An In Situ Impact Sensor on board a UNISAT microsatellite for monitoring the microparticles environment

F. Graziani, M. Porfilio, F. Santoni
Scuola di Ingegneria Aerospaziale,
Università degli Studi di Roma “La Sapienza”, Roma, Italy

Abstract

The Group of Astrodynamics of the University of Rome “La Sapienza” (GAUSS) has developed a low-cost In Situ Impact Sensor (ISIS) for detecting impacts from natural and artificial microparticles. The system is based on piezoelectric patches. When a particle impacts a patch, a piezoelectric voltage is generated depending on the particle momentum. The system electronics processes the signal, stores the data and transmit them to the ground station when requested. ISIS will fly on board a future mission of the UNISAT programme, in the frame of which 3 microsatellite have been already realised.

Introduction

The orbit microparticle environment has been investigated by NASA and ESA, see for instance [1], [4], [6] and [8], since several years, in order to model the natural and artificial micrometric space debris fluxes threatening active satellites and lowering some spacecraft subsystems performances, see for instance [11]. Both active, [3] and [8] and passive, [1], [4], [6], [8] and [9], impact systems have been used for fluxes assessment. Nevertheless, the microparticle environment varies very quickly due to orbit perturbations, so that up to date information is continuously required from any orbital region. Furthermore, the employed systems are typically complex (if active) or they need to be retrieved (if passive). In both cases, the mission is quite expensive.

In [7] several kinds of systems are reviewed, all suitable for monitoring the submillimetric debris environment from small satellites. This idea is *obviously* pursued also by the GAUSS team (Gruppo di Astrodinamica dell’Università degli Studi di Roma “La Sapienza”, Group of Astrodynamics of the University of Rome “La Sapienza”), as it brings on both a microsatellite programme (UNISAT) and a space debris programme.

Since some years, GAUSS has studied the feasibility of using piezoelectric impact sensors for microparticle detection in Earth orbit, [10] and [11]. More recently, the studies and the first prototypes leaded to the realisation of ISIS (In Situ Impact Sensor, [12]), a system based on off-the-shelf piezoelectric patches to be put on the external surface of a spacecraft.

Presently, ISIS is undergoing a number of important modifications, which should yield a second release of the system, which, from now on, we will call "ISIS 2". ISIS 2 should fly on board one of the next UNISAT microsatellites.

The UNISAT programme

In the nineties the Group of Astrodynamics started the UNISAT (UNIversity SAT-ellite) programme, [5] for "hands-on" education of students of the Scuola di Ingegneria Aerospaziale (School of Aerospace Engineering) of the University of Rome "La Sapienza". In the frame of this programme the following outcomes were achieved:

- the SPIV satellite telemetry station was built. The ground station is located in the very centre of Rome, close to the San Pietro In Vincoli church, from which it takes the name;
- the UNISAT microsatellite, the first GAUSS spacecraft; it was launched from Baikonour on September 2000. With this satellite, the Scuola di Ingegneria Aerospaziale came back to space after the pioneering era of the "San Marco" satellites;
- the UNISAT-2 microsatellite, launched from Baikonour on December 2002;
- the UNISAT-3 microsatellite, assembled on the launch vehicle in Baikonour on June 2004; its launch is scheduled for June 29th 2004.
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The next satellite, UNISAT-4, should be launched on October 2005.

The main "payload" of the microsatellites designed and realised by GAUSS, is space education; tens of students were involved in the UNISAT programme while attending to their theses. On the other hand, as the budget for these university satellites is quite small, GAUSS was forced to use non-space qualified materials. As a consequence, each satellite brings a number of technological payloads that are terrestrial components to be tested in the space environment. Of course, this does not exclude that scientific payloads may be put on-board. For instance, UNISAT-3 and its follower will test some sensors which could be used to detect the small variations of Earth magnetic field which seem to happen before earthquakes.

UNISAT and ISIS

As the UNISAT microsatellites were developed primarily for research and educational purposes, GAUSS did not invest so much on the standardisation of electronic subsystems. This was a problem from ISIS standpoint, as a key point in any space subsystem, with an autonomous processor or controller, is how may it communicate with the main satellite computer and, through this, with the ground.

From this point of view, the UNISAT-3 mission is a very important technological mission even for ISIS project: in fact, the satellite computer is a Rabbit microprocessor which is presently the best candidate as the ISIS 2 brain, due to its easiness of communicating through a serial port.

ISIS hardware overview

ISIS consists of a number of couples of piezoelectric sensors, analog boards (one for each couple) and a digital board hosting a dedicated microcontroller.

