A Roadmap for the Development of Miniature Instrumentation for Mars Exploration.

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Introduction: During the last 10 years, the Payloads Technology Area of INTA (the National Institute for Aerospace Technique, Spain) has set up an initiative aimed at achieving a number of capabilities to allow the development of compact instruments for planetary exploration. This initiative includes activities at different levels, such as testing of electronic and optoelectronic parts, and other sensors and materials, under radiation and extreme temperatures, other environmental qualification tests, in-orbit demonstrations and validations and, finally, development of particular instruments for concrete missions. Thanks to this effort, we are now involved in two Mars exploration missions: Mars MetNet Lander, and ExoMars 2016.

Goals of the initiative: As it is well known, the resources in terms of mass, volume and power, available in any planetary exploration mission, very specially if it includes a lander (with or without mobility), are scarce. Besides, the delay in the communications loop requires that some autonomous operation capabilities are implemented in the instruments that operate on surface. For these reasons, any sensor or instrument to be put on-board a landed platform must be compact, light, and low-power demanding. Besides, it must be intelligent enough so as to allow some autonomous operations. Finally, as for any space mission, it must be reliable. It is commonly accepted that instruments to be considered for selection in any announcement of opportunity must have a moderate/high TRL (Technology Readiness Level) by the time of PDR (Preliminary Design Review).

Scientific groups usually focus their efforts in the development of particular instrument suited for their investigations. However, to be able to fulfill all the aforementioned requirements, it is convenient to set-up also technology development plans not designed to cope only with the needs of a particular instrument, but to allow the development of a number of them, by making some common resources available. In this sense, the main Space Agencies have set-up technology programs under a non-mission-oriented philosophy. The NASA's Mars Technology Program (MTP), including the Mars Instruments Development Project (MIDP), or ESA's Mars Robotic Exploration Preparation (MREP), are good examples of these kind of initiatives.

That kind of approach is the one he have followed, at a reduced scale according to the available resources (economic and human), in the last years.

Building Blocks/Required Capabilities: A number and variety of resources and capabilities have been identified as necessary to allow the development of miniature, high-performance instruments for planetary exploration.

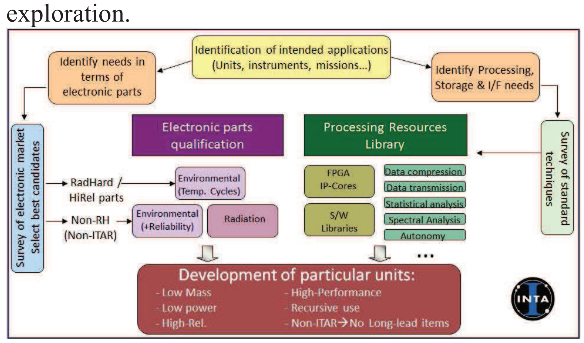

Fig. 1 Diagram of the strategy for developing different electronic resources as building blocks.

Selection and testing of high-performance electronic components, optoelectronics and detectors. The market of Space-grade electronic parts is small. Commercial, industrial or military ones, usually offer improved performances, reduced power consumption, and smaller packaging options. Even when Space-grade parts are to be used, their guaranteed operational temperature ranges don't go beyond -55ºC. However cooler environments must be faced by sensors located outside warm boxes. This means that for using non-Space-grade parts, at least a set of radiation an extreme temperature tests are to be performed. For Rad-Hard parts, still the operation capability under extreme temperature must be proven. Finally, reliability is another critical factor. Any non-high-reliability (Hi-Rel) parts selected, must undergo screening and qualification tests.

All these aspects have been considered. A permanent activity has been maintained in selecting and testing good candidate COTS (Commercial Of The Self) or military parts, adequate for different needs. They include a number of analog parts, such as operational and instrumentation amplifiers with different characteristics, voltage regulators and references, analog multiplexers and switches, etc. (e.g. [4], [5]). Also different mixed-signal parts such as Digital-to-Analog (D/A), Analog-to-Digital (A/D), Voltage-to-Frequency (V/F) converters, or Field Programmable Analog Arrays (FPAA), and finally digital/logic ones, such as FPGAs (Field Programmable Gate Arrays), CPLDs (Complex Programmable Logic Devices) and DSC (Digital Signal Controllers) (e.g. [6], [7]).

