THE PICASSO MISSION

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ABSTRACT

PICASSO is a joint project led by the Belgian Institute for Space Aeronomy (BISA) in collaboration with the Royal Observatory of Belgium (ROB). It aims at building and operating a scientific triple-unit CubeSat. With a payload composed of three scientific instruments, it will contribute to the determination of the ozone distribution in the stratosphere, the temperature profile up to the mesosphere, the electron density in the ionosphere and the Earth Radiative Budget (ERB). PICASSO is foreseen to take place aboard the QB50 precursor flight.

I INTRODUCTION

With the emergence of industrial providers offering both components off-the-shelf and services related to the design, the assembly, the launch and the operation of CubeSats (and, more generally, of nano- and pico-satellites), scientists have now the possibility to design and to carry out spaceborne experiments in a time frame and at a cost much smaller than those offered by traditional satellite platforms.

Anticipating the fact that sensor miniaturisation and tiny satellites will play an ever-increasing role in remote sensing and in situ measurements of the atmosphere of the Earth and of other celestial bodies, PICASSO has three strategic objectives:

1. To perform true science within a scope compatible with the technological constraints and current limitations of CubeSat technology;
2. To anticipate the future of remote sensing and in situ measurements, for Earth and other planets, through miniaturization;
3. To demonstrate that tiny satellites can achieve a very high ratio of "science data versus cost".

PICASSO's schedule is compatible with the QB50 precursor flight [1], which is currently planned in the late 2013. This flight aims at a polar orbit at 500 km, thus enabling a mission with a nominal lifetime of about two years. In addition, with an inclination of 79°, the coverage of the atmosphere will be almost complete.

The paper is organised as follows. Section II gives an overview of the mission and provides early elements of the spacecraft (S/C) design. Its payload instruments are presented in sections III to V. We conclude in section VI.

II MISSION OVERVIEW

As seen above, PICASSO's goals are to build and to operate a triple-unit CubeSat in order to demonstrate that such small and low-cost satellites are valuable for the atmospheric and space sciences. To widen the relevance of the demonstration, PICASSO will embark three independent scientific experiments:

1. VISION, a visible and near-infrared hyper-spectral Fabry-Perot imager (see §III),
2. mNLP, a multi-needle Langmuir probe (see §IV), and
3. μBOS, a micro-bolometer oscillation system (see §V).

The development and operation of the first two instruments and of the S/C bus are BISA's responsibilities; the third instrument is managed by ROB.

BISA and ROB are scientific institutes, not technological ones. And even if both display a sound experience in the development of satellite experiments, it is also their first CubeSat project. Therefore, seen the extremely short time available to prepare the mission, BISA has opted for commercial components off-the-shelf (COTS) when available for VISION, mNLP and the S/C bus.

In practice, BISA will delegate the realisation of VISION and mNLP to two technical partners. Currently, contacts have been established with the Technical Centre of Finland (VTT) for a preliminary design study of VISION. VTT is indeed specialised in miniaturised Fabry-Perot spectral camera systems and is currently working on a similar instrument for the Aalto-1 CubeSat mission.

Concerning mNLP, BISA is collaborating with Prof. Moen's team of Oslo University (UiO) who has built a multi-needle Langmuir probe to fly aboard sounding rockets. That team has also been entrusted with the development of a similar mNLP instrument for one of the common QB50 payload sets. Flying the mNLP aboard PICASSO prior to the main QB50 flight is thus both an opportunity for BISA and UiO.

On its side, ROB will fully develop the μBOS instrument in-house, capitalising on the experience gained with the BOS experiment aboard PICARD.

For the sake of efficiency and risk reduction, BISA and ROB decided to entrust a CubeSat Industrial Partner (CSIP) with the development and the tests of the PICASSO platform from readily available commercial-of-the-shelf (COTS) components. That partner will also be in charge of integrating the instruments and preparing the mission. Optionally, it could be asked to operate the mission too.

II.1 Structure

First technical investigations have shown that the experiment requirements are in the range of the capabilities offered by CubeSat technology available today.

For the sake of illustration, Figure 1 displays one possible configuration for PICASSO. It is a triple unit equipped with four deployable solar panels always facing the Sun. Extra body-mounted panels ensure the powering of the S/C in case of off-nominal orientation. The payload is located in the cube facing the Sun.

VISION's aperture and the solar-pointing μBOS sensor are clearly visible on the Sun-illuminated face. A Langmuir probe is found at the extremity of each solar panel (they are barely visible on Figure 1; see the solar panel magnification in Figure 2 for a clearer view). There is also a μBOS sensor on each other face, but these are not visible from the chosen perspective.

