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Laboratory characterization of HYPSOS, a novel 4D remote sensing instrument

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ABSTRACT

The HYPerspectral Stereo Observing System (HYPSOS) is a novel remote sensing pushbroom instrument able to give simultaneously both 3D spatial and spectral information of the observed features. HYPSOS is a very compact instrument, which makes it attractive for both possible planetary observation and for its use on a nanosat, e.g. for civilian applications. This instrument collects light from two different perspectives, as a classical pushbroom stereocamera, which allows to realize the tridimensional model of the observed surface, and then to extract the spectral information from each resolved element, thus obtaining a full 4-dimensional hypercube dataset.

To demonstrate the actual performance of this novel type of instrument, we are presently realizing a HYPSOS prototype, that is an instrument breadboard to be tested in a laboratory environment. For checking its performance, we setup an optical facility representative of a possible flight configuration.

In this paper we provide a description of HYPSOS concept, of its optomechanical design and of the ground support equipment used to characterize the instrument. An update on the present status of the experiment is finally given.

Keywords: Pushbroom, Stereo imaging, Hyperspectrum

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1. INTRODUCTION

One of the essential tasks of a modern planetary space mission is to provide the digital terrain model (DTM) of the visited planet surface. This is usually realized by means of a dedicated stereocamera on board of the orbiter (see, for example, [1] [2]). The DTM of the planet surface allows to perform several morphological studies of the observed features, but usually it is not possible to get information also on the surface composition. For this, it is necessary to patch the DTM with the spectral data obtained by other instruments, i.e. spectrographs, on board of the orbiter. Merging the data from these two different type of instruments is always very complex: they need to be cross-calibrated, the Fields of View (FoV's) are usually different, the projected pixel size is never the same and varies with the surface slope, the covered regions are often different, and so on. In practice, this is done just for small areas of specific interested, and the 4D information (three spatial and one spectral) of the surface is usually a dataset very difficult to recover. The same problem exists also for Earth observation and, to our knowledge, no present instrument is able to simultaneously provide 4D information of the Earth surface, even with fully attitude controllable satellites.

To override these issues, we thought about the possibility of realizing a single instrument providing both tridimensional information of the observed surface and the spectrum of each sampled area, in practice able to get a spectral DTM (SDTM) as final product. If this is possible, a single instrument would provide practically all the information needed to fully characterize a planet surface element, without the need to merge the data provided by different instruments. When designing this instrument, we had in mind a system configuration with a nadir pointing satellite and a pushbroom stereo camera (with a forward and a backward channels, tilted at $\pm\theta$ with respect to nadir along the flying direction) specific for a planetary observation, and the emphasis was mainly on the scientific return of the observations; however, definitely the same approach can be adapted to realize low-cost Earth 4D-observing systems, like nanosats or Unmanned Aerial Vehicles (UAVs), mainly for civilian applications, for example in agriculture or geology. Obviously, the system optical configuration will have to be optimized for the specific application, but this should be a minor issue if the validity of this novel concept is confirmed.

In any case, the task is not trivial: it requires on one side the capability to merge two different instruments, a stereo camera and a spectrograph, in one; on the other, it is necessary to realize a suitable software able to integrate all the information obtained by this instrument to produce a SDTM. On this respect, new problems will have to be faced: for example, the wavelength dependent characteristics of the instrument and the spectral bidirectional reflectance distribution function of the observed surfaces may impact on the SDTM reconstruction and quality level.

In this paper we are reporting on the development of such an instrument prototype. HYPerspectral Stereo Observing System (HYPSOS) is an innovative pushbroom stereocamera able to simultaneously return both 3D spatial and spectral information of each resolved element of the observed features. Here we concentrate more on the instrument optical design, the prototype realization and the laboratory setup we realized to check the actual instrument performance; all the aspects associated to the data reduction to obtain the SDTM will be provided in a future paper.