Also, given the special interest for many applications, optoelectronic parts and other detectors deserve special attention. Due to the nature of some of the sensors and applications that we have developed in recent years, LEDs, Silicon photodetectors, and different magnetic sensors (Anisotropic Magneto-Resistance, Giant-Magneto-Resistance and Magneto-Impedance) have also been screened and tested (e.g. [8], [9], [10]).

For COTS, we first perform low-temperature tests (down to -130ºC or similar). Then, for those parts that withstand the cold environment, we perform TID tests using gamma ray sources, proton tests at least for Single Event Latch-up (SEL), and Displacement Damage (DD) in case of optoelectronics, as well as additional Single Event Upsets (SEU) susceptibility tests with protons. Some of them have also been performed with heavy ions. Once a part is selected, we perform qualification and screening tests, in a per-lot basis. For Space-grade parts, only temperature tests are performed.

Development of ASICs. In cooperation with the Microelectronics Institute of Seville (IMSE), Spain, we have also started a program for the development of mixed-signal ASICs. Their definition is done by INTA, whereas the development is carried out by IMSE applying radiation-hardening by design techniques. Two first ASICs have been developed: a transceiver for diffuse optical wireless communications, and a signal-acquisition front-end for a number of sensors. The first one includes all the receiver and emitter functions to implement diffuse optical links under a number of modulation and multiple access schemes, as well as data rates [11]. It is digitally configurable by means of discrete inputs. The second one includes conditioning stages for resistive or capacitive bridge sensors, some excitation capabilities (configurable current sources), multiplexing of a number of channels, and several A/D converters. The ASIC is digitally controlled by means of a SPI (Serial Peripheral Interface) bus [12]. First tests show no significant degradation for 60 krad, the ASICs are SEL-protected, and can operate at -130ºC.

IP-cores or S/W libraries. Similar efforts must be done in the software counterpart. For small instruments, mostly programmable logic devices such as FPGAs are used to implement the control, data storage and communication routines. IP-cores are developed, that are re-used from one application to the next, thus decreasing development time. For example, cores for usual interfaces (CAN, SPI, UART…), data compression, statistical analysis (histograms, noise estimation, etc.) or for performing special acquisition sequences (e.g. subranging A/D conversion), are developed.

For the cases in which a Central Electronics Unit is needed, we have manufactured a flexible, medium-cost, high-reliability computer that offers all processing capabilities that may be needed in most instruments, together with SEL-protected secondary power supplies and mass memory. It is based on the combination of a LEON-3 FT processor ASIC, plus a co-processing RadHard FPGA and non-volatile Magnetic memory for data storage [13]. S/W packages such as those related to the Space Packet Protocol [14] and Packet Utilization Standard, have been developed.

Environmental qualification and Planetary Protection. INTA has all the facilities required for a complete environmental qualification campaign. This includes vibration, shock, thermal cycling, vacuum, EMC, etc., as well as other reliability test capabilities, such as X-ray analysis. Other special facilities are available, such as those for solar cell testing, solar-spectrum and different Martian spectrums lamps, or magnetic sensors characterization and magnetic cleanliness.

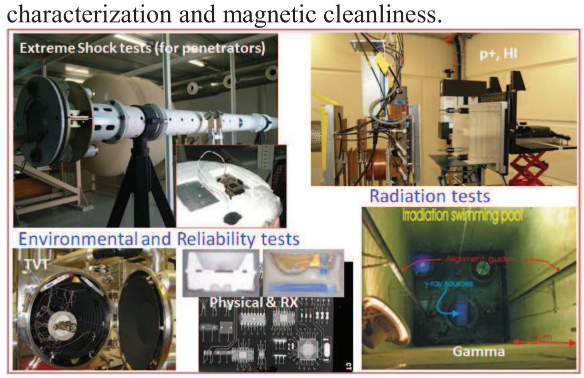

Fig. 2 Some qualification and reliability test facilities.

