulation of the accelerometer signal, which must be taken into account for a final assessment.

5.2.4 *AD Converter Assessment*

The Analog to Digital converter is a fundamental building block of the measurement electronics. The resolution of the converter indicates the number of discrete values it can produce over the range of analog values. In principle, the higher the resolution the higher the measurement accuracy, or for a given accuracy the larger is the covered measurement range. Also the speed of the convert must be taken into account. High accuracies can be obtained for low speeds. The current state of art for AD Converts is shown in fig.. It can be seen that at sampling rates below 10Hz <u>converters with up to 24 bits are available</u>.

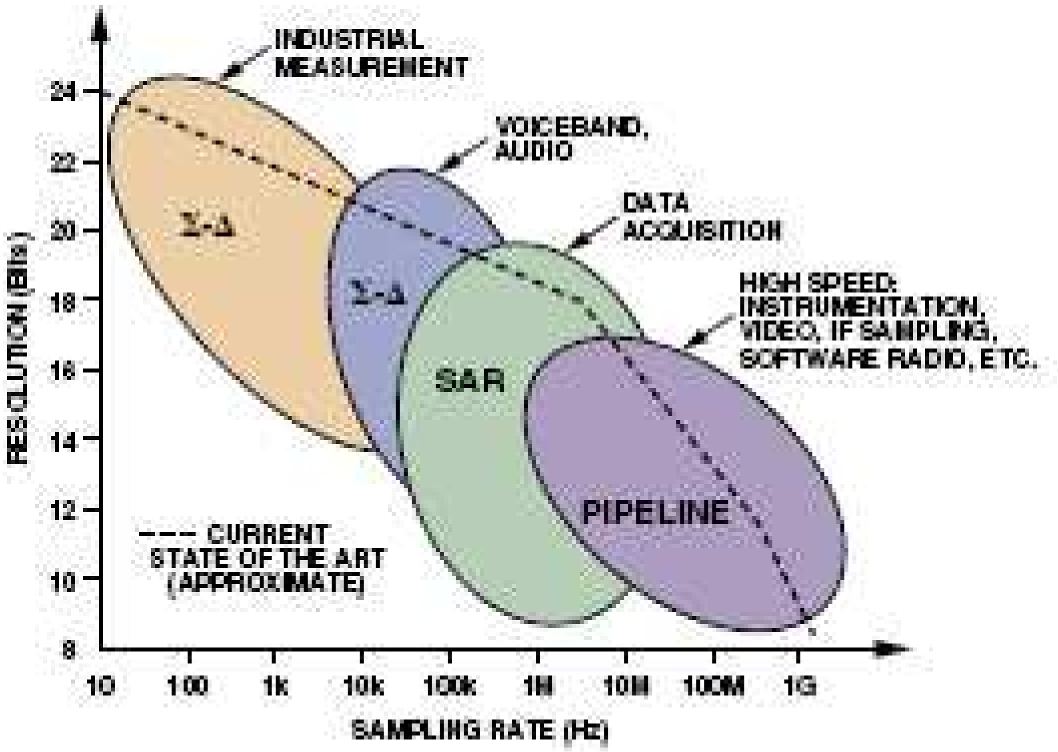


FIGURE ADC resolution as number of bits versus sampling rate. The current maximum resolution (state of the art) is shown as a dotted line
(from: Analog Dialogue vol. 39 n.2 (2005) in http://www.analog.com/analogdialogue).

It must be noted that the effective resolution of given ADC based on the sigma-delta technique depends on the conversion rate. Thus for example for the chips mentioned below (AD-7712) the effective resolution is 22.5 bits at 10 Hz while at 30 Hz it is 21 bits

An example of such an AD converter is the integrated system in the component AD-7712 from *Analog Devices* (see front cover of data sheet in Appendix). It employs a sigma-delta technique to obtain up to 24 bits of no-missing-code performance (for low conversion rates). A similar device is AD-7710.

Both AD-7712 and AD-7710 exist in a version with "extended temperature range" (i.e.-55°C to +125°C) making AD7712 (AD7710) especially suitable for space equipment.

6. INTERFACES

6.1 CPE Dimensions

The preliminary dimensions of the CPE bulk volume (i.e. box excluding mounting feet and connectors) are

250 x 170 x 180 mm3 (TBC).