2. HYPSOS OPTICAL DESIGN

As mentioned in the previous section, the optical configuration of HYPSOS has been obtained joining in a single instrument a stereoscopic pushbroom camera system and a spectrograph. For this we took advantage of our previous experience in the realization of the STereo Camera (STC) [2] of SIMBIO-SYS [3] [4], which is the imaging system on board of the ESA BepiColombo mission [5] [6] to Mercury. The Mercury Planetary Orbiter of BepiColombo is the three-axis stabilized spacecraft that accommodates SIMBIO-SYS; it will orbit Mercury in an inertial elliptical polar orbit of 2.3h period (periherm 480 km, apoherm 1500 km). STC is a very compact instrument, in which two separate optical paths send the light collected at ±20° from nadir (chief ray) on the same bidimensional sensor [7]. In the HYPSOS design we tried to adopt a similar technique for the camera system, that is to send two separate beams of light along the same optical path, so to provide the two images on the same focal plane: this allows to minimize the mass and the total envelope resources. However, for finally providing the spectral information of the observed surface, an imaging spectrograph has to be used; thus the camera optical configuration has to be designed in such a way to send the two collected images on the spectrograph entrance slit.

To better understand the issue associated to joining the two systems, the camera and the spectrograph, we can look at Figure 1 and Figure 2. Figure 1 shows a schematic of the ground projected FoV's of a standard pushbroom stereo camera for a nadir pointing satellite: the sub-satellite track indicates the spacecraft on-ground trajectory and associated motion orientation, Channel 1 represents the forward FoV, and Channel 2 the backward FoV. Figure 2 schematically shows the principle for bringing these two FoV's on the spectrometer entrance slit. On the left there are the two ground projected FoV's: the HYPSOS camera optical system has been designed to provide a 90° rotation of the FoV's and bring them onto the spectrograph entrance slit, which has the function of field stop, as shown on the right. In this way, the two FoV's are entering the spectrograph in different portions of the entrance slit and, by means of a suitable imaging spectrograph, the spectra of the two FoV's are obtained.

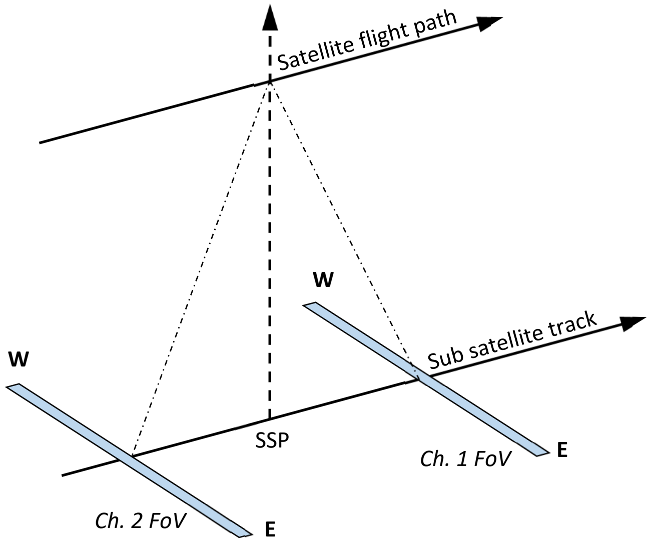


Figure 1. Ground projection of a pushbroom stereo camera FoV's (SSP: Sub Satellite Point).

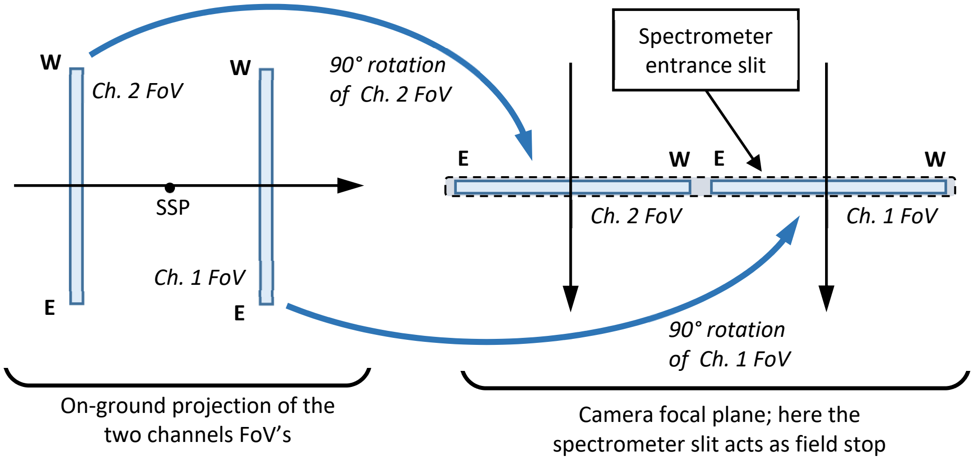


Figure 2. On the left, the on ground projection of the HYPSOS camera system FoV's is shown; on the right, the same FoV's are shown on the camera focal plane, together with the HYPSOS spectrometer entrance slit.

