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TAROT: A NETWORK FOR SPACE SURVEILLANCE AND TRACKING OPERATIONS

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ABSTRACT

The TAROT (Télescope à Action Rapide pour les Objets Transitoires – Rapid Action Telescope for Transient Objects) network of telescopes consists of two 25cm aperture telescopes located at the Calern Observatory (TCA, OCA, France), the La Silla Observatory (TCH, ESO, Chile), and a 18cm telescope at Les Makes Observatory, (TRE, France). In addition we use the Zadko 1m telescope at the Gingin Observatory (ZDK, UWA, Australia). A central service in France, called CADOR (Centre d'Analyse des Données des Observatoires Robotiques, Centre for the Data Analysis of Robotic Observatories), acts as an interface for users, runs the scheduling system over the network, archive the data and run the core database. Since 1999 we perform observations of Resident Space Objects (RSO). Over the time we have implemented the observation of RSOs, mostly debris, on the geostationary orbit, and of passing objects in eccentric orbits, such as the GTO, or MEO/HEO. A specific data reduction pipeline with new methods for the image analysis has been developed and implemented by the CNES space debris modelling and risk assessments office to extract, process Space observations and to catalogue RSOs. As an example, in 2015, TCA has performed over 17000 measurements over the GEO monthly (average). TRE has been adapted to the observation of RSOs in November 2016, and it has made for its first 12 nights over 11000 measurements. In 2016, preliminary results show that the availability of the telescopes (TCA and TCH) is on the order of 90%. The TAROT network was recently used to observe the Arianne V233 Galileo launch, allowing observing the separation of the four satellites from the upper stage of the launcher, acquiring rare images of the passivation phase. We are now implementing operational procedures to use the TAROT network for the support of the CAESAR collision assessment system of the CNES. In this paper we present here the TAROT network, the methods and strategies we have developed, as well as statistics of measurements, some specific examples, and the perspective of the network within the context of Space Surveillance and Tracking.

1 INTRODUCTION

The observation of resident space objects (hereafter RSOs, either active satellites or passive debris) has several objectives: 1) the detection and cataloguing of new objects (from recent launches or losses of satellites), 2) the determination of the initial orbit and update of the orbit parameters, 3) the prevention of collisions, 4) the determination of the orbit of a newly sent satellite as well as of the launch bus after it has been passivated, and 5) the detection of unwanted operations either from an error of the operator or from malevolence. All these tasks are required for the satellite owner operator, for the verification of the respect of policies and international guidelines, as well as for the general surveillance of space. All these activities are usually termed as Space Surveillance and Tracking (SST).

So far most of the SST systems are ground based, though several space based SST systems are proposed (see relevant sections of these proceedings). Space can be surveyed by active or passive means. Radars belong to the first class and they are used widely for the surveillance of the low Earth orbit (LEO); their efficiency decreases as the fourth power of the altitude; they can be insensitive to small sized RSOs, depending on the wavelength used, though short wavelengths start to be absorbed by atmospheric water. Radars require high electrical power, and may require manned operations for security constraints. However they can operate 24h a day even through clouds. LADARs

(LIDAR radars) are efficient for the precise determination of the orbit, but the above mentioned d^{-4} vanishing of the signal applies, implying the need for retro-reflective devices on board the satellite; they cannot operate through clouds, and a prior determination of the orbit is needed, hence they cannot be used for discovery and cataloguing. As tracking radars they have to be manned.

Table 1: Main characteristics of the instruments: BI stands for back illuminated, DD for deep depletion, FI for front illuminated.

