3U TRANSAT: A CONSTELLATION OF NANO-SATELLITES TO SURVEY THE TRANSIENT SKY IN HARD X-RAYS

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Abstract.
The advance of multi-messenger and time-domain astrophysics requires the development of innovative hard X-ray space instrumentation with all-sky capabilities in order to efficiently work in synergy with gravitational wave and neutrinos facilities. In this context, we propose an innovative project called 3U cosmic TRANsient SATellites (3U TRANSAT) based on the deployment of a constellation of nano-satellites in low-Earth orbit. We present the scientific context, the main science requirements & characteristics as well as the status of this project. We also give some highlights on its expected performances.

Keywords: Multi-messenger astronomy, time-domain astronomy, high energy, nano-satellite, constellation, instrumentation, Gamma-ray bursts, transients

1 Introduction

Time-domain and multi-messenger astrophysics are likely to strongly modify our understanding of the contents of the Universe in forthcoming years. This because of the building of game changer technologies offering the possibility in one hand to regularly detect gravitational waves, astrophysical neutrinos & cosmic rays and on the other hand to perform deep monitoring of the transient sky e.g. with the Vera Rubin Observatory [5] in optical and SKA in radio [2]. In this exciting and rapidly expanding fields, the 3U cosmic transient satellites (3U TRANSAT) project ambitions to offer a continuous and all-sky monitoring in hard X-rays in order to detect and quickly (< 2 h) dissiminate to the community the localizations of powerful transients (see Figure 18 in [8]) signaling the birth, feeding through accretion or destruction of compact objects (e.g. white dwarves, neutron stars and black holes). Amongst the zoo of these powerful transients, Gamma-ray bursts (GRBs) are likely the best archetypical sources for both the multi-messenger and time-domain astrophysics since they appear as transient emission across the entire electromagnetic wave spectrum and powerful emitters of GW and neutrinos [e.g. GW 170817/GRB 170817A – see 1]. They are thought to signal the catastrophic formation of stellar mass BHs and the launch of ultra-relativistic jets [9] following core-collapse of > 25 $M_\odot$ stars [6] or binary NS mergers [1; 3]. Studying compact object transient events can shed light on the demography of stellar mass BHs over cosmic time, the role played by stellar and massive BHs in the formation/evolution of the large structures of the Universe (i.e. from galaxy clusters down to star formation within galaxies) and in the reprocessing of baryons at multiple scales (e.g. through r-process nucleosynthesis, accretion/ejection phenomena).

2 3U Transat

Building on the IRAP long experience in the field of GRB detection from space, we propose the deployment of a demonstrator for a constellation of nano-satellites in order to: 1) Learn how to operate in an efficient manner a system of several satellites; 2) Build a scientific and technical expertise in using inorganic scintillators coupled to Silicon photomultipliers (SiPM – see 7) for space high-energy application. As opposed to traditional photomultipliers used for decades in space applications, SiPM are much smaller in size and in mass offering new types of applications; 3) Test new strategies for detection and localization of GRBs and high-energy transients by keeping an approach as simple as possible; 4) Contribute to an international collaborative effort to combine all ressources available in space for the detection and localization of GRBs/high-energy transients, and thus to enhance the findings of electromagnetic counterparts to neutrino and gravitational wave events.

The main science drivers of the project are summarized in the left panel of Figure 1.

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Ensure the continuous all-sky monitoring in the hard X-rays (15–200 keV) for the full constellation
Ensure the detection and the localization of more than 20 short Gamma-ray bursts per year for the full constellation and ~3-5 per year for the demonstrator
Ensure a < 2 h delay from onboard data collection, the on-ground identification and localization of transient events up to the broadcast of the first alert to the community for follow-up purposes
Measure onboard light-curves in 4 energy ranges with a time resolution of 50 ms
Localize the brightest Gamma-ray burst with an accuracy better than 10 deg^2 for the full constellation and better than 50 deg² for the demonstrator, the localization accuracy shall be fixed by the event statistics

Energy range	15 – 200 keV
Illuminated area for 1 cubesat	Up to 38 cm²
Field of view for 1 cubesat	10.9 sr
Field of view for 1 cubesat (with Earth masking)	8.6 sr
Time resolution	50 ms
Peak count rate per detector	1500 cts/cm²/s
Data rate for 1 cubesat	< 100 MB/day
Localization accuracy Err90 for brightest GRBs	< 50 deg²
Mass payload (including all margins)	1.6 kg
Power (including all margins)	4.4 W

Fig. 1. Left: Main science drivers of the 3U Transat project. **Right:** Main characteristics of the science payload.