The footprint area is

290 x 170 mm2 (TBC)

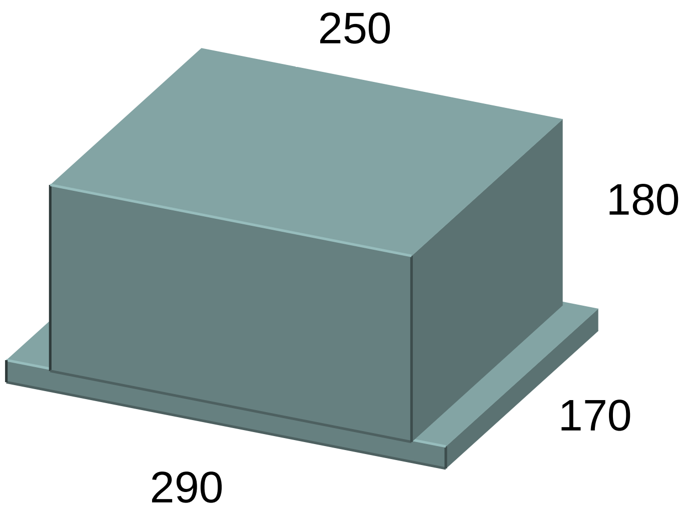


Fig. 6.1-1 CPE box main dimensions (in mm)

6.2 ECE Dimensions

The information in this paragraph is very preliminary as the envelope of the ECE electronics depends of its accommodation on the PGB.

In case the ECE circuit boards can be housed in a box, we here provide the preliminary dimensions of its bulk volume (i.e. box excluding mounting feet and connectors) are

250 x170 x 145 mm3 (TBC).

The footprint area is

290 x 170 mm2 (TBC)

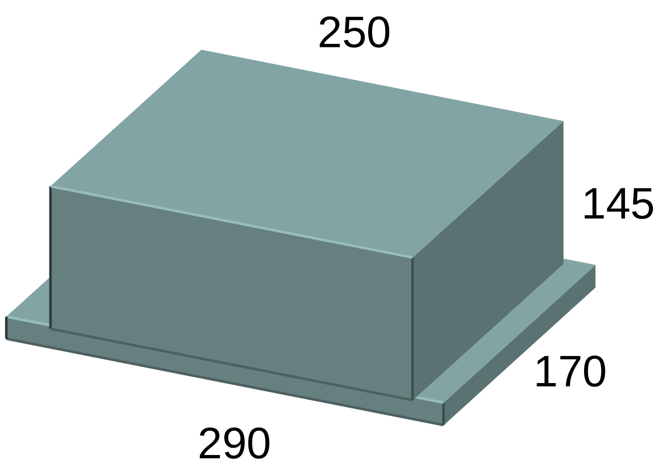


Fig. 6.2-1 ECE possible box main dimensions (in mm)

7. PAYLOAD EGSE

The aim of the GG Payload EGSE is to support testing and operations on the GG payload, Accelerometer & ECE, CPE Unit.

The main functions performed by the GG Payload EGSE may be summarised as follows:

- UART RS422 Exercising, for Command & Control Interface
- Power generation
- Optical data simulation
- Sensor & Actuator simulation and acquisition

The Payload EGSE high level architecture is depicted in the figure:

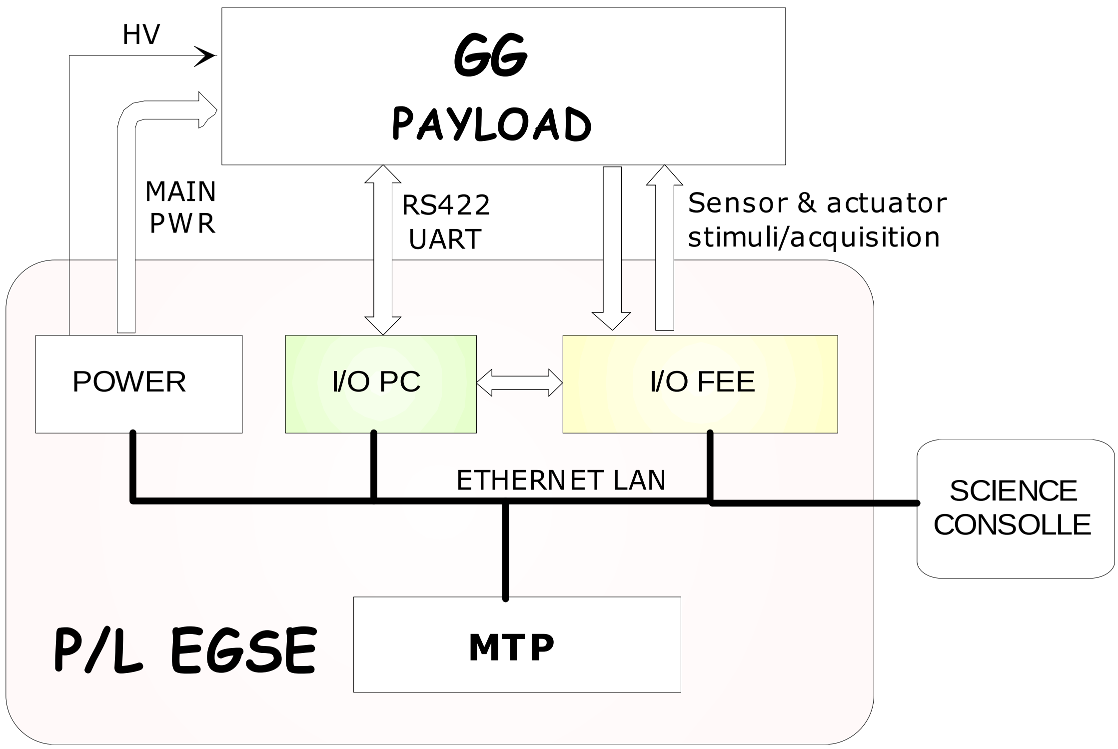


Fig. 5-1 - GG Payload EGSE Architecture block diagram

The GG Payload EGSE shall be supervised by the Master Test Processor (MTP).