Thanks to this design concept, it is possible to obtain simultaneously all the information needed to have a 4D instrument: from the two stereo channels, all the information needed to reconstruct the surface DTM is available; from the spectrometer, the spectral information for each point on the DTM is also obtained.

There are definitely many different possible optical configurations for realizing such an instrument, depending on the required optical performance and on the spectral range of interest [8]. A rather versatile configuration, extending from visible to near infrared, could be realized by using an all-reflective telescope (e.g. a three-mirror anastigmat, TMA) as stereo camera: in this way, the camera is wavelength independent and no chromatic aberration affects the system. Then it is possible to split the beam by means of a dichroic filter at the level of the focal plane, sending the visible and the infrared portions of the spectrum on two separate and dedicated spectrographs.

To verify the goodness and the quality of the just described concept, we decided to realize an instrument prototype. On the basis of the available resources, we designed a HYPSOS prototype working in the visible portion of the spectrum, from 400 nm to 800 nm (but with the possibility in case to be extended in the infrared). The optical configuration of this prototype is shown in Figure 3. A couple of flat mirrors collect the light from two different directions, at ±20° with respect to the optical axis (nadir pointing), folding it at a much smaller ±1° off-axis angle. The two beams of light then pass through two 45° tilted Schmidt-Pechan prisms (SPP), which provide a 90° rotation of the FoV. From here on, all the optical elements are common to both light paths. Light passes through a three-mirror anastigmat (TMA) telescope (M1, M2, M3) and before reaching the focus is folded by a flat mirror (FM). On the telescope focal plane a slit defines the instrument FoV, as shown in Figure 2, with a separation between the two channels. Light passing through this slit then enters a double-pass imaging spectrometer, composed by four lenses (L1, L2, L3, L4) and a concave reflection grating (G). Finally, the two separate spectra are collected by a bidimensional detector. Some optical parameters of the HYPSOS prototype optical elements are summarized in Table 1.

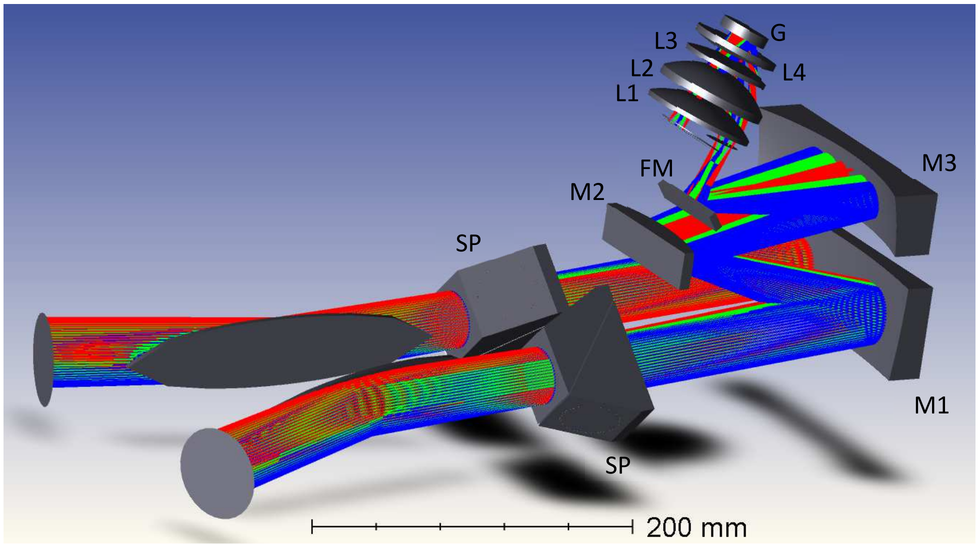


Figure 3. Optical layout of the HYPSOS prototype. For the acronym description, see the text.

