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Event: SPIE Astronomical Telescopes + Instrumentation, 2022, Montréal, Québec, Canada

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## ABSTRACT

Cosmic explosions have emerged as a major field of astrophysics over the last years with our increasing capability to monitor large parts of the sky in different wavelengths and with different messengers (photons, neutrinos, and gravitational waves). In this context, gamma-ray bursts (GRBs) play a very specific role, as they are the most energetic explosions in the Universe. The forthcoming Sino-French SVOM mission will make a major contribution to this scientific domain by improving our understanding of the GRB phenomenon and by allowing their use to understand the infancy of the Universe. In order to fulfill all of its scientific objectives, SVOM will be complemented by a fast robotic 1.3 m telescope, COLIBRI, with multiband photometric capabilities (from visible to infrared). This telescope is being jointly developed by France and Mexico. The telescope and one of its instruments are currently being extensively tested at OHP in France and will be installed in Mexico in spring 2023.

**Keywords:** robotic telescope, transient universe, infrared

## 1. SCIENTIFIC MOTIVATION

### 1.1 COLIBRI in the context of SVOM

At all times, the study of cosmic explosions has been connected with key advances in astronomy. This is especially true now that cosmic explosions are used as standard candles to measure the Universe (type Ia supernovae), as probes of the distant Universe (GRBs), as laboratories to study extreme physics (relativistic jets, production of cosmic rays, etc.), and as outcomes of the birth of compact objects (black holes and neutron stars). In the near future, cosmic explosions will stay at the forefront of astronomy as the astrophysics of multi-messengers

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Ground-based and Airborne Telescopes IX, edited by Heather K. Marshall, Jason Spyromilio, Tomonori Usuda,
Proc. of SPIE Vol. 12182, 121821S · © 2022 SPIE · 0277-786X
doi: 10.1117/12.2627139

(neutrinos and gravitational waves) matures and during the continued development of time-domain (or synoptic) astronomy.

In this scientific context, GRBs play a very specific role, as they are the most energetic explosions in the Universe after the Big Bang. They are associated with the death of the most massive stars (supernovae) or mergers of compact stellar objects (neutron-star/neutron-star or neutron-star/black-hole). The energy radiated by a GRB in its first minute is typically $10^{51}$ erg. Due to these extreme luminosities, GRBs can be used to probe the most observationally difficult and remote regions of the Universe.

The forthcoming Sino-French SVOM (Space-based multi-band astronomical Variable Objects Monitor, Ref. 1) mission will make a major contribution to this scientific domain by improving our understanding of the GRB phenomenon and by using them as tools to understand the infancy of the Universe. It is designed to achieve the best balance between space and ground instrumentation. The onboard instruments will permit the detection of the GRBs, their localization with arcminute to arcsecond accuracy, the study of the prompt emission and the early detection and follow-up of the visible afterglow. The ground segment will permit the fast distribution of the alerts, the localization of GRBs with sub-arcsecond precision and the initial selection of high-redshift candidates ($z > 6$).

In order to fulfill its scientific objectives, the SVOM mission involves two ground-based robotic telescopes, one under French responsibility, COLIBRI[*], and one under Chinese responsibility. These telescopes are at complementary longitudes to provide a continuous and prompt follow-up of the GRBs detected by the instruments on the satellite.

This article focuses on COLIBRI which has a very particular place in the SVOM system by fulfilling the following functions:

- Being able to observe GRBs from visible to infrared, from the first minute to at least one day.
- Being able to locate the GRB with an accuracy better than one arc second, less than 5 minutes after receiving the ground alert (for sufficiently bright GRBs). For reference, the localization accuracy of the alert provided by ECLAIRs onboard SVOM is better than 13 arc-minutes.
- Identifying the low signal-to-noise ratio triggers, for which SVOM will not provide a platform slew. These triggers are expected, for example, from GRBs that are highly extinguished or which occur at very high redshift, and which potentially have a very strong scientific impact.
- Localizing and observing dark GRBs, i.e., events detected in gamma, X-ray, and infrared domains, but not in the visible domain.
- Ensuring the link between the SVOM satellite and the largest terrestrial facilities, as NTT, VLT, ALMA, etc., by being able to provide an estimation of the GRB magnitude and redshift 5 minutes after the alert reception.