II.2 Attitude Determination and Control Subsystem (ADCS)

The major constraint for the ADCS comes from the VISION experiment as the Sun must stay in the imager field of view (FoV) during the whole duration of a spatial sunrise or sunset, i.e. about 2 minutes. With a nominal FoV of 2.5°x2.5° and a solar angular width of 0.5°, the pointing error must be less than 1°. In addition, a precise knowledge of the attitude (a few tenths of a degree) is required to determine the apparent heightening of the Sun due to atmospheric diffraction.

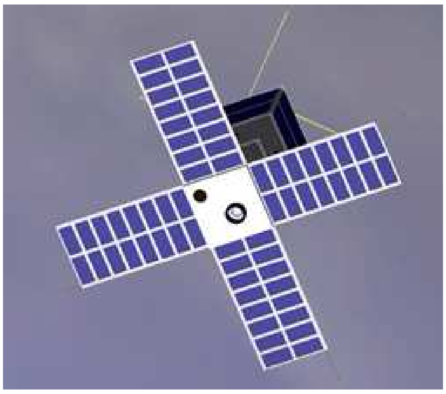


Figure 1: PICASSO early design

In addition, the instrument must stay out of direct sunlight when not taking snapshots in order to avoid an early ageing of the optical elements. This is achieved by rotating the S/C by a few degrees (5 to 10°) after sunrise in one direction and before sunset in the other direction. These requirements can be reached with an ADCS that includes dynamical inertial wheels and accurate Sun sensors.

II.3 Electrical Power Subsystem (EPS)

The electrical power is provided by solar cells mounted on deployable panels. Figure 1 shows four panels 2U-long being deployed at one extremity of the S/C. The determination of the number of solar panels and the sizing of the battery will be part of the mission design subcontracted to the CSIP.

Figure 2 shows one m-NLP probe at the free end of a panel. Positioning the probes there removes the need for a dedicated deployment system for the probes.

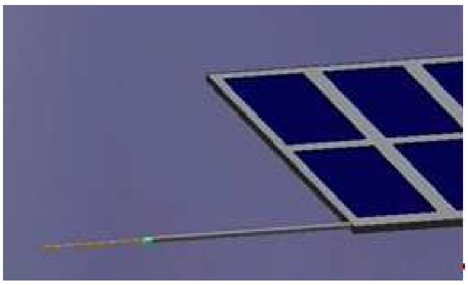


Figure 2: mNLP probe mounted at the extremity of a solar panel

II.4 Onboard Computer (OBC), Onboard Data Handling (OBDH)

The OBC controls all the functions of the S/C bus and issues commands to the payload. The CSIP will be in charge of developing the mission specific software. On the side of the experiments, mNLP and μBOS come with native data processing capabilities embedded.

The processing of the VISION spectral snapshots will be left to a generic data handling unit. Depending on the imager resolution, VISION will generate between 64 and 256 GB of raw data on a daily basis. Fortunately, as the Sun image takes only a 25th of the FoV, that amount of data can easily and quickly be reduced to less than 10 GB a day. But this amount of data is still too large to be downlinked, so the snapshots will be processed onboard and their content will be reduced to meaningful numbers only. At the end of the process, the daily production of data is estimated to be 300 kB (if no pictures are transmitted).

II.5 Telemetry, Tracking and Command (TT&C) subsystem

The TT&C subsystem will be composed of a UHF (uplink)/VHF (downlink) transceiver and of an S-Band downlink unit. VHF alone allows for downlinking 2 MB/day/ground station. An S-Band allows for a band rate at least ten times higher. A GPS may also be part of the system for a precise geolocation of the S/C.

II.6 Mass, Power and Communication Budgets

First estimations indicate that the S/C would weigh about 3.5 kg, i.e. below the upper bound of 4 kg allowed for a triple CubeSat [2].

Concerning the power, estimations based on COTS components or on similar systems show that the payload will consume between 1.5 W and 2 W on average over an orbit if all experiments are active. Estimating the power needed by the platform to be 5 W, 4 deployable solar panels with 4 to 5 cells each should be enough to power the S/C. The battery will be sized to ensure that the S/C remains powered when in the Earth's shadow. The attitude scenario explained in §II.2 is compatible with solar panels facing the Sun most of the time, which increases the average available power.