Table 1. Some parameters of the HYPSOS prototype optical elements. Acronyms are described in the text.

M1	Radius of curvature: 467 mm Concave hyperbolic surface; conic constant: -1.474
M1-M2 distance	135 mm
M2	Radius of curvature: 141 mm Convex spherical surface
M2-M3 distance	135 mm
M3	Radius of curvature: 117.5 mm Concave oblate ellipsoidal surface; conic constant: 0.198

M3-FM distance	225 mm
FM-focal plane distance	41.73 mm
Spectrograph entrance slit(s)	Two co-axial slits (22 µm × 8 mm each), 1 mm central separation
L1	Meniscus R1: 562.7 mm; R2: 61.1 mm Thickness: 13 mm
L2	Plano convex R: 50.78 mm Thickness: 19 mm
L3	Plano convex R: 91.84 mm Thickness: 7.4 mm
L4	Meniscus R1: 104.4 mm; R2: 64.8 mm Thickness: 3.2 mm
G	Concave spherical Radius of curvature: 83.7 mm Ruling density: 678 l/mm

The aperture stops of HYPSOS, one per channel, are located at the input SPP face's, provided by a 35 mm diameter circular mask. The TMA, which has a focal length of 245 mm, is almost diffraction limited at the longest wavelengths: in a 10 µm diameter circle, more than 70% of the total energy is encircled at 400 nm, and more than 60% at 800 nm. Since the spectrograph entrance slit is the instrument field stop, given the slit size of 22 µm × 8 mm it is easy to calculate that the nominal instantaneous FoV of HYPSOS is 18.5 arcsec × 1.87° for each channels. With respect to the TMA axis, the innermost field entering the instrument, that is the one with the smallest angle with respect to the axis, is tilted by 0.125°, while the outermost is tilted by 2°.

The HYPSOS spectrograph has substantially a 1:1 magnification. Some spot diagrams as a function of the field incident on the TMA and of the wavelength are shown in Figure 4. The square box here represented has the same size, 22 µm, of the entrance slit width. Apart from some residual astigmatism at the edges of the spectral band which slightly reduce the spectral performance of the system, more than 80% of the monochromatic energy is always included within this box. The plate scale factor on the spectrometer focal plane is 33.7 nm/mm: assuming a 22 µm sampling, we conservatively obtain a resolving spectral element (double sampling) of 1.5 nm.

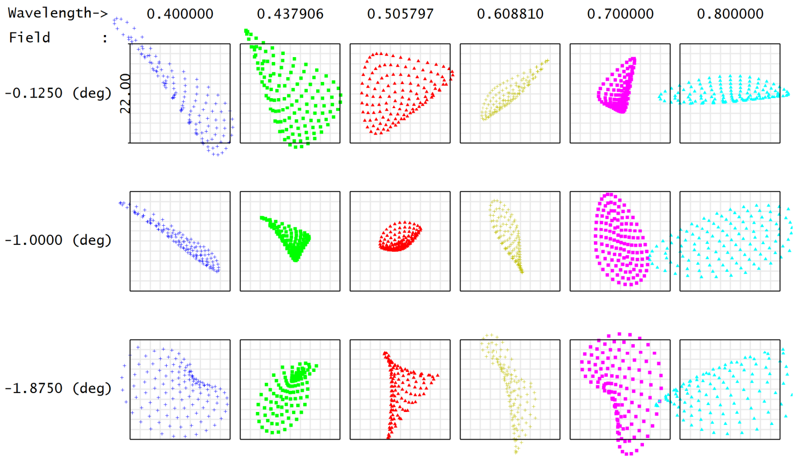
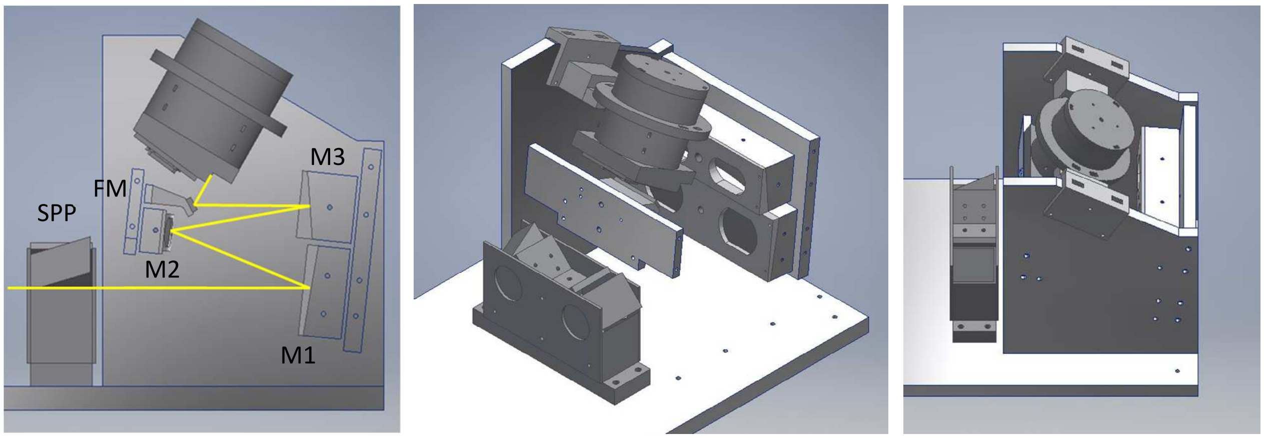