The joint observations by SVOM and COLIBRI will address, in particular, several key scientific questions:

- Due to its rapid response time, which allows observations to start very shortly after receiving an alert, it will be able to study the mechanisms associated with the prompt emission and also the transition between the prompt and the afterglow emissions. Up to now, there have been few observations deeper than magnitude 19 during the two first minutes after the start of the high-energy emission. COLIBRI has a larger aperture than previous telescopes with rapid response, and so will be able to explore fainter GRBs with a time resolution adapted to the fast variability of the emission in this phase. This area is largely unexplored and is precisely one of the main scientific objectives of the SVOM mission.

[*]COLIBRI web site: https://www.colibri-obs.org/

- It will search for highly reddened or high-redshift ($z > 6$) GRBs due to its sensitivity in the infrared domain, since they will remain invisible with the Visible Telescope onboard the satellite. The highly redshifted GRBs are important for the study of the young Universe and the epoch of reionization, and their fast identification deserves special efforts. To achieve this requirement, COLIBRI will provide a photometric redshift with an accuracy better than 10% a few minutes after the alert reception, which allows a reduction of this delay of an order of magnitude compared to current observations. It will be then possible to activate larger facilities, as NTT, VLT, E-ELT, ALMA, etc., immediately from COLIBRI, which is of course critical for the scientific exploitation of these events.

### 1.2 A telescope dedicated to the transient sky

However, COLIBRI goes far beyond the SVOM mission. The current decade will see the operation of several major facilities especially designed to study the transient sky in the electromagnetic domain (LSST, CTA, SKA, LOFAR, etc.). This evolution is accompanied by the progress of all-sky detectors for non-electromagnetic messengers, neutrinos (KM3NeT and IceCube) and gravitational waves (Advanced Virgo, LIGO and KAGRA). This domain has made amazing progress in the last years with the first identification of an astrophysical source producing gravitational waves and very high-energy neutrinos.

Together, these facilities will revolutionize our view of cosmic explosions and of the transient sky in general. All these facilities distribute alerts on timescales of seconds to minutes, offering unique opportunities to study the early phases of cosmic explosions by pointing COLIBRI quickly to the appropriate regions of the sky. The scientific rationale for rapid follow-up includes in the particular the physics of the early stages of cosmic explosions: GRB shocks and interaction with their environment, supernova shock breakout, and binary star mergers physics.

COLIBRI will thus offer the opportunity for follow-up of all these alerts and for important scientific contributions on the study of the most energetic phenomena populating the transient sky.

## 2. THE CONSORTIUM

COLIBRI is the result of a very close collaboration between France and Mexico, with a participation of Arizona State University. The institutional partners are AMU (Aix-Marseille University), CNES and CNRS for France, and UNAM and CONACyT for Mexico. These parties are officially associated by a Memorandum of Understanding (MoU), which was signed in 2018.

COLIBRI will be installed in the Observatorio Astronómico Nacional (OAN) in the Sierra de San Pedro Mártir, Baja California (Ref. 2). More precisely, it will be located at the highest point of the observatory, at the coordinates 31°02'41.52" N, 115°27'52.13" W and an altitude of about 2800 meters.

The suitability of OAN as an observatory has been demonstrated by continuous operation since the 1970s and by independent evaluations for projects on several occasions, including for the Thirty Meter Telescope (Ref. 3). Median seeing is about 0.8 arcsecond with about 80% of nights being observable and 60% being photometric. These parameters are in the range of the world-class astronomical sites such as Mauna Kea, La Silla, Cerro Tololo, and La Palma.

## 3. THE COLIBRI SYSTEM

### 3.1 Main requirements

In order to fulfill its scientific requirements, COLIBRI has very specific requirements (Tab. 1): high availability for alert observations, very good sensitivity, fast pointing speed (on target in less than 30 seconds after the alert reception), multiband photometric capabilities (from 400 to 1800 nm, with three simultaneous cameras), and a field of view covering the SVOM trigger error box (26 arcminutes).