About the communication data rate, it is estimated that

- VISION will produce about 300 kB/day. Transmitting a picture of the Sun adds another 400 kB. A full image of the field of view will take 8 MB (uncompressed).
- The mNLP probes can sample the electron density up to 10 kHz. This leads to 6.5 GB/day (for 2-byte digits). As this is much more than the downlink capability of a CubeSat even in the presence of an aggressive data compression scheme, the measurement periods and the sampling rate will be carefully modulated to limit the data rate to less than 8 MB. Note that an S-Band solution is necessary to cope with the downlink requirements of mNLP.
- Due to its moderate sampling period of 10s, μBOS needs are estimated to 150 kB/day.

III VISION

The *Visible Spectral Imager for Occultation and Nightglow* (VISION) instrument is a tuneable spectral imager based on a Fabry-Perot in the visible and near-infrared wavelength. Its spectral range goes from 400 nm to 800 nm, and its spectral resolution is 10 nm. The FoV per pixel is two thousandths of one degree, in round figures.

With its features, VISION will give access to

1. The monitoring of the concentration of stratospheric ozone in the Polar Regions via vertical profiles retrieval by spectral absorption in the Chappuis band (the absorption band due to O3 around 600 nm) during solar occultation;
2. Profiles of the upper atmosphere temperature obtained by assessing the refraction angle of the sunlight through the atmosphere;
3. The observation of the airglow emissions and of the auroras at 558 nm and 630 nm (atomic oxygen green and red lines, respectively);
4. The observation of the bi-modal oscillation of the mesospheric sodium density through the Na doublet emission at 589 nm [3] (Figure 3).

A short description of the experiments relative to the first two objectives is given below.

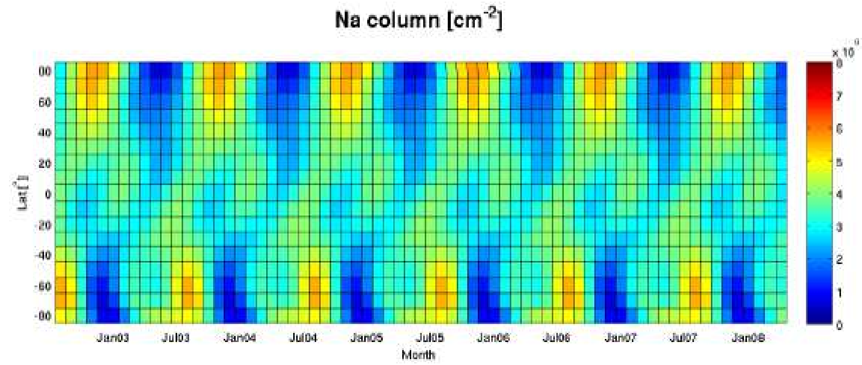


Figure 3: Fit of the Sodium vertical concentration from raw GAMOS Na columns [3]

III.1 Solar Occultation and Spectral Measurements

Figure 4 illustrates the general principles of a measurement by solar occultation. The Earth's atmosphere is represented by the light blue area, the orbit of the S/C by the black circle and the Sun by the yellow symbol. The tangent altitude h_{tg} is defined as the shortest distance between the ray of light under consideration and the Earth's surface.

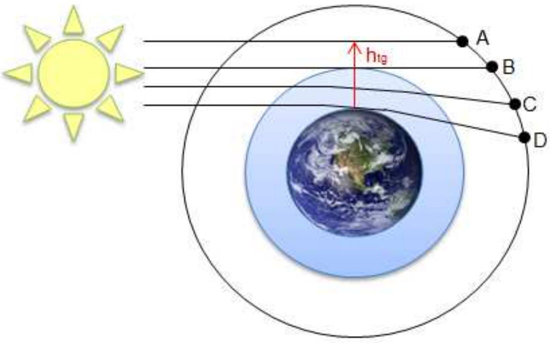


Figure 4: Solar occultation principle

The scenario corresponding to a sunset starts with the S/C at location A and orbiting clockwise. The imager points towards the Sun. The light beam passes above the Earth top of atmosphere (ToA) along a free-atmosphere path. At this stage the Earth is not visible on the imager. The exo-atmospheric Sun radiance is then measured at predefined wavelengths before reaching B, at which the light beam starts interacting with the ToA.

As the S/C pursues its path around the Earth, the Sun radiance gets attenuated by the atmosphere and is measured repetitively at multiple locations, as for instance location C. To reach the imager, the sunlight goes through an increasingly thick atmosphere: on the one hand, the total length of the path in the atmosphere increases; on the other hand the smaller the tangent altitude, the higher the atmospheric density. Finally, the S/C reaches location D where it enters the Earth refracted shadow. Somewhere in between A and D, the Earth appears at one side of the imager. It moves towards the opposite side until it fills the entire image.

