OWLS: A Ten-Year History in Optical Wireless Links for Intra-Satellite Communications

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***Abstract*—The application of Optical Wireless Links to intra-Spacecraft communications (OWLS) is presented here. This work summarizes ten years of developments, ranging from basic optoelectronic parts and front-end electronics, to different in-orbit demonstrations. Several wireless applications were carried out in representative environments at ground level, and on in-flight experiments. A completely wireless satellite will be launched at the beginning of 2010.**

The benefits of replacing standard data wires and connectors with wireless systems are: mass reduction, flexibility, and simplification of the Assembly, Integration and Tests phases (AIT). However, the Aerospace and Defense fields need high reliability solutions. The use of COTS (Commercial-Off-The-Shelf) parts in these fields require extensive analyses in order to attain full product assurance. The current commercial optical wireless technology needs a deep transformation in order to be fully applicable in the aforementioned fields.

Finally, major breakthroughs for the implementation of optical wireless links in Space will not be possible until dedicated circuits such as mixed analog/digital ASICs are developed. Once these products become available, it will also be possible to extend optical wireless links to other applications, such as Unmanned Air and Underwater Vehicles (UAV and UUV).

The steps taken by INTA to introduce Optical Wireless Links in the Space environment are presented in this paper.

***Index Terms*—Optical Communication, Wireless LAN, Optoelectronic devices, Space technology, Space vehicle electronics, Space vehicle communication.**

I. INTRODUCTION

ALMOST two decades ago, harness reduction in Space systems was identified as a promising step forward in the conception of Space platforms, which was further emphasized by the growing interest in miniaturization of equipments and platforms [1]. A satellite's harness can be considered to account for 7-10% of its total dry mass. More than one half of this mass is data wires [2]. Some benefits in weight reduction are related to launch costs and fuel requirements. Alternatively, new payloads may replace the removed harness. Beyond these advantages, integration and test activities may benefit from wireless systems: Real-time monitoring of data traffic without traditional Break-Out-Boxes is possible; connector savers or connection/disconnection control sheets are no longer needed; routing of the remaining harness is easier, etc. In summary, the time and risk for such a critical phase in the development of a spacecraft, as is the AIT, may be significantly reduced.

Among the different possibilities that exist for harness reduction, Optical (or infrared – IR) Wireless and Radio Frequency (RF) seem to be promising technologies for the substitution of data cables. The optical solution presents a clear advantage due to the lack of Electro-Magnetic Interference/Compatibility (EMI/EMC) concerns. Since the first reference [3] to an application using IR transmission, our bibliographic studies show several hundreds of papers and proceedings in support of the above. This reinforces the fact that it could be an enabling technology for a specific sector such as Space. Another favorable indicator is its strong relation with Optoelectronics, a discipline which is undergoing continuous improvement.

However, the Space sector is highly conservative and an innovative solution is only accepted if its benefits are not only outstanding, but also if the reliability at system level is maintained or even increased. Any flight technology is systematically tested in relevant environments, following a progressive model philosophy [4]. There are two main features of Space missions that make them different from other domains of application: the impossibility to perform in-orbit repair work and the harsh Space environmental conditions (temperature, vacuum, radiation, and vibration and shock during launch). At system level, a full set of tools and strategies takes decades to be developed. This know-how and way of proceeding is not easy to change. With respect to the parts, COTS must not be used in Space prior to their reliability verification. Therefore, introducing new successful ideas based on elements developed for non-Space applications, is not an easy task.

At the end of the 90's, the National Institute for Aerospace Technique of Spain (INTA) proposed optical wireless as a solution for interconnections between future micro/nano devices [5]. This was motivated by the paradox that the connectors and harnessing needed for Micro/Nano-Technologies (MNT) in Space platforms were larger than the microsystems to be connected. The name given to this initiative was OWLS (Optical Wireless Links for intra-Satellite communications). To our knowledge, this had previously been proposed in 1991 in a French patent by Alcatel (now Thales Alenia Space - TAS) [6]. This initiative was also suggested by COMSAT Laboratories of Maryland (US) [7] and by Matra-Marconi/UK (now EADS Astrium) [8]. The first practical developments were attained by a Spanish team led by INTA, as a result of

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a study carried out for the European Space Agency (ESA) in 2000, described in III.A ([9]-[11]).

In Europe, during the period 2002-2005, the prime satellite manufacturers (EADS Astrium and TAS) also started to work in this field [12]-[17]. In the US, several activities were carried out with NASA financing by the Laboratory of Applied Physics of Johns Hopkins University [18]-[21]. On the Chinese side, OWLS activities were detected in the University of Electronic Science and Technology of Chengdu [22]. There are some groups that address the inter-satellite optical communications and also point to the intra-spacecraft capabilities [23]-[25]. Recently, a related Patent Application has also been presented by the Howard Hughes Center of Boeing [26].

The work developed by INTA in this area has taken place in the framework of several ESA contracts and the Spanish National Space Program. EADS Astrium, Thales Alenia Space, and up to seven public Institutions and Companies (ALTER, CEA, CNM/CSIC, CRISA, SCK-CEN, UPLGC, UPM) have participated in different stages of this long process.

The main target was to develop fully operative optical wireless technologies for wide use inside future space platforms. A two-fold approach was maintained throughout. First, to work on the basic "building blocks" needed to build-up the complete optical system. This includes optoelectronic and electronic parts for Space qualification, selection of adequate network topologies and modulation schemes, development of generic optical ports, etc. Second, an application/system point of view has always been kept in mind. Relevant scenarios were characterized, the effect of the Space environment was studied, etc. As a result, several in-orbit experiments were successfully carried out. All these aspects are presented hereafter.

II. OWLS ENABLING TECHNOLOGIES AND BUILDING BLOCKS

A. *General Constraints*

The objective of OWLS is to communicate devices in a small and closed volume (in the range of cubic meters and with traveling distances from 0,1 m to 2-3 m). The Line-Of-Sight (LOS) is not guaranteed, and working in diffusion [27] is required. The position or location of the equipments inside a spacecraft (S/C) must be constraint-free. Because of the thermal power management, the internal surfaces are black or white (diffusion with Phong reflectance), and frequently we find multilayer insulators made of mylar or kapton (specular reflectance and usually with a wrinkled surface). S/C can be quite full of equipments and payloads, and the opto-mechanical environment can be very different from one application to the other.

OWLS communication modules are intended to substitute a simple data connector and the associated cables. A harness has maximum reliability, and so must the OWLS counterpart solution. The volume of the optical transceiver module should be, at most, comparable to that of the connector that is being replaced. Therefore, solutions with added optical elements that increase the volume of the module in height [28] are not welcome.

The available electrical power inside a spacecraft is very limited. Electrical power for transmission and reception in OWLS systems need to be as small as possible. Finally, a very attractive solution would be to avoid the power harness. Removing data and power harnesses is the real full advantage of OWLS, because it enables time reduction in the AIT phase, and confers flexibility for "last minute" incorporation of initially not planned sensors or payloads.

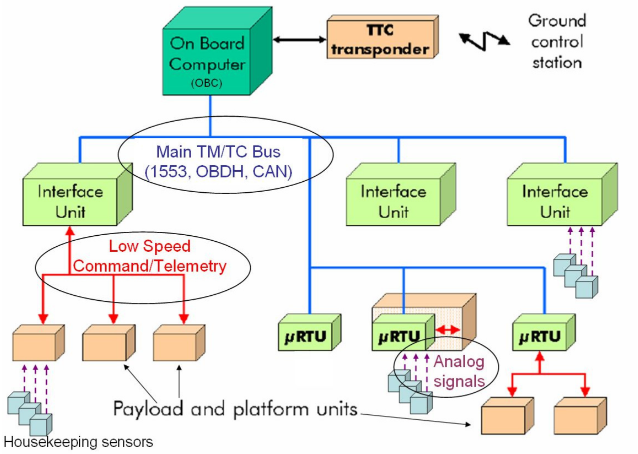


Fig. 1. Main buses / signals susceptible of OWLS application in a generic Data Handling architecture (Note: TM/TC= Telemetry/Telecommand; TTC=Tracking, Telemetry & Command; RTU=Remote Terminal Unit).