System	TCA	TCH	TRE	ZDK
Longitude	6°55’26”E	70°43’56”W	55°25’E	115°452’49”E
Latitude	+43°45’08”	-29°15’39”	-24°11’	-31°21’24”
Altitude	1270m	2347m	1000m	50m
Telescope Manufacturer	CNRS	CNRS	Takahashi/CNRS	DFM
Optical system	Newton hyperbolic	Newton hyperbolic	Newton hyperbolic	Cassegrain
Aperture	0.25m	0.25m	0.18m	1.0m
Focal ration	f/3.2	f/3.2	f/3.2	f/8
Mount type	Equatorial	Equatorial	Equatorial	Equatorial
Axes maximum speed	60°/s	60°/s	60°/s	5°/s
Axes maximum acceleration	120°/s^2	120°/s^2	120°/s^2	10°/s^2
Maximum pointing time	3s	3s	3s	60s
Pointing precision	5arcmin	5arcmin	20arcsec	20arcsec
Precision of tracking (no guiding)	5arcsec / 5min	5arcsec / 5min	3arcsec / 5min	3arcsec / 5min
Filters	Sloan g’, r’,i’, z’, clear, Density 100	Sloan g’, r’,i’, z’, clear, Density 100	No filter	g’, r’,i’, z’, clear, Density 100
Camera manufacturer	ANDOR	ANDOR	FLI	ANDOR
Camera model	IKON L936 BEX2 – DD	IKON DW 436 N – BV	Proline PL16803	IKON L936 BR - DD
Sensor	E2V4240, BI, DD	E2V 4240, BI	KAF 16803	E2V4240 BI, DD
Diagonal of active area	37.7mm	37.7mm	52.1mm	37.7mm
Number of pixels	2048 x 2048	2048 x 2048	4096 x 4096	2048 x 2048
Size of pixel	13μm	13μm	9μm	13μm
Readout speed (usual)	1MHz / 5s	1MHz / 5s	1MHz / 5s	1MHz / 5s
Readout noise (1MHz)	7e^-	8e^-	11e^-	7e^-
Thermal noise @ -80$^{\circ C}$	0.006 e^-/px/s	0.0015 e^-/px/s	0.05 e^-/px/s	0.006 e^-/px/s
Typical exposure time for SST	10 – 30s	10 – 30s	10 – 30s	10s
Sensitivity (R_{mag}) in 1 min	18	17	16	20

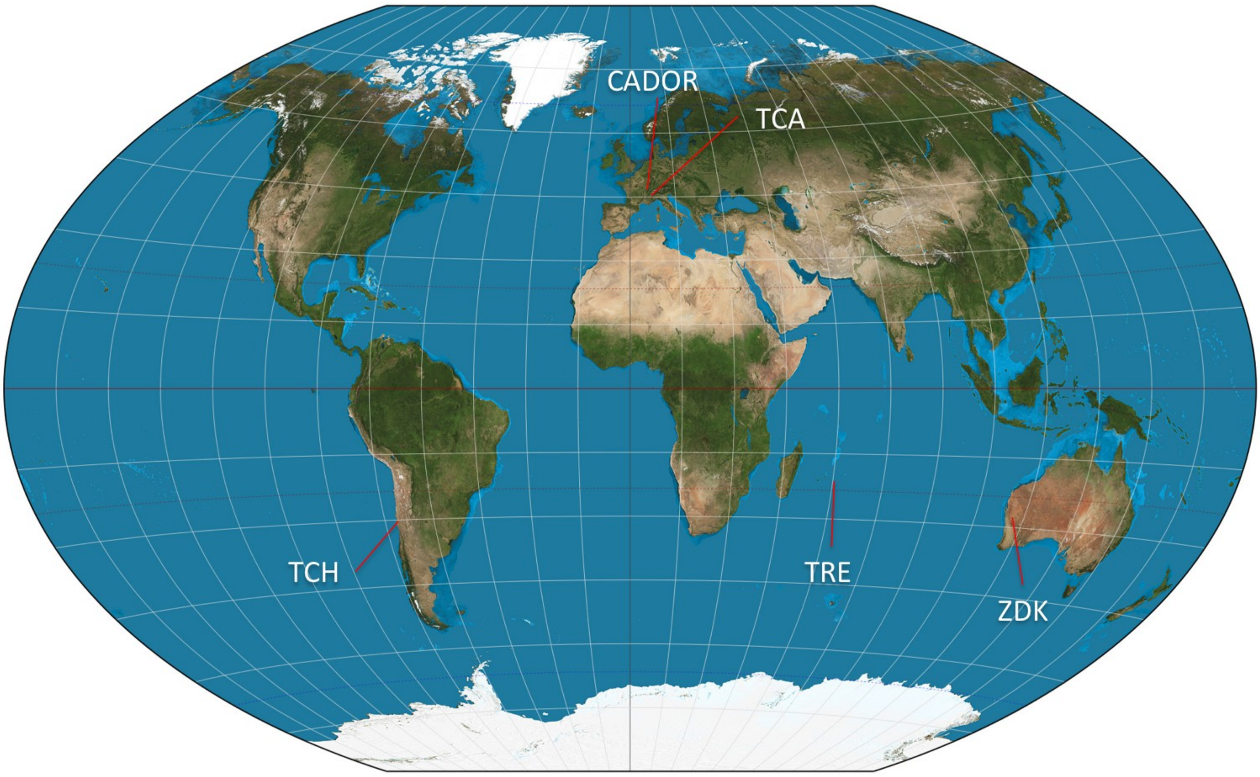

Figure 1: World map (source Wikipedia) featuring the locations of the telescopes of the TAROT / Zadko system, and of CADOR.