Obviously, the case of an orbital sunrise is similar, the event sequence being simply reversed as the S/C rotates counter-clockwise from location D to A.

In the atmosphere the beam is refracted and it bends towards the Earth. From the imager perspective, refraction leads to two phenomena. Firstly the Sun's apparent position is displaced away from the Earth, as if the Earth was repelling it. This displacement is maximal at location D just before the Sun disappears behind the Earth body. Secondly, as illustrated in Figure 5, the apparent shape of the solar disk shrinks along the vertical dimension (relative to the Earth image). This deformation comes from the fact that rays emanating from the bottom of the Sun propagate into denser atmospheric layers than those emanating from the top. By solving the inverse ray-tracing problem of the photon propagation in the atmosphere, mesospheric and stratospheric temperature profiles can be retrieved.

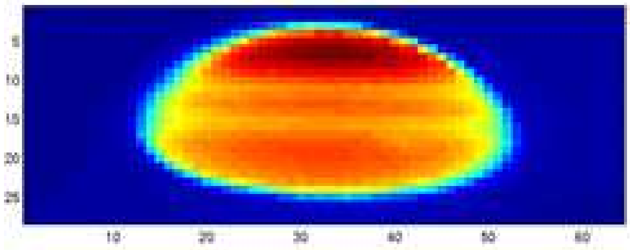


Figure 5: Example of sun image flattening due to atmospheric diffraction

Spectacular results have recently been obtained by the SOFIE instrument aboard AIM by detecting the Sun edges and the related refraction angle [4]. Here we expect to improve the method by making use of the full solar disk.

The solar brightness (i.e. the solar irradiance) is also attenuated by scattering, absorption and diffusion processes along the optical path in the atmosphere. Profiles of physical properties and chemical components in the atmosphere can then be retrieved by spectral analysis of the attenuation. This attenuation is illustrated in Figure 6 for a few tangent heights [5]. The photon depletion around 600 nm corresponds to photon absorption by ozone in the so-called Chappuis band. Resolving it gives access to the ozone profile.

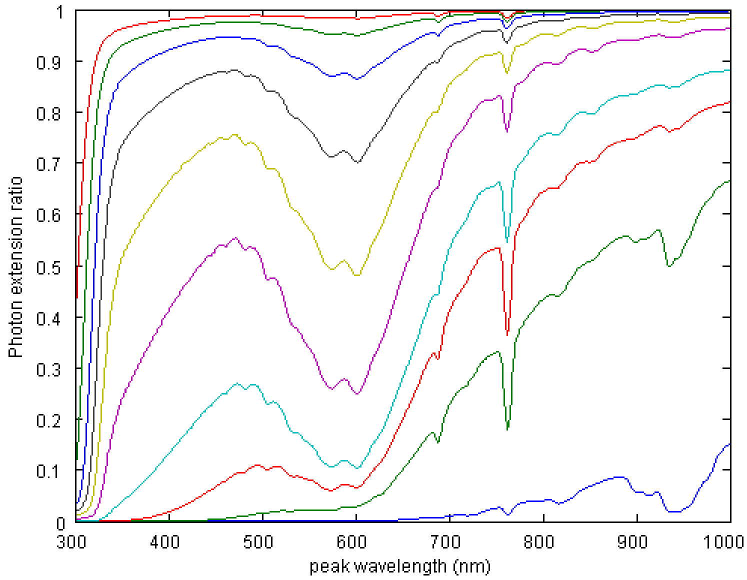


Figure 6: Spectral photon depletion for tangent heights ranging from 5 km to 50 km (from bottom to top curves). Spectral averaging over 5 nm.

III.2 Main technical features

Draft estimations made by VTT lead to the following features:

Attitude: The attitude determination and control are very critical for VISION. Maintaining the attitude to within 1° is required for an imager FoV of 2.5°. The estimate of the tangent height also requires a very precise attitude determination. Fortunately, these requirements are within the possibilities offered by the CubeSat technology.

Mass: < 700 g

Power < 4 W in average during an occultation; orbit averaged power: 250 mW

Size $90x90x40\ mm^3$; aperture diameter: 15 mm

Data Data will be processed onboard with a dedicated data processing unit. About 300 kB data will be produced daily. Another 400 kB and 8 MB are needed to transmit a snapshot of the Sun and of the whole FoV, respectively.