Figure 4. Spot diagrams on the focal plane of the HYPSOS spectrograph. Wavelengths are in µm; the square box size is 22 µm. Three fields are shown, representative of the whole spectral range covered by HYPSOS prototype.

3. HYPSOS PROTOTYPE REALIZATION

After the consolidation of the optical design, we moved on the realization of the instrument. Not being necessary to satisfy the typical strict requirements about mass and envelope of a space instrument, we realized a rather solid mechanical structure holding all the optical elements, and allowing all the degrees of freedom needed to perform a proper system alignment (for this, a specific tolerance analysis of the optical design has also been done). A schematic view of the HYPSOS mechanical structure is shown in Figure 5. In (a) we can see also the optical path for the central ray: after crossing the SPP on the left, the light beam is reflected by M1, M2, M3, and FM before entering a cylinder which hosts all the spectrograph elements. In (b) it is possible to see the SPP's holder which includes the instrument aperture stops. Also the mirrors have a mask in front: these masks have the function of limiting the beam aperture and to minimize the possible stray light. On this respect, it is important to have in mind the possible cross-talk between the two channels, i.e. light from one channel outside the nominal FoV entering the other. To limit this, a baffle should be considered in front of the instrument aperture, as well a vane in between the two optical paths in proximity of the spectrograph entrance slit. Since this is not an issue with this prototype, as will be explained in the next chapter, we did not implement them; however, some care has to be taken when designing an actual flight instrument in order to avoid this type of problem. Finally, (c) shows a view of the complete instrument: the cylinder, visible on the instrument top, holds all the optical elements of the spectrograph, from the entrance slit to the lenses, to the grating and the detector. A couple of section views of the spectrograph are shown in Figure 6. All the lenses will be mounted in their nominal position by simple mechanical tolerance, while the grating is mounted on a dedicated holder to be fixed to the top cylinder closing flange by a system which allows its alignment. Internally, we also included a zero order light trap to minimize the stray light inside the cylinder. The detector will be attached to the bottom cylinder flange; the latter also hosts the spectrograph entrance slit.

HYPSOS mechanical structure has been realized in our internal workshop, with the exception of few pieces done by a local company by means of 3D additive manufacturing. All the optical elements have been realized by local Italian companies, with the exception of the grating which is off-the-shelf. The spectrometer entrance slit has been realized by means of nanotechnologies, as already done for the ELENA shutter on board of BepiColombo [9] [10]: first a mask is realized by electron beam lithography on a Si_3N_4-Si- Si_3N_4 sandwich, then an aperture is realized on the Si_3N_4 layer by reactive ion etching and the 400 μm thick {100}-silicon substrate is removed by KOH etching. Thanks to this technique it has been possible to realize the significantly long slits required for this instrument; also a line of 8 equi-spaced pinholes have been realized by the same technique, for spectrograph calibrating purposes. Concerning the detector, to have a good coupling with the slit width, we have been looking for sensors with relatively large pixel size, of the order of 20 μm. Unfortunately, the choice is rather limited, also on the basis of the relatively large size it has to have and the need to fit within the relatively small available room. Thus, at the end, we selected a smaller pixel-size detector, and acquired an active CMOS 6480H×4856V, 3.45×3.45 μm^2 pixel. This sensor has a 12 bits ADC, it is binnable, it is possible to make windowing, and allows readout rates up to 12 full frames/s. The latter is an important characteristic to be able to reproduce the instrument push-broom acquisition mode.