The Space environment and reliability requirements pose strong constraints on parts and components. In this connection, OWLS need to be built from scratch, with "raw" optoelectronic emitters and detectors. They must be pre-screened as per technical specifications (at datasheet level), and later need to undergo radiation, temperature, vacuum and vibration tests; the same applies to many critical electronic components. Finally, the wireless solution should impose no restrictions on the higher level protocols usually employed in Space systems.

B. *Network Architectures and Communication Protocols*

The philosophy adopted by INTA since the beginning of the OWLS development was to make use of the Data Handling architectures and associated communication buses most commonly employed on board spacecrafts. In this regard, OWLS should be seen a mere physical-layer substitution with zero or minimum impact on the network architecture, and transparent to the communication bus nodes/users. Only in those cases in which the use of wireless links implied the introduction of a completely new approach (e.g. when applying them to sensors that in common S/C provide analog signals), ad-hoc topologies or protocols were defined.

A general S/C's Data Handling architecture involves many different kinds of signals and buses, including low and high-level on/off commands, analog signals, digital bi-level signals, different kinds of serial buses, etc [4]. Not all of them are adequate for the application of optical wireless transmission. Fig. 1 depicts the main intra-satellite links that can benefit from OWLS.

As shown, and regardless of the type and size of the satellite, a classical topology would include some kind of On-Board Computer (OBC) linked to other Interface (I/F) Units, Remote Terminal Units (RTU), Payload I/F Units, etc, by means of a main Telemetry and Telecommand (TM/TC) bus, typically a medium data-rate one (∼1Mbps), such as MIL-STD-1553, OBDH or CAN. A second type of serial buses are used to give service to different sensors, actuators, payloads, etc, from the corresponding I/F Unit. These are low-speed buses (∼10-100kbps) such as Astrium's *Low Speed Serial Bus* (LSSB) or former Alcatel's *Memory-Load/Data-Storage 16* (ML16/DS16), or even commercial standards similar to Motorola's *Serial Peripheral Interface* (SPI). These two kinds of buses define the backbone of the architecture and they are the main field of application of diffuse optical wireless links. Additionally, specific solutions can be defined to allow the wireless interconnection of housekeeping sensors (e.g. temperature sensors), that usually provide analog signals that are multiplexed and sampled with very low refresh periods (∼0.1-1Hz). Finally, specific high data-rate (e.g. video) links may also be addressed by means of pointed links, although fiber optic systems seem to be more adequate. The following paragraphs summarize the developments already done by INTA related to this architecture.

a) Main TM/TC Buses:

MIL-STD-1553: We undertook the first optical wireless implementation of a MIL-STD-1553 bus, a natural step forward after the existing fiber-optic version MIL-STD-1773, which was already experimented in orbit [29]. This was carried-out in the framework of a ground-demonstrator for ESA (see III.A). It worked at 1Mbps in a fully diffuse configuration [30]. A transformer and a differential line driver/receiver were used to convert the 3-level 1553 signal into a TTL signal and vice-versa. Thus, the 0V (idle) and -25V levels of the 1553 signal were converted to a logic '0', and the +25V level, to '1'. A couple of envelope detectors were added, the first one applied to the signal coming from the 1553 terminal and the second one to the signal detected by the optical receiver. They were used to set the differential transceiver into the receiver or driver mode, thus managing the sense of the data traffic (conversion from electrical to optical or vice-versa).

CAN: Selected as a promising bus for diffuse optical wireless link due to its inherent Multi-Master nature. The standard does not define a specific physical layer, as long as two types of symbols are used, namely the *dominant* and *recessive* (in case of collision the dominant symbol must appear in the bus). An optical physical layer is a very adequate solution, as light is dominant over no-light. OWLS-CAN was successfully used in-orbit in the FOTON-M3 mission [31], as well as in the Venus Express OWLS Flight Technology Demonstrator [32] (III.D, III.B).

b) Low-Speed Serial Buses:

SPI: An adaptation of this serial synchronous standard to diffuse wireless was implemented at ground-demonstrator level. To convert the four signals involved (Master Output, Master Input, Clock and one Chip Select per slave) into a single optical channel, a minimum *glue-logic* was added, although it was done in a transparent manner for the final user. It carried out the following tasks: use of half-duplex transmission only, encoding of the clock into a Manchester code, and addition of an Identification Header to the packets from each different unit [30].

c) Ad-Hoc Developments for Analog Sensors:

Low-Speed Non-Addressable Master/Slave (M/S): This is the name given to a special protocol developed to allow the wireless acquisition of low-data rate housekeeping sensors. Their number can be as high as several hundreds, and they are usually wired to acquisition units. INTA has developed completely wireless battery-powered temperature and radiation sensors that transmit a packet of data after reception of a wake-up (WU) command from the acquisition unit. The rest of the time they remain in an ultra-low-power idle state, which allows for a 5-year lifetime. Time-slot allocation of sensors' responses is used to identify them.

Medium-Speed Addressable M/S: A different protocol that can coexist with the previous one was defined for medium data rate sensors or actuators, that could need a continuous communication with the acquisition unit for short periods of time. In this case, they work in a M/S configuration with direct addressing. An important power-management protocol was defined in parallel, in order to maximize the life-time for these kinds of sensors, which are also battery-powered. The units are in idle state most of the time. They wake-up periodically to allow the Master unit to interrogate them. Once a first interrogation has taken place, the Master can ask the unit to remain active during a certain period of time to perform a continuous interrogation. Thereafter, the sensor enters into an idle mode again.

All the described scenarios involve a high number of units communicating through different bus configurations. As the use of OWLS must not impose a constraint on the location or orientation of those equipments, diffuse links must be employed. In other words, no pointing capability nor LOS is assumed. Pointing strategies are never used and the optical power budget simply relies on reflection and diffusion on the internal surfaces of the S/C. Direct LOS may or may not exist for a given pair of units, depending on the mechanical design of the satellite.

C. Modulation and Multiple Access

According to the described approach (direct electrical / optical conversion), the most immediate modulation scheme would be On-Off Keying with No-Return to Zero (OOK-NRZ), unless the protocol used has an inherent coding such as Manchester in 1553. However, different considerations have been taken into account when selecting the modulation technique for each application. First, simplicity and straightforward optical conversion, as explained above. Power and bandwidth requirements, ease of isolation from lighting, bounding of duty-cycle to facilitate receiver design, and multiple access have also been taken into account [33], [34], [27]. Despite the advantages of Pulse Position Modulation (PPM) schemes, they have been discarded due to the synchronization requirements. OOK-NRZ has also been discarded due to power efficiency, non-bounded duty-cycle, and sensitivity to lighting interference for low data rates. Amongst the baseband solutions, Return-to-Zero (OOK-RZ) 0.25 to 0.5 was more generally used, given that it can be handled with very little logic and it offers advantages with regard to the aforementioned parameters. Only when an unsynchronized multiplexing/multiple access was needed beyond the possibilities of wavelength separation (see II.F), sub-carrier modulation was used, specifically a binary Amplitude Shift Keying (ASK), again to maintain simplicity and minimize optical power (only one symbol is signaled).