2.1 *Mission profile and science payload*

3U Transat will be made of 3 clone satellites in a 3U* configuration (see Figure 2) placed on a low-Earth Sun-synchronous orbit anticipating an opportunist launch. Each satellite will have a geocentric pointing direction and be spaced from each other by more than 20°. We expect to launch these nano-satellites from mid-2026 in order to participate to the world effort of finding electromagnetic counterparts of binary neutron star mergers detected by Ligo/Virgo/Kagra (LVK – run O5†). Flying from mid-2026 will also allow us to work in synergy with other flying high-energy missions like SVOM [8] and other small satellites similar to 3U Transat. The later will offer us the opportunity to investigate how to combine on-ground high-energy data from different missions to enhance the GRB detection and localization performances. The mission lifetime is expected to be 3 years.

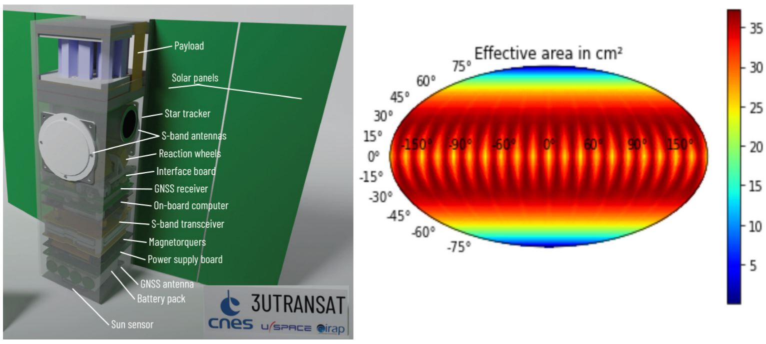

Fig. 2. Left: Schematic of one 3U Transat satellite: 1U for the science payload and 2U for the platform. **Right:** Illuminated surface of the science payload as a function of the source azimuthal and zenithal directions. The resulting azimuthal modulation of the detector surface allows to provide a 1-D localization of the detected events.

Each satellite will consist of a 1U science payload and a 2U-platform oriented "high performance" i.e. we priviledge localization capability for the demonstrator with respect to the detection performance. Thus the platform will embark components (e.g. star tracker, Sun sensor, magneto-torquers, reaction wheels, GNSS ‡) enabling a good restitution of the attitude and pointing direction of each satellite. So, the localization accuracy will be only limited by the event statistics.

The science payload will be made of a cylindric arrangement of 7 to 10 detectors (i.e. a 45 mm-high and 12 mm in diameter NaI(Tl) scintillator bar coupled with SiPM – see the left panel in Figure 2). This provides a modulation of the detector effective area as a function of the source azimuthal direction because of the screening induced by nearby detectors (see the right panel in Figure 2). As such, the illuminated surface of the payload could reach up to 38 cm^2. This provides a 1-D localization of the detected events. By combining the data from the three satellites with different pointing directions we can reconstruct a more accurate localization. The right panel in Figure 1 summarizes the main characteristics of the science payload.