Passive optical systems, i.e. telescopes with electronic detectors of all sizes, have been developed for the surveillance of the geostationary orbit (GEO) and orbits close to it (e.g. debris leaving GEO and drifting along the equator). They are usually working in the visible domain, though the infrared has been explored [1]. Passive optical systems, even of moderate size, can detect small objects at low and high altitude, thanks to the Sun as the illumination source [2,3]. Telescopes are easy to automatize [4,5], they are economical in terms of the use of resources, they can operate in full autonomy, and the data reduction methods are known, though there is a vast literature to achieve better performance [2,6-10]. The main disadvantages of optical telescopes are: 1) they require good weather to work (i.e. no clouds), and 2) they are restricted to nightime observations, while the RSO must be lit by the Sun. The later is mostly a problem for LEO, while RSOs in high altitude orbits are visible along the night, excepted short periods around the equinox; the use of infrared detectors can also expand the detectable time, which is of interest mainly for LEO.

The TAROT (Télescope à Action Rapide pour les Objets Transitoires – Rapid Action Telescope for Transient Objects) network of telescopes belongs to the class of passive systems for the SST. Its development dates back to the mid-nineties, and it features now three small telescopes with the addition of a large 1m telescope. It is fully robotized: robotization here means that there is no human in the loop, either for the requesting, scheduling, operations, data processing and archiving.

In this paper we present the network and its architecture, its performances for SST, some featured results, and the planned evolutions. This paper is structured as follows: in the next section we present the history and the main hardware features of TAROT; in section three we describe the software used for the scheduling and the data processing and archiving, then we present the perspectives of the network, before the concluding remarks.

2 THE TAROT NETWORK

The first TAROT telescope saw its first light in 1998 and it was designed for the observation of the visible counterpart of cosmic gamma ray bursts (GRBs)[11]. It is located in France, on the Plateau du Calern of the Observatoire de la Côte d'Azur (OCA). As of 2000 TAROT Calern (now named TCA) started to observe the GEO in collaboration between the Centre National de la Recherche Scientifique (CNRS – National Centre for Scientific Research) and the Centre National d'Etudes Spatiales (CNES – National Centre for Space Studies, French Space Agency). In 2002 a new

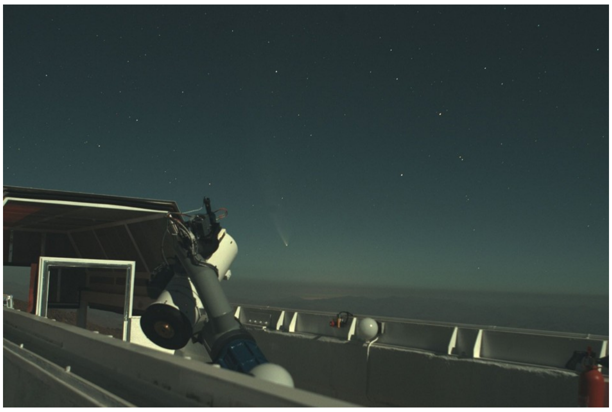

Figure 2: TCH operating at night, with the comet Mc Naught.

In 2002 a new instrument, now named TCH (Fig. 2), was setup at the La Silla Observatory (LSO) of the European Southern Observatory (ESO), and from the beginning used both for astrophysical research and SST [12,13]. In 2003 the University of Western Australia 1m *Zadko* telescope (ZDK) joined the network [14,15]. Finally, by the fall of 2016 a telescope was refurbished and installed at the Les Makes Observatory on the La Réunion Island (France), and named TRE.

In addition to the telescopes we have installed at the Haute Provence Observatory (OHP) the CADOR system (Centre d'Analyse des Données des Télescopes Optiques Robotiques – Data Analysis Centre for Optical Robotic Telescopes) that is a single interface for the sending observation requests, planning the schedule of individual telescopes, getting, archiving and analysing the data offline.