Regarding multiplexing and multiple access, time, frequency and wavelength separation were used in different scenarios. As already stated in II.B.c), time multiplexing was used to allocate hundreds of temperature and radiation sensors in different slots, where a Wake-Up command provided the necessary network synchronization. To avoid the need for such a synchronism, and moreover, to allow the coexistence of different buses working in parallel (according to Fig. 1), Wavelength and Frequency Division Multiple Access (WDMA , FDMA) were employed.

WDMA was mainly used to separate a main TM/TC bus from a low-speed serial bus. For example, the simultaneous operation of a CAN bus, working on 670nm, and a low-speed bus used to acquire data from different sensors, working on 950nm, is described in III.B [32]. FDMA with ASK was employed to further increase the data capacity on each wavelength, avoiding synchronization needs. A network with two different wavelengths and three different sub-carrier frequencies on one of them, was demonstrated in [30] (see III.A).

It is also important to mention that a typical medium-large S/C contains different separate cavities. This allows for the reuse of resources (time, wavelength, frequency) from cavity to cavity, in what could be termed as a special Space Division Multiple Access (SDMA). The problem of inter-cavity connections was solved in [32] by means of the so-called Secondary Optical Access Points (SOAP). These units are optical ports located in different cavities and wired to the main OBC or to a Master Optical Access Point.

Code Division (CDMA) has only been considered recently as a solution to the interconnection of hundreds of low-speed sensors, thus avoiding the network synchronization required by the presented Time Division (TDMA) solution. A demonstration with random codes was carried out by the Polythechnical University of Madrid (UPM) [35], within the project described in III.B.

D. Receiver Modules

The optical receivers are designed as standalone modules packaged in their own metal case in order to have the best EMI protection. Except for the cases in which subcarrier-modulation was used, when the demodulation capability was incorporated, the general approach was to avoid any signal processing inside those modules. They were designed on the basis of a direct optical-to-electrical conversion, just providing a digital output according to the incoming optical pulse. In this manner, they are universal receivers ready to be used in any kind of protocol within their bandwidth capability, assuming that any needed glue logic is externally added. Fig. 3 shows a block-diagram that describes the most general topology of the designed modules.

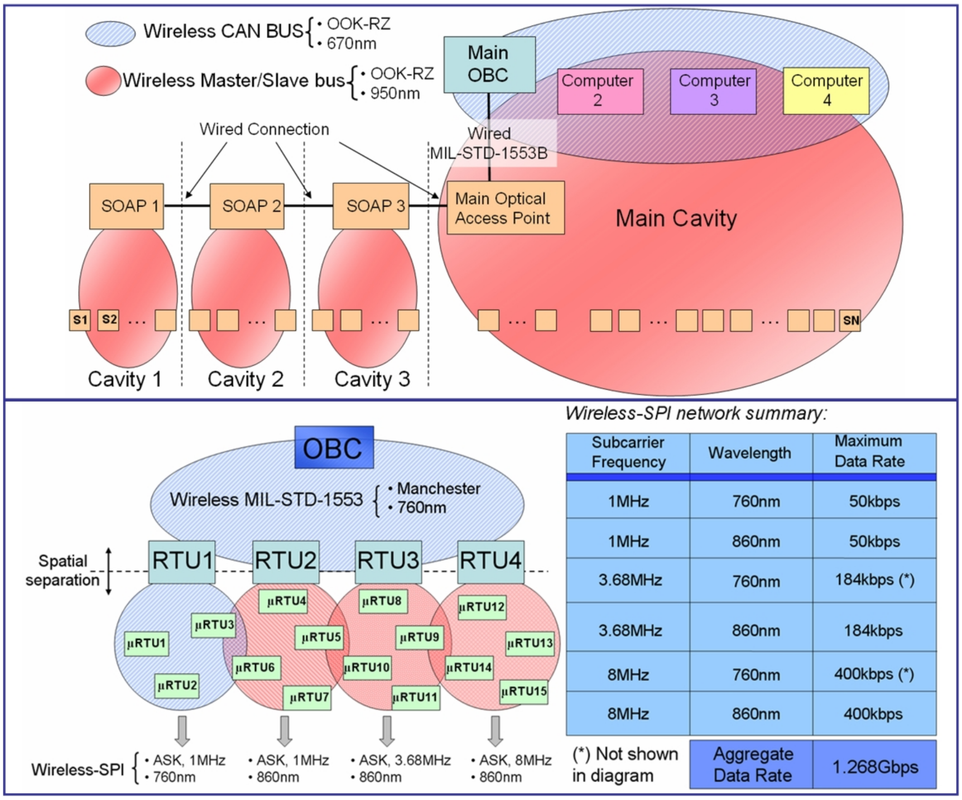
The main aspects or blocks considered in that diagram are described hereafter:

1) Blocking or cancellation of ambient-light photocurrent in the first stage to avoid its saturation [36], [37]. It must be noted that for intra-satellite applications no background light is present. However, it is present during the AIT phase. Moreover, some applications outside the S/C are also foreseen in the near future, such as links from instruments on booms.
2) To take advantage of high effective-area photodiodes (tens of mm^2), while ensuring amplifiers stability despite the big photodiodes parasitic capacitance, cascode or bootstrap schemes were used to isolate the front-end amplifier from that capacitance [37], [38], [39].
3) Dynamic range: Bi-linear [40], logarithmic or limiting amplifiers were used in almost all cases, at least in the post-amplification chain.
4) Threshold determination at decision stage. A DC-extraction was used in those cases where the duty-cycle of the incoming signal is bounded to a small margin, for example in the case of Manchester coding, thus optimizing the resulting Bit Error Rate (BER) [34]. However, for the most generic case, and especially when instantaneous (from bit to bit) changes in the received optical power must be accepted, a fixed threshold was employed. This happens in CAN buses within its arbitration field and acknowledgment bit [41]. The use of limiting amplifiers helps to deliver an almost constant-amplitude signal to the decision stage, thus facilitating the use of this fixed threshold. Fig. 4 shows the behavior of one of the modules, based on the Radiation Hardened (Rad-Hard) operational amplifier LM6172 from National Semiconductors.

Regarding the sensitivity and bandwidth of the modules, the usual achieved values are in the order of 20 nA to 200 nA for 50 kbps to 1 Mbps links, for BER$<10^{-8}$. It must be taken into account that all applications developed up to-date are intra-S/C. This means that the main source of noise is the voltage-noise inherent to the front-end amplifier [42], instead of the background-light photocurrent's shot noise, as in ground scenarios [27], [34]. To convert the given values of photocurrent into a more usual figure in W/cm^2, the effective detector area must be taken into consideration. The most widely used configuration includes one S5106 (25 mm^2, from Hamamatsu), usually coplanar with the main surface of the equipment, and four TMD-5110 (7.5 mm^2, from Vishay) located on the side surfaces. Considering an average responsivity of 0.7A/W (for 950 nm), this renders sensitivities in the range of 50 to 500 nW/cm^2. Fig. 5 shows a picture and the main characteristics of the optical receivers developed for the FOTON-M3 mission, that used a lens to increase the detector's area. As it can be seen, they are placed in a stacked configuration with vertical interconnections to reduce volume.

It is worth mentioning that for in-orbit applications currently under development (mainly for INTA's OPTOS satellite), a new stack-level has been added, which contains a programmable device that will allow some logic capabilities in the modules. It is a low-power Coolrunner CPLD from Xilinx that was tested under Total Ionizing Dose (TID) and protons [43].