IV mNLP

At 500 km altitude, PICASSO is flying through the upper layers of the ionosphere with an orbital period of 94 minutes. Given its high inclination PICASSO will sample the ionosphere at this altitude rather globally. It is therefore obvious to use PICASSO as a platform for a global monitoring of the ionosphere. To that end, *the multi-Needle Langmuir Probe* (mNLP) is an ideal instrument as it can measure the amount of ionized particles.

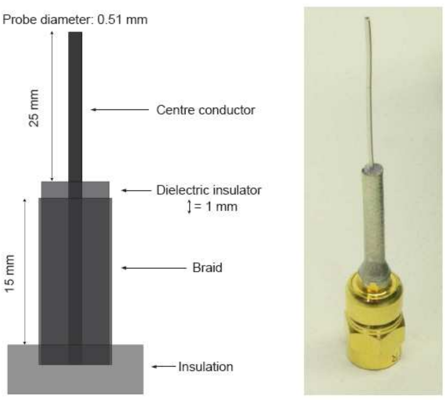
mNLP will offer a continuous, in-situ, and high-frequency (when needed) monitoring of the upper ionosphere with a rather global geographic coverage. In particular, mNLP will address the following topics:

1. Ionosphere-plasmasphere coupling;
2. Subauroral ionosphere and corresponding magnetospheric features;
3. Aurora structure (thanks to the high frequency capability of mNLP);
4. Study of polar cap arcs;
5. Ionospheric dynamics via coordinated observations with EISCAT's heating radar [6];
6. Turbulence in the partially ionized ionosphere;

Coordinated observations with EISCAT Radar are also foreseen. They will validate mNLP data and will provide the overall ionospheric context into which the mNLP data have to be interpreted.

IV.1 Overview of the measurement principle

The multi-needle Langmuir probe instrument is an upgraded version of the traditional Langmuir probe. It is designed specifically for electron density measurement at high space and time resolution. It is based on four fixed-bias cylindrical needle probes set to four different positive potential biases well above the S/C potential (i.e. in the electron saturation region), see Figure 7 and Figure 8.



(a) Technical probe drawing (b) Manufactured probe

Figure 7: Cylindrical Langmuir probe needle [7]

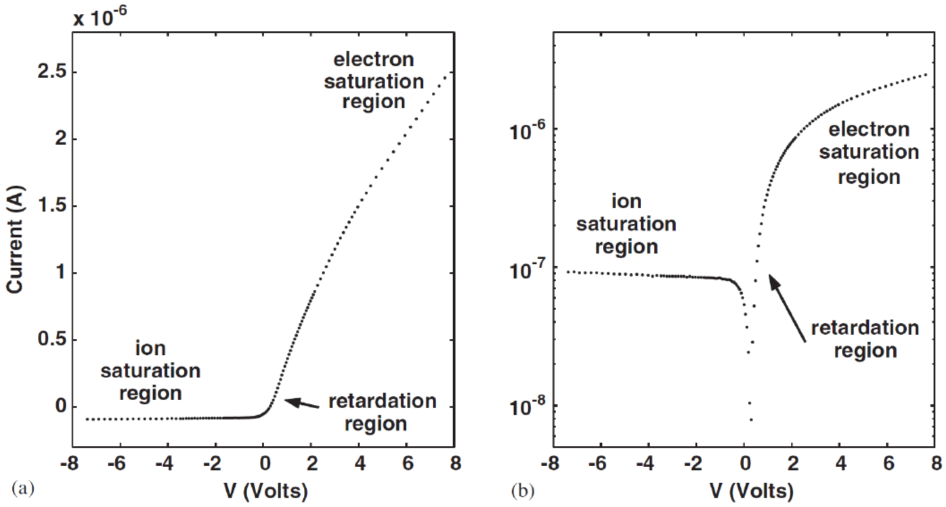


Figure 8: Langmuir probe characteristics: (a) linear and (b) logarithmic current axis

The needles are placed at the extremity of short booms. By sampling simultaneously the electric current flowing from each probe, the plasma electron density can be derived with high time resolution without the need to know the electron temperature or the spacecraft potential from the ratio $\Delta I^2/\Delta V$.

Figure 9 shows how that ratio is measured from an I2-V graph. The electron density is proportional to the square of the slope of the straight line. Theoretically, only two probes are enough to derive the electron density, but in order to check that at least two probes are not in the wake of the S/C and to improve the reliability, mNLP will have four probes. A similar instrument has already been operated successfully on sounding rockets (ICI-2 and ECOMA 7, 8 and 9) in 2008 and 2010.