Given that detection and localization will be done on ground, the science payloads will record count rates in four energy ranges from 15 to 200 keV with a time resolution of 50 ms. At each orbit these count rates will be downlinked through S-band telemetry to search for coincidental excesses exceeding the detection threshold by combining the data from all the satellites. Once an excess will be found, its localization will be computed through

*1U corresponds to a 10 cm cube.
†https://observing.docs.ligo.org/plan/
‡Global Navigation Satellite Systems

a maximum likelihood approach by comparing the counts measured on each detector with those expected from the detected event at different sky positions (see Figure 4). The resulting likelihood maps will be generated using the healpix format [4] to ease the comparisons with other missions. As mentionned in the left panel of Figure 1, the delay from onboard data collection to the broadcast of the first alert to the community shall not exceed 2 h.

2.2 *Project status*

Since the start of the project, we passed several important milestones.

- We have conducted with the help of the CNES/PASO [§] and the U-SPACE company a ~ 2 yr phase 0 on the 3U Transat project. The phase 0 final review will occur at the end of September 2022. This phase 0 study enabled us to endorse the proposed technical and programmatic operating point consisting of three clone 3U-satellites oriented towards a high-performance platform, to consolidate the architecture of the platform and payload as well as the mass & power budgets, to elaborate a realistic development schedule from phase A to phases C/D, to have an estimate of the total costs of the project;
- We received positive feedback from the CNES/GTAA for the project;
- We obtained with the help of the MECANO-ID company some funding for our proposal "Mechanical Architecture for Gamma-Ray Explosions Tracker" (MAGRET) from the French government through a CNES-led "New Space" initiative. This will allow us to build over the next 1.5 yrs a complete prototype of the science payload including a full thermal and mechanical characterization, helping to reach a TRL6.

2.3 *Expected performances*

To assess the performances of the constellation, we have built a dynamical simulator including various input parameters (e.g. a large population of GRBs of all types from the Swift/BAT and Fermi/GBM catalogs, CNES ephemerides including the orbits, attitude and pointing direction of each satellite, the cosmic diffuse X-ray background as source of noise, the effects of Earth blocking the instrument field of view and non operational parts of the orbit when the satellites cross the auroral areas and the South Atlantic Anomaly). The simulator also allows us to optimize the payload design & the satellite configuration as well as to predict the performances of a more ambitious constellation from the measures that will be done on the demonstrator.

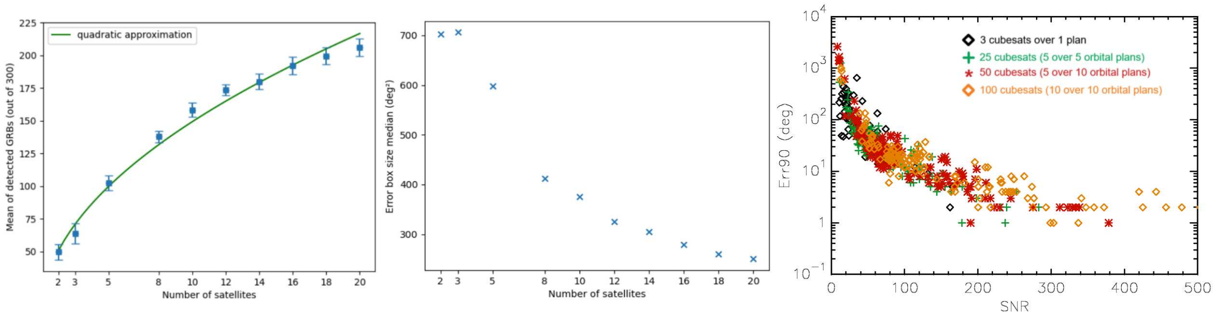

Fig. 3. . **Left:** Evolution of the GRB detection rate with the number of nano-satellites ($N_{\rm sat}$). For each simulation, the satellites are equally spaced on the orbit. For each datapoint, we ran 5 simulations taking into account different GRBs within our input source sample; which gives an estimate of the dispersion for each N_{sat}-value. **Middle:** Evolution of the median size of the 90% c.l. error box with $N_{\rm sat}$. **Right:** Ultimate localization accuracy for bright GRBs with T90-photon fluence $F > 20$ ph cm^{-2} as a function of $N_{\rm sat}$. For simulations done with $N_{sat} \geq 25$, the satellites are equally spaced on their orbits while for the demonstrator the 3 nano-satellites are spaced by more than 20°.