Table 1. Main requirements on COLIBRI

| | |
|---|---|
| Observatory location | Observatorio Astronómico Nacional, San Pedro Mártir, Mexico |
| Delay for pointing | $<$ 30 seconds (goal: $<$ 20 seconds ) |
| Precision of localization | $<$ 0.5 arcsec |
| Primary mirror diameter | 1.3 m |
| Photometric channels | Three simultaneous arms: two in the visible ($gri$ and $zy$) and one in the NIR ($JH$) |
| Field of view | 26 arcmin |
| Pixel scale | 0.38 arcsec/pix in the visible and 0.64 arcsec/pix in the infrared |
| Real-time data processing | $<$ 5 minutes |

## 3.2 The observatory

The observatory is essentially composed of (Fig. 1):

- An enclosure and services building with all the equipment required to operate the telescope.
- An Alt-Az telescope equipped with a 1.3m primary mirror which feeds an instrument composed of three channels: two operating in the visible (DDRAGO) and one in the near-infrared (CAGIRE).
- A safety system to manage the security of the entire observatory (from the dome to the instruments and the Control Center): personnel safety (the telescope turns very quickly and we must be sure that no one is in the dome during the observations), weather management (automatic closing of the shutter in case of clouds or wind gusts, etc.), among others.
- A Control Center managing, not only the observatory and its environment, but also the observation program, the automatic data processing, the database, and all that is required for observations. It is linked to the French Science Center (FSC) of SVOM in order to provide an accurate photometric redshift and the position of the afterglow candidate less than 5 minutes after the alert emission.

### 3.2.1 The infrastructure

COLIBRI will be housed in two new buildings at the at the highest point of the OAN (Ref. 4). The main building houses the observing room for the telescope and the (robotic) control room underneath the observing room. The the services building houses the transformers and air-conditioning units. The design of the main building is shown in Figure 2.

In order for the fast response of the telescope not be unduly limited by the dome, we commissioned a custom dome of the German company ASTELCO and the Italian company Gambato. This dome is able to rotate at up to 30 deg/s and allow the telescope to observe any position on the sky in less than 30 seconds.

The building presented several challenges. Some are well known, such as ensuring that heat does not leak from the control room to the observing room and ensuring that the observing room is adequately ventilated at night, and several were new to us. First, we had to ensure that the building structure was sufficiently rigid to handle the torques from the very fast dome (Ref. 4). Another is that the optically fast telescope allows us to use a very compact 7.5 meter dome, but this means we needed to find innovative solutions for the handling of the mirrors and instruments in such a small space (Ref. 5). Finally, while the site gave excellent all-round access to the sky, we needed to reinforce the terrain on two sides of the telescope enclosure against subsidence (Ref. 4).

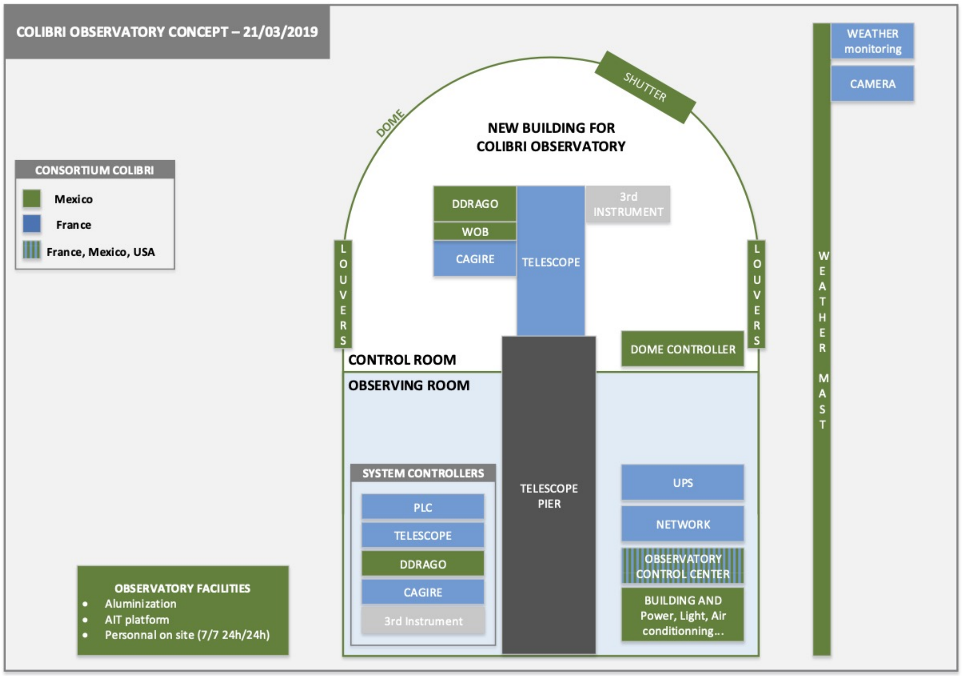


Figure 1. Diagram describing the main blocks and the responsibilities that constitute the COLIBRI observatory.