Regarding the electronic components used in the receivers, the main effort carried out was the selection of adequate Operational Amplifiers (OpAmps). Alternatives are very lim-



Wireless-SPI network summary:

Subcarrier Frequency	Wavelength	Maximum Data Rate
1MHz	760nm	50kbps
1MHz	860nm	50kbps
3.68MHz	760nm	184kbps (*)
3.68MHz	860nm	184kbps
8MHz	760nm	400kbps (*)
8MHz	860nm	400kbps
(*) Not shown in diagram	Aggregate Data Rate	1.268Gbps

Fig. 2. Communication architectures implemented in two different applications (Note: SOAP=Secondary Optical Access Point; OBC=On-Board Computer; RTU=Remote Terminal Unit; Si=Slave/Sensor).

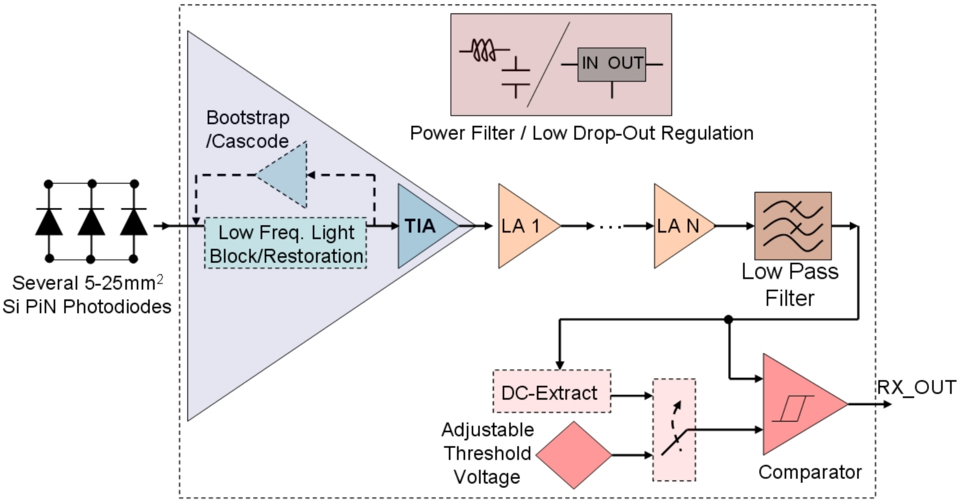


Fig. 3. General Architecture of the Receiver Modules (Note: TIA=Trans-Impedance Amplifier; LA=Limiting or Logarithmic Amplifier).

ited when Rad-Hard components are to be selected, and even more so for wide-bandwidth (BW) and single supply OpAmps. More than 20 OpAmps were considered from the first designs. Several Rad-Hard components were used, such as the aforementioned LM6172 or the AD8041 from Analog Devices. Military-grade AD829 was used in Nanosat-01 experiments, whereas commercial-grade OPA354 (Burr-Brown) was used in FOTON-M3 and is to be used in OPTOS satellite. AD829 was satisfactorily tested by JPL/NASA [44] and OPA354 was tested by INTA for TID and protons, with good results. It is a wide BW, single supply, SOT-23 packaged OpAmp.

E. Optoelectronic Components

OWLS emitters were selected from typical semiconductor sources among Light Emitting Diodes (LED) and InfraRed Emitting Diodes (IRED), Laser Diodes (LD) and VCSELS (Vertical Cavity Surface Emission Lasers). Due to “eye safety” considerations as per the Maximum Permissible Exposure (MPE) [45], and a common sense requirement of not modifying the personnel’s working conditions (wearing protective goggles) during the AIT phase, the laser based solutions were discarded. From the power efficiency point of view, a com-

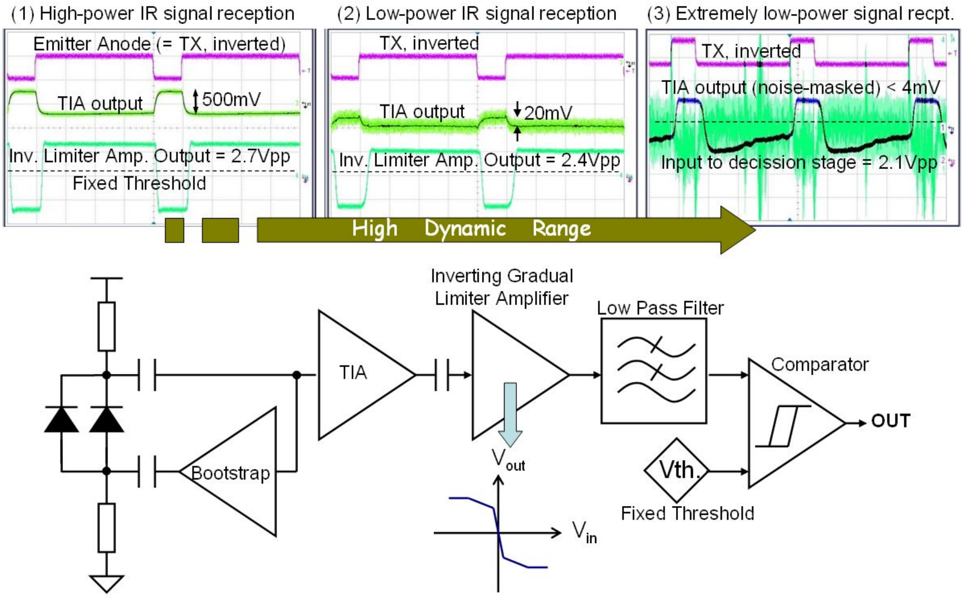
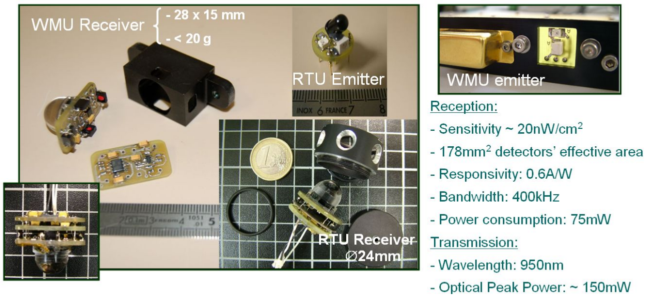


Fig. 4. Block diagram and significant signals on a receiver module based on Rad-Hard LM6172 OpAmp.



Reception:

- Sensitivity ~ 20nW/cm^2
- 178mm^2 detectors' effective area
- Responsivity: 0.6A/W
- Bandwidth: 400kHz
- Power consumption: 75mW

Transmission:

- Wavelength: 950nm
- Optical Peak Power: ~ 150mW

Fig. 5. Receiver Modules and Emitters used in FOTON-M3 mission (Note: WMU=Wireless Master Unit; RTU=Remote Terminal Unit).

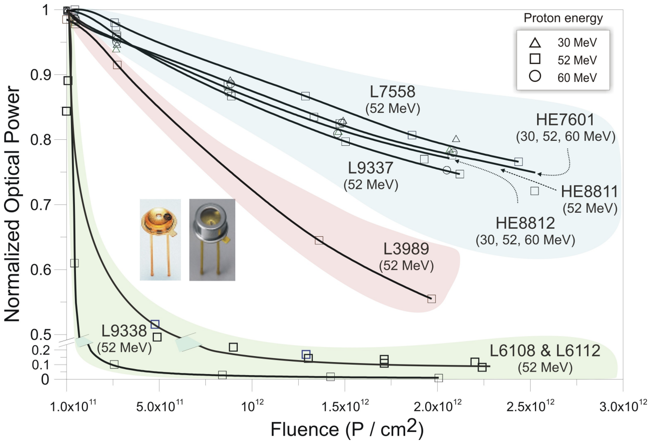


Fig. 6. Normalized optical power of several emitters (Hitachi and Hamamatsu) versus proton fluence [46].

parison between IREDs and commercial LDs in wavelengths for the first IR window (780 to 950 nm of central wavelength) was performed and showed that using IREDs instead of LDs or VCSELs is not a bad solution. A comparative study between the best 50 OSRAM IR emitters, with more than 20 LD from mid to high power (Hitachi, Mitsubishi, OSRAM, Toshiba, Sanyo) and 15 different VCSELs (Roithner, TrueLight / Honeywell) showed a power efficiency (optical to electrical, in mW/W) in the ranges of: 60-324 (VCSELs); 125-486 (LD); and 135—333 (IREDs). In this regard, there is not a significant barrier against the use of IREDs. The advantages in the components manipulation, reliability and specified temperature range (-40°C to +100°C for IREDs; -10°C to +70°C for most LDs) are enough to choose these emitters. However, their lower switching speed (up to the 100 MHz range) and non-monochromatic emission (close to 100 nm at 5%) are medium drawbacks.