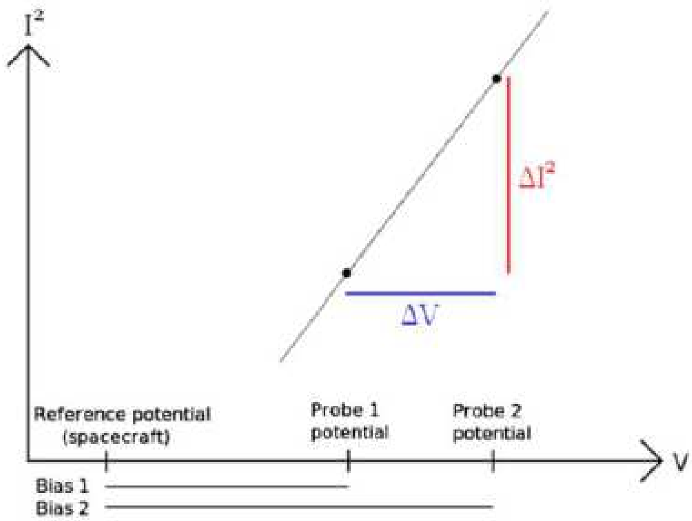


Figure 9: Determination of the ratio $\Delta I^2/\Delta V$ with two probes at different potential

IV.2 Main technical features

According UiO, the main features of mNLP are as follows:

<u>Attitude</u>	The attitude determination and control are not critical for mNLP. An accuracy of about 5° is sufficient.
<u>Mass</u>	100 g
<u>Power</u>	500 to 1000 mW (peak)

Size The four probes have to be located away from the body to stay out of the S/C wake as much as possible. Placing them at the extremity of the 2U-long deployable solar panels, at the top of a ~50 mm-long boom, meets that requirement.

PCB board size: 75*80*15 mm^3; probe length: 25 mm; probe diameter: 0.5 mm

Data Data will be processed onboard with an FPGA included in the electronics board of the instrument. About 6 MB of data will be produced daily.

V µBOS

In order to better understand the delicate balance in the Earth's climate and its variations caused by both anthropogenic and natural causes, outgoing and incoming radiative fluxes need to be observed precisely over various time periods spanning from seasonal to inter-annual. The *micro Bolometric Oscillation System* (µBOS) experiment will monitor variations in the short wave (visible and reflected solar radiation) and long wave (infrared and emitted by the Earth) radiations outgoing from the Earth ToA as well as the variations in the incoming short wave Total Solar Irradiance (TSI).

The solar and infrared spectra are well separated above and below 5 µm, the overlap between them being very small. This distinction makes it possible to treat the two types of radiative transfer and source functions separately and thereby simplify the complexity of the radiative transfer problem.

As a consequence, µBOS will host two sets of detectors. The first one, an improved and adapted sensors inherited from the ongoing BOS/PICARD and LYRA/PROBA2 missions, measures the variation of solar irradiance in the visible, extreme ultraviolet (EUV) and soft X-ray (SXR) bandwidths. The other one measures the variation of the outgoing radiation of the Earth.

The proposed µBOS experiment will complement existing Earth/Sun observation missions with a unique ability to simultaneously measure irradiance variations of the Sun and the Earth from the same platform with high precision. The monitoring of temporal variations on the outgoing and incoming radiative fluxes of the Earth will allow to quantify the lags between the different fluxes over land and oceans. The measurements will also provide information on the Earth energy imbalance, which was shown to be extremely challenging for remote sensing from an orbit around the Earth. µBOS will provide a unique test in terms of technology and mission concept for future space-borne observations targeting the Earth as well as the other planets of the solar system.

µBOS is supporting four main objectives:

1. Measurement of the solar irradiance, for this quantity is essential to understand the Earth climate and give access to solar flares, solar storms, TSI and p-mode oscillations. In addition, there might be an instrumental gap from 2014 that would be detrimental to long term study of the TSI.
2. Measurement of the Earth's outgoing radiation (illustrated in Figure 10), with a focus on the temporal and spatial variability, variations in the Earth albedo (coverage change), the effects of natural hazards and cloud coverage estimation.
3. Measurement of the Earth energy imbalance which also is of prime importance to understand the climate evolution.
4. Preparation and validation for future planetary missions (i.e. Marco-Polo).

V.1 Measurement principle

The measurement principle of the µBOS is similar to the BOS aboard PICARD even if the configuration of the sensors is optimized to accommodate the dimension of CubeSats. In addition, the sensor and the electronics will be improved in order to measure precisely the irradiance variation of the Sun and Earth origins.