The observatories and the telescopes

TCA and TCH are custom made 25cm telescopes equipped with ANDOR cameras, and are almost identical. TRE is a Takahashi 18cm aperture telescope with a FLI camera. ZDK is a 1m telescope from DFM with an ANDOR camera. Tab. 1 summarizes the main characteristics of the telescopes, and Fig. 1 displays a world map with the location of the elements of the system.

The choice of a Newton hyperbolic configuration guaranties a wide field of view (1.8° x 1.8° for TCH and TCA, 4° for TRE) while keeping the obstruction by the secondary at a minimum. For ZDK the large aperture makes the choice of the Cassegrain configuration with a 2 lenses corrector appropriate; its field of view is 20 x 20 arcmin^2 on the camera.

The mounts are equatorial. TCH and TCA were designed and built by the CNRS – INSU Technical division. They are able to slew at a maximum speed of 60°/s, i.e. within 1s for most of the points in the sky.

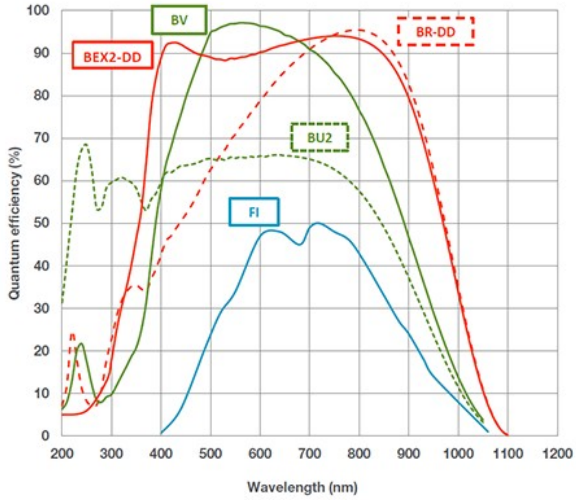

Figure 3: Quantum efficiency of the various models of the IKON L936 ANDOR cameras (courtesy ANDOR).

This performance was requested by the prime objective of the observation of gamma-ray burst positions on alerts from the GCN/TAN system (Gamma-ray Coordinates Network – Transient Astronomy Network, full description available at https://gcn.gsfc.nasa.gov/). The combination of a rapid mount and rapid readout from the camera is still very attractive for SST as it gives a high throughput and enables to survey a large part of the GEO belt along the night, or to image RSO positions several times during the night.

The mount of TRE has been designed and built at CNRS – IRAP and we see it as a new concept of rapid, precise, versatile yet cheap mounts for our future telescopes. It is capable of slewing at large speed (> 60°/s) with 20 arcsec precision to any point of the sky, while tracking within a pixel for at least 10 minutes. It can be used either in equatorial or alt-azimuthal mount configuration.

All telescopes are fully automated and the system monitors the weather, primary electrical power supply, and various housekeeping parameters to keep operations safe. Before and after the night the system runs a sequence of dark and bias frames, as well as flat field exposures on a dedicated screen inside the building. The on-site maintenance for distant telescopes consists of two periods of 10 days each year.

The detectors

After several trials the choice has been made to use the ANDOR cameras for TCA, TCH and ZDK. For TRE, as we see it as a prototype before installing a larger instrument, a relatively cheap, yet of good quality, Finger Lake Instrument (FLI) PL 16803 camera has been chosen.

The first generation of ANDOR cameras were the DW 436 equipped with the E2V 4240 back illuminated CCD. They were bought between 2003 and 2006. TCH is still using a 2003 camera that has excellent quality and no noticeable problem since 14 years. In 2015 we replaced the ZDK camera, and in 2016 the TCA camera with the new Ikon L936 ANDOR camera still based on the E2V 4240 CCD. ZDK features a deep depletion CCD that supresses the fringes in the infrared; TCA has a deep depletion layer with enhancement (BEX2 – DD) of the response in the blue part of the spectrum that makes its quantum efficiency above 50% between 350 and 980nm, with the response above 90% between 400 and 850nm (Fig. 3).

As it can be seen from Tab. 1 the noise performances of the ANDOR IKON cameras are excellent, especially with regards to the speed at which the camera is read (1MHz usually, but we use sometime the 3MHz mode).

The FLI PL16803 camera has a large 52mm diagonal KAF 16803 CCD from Kodak. Though front illuminated, the efficiency is above 50% between 450 and 650nm. The resulting field is 16 deg^2, and excellent choice for the survey tasks. This system can be seen as a good compromise for a prototype instrument, when a large field of view is searched for, with no absolute performance. The results described in section 4 validate it, for an instrument that started its first light for SST in 2016.