Once IREDs and LEDs were selected because of their standard specifications, the resistance to radiation needed to be checked. As it is well known, optoelectronic parts are slightly affected by ionizing radiation, such as that of gamma photons. However, they are susceptible to permanent damages due to high energy particles as protons (Displace Damage Dose, DDD). Thus, systematic tests with protons (50 MeV) are usually conducted. Fluences as high as 10^{12} (p+/cm^2) are representative of a 15-year geostationary mission without any aluminium shielding protection. Our proton tests in this respect were extensively carried out on more than 40 types of commercial emitters. An example of different degradations is displayed in Fig. 6 [46].

With regard to the detectors, we took the option of using silicon ones. GaAs could be an option, because they are intrinsically more resistant to radiation. Also, Avalanche Photodiodes (APDs) could be considered. We chose p-i-n silicon photodiodes because of their good quantum efficiency, low voltage operation, low temperature dependence and high linearity. This decision was also influenced by the great number of parts and manufacturers available. Shapes, sizes, encapsulations and performances, also make them much more attractive.

As with emitters, major radiation effects in in-orbit operations are expected, due to trapped and solar protons DDD. Such effects are a decrease in efficiency and an increase of dark current. Fig. 7 shows these effects after our irradiation tests on the S5106 photodiode [47].

Finally, it is worth noting that the emitters and detectors being used offer wide Fields-Of-View (FOV). The LEDs present Full-Width Half-Maximum (FWHM) apertures in the order of 40 to 120, whereas the most commonly used photodiodes are flat ones with no additional optics. Moreover, several LEDs and photodiodes are used in a same transceiver, each one presenting a different orientation, so as to guarantee a hemispherical emission/reception profile.

F. *Optical Elements*

As stated in II.A, the use of large optical elements to act as concentrators for filters –even with integrated filters–, is not practical for OWLS. In general, optical modules as flat as possible are required for compactness and volume considerations. The problem of separating several wavelengths was addressed in order to achieve up to three wavelength channels. The conclusion was that complete wavelength isolation is almost impossible working in total diffusion with LEDs and IREDs. In Fig. 8, experimental data is presented in support of this statement. The angular response of a 40 nm FWHM bandpass filter was tested. The detector used was a 25 mm^2 silicon photodiode. The system responsivity below 5% at 0° of incidence, is $\sim$60 nm. The same measurement up to 70° of incidence shows that responsivity is increased from $\sim$60 nm to $\sim$160 nm.

After these experimental data, it seems impossible to obtain wavelength isolation for three channels with emitters in the usual range of 650 to 950 nm (still good enough for silicon responsivity and for the typical families of emitters centred in 650 nm, 750-780 nm, 820-850 nm, and 950 nm). Two wavelength channel separation in diffusion was used for emitters in 670 nm and 950 nm (280 nm apart!). Custom interferential filters, long-pass and short-pass, with a high step wavelength response for each band, were used. The results after the tests were performed showed that between 1-3 % of the light passes from one channel to the other. To achieve a better wavelength separation, we will only have the option of using a lateral baffle to avoid high angle incidence (over 40), or else just change to laser emitters and use narrower filters.

III. DEVELOPMENTS, DEMONSTRATIONS AND IN-ORBIT APPLICATIONS

A. *First Ground Demonstrators*

The first demonstrator was a set of units built in a modular way by means of three *building-blocks* manufactured inside LEGO pieces [48]. It was developed in the framework of a preliminary study called *Study on Optical Wireless Links for intra-Satellite communications (OWLS),* funded by ESA in 1999/2000. The referred blocks are: 1) Power-Supply (with batteries), 2) Control/Logic and 3) Optical-Port. By combining them, different units were manufactured: an adaptor for an OBC emulated by a laptop, a Magnetic Sensor, a Solar Sensor and two Rotating Mechanisms. All these units, located inside a methacrylate case (1.5x1x1m^3) with a reflecting ceiling, were commanded and their data gathered by means of a low-speed quasi-diffuse [27] serial link. Time multiplexing and baseband OOK signaling were used. An analog TV signal (475 MHz) was also transmitted through direct modulation of a VCSEL. A demonstration inside a NANOSAT mock-up with IrDA modules was also carried out.

After that demonstrator, a new one was manufactured in a more realistic scenario in the framework of an ESA *General Studies Program* (GSP) contract during 2003 and 2004. The mechanical environment was a 2m-high hexagonal-cylinder with several semi-isolated cavities. The implemented architecture was the one shown in Fig. 2 (bottom). As it can be seen, there is a main OBC and four RTUs communicated by means of a Wireless-MIL-STD-1553 bus. Those RTUs controlled fifteen so-called μ-RTUs. These are acquisition units that interface with different sensors and actuators (not shown in the diagram) through wired connections. The communication from each RTU to its associated μ-RTUs was done by means of a Wireless-SPI using ASK modulation. To allow asynchronous simultaneous communication in the four RTU/μ-RTUs sets, WDMA with two different wavelengths and FDMA with three carrier frequencies (1 MHz, 3.68 MHz and 8 MHz) were used. In total, there were 80 analog signals being acquired (from solar, magnetic, and temperature sensors) and 40 control signals being provided to different actuators (step-motors, lamps, and magnetic-field generators) with no wires.

To maintain low costs and simplicity, ASK signals were incoherently [49] demodulated by means of 4-element passive LC filters. The subcarrier frequencies were selected to minimize the harmonic contents of each ASK signal on the other channels' bandwidth. The performance of the receivers was characterized for a BER of 10^{-8}, the resulting sensitivities being 180 nW/cm^2, 720 nW/cm^2 and 2.5 μW/cm^2 for the three channels. Those optical power densities refer to the average optical power of the ASK subcarrier during the reception of a '1'-valued bit ('0' is not signaled). The same receiver design was used for the three subcarrier frequencies, which accounted for the different sensitivity, conditioned by the Gain/Bandwidth compromise inherent to the amplifying stages. The channel separation was found to be sufficiently good, despite the simplicity of the described solution. The most-degraded channel due to interferences was the 1MHz one, whose filter presented the worst quality factor. BER was still $\sim 10^{-7}$ for the worst interference case, i.e. when receiving a 3.68 MHz signal with the same optical power as the signal of interest. This result was good enough for the application.

B. *Venus Express Flight Technology Demonstration*

During 2007 and 2008, a fully representative demonstrator of a flight application was developed in the framework of the ESA *Technology Research Program.* The units were manufactured as *Engineering Models* fully equivalent to *Flight Models*. The architecture is shown in Fig. 2 (upper diagram) and the operational scenario was a Venus Express (VEX) full-size mock-up (1.5x1.5x1.7m^3). This S/C presents six cavities with different finishing surfaces and equipments. The four most representative ones were selected for the demonstration. Three kinds of units were developed: Data Handling Units, Sensors, and AIT-Support Units.