The piezoelectric elements can measure acoustic waves propagating through the satellite structure after an impact of sufficient momentum. Moreover, other effects might be measured in case of direct impacts on the sensors surface (for instance, some piezoelectric materials also show a pyroelectric behaviour). This is why we thought to install the patches on the external surface of a satellite. Hypervelocity impact tests are needed to assess the sensors response to both kinds of impact.

The patches of the same couple should be placed as close as possible to each other, so being exposed to the same environment and disturbances. Hence, the signals from the two sensors can be subtracted (via software) in order to most easily detect small particles which eventually impacted one of the patches' surface.

Figure 1 shows the ISIS block diagram (with reference to the first release configuration, based on 4 couples of patches), with the sensors, one of the analog boards and the digital board.

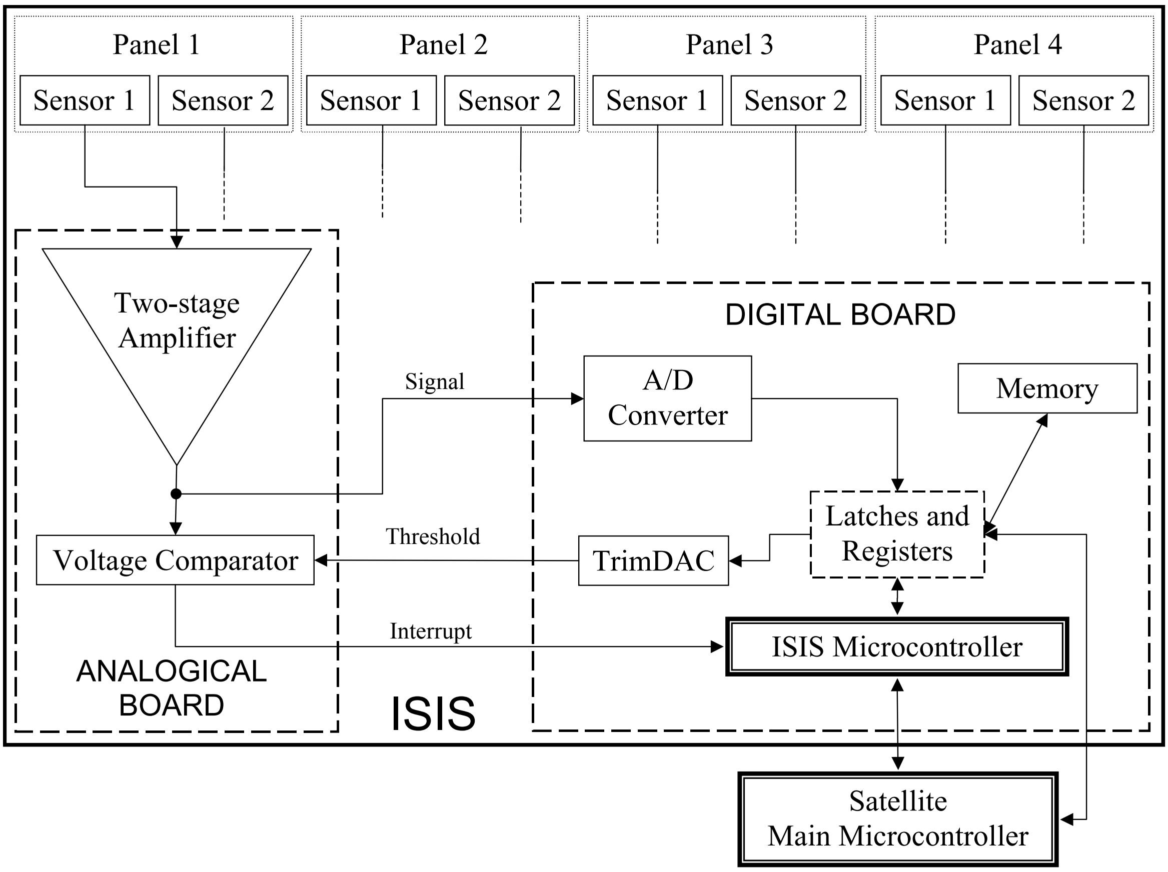

Figure 1: ISIS block diagram.

The analog boards

The analog boards are devoted to the amplification of the sensors signals. They are located inside the satellite, but they must be as close as possible to the sensors. Each board gets as input the signals from a couple of piezoelectric patches; these signals are separately dealt with. A two-stage amplification is performed: the first one is carried out by a very low input operational amplifier, while the second stage is managed by a more usual device. Each amplified signal (see Figure 1) is both sent to the digital board and additionally handled so as to be a suitable input for a voltage comparator. This component also receives, from the digital board, a threshold to compare the signal with. Note that two different thresholds can be imposed to the two sensors. When a threshold is exceeded, an interrupt signal is sent to the digital board.