### 3.2.2 The telescope

The telescope has an alt-azimuth mount with two Nasmyth foci equipped with two derotators. The telescope has been built by the German company ASTELCO and the two main mirrors were polished by the French compagnies AstroOptique Cardoen for the M1 and Winlight for the M2. The main characteristics are summarized in Tab. 2.

The project made the choice to have an unprotected coating (pure aluminium) for the two main mirrors, M1 and M2, of the telescope. This choice was driven by the fact that the observatory has equipment on site to carry out periodic recoatings. A complete set of tools has then been developed to carry out this task every two years (Ref. 5).

Table 2. Main characteristics of COLIBRI telescope.

| | |
|---|---|
| Delay for pointing | $<$ 20 seconds |
| Maximum settle time | $<$ 1 second |
| Minimum elevation | 15° |
| Absolute localization accuracy | $<$ 2.5 arcsec RMS |
| Tracking accuracy for 90 seconds | $<$ 0.2 arcsec RMS |
| Tracking accuracy for 10 minutes | $<$ 0.3 arcsec RMS |
| Tracking accuracy for 30 minutes | $<$ 0.5 arcsec RMS |
| Maximum load on the derotator | 350 kg |

### 3.2.3 The instruments

The primary instrument for COLIBRI will be the DDRAGO/CAGIRE imager. DDRAGO provides optical imaging with two channels, *gri* and *zy*, and feeds a faster infrared beam to CAGIRE (Refs. 6, 7, and 8).

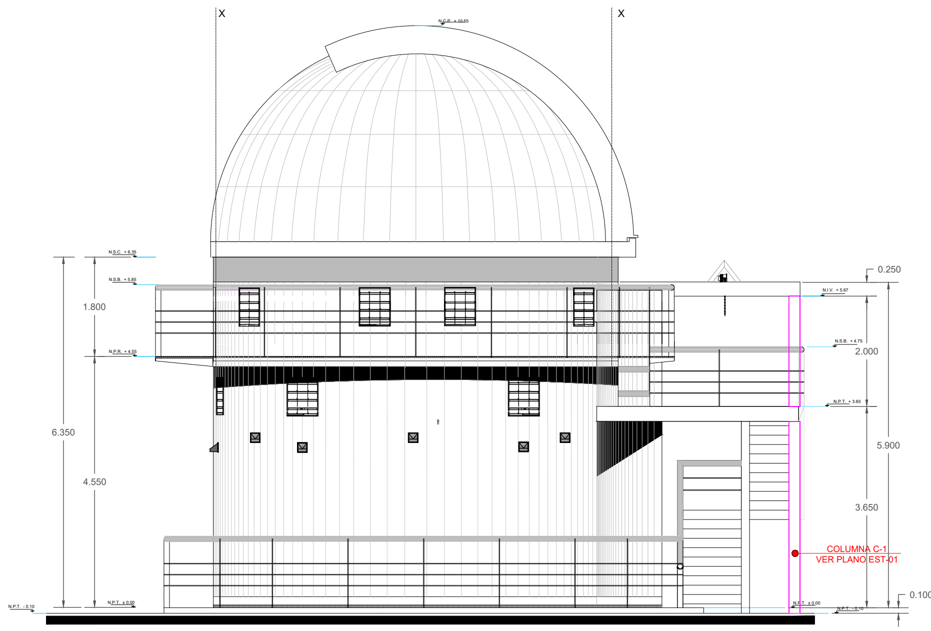


Figure 2. The main building, which houses the observing room and control room.

CAGIRE then provides infrared imaging in $JH$. DDRAGO is being developed by the Instituto de Astronomía of the Universidad Nacional Autónoma de México and CAGIRE by IRAP at the Université de Toulouse.