In the first class of units, two Master Optical Access Points (Main and Redundant), three Secondary Optical Access Points

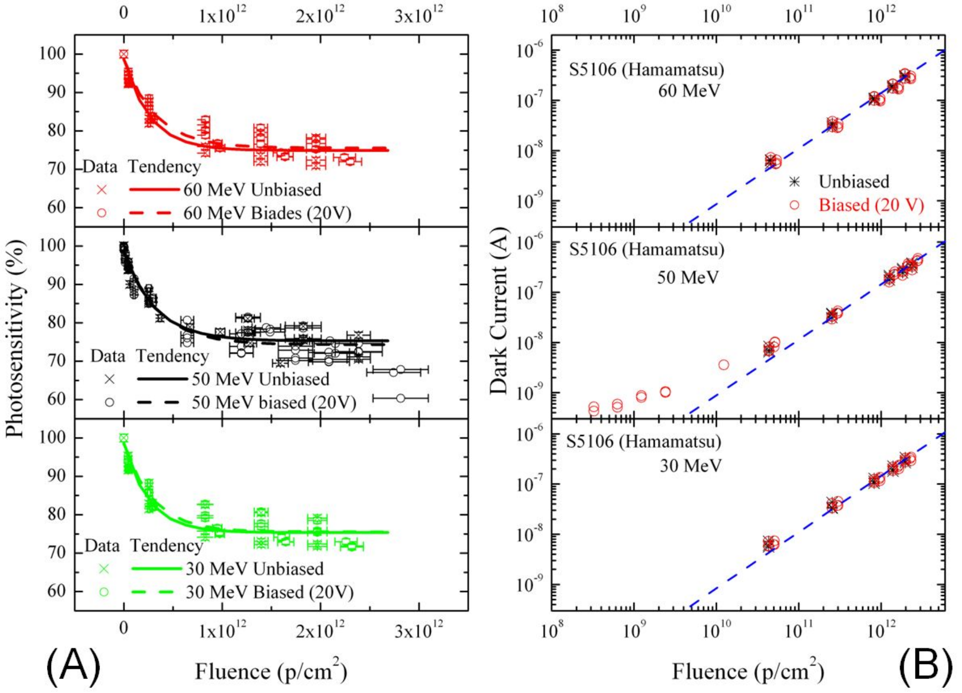


Fig. 7. Photosensitivity degradation (A) and Dark Current increase (B) of S5106 photodiode under 30, 50 and 60 MeV proton irradiation [47].

(SOAPs) and three Distributed Computers were included. The existing sensors were: one Solar Sensor, one Magnetic Sensor, one Accelerometer, sixteen Temperature Sensors and four Radiation Sensors. Finally, to support the AIT phase, a Repeater/Monitor Unit was also manufactured.

The Master units were connected to an OBC (emulated by a PC) by means of a wired MIL-STD-1553. This was done in this manner in order to allow these Master Optical Access Points to be integrated into many "standard" satellites that make use of the 1553 bus. This way, an optical access is gained without major intrusion in the architecture of the S/C. The Master units have wired extensions to the SOAPs in different cavities, thus allowing inter-cavity connection. From all those different optical ports, the sensors are commanded by means of a Wireless M/S protocol especially designed for this application (II.B.c). All the sensors are powered with Lithium batteries. To achieve an efficient power management, most of the time they are in a low-power state. They wake-up only when interrogated. Since there are different requirements regarding availability or addressability of the units, the protocol includes two parts, named Addressable and Non-Addressable, as already mentioned. For example, all the temperature sensors are sampled together according to a cycle of 1 to 10 seconds. However, the accelerometer can be sampled continuously during long periods of time at up to 30ksps.

The Distributed Computers communicate among themselves and with the OBC through a Wireless-CAN that works in a different wavelength than the previous M/S protocol. This set of units demonstrate a new concept for future S/Cs. The idea behind this is to use distributed intelligence instead of central computers, thus allowing some collaborative action in the sharing of information, by means of this Multi-Master bus. Different computers can develop complementary tasks, and at the same time they can substitute another faulty computer, reconfigure, re-distribute traffic, etc, and confer inherent redundancies and added capabilities.

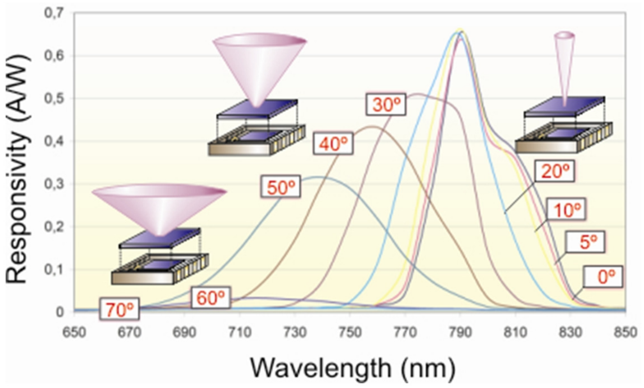


Fig. 8. Spectral response of a silicon photodiode (S5106) with a bandpass filter (centred in 805 nm) as a function of the angle of incidence.

Finally, it is important to pay attention to AIT. One advantage of OWLS is the possibility of monitoring all the signals present in the different buses in a non-intrusive way. However, a potential problem must be solved: OWLS rely on diffuse links inside closed environments, but during "on-the table" integration and with the satellite in an "open-configuration", many links may not be ensured. Active repeaters can be used to solve this problem. A unit performing both tasks (repetition and monitoring) was developed and successfully applied. Furthermore, smaller temperature sensors ($23x17x9mm^3$) were developed to be used during qualification tests (e.g. vibration), and were designed to last several weeks (using coin-cell batteries).

Regarding the optical transceivers, four main types may be distinguished, depending on the unit to which they belong:

1) Optical Access Points: they are powered from the satellite's main power bus and can transmit high optical

TABLE I

OPTICAL TRANSMISSION MAIN PARAMETERS FOR THE DIFFERENT KINDS OF UNITS INSIDE VEX DEMONSTRATOR

Unit/Network	λ (nm)	LEDs configuration	Optical Peak Power	Electrical Peak Power	Electrical Avg. Power	Data Rate and Coding
Opt. Access Point / Non-Addressable	950	4 branches 2 series LEDs each	0.5W	3.6W	<18mW	1kHz tone @ 10ms Sample rate <1Hz
Opt. Access Point / Addressable	950	Same LEDs as previous	0.5W	3.6W	<450mW	500kbps, RZ-0.5
Sensor/Non-Add.	950	2 parallel LEDs	0.1W	1.1W	<30μW	125kbps, RZ-0.25
Sensor/Add.	950	2 parallel LEDs	0.1W	1.1W	<140mW	500kbps, RZ-0.5
Distrib.Comp./CAN	670	2 series LEDs in parallel with a 3rd one	0.085W	1W	<65mW	125kbps, RZ-0.5

power. They work on 950 nm using eight OSRAM's SFH4200 LEDs and twelve photodiodes (two S5106 and ten TEMD5110). The optical peak power during the transmission of a '0' (the signaled symbol) is about 0.5W, whereas the total detectors' area is 1.25cm^2. Sensitivity is ~150 nW/cm^2.

2) Non-Addressable sensors: they are powered with 3.6V Lithium batteries providing 1.1 Ah (LS14250 from SAFT). They remain in an idle state until they receive a Wake-Up command sent by the Optical Access Points (a 1 kHz tone during 10 ms on 950 nm). Their low-bandwidth optical receiver is the only permanently-powered part of the sensor. Its detecting area is 0.15 cm^2 and the current consumption is 800 nA. Sensitivity is ~1.6 μW/cm^2.
3) Addressable sensors: These are bigger sensors that are present in a smaller quantity in a satellite. A larger battery was used (LS26500, 7.7 Ah). The receiver's detecting area is 0.55 cm^2 and they transmit ~0.1 W peak power (also on 950 nm). Sensitivity is ~300nW/cm^2.
4) Distributed computers: They use 670 nm transceivers to communicate through the wireless CAN. The transmitted power is lower and the photodiodes' responsivity is about 65% of that for 950 nm, but still the sensitivity is ~220 nW/cm^2 thanks to the reduced data-rate.