(a) (b) (c)

Figure 5. In (a) a section view of the HYPSOS structure with the central ray optical path. In (b) an open view of the whole structure. In (c) the complete view of HYPSOS prototype. The approximate envelope is 310×310×320 mm^3.

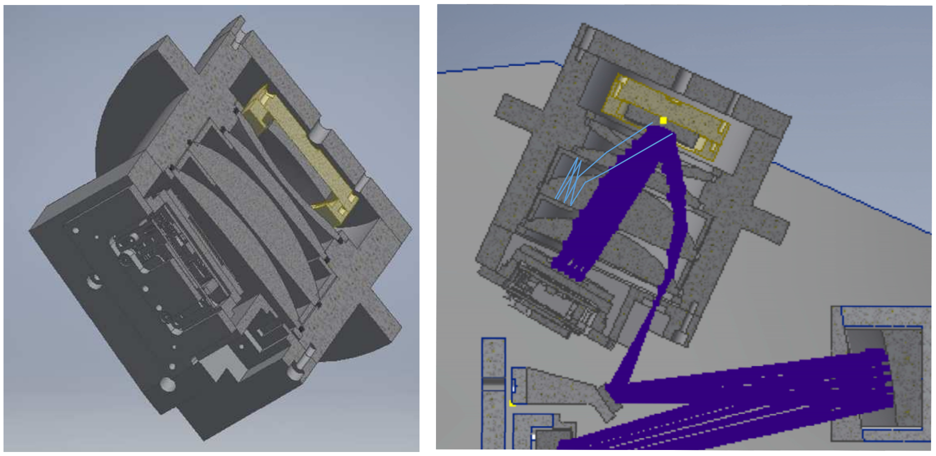


Figure 6. Section views of the HYPSOS spectrograph. On the right also the light beam is shown, for the spectrum of interest and for the zero order.

4. LABORATORY SETUP

To reproduce in the laboratory the acquisition mode of HYPSOS (see Figure 7), we modified the facility used to calibrate STC [11] [12] and introduced some fore-optics to HYPSOS. The basic idea is to send on one of the two HYPSOS apertures at the time a FoV representative of a planet surface, scanning it as if the instrument was flying on a satellite. Having the preliminary knowledge, by suitable calibration, of the 3D profile of the surface and of its spectral characteristics, it will be possible to compare the final HYPSOS SDTM product to verify the goodness of the obtained results.

As observational target of HYPSOS we use a relatively flat stone with spectral variegations (as an example, we will use an anorthosite sample already used for calibrating STC) that can be illuminated by a halogen lamp at different angles of incidence to reproduce different Sun illumination conditions (see Figure 8). To reproduce in the lab the pushbroom target scanning, the target and illumination system have been mounted on a linear stage, which moves the stone surface over the HYPSOS object plane. To provide the condition of a target at very large distance from the instrument aperture, the target surface is positioned on the focal plane of a fixed collimating lens, with 1 m focal length: the light diffused by the target and collected by the lens then enters the HYPSOS apertures practically as a source at infinity. Since the same surface has to be acquired by HYPSOS from two different perspectives, i.e. the incidence angle of the central ray of the two channels are tilted by ±20° (see Figure 7), the whole system is on top of a rotating stage, that can tilt the target with the right orientation with respect to the HYPSOS acquisition perspective (see Figure 9).