The opto-mechanical design of the instruments is inspired by RATIR, a four-channel imager with two visible CCDs and two H2RG near-infrared imagers which was operated on the Harold L. Johnson 1.5 m telescope at OAN from 2012 to 2022 (Ref. 9). The instrument optical design (Refs. 10 and 11) is driven by the possibility of direct imaging for the visible channels (i.e., with no reimaging optics). The infrared channel does have reimaging, but following RATIR uses ambient-temperature optics to form an image of pupil within the cryostat. This allows the use of a very compact cryostat with only one cryogenic lens close to the detector. This simplifies the development of the instrument by greatly reducing the cryogenic complexity.

CAGIRE will be the first astronomical camera equipped with the Astronomical Large Format Array (ALFA) detector manufactured by the French company LYNRED (Ref. 12) and based on the HgCdTe (Mercury–Cadmium–Tellurium) technology developed at CEA-LETI. This new sensor represents a major development in Europe that has been supported by the ESA, the Labex FOCUS and the CEA-LETI. The detector covers a spectral range from 0.8 $\mu$m to 2.1 $\mu$m, but will be used in CAGIRE with a blocking filter for wavelengths longer than 1.8 $\mu$m. We will use ramp reads to improve dynamic range, mitigate radiation events, and reduce the read noise (Ref. 13).

The main properties of the DDRAGO/CAGIRE instrument are given in Tab. 3. The efficiency of the overall system is given in Fig. 3.

It should be noted that only one of the two Nasmyth foci is currently used. In the future, we envisage installing a low resolution spectrograph on the remaining focal station.

#### 3.2.4 The safety system

The safety system, PLC (Programmable Logic Controller), is an important component as it manages the safety of the entire observatory (from the dome to the instruments and the Control Center):

- The safety of personnel is the very first priority of the PLC as COLIBRI is a robotic observatory with a very fast telescope. When the telescope is in remote mode, it can move at any time. For that reason, the

Table 3. Main characteristics of DDRAGO/CAGIRE instruments.

| | DDRAGO | CAGIRE |
|---|---|---|
| Sensor | e2v | Lynred |
| Wavelength coverage | 400-1000 nm | 1000-1800 nm |
| Number of pixels | 4096x4096 | 2048x2048 |
| Pixel size | 15 $\mu$m | 15 $\mu$m |
| Well capacity | 350000 $e^-$ | >80000 $e^-$ |
| Readout noise | 8 $e^-$ | <40 $e^-$ |
| Operating temperature | 163 K | 100 K |
| Dark current | <0.001 $e^-$/pix/s | <1.0 $e^-$/pix/s |
| Pixel scale | 0.38 arcsec/pix | 0.63 arcsec/pix |
| Field of View | 26 arcmin | 21.7 arcmin |

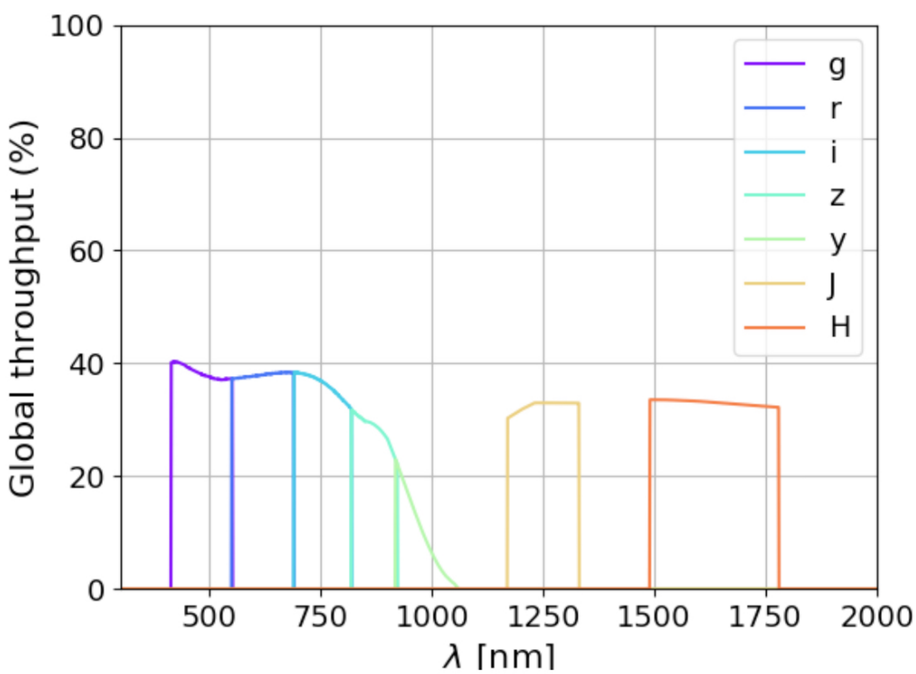


Figure 3. Global transmission curves for the different filter bands of COLIBRI, including all optical elements and their coatings, and the detector quantum efficiency (Ref. 14).