Table 1 shows the main parameters related to the optical transmission in this demonstrator. The LEDs' radiant flux for a direct current of 100 mA is 35 mW for the 950 nm ones, and 28 mW for 670 nm. All the sensors operate at 3.6 V, whereas the rest of units use 5 V. The average power was calculated taking into account the transmission duty-cycle for each case, which depends on the protocol (interrogation/response), the RZ coding and the statistical distribution of '1s' and '0s'.

The optical power density distribution inside the demonstrator, was measured in order to determine an adequate transmission power. These measurements were taken by locating LEDs in different positions of each cavity, with different axial orientations, and measuring the power received in several positions and orientations of a reference detector. Fig. 9 shows one of these characterizations for three cavities of the VEX mock-up. A simulation tool was also developed by EADS-ASTRIUM, with the support of ULPGC for ray tracing algorithms [50].

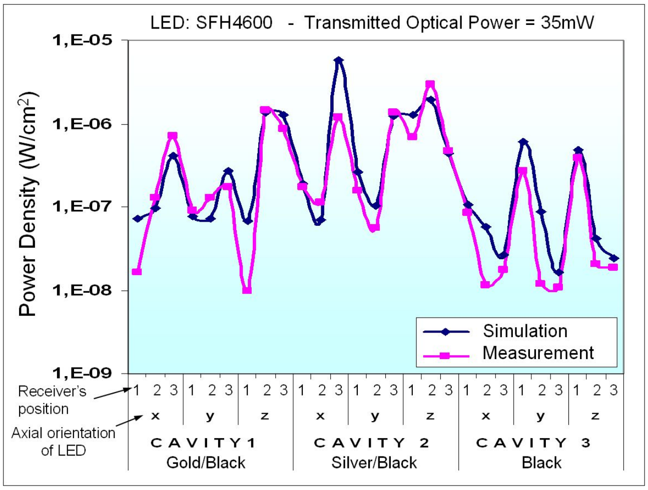


Fig. 9. Characterization of the optical power distribution in different cavities of the VEX demonstrator.

TABLE II

MAIN BER MEASUREMENTS WITHIN THE VEX DEMONSTRATOR

Network	Main Cavity	Cavity 1	Cavity 2	Cavity 3
Non-Addressable	Not measured	3.6x10^{-7}	1.87x10^{-7}	3.38x10^{-6}
Addressable	Not measured	4x10^{-8}	2x10^{-8}	4.2x10^{-8}
CAN	1.86x10^{-5}	Not applicable	Not applicable	Not applicable

Table 2 summarizes the measured BER of the different networks in this demonstrator, averaged for all the units present in each network and cavity (refer to Fig. 2):

Note that thanks to the error detection of the CAN bus, a degraded BER can be accepted with a minor penalty in terms of packet repetition. A BER ~10^{-5} entails (statistically) 1 repetition out of 925 CAN frames, assuming a maximum length of 108 bits/frame, i.e. an overhead of 0.11%.

C. *NANOSAT-01:The First In-Orbit Experience of OWLS*

NANOSAT-01 is the name of a small satellite (~20kg) developed and manufactured by INTA, and launched in December 2004 from French Guyana [51]. A couple of OWLS experiments were put on-board [52] with a two-fold purpose: to perform an in-orbit demonstration of a wireless application, and characterize some aspects related to the behavior of OWLS in Space.

Fig. 10. A comparative view of the different ground-demonstration scenarios

The first experiment is a redundant wireless link from a 3-axis Magnetometer to the OBC. Wired connection also exists, in such a way that data can then be compared. Besides its functional application [53], the intention was to measure the occurrence of Single Event Transients (SETs) in the optical detectors mainly due to protons incidence.

The experiment performs a voltage-to-frequency (V/F) conversion of the magnetic field measurement and transmits trains of optical pulses in fixed time-intervals, the number of pulses being proportional to the value of the signal. An additional channel was added, which theoretically sends zero pulses. Thus, all pulses appearing when measuring that channel are associated to particle incidences on the detector, the main source of errors of in-orbit optical links [28], [54], [55]. The receiver being used presents a sensitivity of 700nW/cm^2 with 25mm^2 of photodiode area, and 1.5MHz BW. The emitter's optical peak power is 15 mW. The in-orbit data show that the only area where the effect of SETs is really important is the South Atlantic Anomaly (SAA), as expected. There, the measured BER is in the order of 10^{-6}. Fig. 11 shows the location of transients detected during the year 2008.

The second OWLS experiment performs a closed-loop link in an SPI bus on the OBC. Data is sent from optical emitters towards the walls of the satellite, and the diffused light is collected by the receiver. Then the OBC performs a comparison of transmitted and received data to calculate BER. In this case, ASK is used with a 4 MHz sub-carrier frequency. An interfering channel was added at a different frequency to test FDMA capability. Both the on/off status of the interference and the data rate (from 100 kbps to 1 Mbps) can be commanded from ground.

Besides this, a means of estimating the in-orbit permanent degradation of the emitters and detectors affecting the optical power-budget was foreseen. It is based on the variations of BER for a margin of data rates (above 300 kbps) for which an intentional Inter-Symbol Interference (ISI) was introduced. This ISI is very dependant on rise and fall times on the receiver's amplification chain, and those are dependant on the optical power (LEDs' efficiency) and photodiode's responsivity. BER for data rate up to 200 kbps remains by far below 10^{-8} since the launch, but this result is normal given that a high optical power was ensured at the receiver. This was done in order to avoid noise-induced errors, and to try to measure the power budget degradation through the referred ISI. Also, the ASK demodulation scheme helps to filter the SETs. A precise laboratory test is currently being set-up to reproduce the in-orbit measurements to try to find the exact percentage of degradation (from higher data rate BER results), as preliminary data show a minor effect.

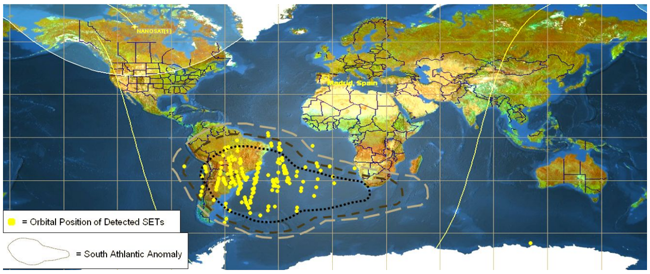


Fig. 11. Single Event Transients measured by one of the OWLS experiments on-board Nanosat-01 in 2008.

The satellite and all the experiments continue to be fully operative after 4 years of mission.

D. *FOTON-M3: A Practical Flight Application*

FOTON is a ~2m-diameter spherical Russian capsule used for scientific experimentation in micro-gravity. Typical missions last two to four weeks in-orbit, and subsequently re-entry is forced and the whole payload is recovered. The FOTON-M3 mission was launch from Baikonur in September 2007 and carried out a two-week mission.

The demand from the scientific community for this kind of flight opportunities is so high that FOTON capsules are completely full of payloads. Harnessing is extremely complex and volume and weight consuming. There are several hundreds of wire-bundles and connectors, about one half of them being for data transmission. The present configuration with regard to the scientific equipment includes a central *Telesupport Unit* that controls all the payloads, stores data and sends some parts of these data to ground. Connections from payloads to that unit are done by means of dedicated point-to-point low-speed (19.2 kbps) serial ports. The result is an overcrowded and complex S/C that requires a very careful and time-consuming AIT.