Given INTA involvement in one penetrator-type mission to Mars (Mars MetNet Lander, presented later on), we have also developed a particular facility, based on an compressed-air canyon, to be able to emulate the expected shock profiles suffered by this kind of landers. All scientific instruments that will be put on board the first MetNet penetrator, have been tested with this facility. Required profiles were semi-sine ones, with peak values ranging from 500 to 2000 g and durations of 5 to 20 ms [15].

External radiation test facilities are used. For TID and low-energy particles, they are located also in Madrid or other Spanish cities. For high-energy particles, we use other European facilities mainly in Switzerland.

Finally, compatibility with DHMR (Dry-Heat Microbiology Reduction) process, is also tested.

In-orbit testing and validation: INTA started in 2000 a program for the development of small satellites. They are mainly used as in-orbit test-beds for new technologies or concepts. The 2 first ones, called Nanosat-01 and Nanosat-1B, were launched in 2004 and 2009 and their mass is around 20 kg. The third one, called OPTOS, is a 3U-Cubesat launched in 2013. All of them lie in helio-synchronous polar orbit.

We use this kind of platforms to validate the use of different components, designs, or architectural concepts, as well as complete compact sensors. This is a last step in the development of space hardware, that allows us to reach the highest Technology Readiness Level (TRL).

In Nanosat-01, we tested a new wireless data transmission method, based on optical diffuse links (called OWLS), and characterized the effects of Space environment on it [16]. This technology was later used in the Russian-European capsule FOTON-M3 in 2007 [17], and is used in one of our sensors on-board the first MetNet penetrator. Besides, we used AMR technology to develop the Attitude Control System magnetometer [18]. We have used the same technology, once validated, in the following satellites, as well as in the magnetometer developed for MetNet. Besides, we tested several electronic and optoelectronic parts.

In Nanosat-1B we tested new magnetic sensor technologies, after they had been qualified in ground facilities. We also developed a proton monitor, capable of measuring flux and fluence of protons and performing energy analysis, through the study of DD effects in stacks of photodetectors [19].

In OPTOS we validated a new concept of distributed computer, on which a number of low-cost COTS logic devices perform the tasks of a traditional central computer, by means of a collaborative strategy that provides redundancy and adequate reliability. Also, new devices were tested in-orbit , ranging from amplifiers to an Active Pixel Sensor.

At present we develop a complex space-weather monitor to be put on-board the Spanish Earth Observation Satellite (SEOSAT-INGENIO), that makes use of many of the technologies and concepts previously qualified and validated through the activities shown [20].

The same philosophy is applied to face the participation in Mars Exploration missions: we take profit of previous selection and qualification efforts, instrument developments and in-orbit experiences, to tackle the development of different sensors to be operated on Mars surface, with the best guarantees of success and from the highest possible TRL.

Fig. 3 provides a visual summary of our test-bed missions in the last 10 years, and the corresponding technologies developed or tested on each one.

Involvement in Mars exploration: With this gained know-how, we successfully applied to 2 different opportunities for Mars exploration missions. The first one, Mars MetNet Lander Precursor, is a Russian-Finnish-Spanish mission in which INTA leads the Spanish contribution. The aim is to land the first penetrator-type lander on Mars, and deploy a meteorological station [21]. The second one is the ESA ExoMars 2016 mission. It will carry the first European Martian Lander (Beagle not considered), the EDM. We have developed one of the sensors on board the EDM, within the package called DREAMS (Dust characterization, Risk assessment and Environment Analyzer on the Martian Surface) [22].

Instruments for Mars MetNet Lander Precursor. The Spanish contribution to the first MetNet penetrator include a Solar Irradiance Sensor (MetSIS), a Magnetometer and a Dust Sensor [23]. The 2 first ones are

Fig. 3 Visual summary of the previous in-orbit test-bed experiences, and the evolution towards miniature instruments for Mars exploration.

developed by INTA. They make intensive use of the previous heritage.

MetSIS is based on optoelectronic and optic parts previously qualified, as well as COTS amplifiers. Only by making use of these components, it was possible to develop this sensor, that includes 32 sensing channels, with 11 spectral bands, Solar angle sensors, temperature and Displacement Damage ones, with only 120 g of mass and 0.5 W of power. MetSIS is composed by several PCBs stacked inside and connected through vertical wires, thus achieving a high degree of compactness thanks to this 3D integration.