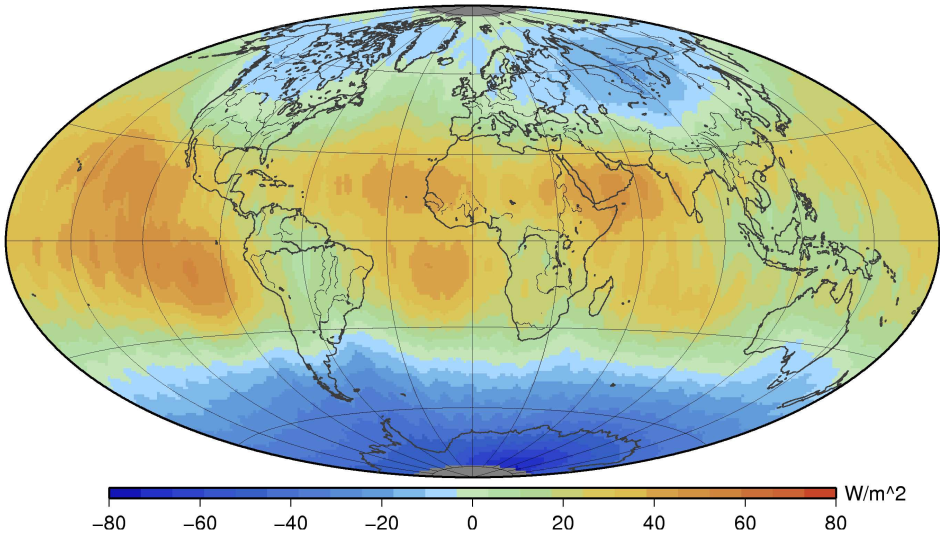


Figure 10: Long wave irradiation of the Earth from Jul 2010 to Jul 2011 derived from the BOS measurements on PICARD (ref: ROB).

The thermal sensors are based on two absorbing masses. As shown in Figure 11 for the BOS, the round black-painted absorber (m_1) is surrounded by a white-painted circular plate (m_2). Both receive irradiance flux and re-emit heat flux back to the space. As the mass of m2 is 200 times greater than m_1, m_2 presents a higher thermal inertia than m_1. Two thermistors measure the temperatures of the absorbing surfaces in order to determine the energy budget. The first one (T_1) is placed below m_1 and the second (T_2) is set at the bottom of a metallic bar, which is thermally connected with m_2. In order to minimize the heat leakage, the bar will be isolated from m_2 by a five-layer thermal blanket including a bridal veil. T_1 is measured with a thermistor set at the top of the sensor. Instead of recording T_2 directly at the end of aluminium shunt, we will measure ($T_{12}= T_1 - T_2$).

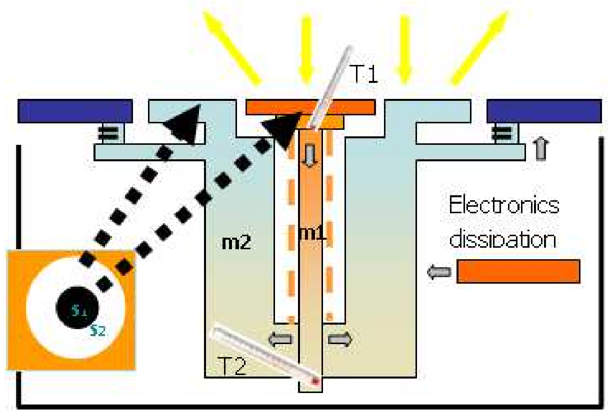


Figure 11: BOS principle and configuration

The advantage of such design is that we can increase the gain of the amplifier by three times compared to measuring T_2 alone. It essentially increases the signal-to-noise ratio of heat flux measurements. The physical values of T_1 and T_2 are obtained through calibration functions using the reading of T_1 and T_{12}.

When photons from either the Sun or from the Earth impinge the front absorbing surfaces, m_1 and m_2 heat up. Given their mass ratio, m_1 temperature rises faster than m_2 temperature and a thermal flux flows from m_1 along the shunt to m_2. At the top of the instrument, the heat conductivity is negligible between m_1 and m_2, except at the bottom of the shunt. Consequently, T_{12} and T_2 are different, and T_{12} measures the rapid power input change while T_2 provides the slow power input change, respectively.

V.2 Instrument

As mentioned above, µBOS contain two different thermal detectors to observe the Sun and the Earth:

1. One thermal sensor of 2 cm-diameter is placed at the front of the satellite to measure the variation of the solar irradiance.
2. Radiation from the Earth is monitored by 4 thermal sensors (4 cm-diameter) found on each lateral side of the S/C (Figure 12). When directed to space, these sensors are also used for calibration.