ISIS first release digital board

In the first release of ISIS, the system "brain" is a 8051 family microcontroller, which can manage a 128 kilobyte external random access memory (RAM). The size of the memory is quite small due to the fact that, so far, the UNISAT microsatellites can only transmit a limited amount of data. Of course, the available memory could be very usefully increased, should ISIS be placed on board another spacecraft, capable of wider band transmission.

Since the microcontroller and the RAM are only devoted to ISIS, the system is quite independent on the peculiar spacecraft electronic architecture. Of course ISIS must interface with the main satellite computer both to receive commands from the ground station and to transmit the collected data, so a certain amount of software must be programmed on the main spacecraft computer.

An 8 channels, 12 bit analog to digital converter (ADC) is devoted to sampling the amplified signals from the 8 sensors (see Figure 1), while an 8 channels TrimDAC (trimming digital to analog converter) is assigned to generating the voltage thresholds.

ISIS first release software

The software must both manage the hardware functioning and process the information received from the sensors in order to download to the ground a quantity of data as small as possible.

The software has been written in a "hardware oriented" non-standard C language. Therefore, the software will undergo a revision once the hardware of ISIS 2 will be ready.

Hardware management

As an interrupt is received from one of the analog boards, the 2 output from that board are controlled in order to discriminate which sensor exceeded the threshold. After that, a number of preliminary data are stored into memory: the number of the sensor whose threshold was exceeded, the value of its first available sample, the epoch of the threshold surpassing, the value of the first available sample from the other sensor on the same satellite face. Moreover, an impact counter array (one scalar variable for each piezoelectric element) is updated. After that, the sampled signal from the "exceeding" sensor and from the other on the same face are buffered into memory and stored for a successive analysis, which is performed (if required, see hereafter) by the algorithm described in the next sub-section. The time length of the buffering is specified by the user, compatibly with the limits of the available memory.

As the main goal of the first test flight would mainly be analysing noise and disturbances the system is submitted to, it is very useful to have another way of recording: starting from an interrupt or even from any time decided by the user, the signals from a couple of patches are stored not to be analysed on board, but on the ground. The successful transmission of the whole signal could require more than one passage on the telemetry ground station (for a narrow band UNISAT satellite), hence such a way of functioning can not be often employed.

When the memory is completely filled with data, ISIS must switch its operating mode to "low memory consumption": just the dust counter has to be updated. This switching is imposed automatically by the system, but can also be selected manually by a command from the ground. Should the memory allocated for the dust counter be full too (this is the case when a too low threshold is imposed), the counter has not to be incremented anymore, for avoiding unpredictable results, and its limit value must be frozen until a deletion command occurs.

The memory is completely available again when an erasure command is received from the ground.

Data handling

Once an interrupt has been received, some preliminary data are stored in memory and the dust counter array is updated. The signals from the sensors located on the face where a threshold was exceeded are also temporarily stored into memory for a certain extent of time. The following analysis allows to extract a small number of significant data to be transmitted to the ground. This processing is carried on for both the signal exceeding the threshold and the difference between this signal and that from the other patch of the same couple.

The algorithm aims to detect the signal's 10 highest "decreasing" maxima and 10 lowest "increasing" minima, and store their values and the relevant epochs. With the words between quotation marks we mean that we are looking for the highest maximum (first stored information) followed by a relative maximum higher than any other following but lower than the previous one, and so on. The same is valid for the minima. Selecting decreasing maxima (and increasing minima) allows to eliminate relative extrema which are due to noise, since we expect to have a damped oscillation after the impact. Should a maximum be detected which is greater than a number of previously stored maxima, the lower maxima are deleted while the search goes on.

The described algorithm only deletes a part of the disturbances contribution, since it definitely may reject some good (i.e. signal) points. Moreover, in case of low signal to noise ratios, the signal processing might result in not collecting a decreasing sequence of 10 relative maxima and/or an increasing one of 10 minima. Despite this weakness, the great advantage of the algorithm is that it is very simple and suitable to be run in orbit. Even in presence of moderate noise, a simulation reported in [12] shows that, not only the damping characteristic, but even the frequency of the signal can be inferred from the stored information.

After data analysis, the number of significant values to be transmitted (excluding the few preliminary information) is 80: 20 extreme points for the signal exceeding the threshold, 20 for the differential signal and 40 for the respective epochs.

Towards ISIS 2

As we said, ISIS project is presently undergoing a redesign phase. The main problems to face are:

1. selection of a new reliable and versatile microprocessor, capable of easily communicating with other processors; as we said, a possible candidate is going to be tested on-board UNISAT-3;
2. development and test of the new digital electronics around the new processor;
3. development of the software for managing the communications (data and commands) with the main satellite computer;
4. analog electronics revision for interfacing it with the new digital electronics;
5. adaptation of both the “hardware management” and “data handling” software to the new digital hardware;
6. sensitivity test of the piezoelectric transducers and possible selection of off-the-shelf more sensitive devices.