The left panel in Figure 3 shows how the detection rate evolves with the increase in the number of nano-satellites. Here in each simulation the satellites have been equally spaced over a polar orbit. The detection threshold is set arbitrarily at a signal-to-noise ratio of $SNR = 8$. In this satellite configuration, the rate of

[§] Plateforme Architecture Systèmes Orbitaux detection appears to flatten above 15 satellites, because the increase in the effective area is less effective to probe the faint end of the GRB brightness. For the demonstrator with the satellites equally spaced over the orbit, the GRB detection rate is around 40–50 GRBs per year (of which $< 10\%$ short GRBs and $\sim 6\%$ have 90% c.l. error box (Err90) size less than 50 deg^2). The middle panel in Figure 3 shows how the median Err90 size improves with the increase in the number of nano-satellites because there are more satellites with different pointing directions available to see a given GRB. The right panel in Figure 3 shows the ultimate localization accuracy for bright GRBs with T90[¶]-photon fluence $F > 20$ ph cm^{-2} as a function of the number of nano-satellites. In this example, the satellites could be placed on different orbital planes. Even for the demonstrator, the Err90 size for very bright GRBs (with a F-value larger than a few hundreds of photons cm^{-2}) could be of a few deg^2.

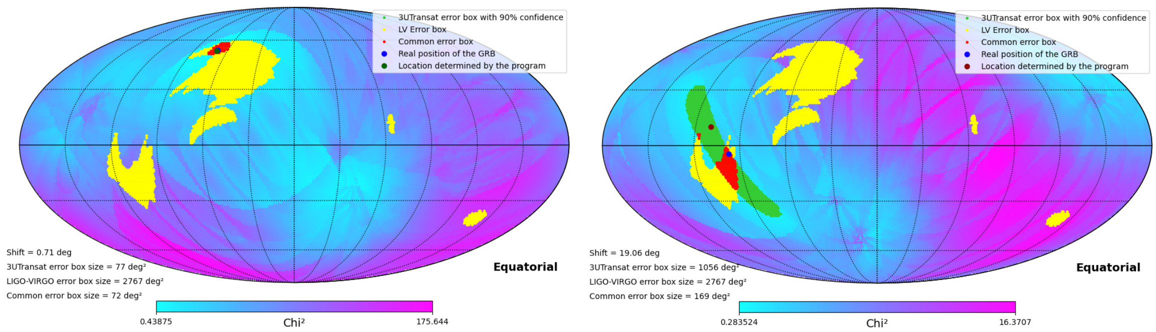

Fig. 4. Crossmatch of 3U Transat and LVK Err90 from coincident detections of short GRBs by 3U Transat (3 satellites – in green) and BNS mergers through gravitational waves (in yellow). **Left:** For a bright short GRB. **Right:** For a faint short GRB. Note that in both cases the reduction by more than one order of magnitude of the original LVK sky area.

In Figure 4, we show how 3U Transat could help improving the LVK Err90 size for BNS mergers by performing coincident detections of short GRBs. Our preliminary simulations shows a median reduction by a factor of ~ 7 of LVK Err90 size by cross-correlating 3U Transat and GW localization maps. Even for faint GRBs with large Err90 values, it is possible to significantly reduce the GW Err90 size. This could even be enhanced by using 3U Transat sensitivity maps (i.e. maps showing over which fraction of the sky a detected event could have been detectable by the constellation) to further improve the localization maps of faint events.

3 Conclusion

3U Transat is a 3 yr space project for demonstrating the benefits to deploy a constellation of three clone 3U-satellites operated in a low-Earth polar orbit to detect GRBs and other high-energy transients in synergy with multi-messenger detectors, VRO/LSST and high-energy satellites from mid-2026. The particular focus of the project is to assess the ultimate localization performance for bright GRBs reachable with our proposed science payload in the framework of nano-satellite technology. We plan to submit a phase A proposal to CNES by the end of 2022.

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