The two types of thermal detectors are coated by the same black absorbing surface.

In order to increase the precision of the flux measurements, a thin shunt (radius of 0.3 mm) is connected to the black absorbing surface with a heat sink. Two thermistors are set up to measure the temperature under the absorber and at the end of the shunt. With such configuration, the contamination of common modes from the satellite and non-linearity of thermistors is effectively reduced.

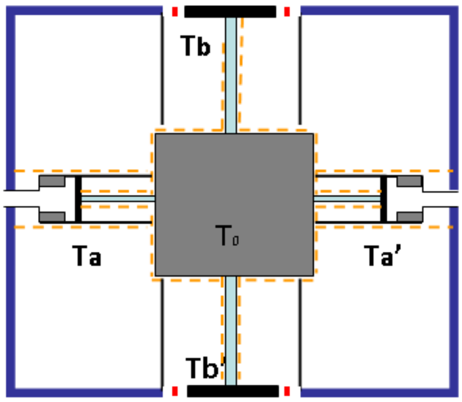


Figure 12: Earth sensors concept (the blue thick lines are the S/C walls)

There will be 2 additional optical channels to monitor the Sun in EUV and SXR. They will be placed next to Sun thermal sensor. A VIS-IR sensor (0.3-5 µm) is also set on each lateral side near the µBOS sensors.

V.3 Main technical features

First estimations made by ROB leads to the following quantities:

Attitude	The axe of the S/C front face must be aligned on the Sun within a 5° tolerance.
Mass	200 g
Power	500mW (peak), 100 mW average, 25 mW (sleeping)
Size	Sun (resp. Earth) sensors radius is 1 (resp. 2) cm; thickness is 5 cm. No PCB card is needed as the electronics is put in the free volume of the sensors.
Data	Data will be processed by the embedded electronic components. The daily data production rate is 150 kB.

An engineering model of the instrument including mechanical parts, electronics and thermal sensors has already been realized by ROB (Figure 13). The performances of this prototype in laboratory conditions will now be assessed.

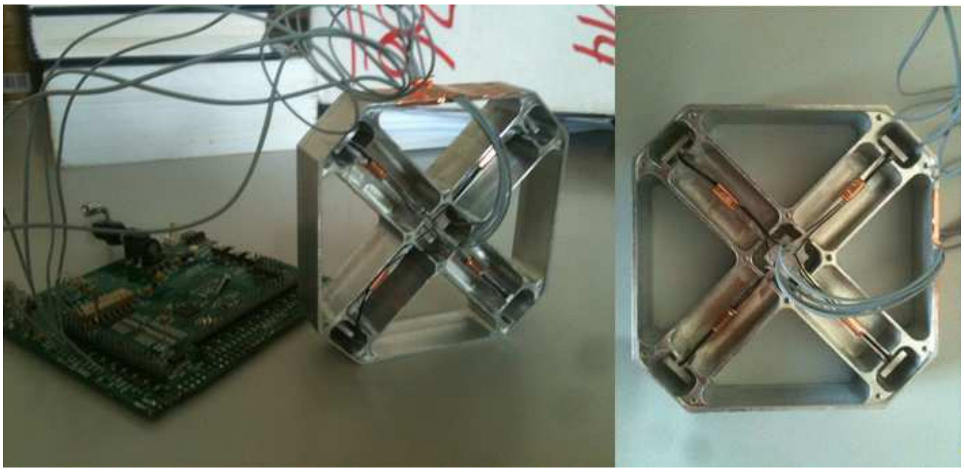


Figure 13: µBOS engineering model

VI CONCLUSION

In this paper, we have presented the PICASSO mission currently in preparation at BISA and ROB for a launch on the QB50 precursor flight.

While most existing CubeSats are either educational artefacts or technology enablers, PICASSO is a scientific demonstrator driven by specific scientific objectives. Thanks to its compound payload made up of three independent instruments dedicated to the remote and in situ study of the Earth's atmosphere and incoming/outgoing radiation fluxes, it will contribute to specific areas in a fairly broad scientific research domain.

With a short mission preparation time and a relatively small cost, PICASSO will demonstrate that solutions based on tiny satellites are compatible with scientific experiments that would be very hard, if not impossible, to carry out in the frame of a more traditional approach.

It is indeed our belief that Cube-, pico- and nano-sats have a genuine role to play in the observation of the Earth and, more generally, of the planets of the solar system, along with larger and (much) more expensive systems.

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