Once ISIS 2 is assembled, it would be useful to execute some hypervelocity impact tests. After this, the system will be ready to experience its first flight on-board a UNISAT microsatellite.

On-orbit debris environment

The system will be useful only if capable of detecting impacts from sub-millimetric particles. Figure 2 shows a MASTER 2001, [2], forecast (for the year 2004) of the flux of sub-millimetric meteoroids, man-made debris and their sum on a tumbling surface orbiting in a circular, 650 km high, 64.5° inclined orbit. The flux is cumulative, i.e. the information on the y axis is the flux from particles greater than the dimension on the x axis. According to this model, in one year of orbital lifetime, on a square decimetre we should have about 17-18 impacts with particles greater than 1 μm, 4-5 with objects greater than 10 μm while we should have a probability of about 10% of a single impact with a particle larger than 100 μm. From these predictions we deduce that the system would provide useful results only if it could detect 10 μm debris *impacting on the whole satellite surface* or 1 μm debris *directly impacting on the sensors*. In the latter case, the number of sensors should be high enough to cover a surface of the order of a square decimetre.

The required sensitivity is quite challenging even for piezoelectric devices: the momentum transferred by a microparticle impact is extremely small if compared with the phenomena we usually deal with in every day life. For instance, the momentum of a 1 μm aluminium sphere whose velocity is 10 km/s, is only $1.4 \cdot 10^{-9}$ N·s (this is, obviously, the same momentum of a 1 mm sphere at a velocity of just 10 μm/s!).

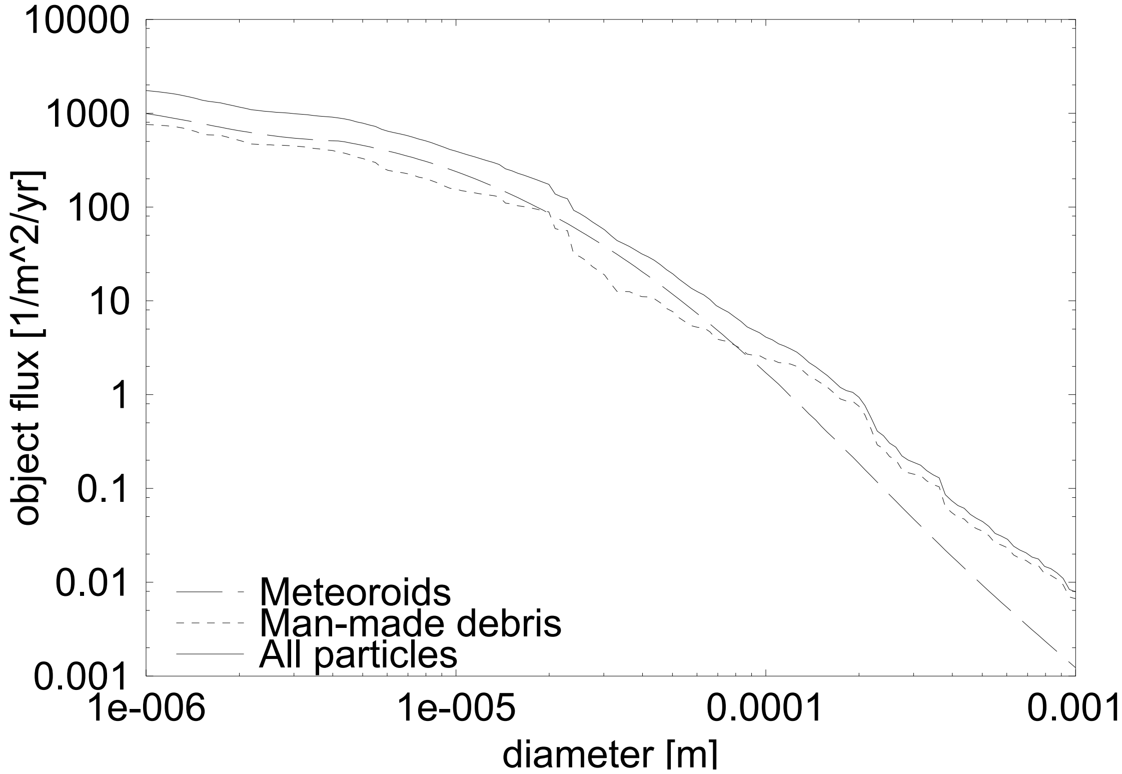

Figure 2: Cumulative flux of sub-millimetric particles on a tumbling surface in a circular, 650 km high, 64.5° inclined orbit.

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