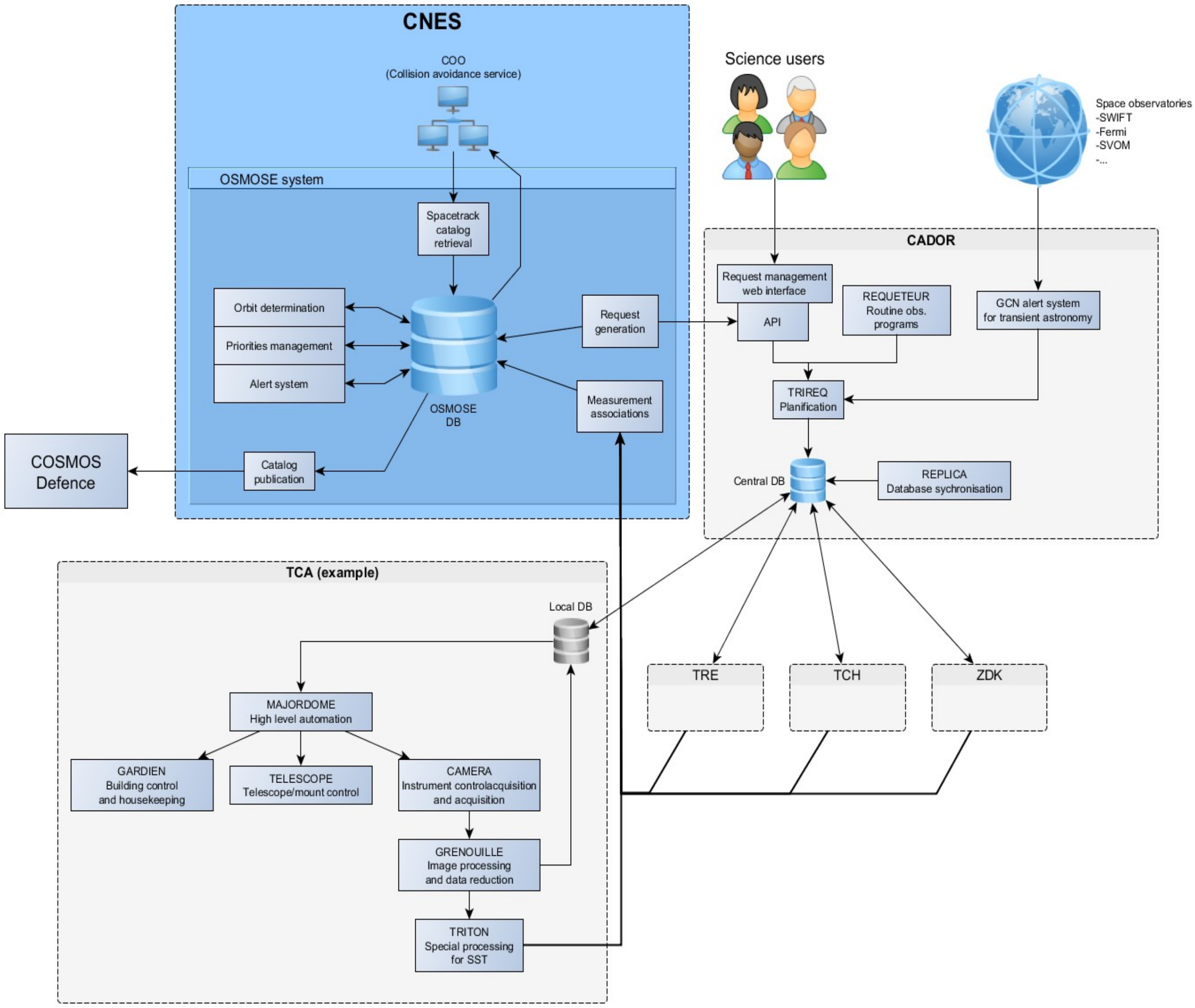

Figure 4: Overview of the software chain of the TAROT system.