The MTP main tasks are:

- System start-up and EGSE initialisation
- EGSE FEEs control
- Command processing
- Data acquisition & process
- Man-Machine Interface

An external workstation (science console) may be connected to the Ethernet LAN.

The science console and in particular the science SW is provided by the GG science team.

Annex 1: AD 7712 DATA SHEET

ANALOG DEVICES

LC²MOS Signal Conditioning ADC

AD7712*

FEATURES

Charge Balancing ADC
- 24 Bits No Missing Codes
- ±0.0015% Nonlinearity

High Level and Low Level Analog Input Channels

Programmable Gain for Both Inputs
- Gains from 1 to 128

Differential Input for Low Level Channel

Low-Pass Filter with Programmable Filter Cutoffs

Ability to Read/Write Calibration Coefficients

Bidirectional Microcontroller Serial Interface

Internal/External Reference Option

Single- or Dual-Supply Operation

Low Power (25 mW typ) with Power-Down Mode (100 μW typ)

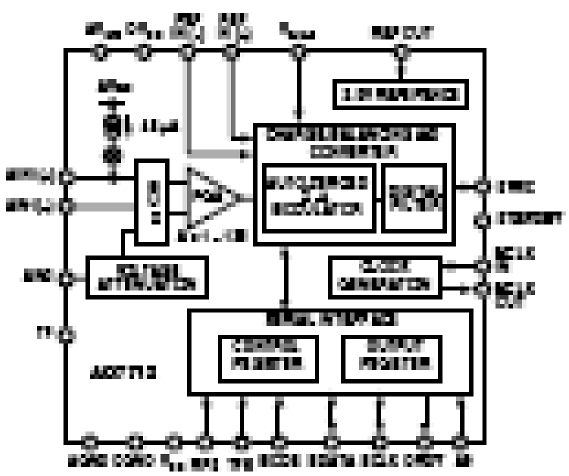
APPLICATIONS

Process Control

Smart Transmitters

Portable Industrial Instruments

FUNCTIONAL BLOCK DIAGRAM



GENERAL DESCRIPTION

The AD7712 is a complete analog front end for low frequency measurement applications. The device has two analog input channels and accepts either low level signals directly from a transducer or high level (±4 × V_{REF}) signals, and outputs a serial digital word. It employs a sigma-delta conversion technique to realize up to 24 bits of no missing codes performance. The low level input signal is applied to a proprietary programmable gain front end based around an analog modulator. The high level analog input is attenuated before being applied to the same modulator. The modulator output is processed by an on-chip digital filter. The first notch of this digital filter can be programmed via the on-chip control register, allowing adjustment of the filter cutoff and settling time.

Normally, one of the channels will be used as the main channel with the second channel used as an auxiliary input to periodically measure a second voltage. The part can be operated from a single supply (by tying the V_{SS} pin to $AGND$), provided that the input signals on the low level analog input are more positive than −30 mV. By taking the V_{SS} pin negative, the part can convert signals down to $-V_{REF}$ on this low level input. This low level input, as well as the reference input, features differential input capability.

The AD7712 is ideal for use in smart, microcontroller based systems. Input channel selection, gain settings, and signal polarity can be configured in software using the bidirectional serial port. The AD7712 also contains self-calibration, system calibration, and background calibration options, and allows the user to read and to write the on-chip calibration registers.

CMOS construction ensures low power dissipation, and a hardware programmable power-down mode reduces the standby power consumption to only 100 μW typical. The part is available in a 24-lead, 0.3 inch wide, plastic and hermetic dual-in-line package (DIP), as well as a 24-lead small outline (SOIC) package.

PRODUCT HIGHLIGHTS

1. The low level analog input channel allows the AD7712 to accept input signals directly from a strain gage or transducer, removing a considerable amount of signal conditioning. To maximize the flexibility of the part, the high level analog input accepts signals of ±4 × V_{REF}/GAIN.
2. The AD7712 is ideal for microcontroller or DSP processor applications with an on-chip control register that allows control over filter cutoff, input gain, channel selection, signal polarity, and calibration modes.
3. The AD7712 allows the user to read and to write the on-chip calibration registers. This means that the microcontroller has much greater control over the calibration procedure.
4. No missing codes ensures true, usable, 23-bit dynamic range coupled with excellent ±0.0015% accuracy. The effects of temperature drift are eliminated by on-chip self-calibration, which removes zero-scale and full-scale errors.

*Protected by U.S. Patent No. 5,134,401.

REV. F

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