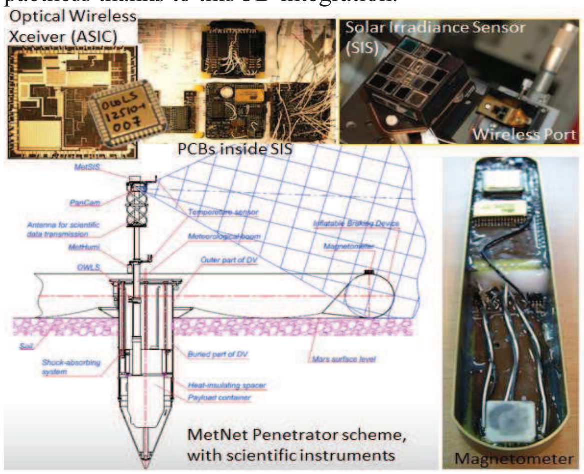

Fig. 4 Bottom left: scheme of MetNet penetrator and deployed sensors. Bottom-right: magnetometer. Top: Solar Irradiance Sensor and associated optical wireless port.

The sensor is located on top of a deployable boom. At the moment it was included, there was no space available for routing data harness inside that boom (only 2 wires for power). To solve that problem, we made use of our previously developed optical wireless communication technology. Thus, an optical port is integrated inside MetSIS, and another one is added to the central computer, 1 meter away. The main characteristics of MetSIS are summarized in Table 1.

MetNet Solar Irradiance Sensor - MetSIS	
Sensing elements	Si-photodiodes + interference filters + density filters + FoV shaping elements
Power supply	5 V
Current consumption	<102 mA, including optical wireless port at central computer
Data I/F	Serial, through optical wireless port
Mass	120 g
Dimensions	48x45x27 mm
Operating temp.	-120 to +125 ºC
Optical bands (nm)	[200-310], [245-290], [280-315], [300-345], [315-400], 440, 600, [400-700], [700-1100], 940, [230-1200]
Additional sensors	Temperature (PT-1000, x2), Solar angle (x2), Dark Current for DD estimation.
Operation and others	Fully digital. RadHard FPGA used. Allows autonomous operation under configurable parameters: channels to acquire, sampling period, etc. 128 kB internal RadTol memory.

Table 1 Main characteristics of MetSIS.

The magnetometer is also based on a previously qualified technology (AMR). Besides, a big effort was done to characterize the magnetic properties of the electronic parts to be used. A minimum distance and recommended orientation with regard to the position of the AMR, was determined in order to ensure no significant magnetic contamination. The package of some RadHard parts was found to be so ferromagnetic, that COTS counterparts had to be selected, qualified and screened. Different PCBs were stacked with vertical interconnections, and special foam added to dump the intense shock level the unit will suffer, due to its position in the penetrator. The unit can also be seen in Fig. 4. Table 2 shows its main characteristics.

MetNet Magnetometer	
Sensing elements	Aniostropic Magneto-Resistance (AMR) COTS, qualified and screened by INTA.
Power supply	5 V, 12 V
Current cons.	<85 mA @ 5V, <0.5 mA @ 12 V
Data I/F	Serial, RS-422
Mass	72 g
Dimensions	150x30x15 mm
Operating temp.	-120 to +125 ºC
Number of axis	6: 2 sets of tri-axial magnetometers (X, Y, Z)
Range	±130 µT
Resolution	2 nT
Noise	0.2 nT (@ 0.5 Hz Bandwidth, 128 samples averaged)
Additional sensors	Temperature (PT-1000, x3), Accelerometers (x3: X, Y, Z) for inclination measurement.
Operation and others	Magnetic field for offset compensation can be generated to extend range (current mode D/A, 12 bits). Fully digital. RadHard FPGA used. Allows autonomous operation under configurable parameters: Set/Reset configuration for AMR, channels to acquire, sampling period, offset compensation, etc. 128 kB internal RadTol memory.

Table 2 Main characteristics of MetNet magnetometer.