To optimize the setup on the optical bench, it has been more convenient to replace the two folding grazing incidence mirrors before the SPP's by two couples of smaller folding mirrors at 55° and 45° incidence angles, as schematically shown on the right of Figure 9. Thanks to this fore-optics system, and mounting HYPSOS on a second rotating stage, it is possible to reproduce the acquisition from either the forward of the backward channels by a simple rotation of the whole instrument. The acquisition modes through the two HYPSOS channels, forward and backward, is shown in Figure 9: comparing them with the configuration shown in Figure 7, it is evident that the acquisition geometry is the same in the two cases. The practical difference is that in the lab we are moving the target relatively to the fixed instrument, while in-flight it is the instrument moving with respect to the target.

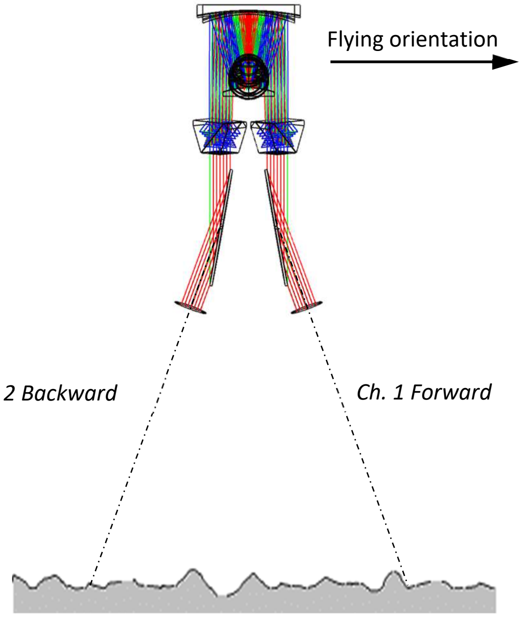


Figure 7. Schematic view of the nominal HYPSOS in-flight acquisition mode.

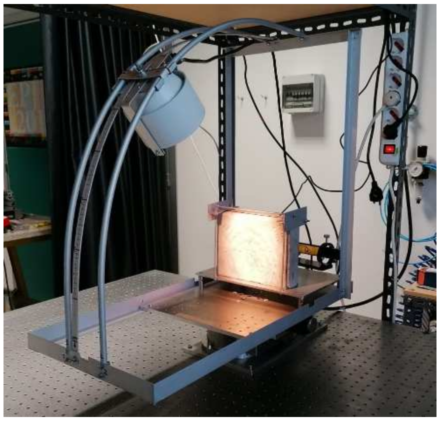


Figure 8. The stone illuminated by a halogen lamp used as HYPSOS source.

5. ON GOING ACTIVITIES

Presently, we have in house essentially all the basic hardware to assemble the prototype, to align the telescope and the spectrograph, and to start the validation activity. We are now in the process of both aligning the foreoptics and the TMA, and to provide an independent calibration of the grating (the calibration curve provided by the supplier has been measured in a different condition with respect to the one we are going to use). Then, we will integrate the spectrograph and independently align it, including entrance slit and bidimensional detector. Finally, we will interface telescope and spectrograph for completing the instrument integration.