PLC verifies that nobody enters in the telescope room during the observations. If an intrusion is detected, the telescope is instantaneously stopped and put in stand by mode.

- Depending on the environmental conditions, the PLC can decide automatically to put the observatory in the safety configuration. This safety configuration consists of closing and parking the dome, closing the mirror shutter, then finally parking the telescope. The environmental conditions monitored are the weather conditions with the wind, the rain, the sky cloud coverage, the humidity and the dew point. In addition to this, the UPS (Uninterruptible Power Supply) is supervised to put the system in the safety configuration in case of general power failure. Also, the computer which controls the telescope is monitored.

In addition, the PLC controls the operating mode of the installation (local or remote), as well as all the actuators and sensors like the louvers, which allow the cooling of the telescope room before the night, the building lights and some of the environmental sensors.

#### 3.2.5 The Control Center

In order to manage the whole observatory, the choice was made to make the most of the experience acquired on other projects, such as RATIR, and to use as much as possible existing and already validated developments. The Control Center is thus composed of:

- The Telescope Control System (TCS): it ensures the hardware interface with the different components of the system and coordinates the other components of the system (telescope, instrument, dome, etc.) during the observations.
- The scheduler and its user interface: COLIBRI works in robotic mode and observers cannot access its control interface. They have to submit observations on a web interface and the scheduler will then automatically optimize the observation schedule according to many criteria (observability of the object, current weather conditions, priority of the target and of the observer, etc.).
- The database: all the data are automatically archived and saved in a dedicated database hosted in France, with a complete mirror in Mexico. It serves as an interface for users to retrieve their data based on the AstroNomical Information System (ANIS) developed at Centre de donnéeS Astrophysique de Marseille (CeSAM). It is a web generic tool aimed at facilitating and homogenizing the implementation of astronomical data of various kinds and catalogues in dedicated Information Systems. It provides high level services like: search, extract and display imaging and spectroscopic data using a combination of criteria, an object list, a sql query module or a cone search interfaces, as well as download of catalogues and complete datasets.
- The Instrument Center: it is a dedicated facility that stores all telescope, detectors, PLC, software status, current strategy and is able to give statistics on those data. It also generates and offers observation strategies and finally, stores and offers reference calibration data.

COLIBRI's data flow will ultimately be relatively high as it is expected to handle about 60 Gigabyte for the two cameras of DDRAGO every night (18 Terabyte per year) and about 13 Gigabyte for CAGIRE every night (4 Terabyte per year).

## 4. SCIENTIFIC PERFORMANCES

### 4.1 Limiting magnitudes

The scientific performances of COLIBRI have been modelled with great care. For this, it was necessary to take into account the observation site characteristics (atmospheric transmission, seeing and sky background), the telescope characteristics (aperture, focal length, wavelength dependent transmission of each optical element, etc.) and detector characteristics (quantum efficiency, dark current, readout noise and gain) (Ref. 15).

Tab. 4 gives the sensitivity limit of COLIBRI at 10 $\sigma$ for a typical observation sequence associated to the follow-up of a GRB.

### 4.2 Photometric redshift

One of the critical scientific requirement of COLIBRI is to provide a photometric redshift during the first minutes of observations of the GRBs by the SVOM mission. This information is strategic in order to optimize in quasi-real time the observation program carried out on the GRB.

To fulfill this requirement, a special attention was paid to the SED fitting procedure to obtain quickly an accurate photometric redshift. This is based on the fit of the overall shape of the spectra and on the detection of the strong spectral properties. In fact only two prominent signatures can really hint information about the redshift: the Lyman-break at 912×(1+z) Åand the Lyman-$\alpha$ at 1216×(1+z) Å.