Instrument for ExoMars EDM (2016). A reduced version of MetSIS was manufactured for DREAMS package on ExoMars EDM. The reason was that the mass available for it on top of the mast that allows unobstructed Field-of-View (FoV), was only 25 g with an extremely reduced envelop volume. Due to this, the instrument was separated into 2 parts: Optical Head (OH), on top of the mast, and Processing Electronics (PE), inside the warm box of EDM.

The OH presents a tetrahedrical shape. Each lateral face contains 2 detectors (UV and NIR). Their FoVs are approximately ±35º to 5% of maximum sensitivity. An additional hemispherical detector is added on top.

Thanks to the previous efforts and the high starting TRL, the complete development of DREAMS SIS was done in only 10 months, including Engineering, Qualification, Flight, Space and Field-Test models. Planetary Protection considerations were observed. Fig. 5

and Table 3 show some details and the main characteristics of this sensor.

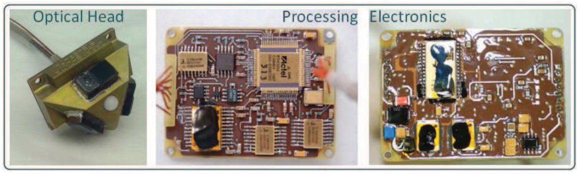

Fig. 5 Detail of the DREAMS SIS OH and PE.

ExoMars EDM Solar Irradiance Sensor – DREAMS SIS	
Sensing elements	Si-photodiodes + interference filters + density filters + FoV shaping elements
Power supply	5 V
Current cons.	<58 mA
Data I/F	Serial, RS-422
Mass	25 g OH + 52 g PE
Dimensions	OH:42x33.7x22.5 mm; PE:80x50x13.5 mm
Operating temp.	-120 to +125 ºC
Optical bands (nm)	Total:[220-1200], UV:[315-400], NIR:[700-1100]
Range / resolution (W/m^2)	Total: 1050 / 10^{-3}, UV: 110 / 10^{-4}, NIR: 390 / $3.7x10^{-4}$
Additional sensors	Temperature (PT-1000, x2: OH and PE), Dark-current for Displacement Damage estimation.
Operation and others	Fully digital. RadHard FPGA. Autonomous operation under configurable sampling period. 128 kB internal RadTol memory.

Table 3 Main characteristics of DREAMS SIS.

With MetSIS we expect to be able to estimate the Optical Depth of Mars atmosphere in real time. Thanks to its sectored configuration, there are always 2 sets of sensors receiving only diffuse light. The third one will be, in general, receiving a combination of direct plus diffuse light. A model can be developed to derive the diffuse contribution on this face, from the measurements on the 2 other ones, and subtract it. Then, by knowing the relative position of the Sun, we know the amount of direct solar flux that corresponds to the measured signal. The relative orientation of the sensor after landing, has to be determined by adjusting the signals obtained in the first Sol to the modeled ones for the actual location and day of the year.

Recently, a field test campaign has been carried out in the South-East Moroccan part of Sahara desert during sand storm events. Several reference instruments (two pyranometers, one of them with shadow ring for diffuse light measurement, one spectral-radiometer and one Cimel photometer) were used together with both MetSIS and DREAMS SIS field-test models.

Future steps and conclusion: In near future the activity of selection and qualification of promising COTS will be continued. New ASICs are to be developed, including a small RadHard microcontroller with a number of integrated mixed-signal capabilities. Also, the development of complex parts through the de-encapsulation, die-level integration, and re-encapsulation of selected COTS plus ad-hoc designed protection circuitry is a path that will be explored.

A new version of the magnetometer will be manufactured making use of the front-end ASIC. This ASIC is being packaged in a special way to avoid ferromagnetic materials, so that it can be used as close to the AMR sensors as possible, thus reducing noise. Regarding the scientific data retrieval of both SIS, we are working in the empirical models for deriving the diffuse-light contribution on the sensors for which Sun is in the FoV, from the signals provided by the others.

Thanks to the presented roadmap, we have gained considerable know-how and heritage to be in the best position to develop future miniature, high-performance sensors for Mars exploration.

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