Due to the aforementioned reasons, ESA proposed the inclusion of an OWLS experiment inside the M3 mission. The idea was to test the feasibility of optical wireless links in that scenario, in order to evaluate the possibility of a re-design of the inner data communications architecture for future capsules. One important aspect that must be kept on mind is that, despite the reduced volume of S/C's, optical wireless links may be very complex due to the high *fill-factor* (volume of equipments / total inner volume) and the surface finishes of the units.

Two kinds of units were developed, a *Wireless Master Unit* and two RTUs. The first one was integrated inside the *Telesupport* computer, and the RTUs were located in different positions of the capsule, attached to other existing payloads. A Wireless-CAN bus was introduced, making use of 950 nm emitters and the optical receivers described in Fig. 5. One of the remote units was located in a relatively favorable position, not far from the Master, although with no LOS. The other one

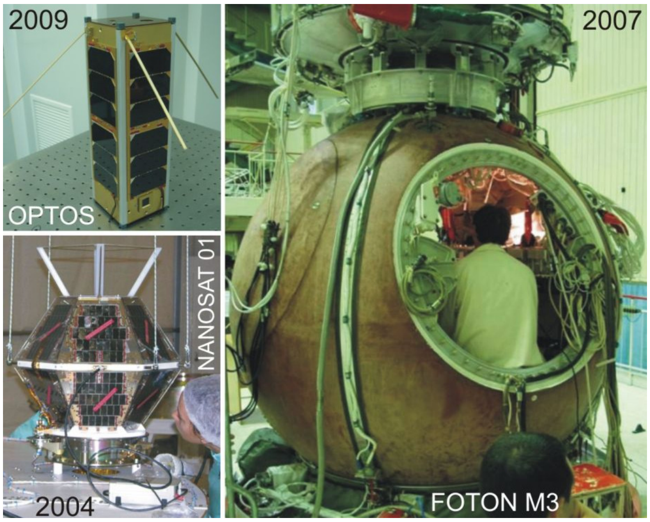


Fig. 12. OPTOS, NANOSAT and FOTON-M3 – Three in-orbit experiences of OWLS.

was located in an extremely shadowed position far away from it, and also with no LOS. Used data rate was low, 62.5kbps, in order to maximize the receivers' sensitivity.

Different data were sent from the terminals to the Master unit, including housekeeping information, such as temperature and battery status (remote units were battery-powered), and also long fixed patterns for BER measurements. Thanks to the CAN error detection and repetition, the final effective BER was 0 for both RTU's, whereas the estimated uncorrected link BER was found to be better than 10^{-7} for the first RTU and better than 10^{-4} for the second one. Taking into account CAN properties, even that worst value only entails 1-2% of overhead traffic due to packet repetitions, which is very acceptable for a final link virtually error-free. Active repeaters were proposed in order to ensure the link quality in all capsule positions in future, if needed. All the equipments were recovered after re-entry and remain perfectly functional.

E. OPTOS: The All-Optical Satellite

As a final step in the OWLS development, a demonstration satellite called OPTOS will be launched by INTA at the beginning of 2010. It makes intensive use of optical wireless links. Moreover, there are no data wires and all the units are communicated through a Wireless-CAN, working on 950nm at 125kbps. Given that it is a satellite conceived as an in-orbit test bed of different technologies and Microsystems, it is based on the triple configuration of the popular Cube-Sat developed in 1999 by CalPoly and Stanford University [56]. In spite of the reduced volume, there are two main relevant aspects with regard to optical wireless links.

On the one hand, the optical communication modules are being manufactured as a three-level stack of small PCB's of 23x12mm^2 packaged in their own metal case (25x14x14mm^3). They incorporate through-hole pins for connections, thus resulting in a complete component from the user point of view; this can be understood as a precursor of a future ASIC. As stated in II.D, some programmable logic has been included. A reduced CAN IP-core has been introduced in it.

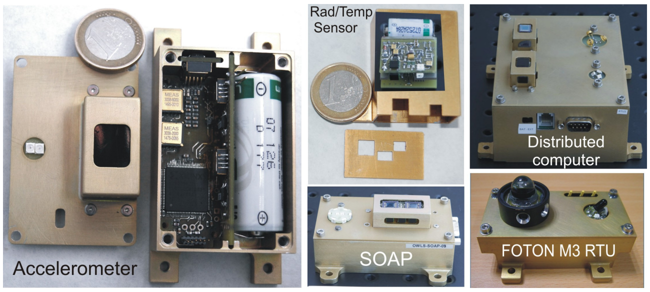


Fig. 13. Some of the OWLS flight units developed for different applications.

On the other hand, the Data Handling architecture is a step-forward towards the already mentioned possibility of distributed intelligence inside S/C's. All the subsystems and payloads incorporate a small computer also based in low-size, low-power, programmable logic. It acts as a controller of the associated unit (a sensor, an experiment, an actuator). All those computers (nine in total) perform the whole Data Handling and Control of the satellite, and communicate among themselves through the Wireless-CAN. Some tasks are shared, such as time distribution, housekeeping telemetry acquisition, or time-tagged telecommand execution. OPTOS will be the most complete in-orbit demonstration of an optical wireless S/C.

Fig. 12 and Fig. 13 show some of the Flight Units described above, as well as the referred S/Cs.

IV. FUTURE WORK

Miniaturization appears to be the key factor to attain standardization of OWLS as a firm solution for future Space Systems. The next step is to miniaturize the front-end electronics and integrate additional programmable logic. In other words, to achieve the development of mixed signal ASICs. This has been initiated in the framework of the MetNet Precursor Mission, a Finnish-Russian-Spanish mission that will launch a meteorological lander to Mars at the end of 2011. In this mission, an optical link is needed to communicate an instrument located on top of a boom with no space for wires. It is a clear example of how OWLS offers a real solution to an existing connectivity problem.

With miniaturized optical receivers (emitters are already small enough), other photonic concepts will be achieved. Our final target is to manufacture IR directional antennae, where configurable directionality in detection and emission will guarantee optical interconnection in almost any situation.

V. CONCLUSION

The rationale for the application of Optical Wireless Links to spacecrafts has been presented here, together with its advantages, constraints and the philosophy adopted by INTA during the last ten years to introduce OWLS in Space, always bearing in mind the stressing conditions of the space environment, as well as the Product Assurance requirements of Space programs.

Several network topologies were implemented and different communication standards adapted to OWLS. This includes MIL-STD-1553, CAN, SPI, and some ad-hoc developments for analog sensors. Besides, a variety of modulation and multiple access techniques were used (Manchester, OK-RZ, ASK; FDMA, WDMA, TDMA).

An important effort was done with regard to optoelectronic and electronic components qualification for Space. Some results of degradation of emitters and detectors have been presented, as well as the main considerations for their selection. Different optical modules were developed, which made use of those components. All of them are designed to be used in completely diffuse links, with hemispherical FOV and sensitivities in the range of 50 to 500 nW/cm^2, depending on the data rate.

Several demonstrators were developed with different goals and scenarios. Optical power distribution measurements and simulation for the intended environment were identified as helpful tools for the designers of the OWLS system. A complete set of units was developed, including Optical Access Points, sensors and AIT tools.

Finally, the main results of the in-orbit experiments have been described. Measurement of SET-induced errors in optical wireless links was performed on-board Nanosat-01, whereas FOTON-M3 points to the feasibility of using OWLS even in extremely crowded spacecrafts.

Future activities have been outlined, focused on the development of ASICs that would help in manufacturing directional IR antennae. Also, up-coming flight opportunities have been presented, in which the OPTOS satellite will be a further step in the direction of new architectures based on wireless communications.

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