The relative accuracy is found to be about 10% for $3.5 < z < 8$ and ∼13-14% for $z > 8$ (Ref. 14). It confirms the ability of COLIBRI to detect dusty and highly redshifted GRBs, and to reliably estimate their photometric redshift in less than 5 minutes.

Table 4. $10\sigma$ Limiting Magnitudes. Due to the sky background in the H band, the exposure time is limited to 13 seconds.

| Filter | Exposures | Dark night | Bright night |
|---|---|---|---|
| g | 8×30s | 22.22 | 21.16 |
| r | 8×30s | 22.00 | 21.38 |
| i | 8×30s | 21.42 | 20.87 |
| z | 8×30s | 20.51 | 20.21 |
| y | 8×30s | 19.52 | 19.52 |
| J | 8×30s | 19.73 | 19.73 |
| H | 16×13s | 18.85 | 18.85 |

## 5. PRELIMINARY PERFORMANCE TESTING

### 5.1 Test plan overview

We have defined a test plan to verify the telescope performance against the technical requirements at the Observatoire de Haute-Provence (OHP) before shipping it to Mexico. This approach was decided by the consortium given that both the mirror polisher and the telescope manufacturers are in Europe.

The test plan is defined in such a way that the system is tested at each phase of the development plan. The first phase concerned the commissioning of the telescope at ASTELCO's facility. Visual, mechanical and electrical inspections were carried out, and telescope movements verified. The telescope was then shipped to the OHP site, assembled, optically aligned, and the motors were tuned. This was done under ASTELCO's responsibility. They then left the telescope to the project team for the next phase: the verification of the telescope alone, without instrument. The last phase concerns the testing with the final instrument, which began in September 2022.

We give here a brief summary of the second phase, the verification of the telescope alone. The tests are divided into two categories: mechanical tests (tracking, pointing errors, etc.) and optical tests (image quality, field of view, throughput, etc.)

### 5.2 Mechanical tests

We have carried out an extensive program of tests to verify the mechanical performance of the telescope. The main results are the following:

- Pointing speed: we verified that the telescope moves fast enough so it can be on any target in the sky in much less than 30 seconds.
- Pointing accuracy: after building a pointing model, we pointed the telescope to a set of random star and measused the pointing error. We found a very good accuracy, with a RMS error below 2.5″ (see figure 4). We also measured the pointing repeatability to be better than 2.3″ peak-to-valley.
- Damping: we measured the time the telescope takes for the telescope to settle and after a slew using a camera with a high frame-rate. We found that the damping time is less than 1 second, which fulfils our requirement (see figure **??**).
- Tracking: we verified the quality of the tracking of the telescope by observing a star during one hour with an acquisition rate of 3.3 Hz. We saw no periodic tracking error, confirming the excellent quality of the mechanical parts. On top of high frequency fluctuation (due to wind and seeing), we observed a small drift. We measured a tracking error of less than 0.4″ RMS over 10 minutes, which is very satisfactory (see figure 5).

We also performed tests to confirm the repeatability of the M2 focusing system, the repeatability of the M3 positioning system, and the performance of the derotator. All those subsystems behave as expected and fulfil their requirements.