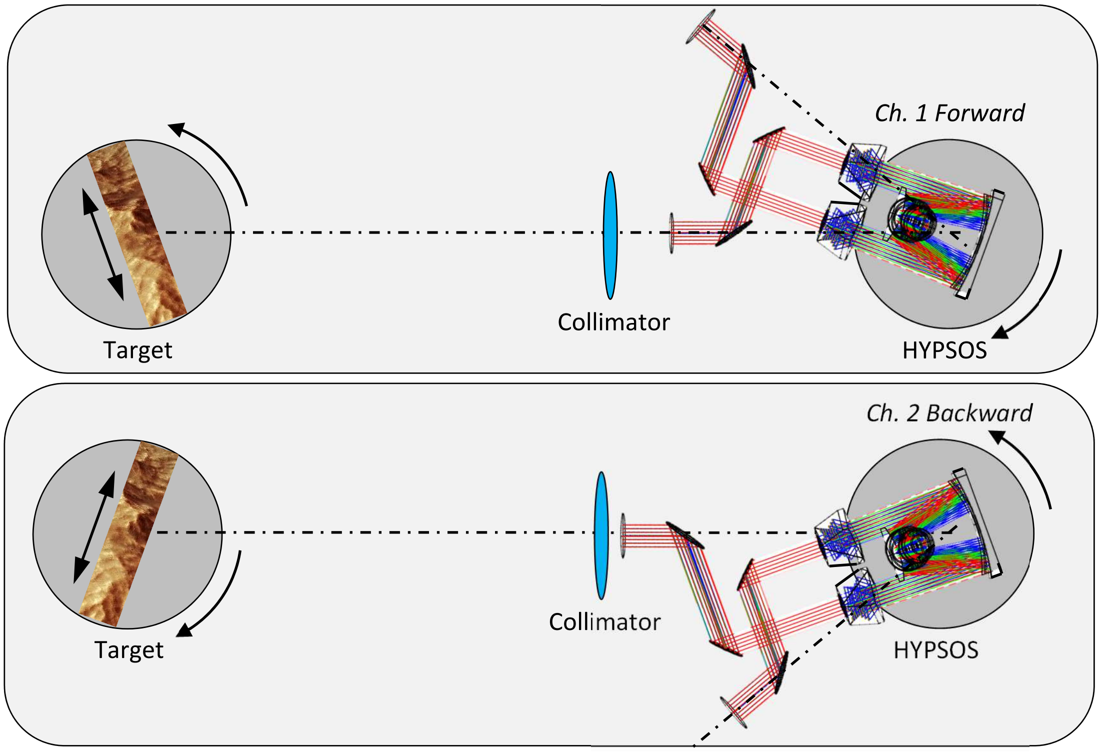


Figure 9. HYPOS acquisition configuration scheme. On top, the configuration for reproducing the acquisition with the forward channel is shown; on bottom, the same for the backward channel.

With the complete instrument, we will start the measurement session. The 3D surfaces of the target stones have already been fully characterized by means of a suitable no-contact coordinate measuring machine, i.e a 50 Mpx range camera, with a spatial and vertical accuracy of 20 μm: these profiles will be compared with those obtained by HYPSOS, to evaluate its photogrammetric quality. The acquisitions will be realized with the setup shown in Figure 9, moving the target by means of the translation stage at a speed synchronized with the acquisition frame rate of the sensor, in such a way to reproduce the pushbroom acquisition mode. Finally, the collected data will be reduced by means of suitable software to extract the 4D information from each resolved element of the observed surface: this will be an ad hoc dedicated software, derived by 3DPD [13], a photogrammetric pipeline we developed for processing the stereo images from the Colour and Stereo Imaging System (CaSSIS) [14] on board of ExoMars Trace Gas Orbiter (TGO).

6. CONCLUSIONS

In this paper we described the activities relative to a novel remote sensing instrument, HYPSOS, which merges the capabilities of a stereo pushbroom camera, to provide a DTM of the observed surface, and of a spectrograph, to simultaneously give also the spectra of the observed features. Merging these two different information allows to obtain a full 4D dataset of the target, that is a spectral DTM. To our knowledge, HYPSOS is the first instrument able to simultaneously provide such a complete information dataset.

We are presently in the process of realizing a prototype of HYPSOS, to be tested in a laboratory environment. We designed a stereocamera based on a TMA which sends the observed FoV’s from two different aperture stops on the entrance slit of a lens spectrograph; this prototype works in the visible portion of the spectrum, but it has the possibility to be expanded to operate also in the infrared if additional resources will become available in the future. The nominal optical performance of HYPSOS are excellent and it is possible to get a very high spectral resolution. To reproduce in laboratory a pushbroom acquisition mode, we modified a facility already used to test the SIMBIO-SYS STC on board of BepiColombo: the basic concept is to keep HYPSOS in a fixed position, one channel at the time, and to move the target to reproduce the flight motion. Also, a significant amount of work is under going to get the new software routines to allow to reduce the raw data in a SDTM, but this is out of the scope of this paper. We are now integrating the whole instrument, planning to be ready to realize the first measurements in a few months from now.

We are really confident about the goodness of this project, and we envisage several possible applications of this instrument: not only for space exploration, but also for civilian aims. In fact, such an instrument could be integrated in small satellites dedicated to Earth observations, for example for agricultural application, for geological exploration, for environmental monitoring. Also, HYPSOS can be made more compact [8], to be mounted on a small nanosat array, so strongly reducing the cost of the mission. In practice, HYPSOS is a very promising innovative and unique instrument, that can potentially have a rather large range of future applications.

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