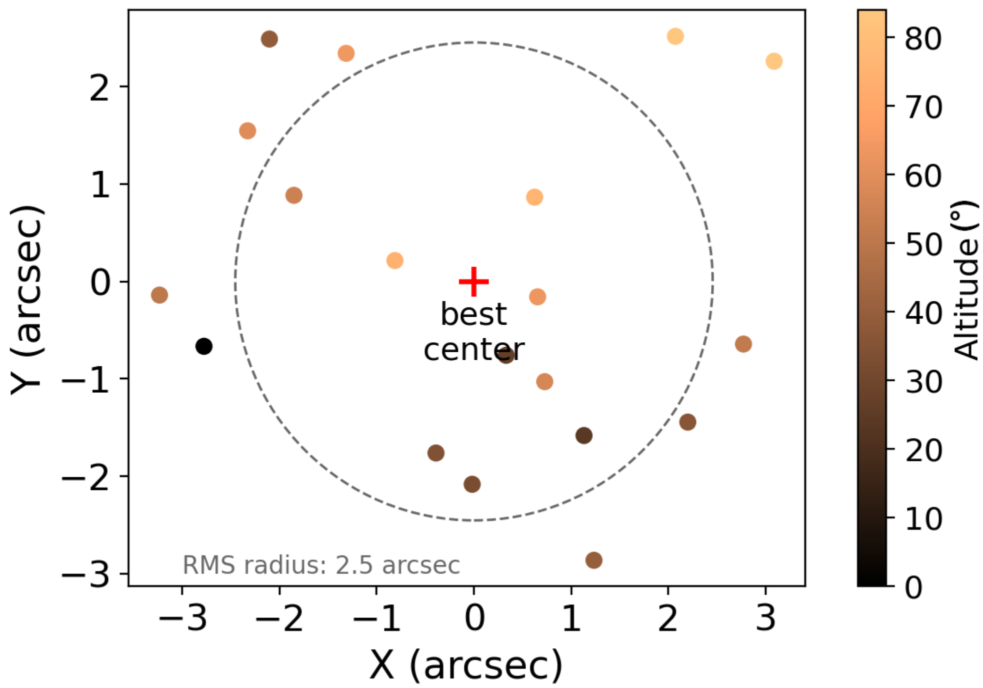


Figure 4. Pointing accuracy. Targets chosen randomly are pointed with an accuracy better than 2.5″ RMS

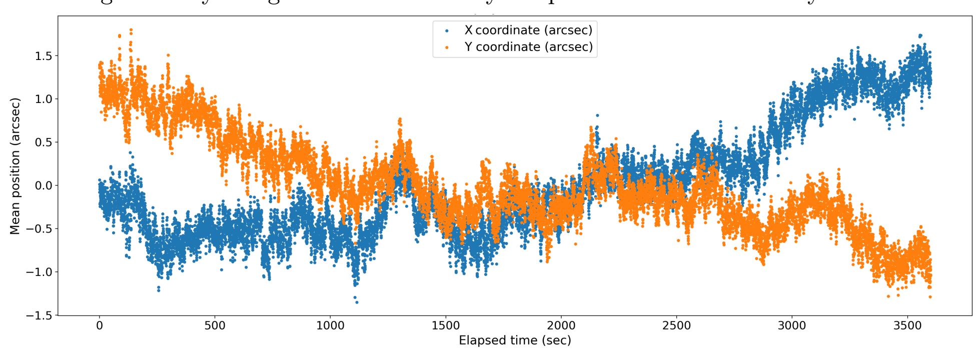


Figure 5. X and Y position measured during one hour on a single target, for testing the tracking accuracy. The values are given in arcseconds on sky.

### 5.3 Optical tests

We have carried out many tests to verify the optical quality of the telescope. These have not yet been successful since the first tests very quickly resulted in the identification of an optical alignment problem. These issues have been taken over by the ASTELCO company and the tests will resume in September 2022 when all the issues have been resolved.

## 6. STATUS OF THE PROJECT

The project officially started in 2015. Originally, COLIBRI was expected to be operational for the planned launch of SVOM in December 2021. Of course, the international pandemic has a direct impact on the development plan of both the SVOM satellite and the COLIBRI telescope. The probable launch date for SVOM is now the end of 2023.

The project made the strategic choice to carry out tests at the Observatoire de Haute-Provence in France of a representative system, namely the telescope, a simplified version of DDRAGO with only one channel (DDRA-

GUITO) and its Control Center. The objective is to validate a system as representative as possible of the one that will be installed in Mexico. This testing began in January 2021.

Testing is scheduled to be completed by mid-November 2022. The telescope will then be dismantled and shipped to Mexico for installation on its definitive site of observation at the beginning of April 2023. The scientific observations will thus begin in the summer of 2023, approximately 6 months before the launch of SVOM.

## ACKNOWLEDGMENTS

COLIBRI received support from the French government under the France 2030 investment plan, as part of the Initiative d'Excellence d'Aix-Marseille Université-A*MIDEX through (ANR-11-LABX-0060 - OCEVU) and (AMX-19-IET-008 - IPhU), from LabEx FOCUS ANR-11-LABX-0013, from ECOS program (grant M17U01) and from CSAA-INSU-CNRS support program, and in Mexico from UNAM (Secretaría Adminstrativa, Coordinación de la Investigación Científica, Instituto de Astronomía and PAPIIT grant IN105921), and CONACyT (Ciencias de Frontera 1046632 and Laboratorios Nacionales).

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