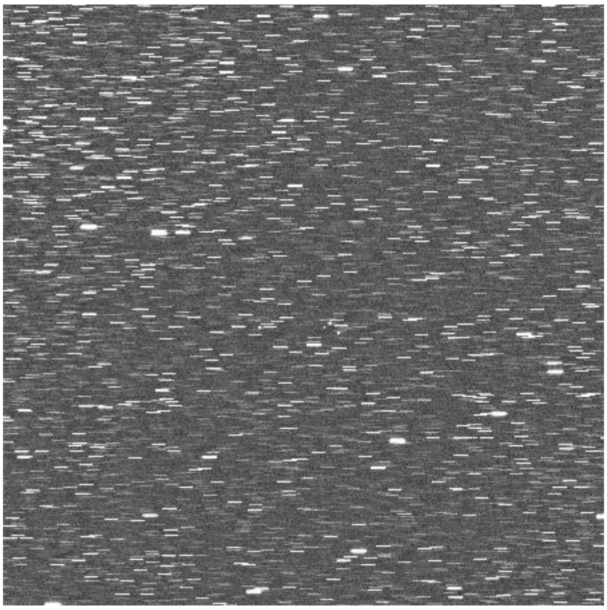

Figure 5: A typical image of satellites in GEO taken from TCA

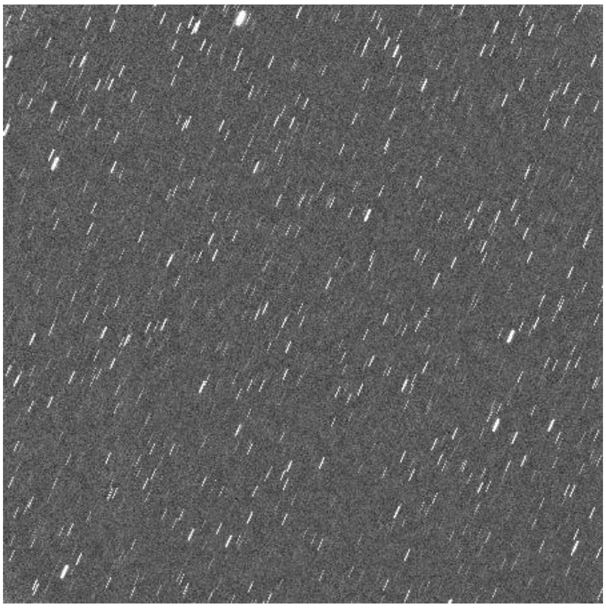

Figure 6: A satellite tracked by TCA.

3 OPERATIONS AND SOFTWARE

Overview

A general view of the system is given in Fig. 4. The system has some centralized parts, such as OSMOSE in the CNES and CADOR (Centre d'Analyse des Données des Observatoires Robotiques – Robotic Observatories Data Analysis Centre) at OHP – CNRS, and distributed softwares that run with the telescopes: this philosophy makes the system more robust in the event of a loss of communication. In this eventuality, the service may be degraded.

Users and requests

TAROT has different types of users. The science users generate the requests through a web interface, either filling a form or uploading a file containing the scenes, i.e. the location, telescope, specific requirements such as the axes speed (e.g. for solar system objects), the filters and exposure times, etc.

A specific type of "science user" is the GCN that generates alerts either from satellites (*Swift*, *Fermi*-GBM, INTEGRAL, in the future SVOM) or from the LIGO and Virgo gravitational wave observatories. Alerts may be generated directly by the ANTARES neutrino observatory. An interface has been build between the CNES and the CNRS for TAROT, that prepare requests either from a survey program of the GEO, from the CAESAR (Conjunction Analysis and Evaluation Service, Alerts and Recommendations) collision avoidance service, or from other external users.

The requests are all managed by the CADOR system at OHP (Observatoire de Haute Provence) on virtual machines. After the initial checks, the requests are saved in a central database system and the REQUETEUR software prepare them. Then they are all (SST and science requests) sorted by the TRIREQ program that prepares the schedule for each telescope and stores it in the database, before the REPLICA system synchronises the central CADOR database with the local databases located at each telescope (ZDK, TCA, TCH, TRE).

Should an alert occurs, TRIREQ insert the specific observations in the timeline, and all observations are stopped to run the alert program at the telescopes that are able to observe it.

Local operations

Each telescope runs the same high-level programs, albeit they can be customized according to the specific sites. The maintenance is centralized in CADOR.

The MAJORDOME program is the central piece of the high level automation. It uses the information from the GARDIEN program for the housekeeping and weather parameter, and of the various parameters given by the TELESCOPE and CAMERA programs; then it schedules the various requests according to the timeline stored in the database, send the appropriate orders to the TELESCOPE and CAMERA program. As soon as a new image appears, the GRENOUILLE software processes it. For science users (including alerts), the GRENOUILLE makes the basic reduction steps (flat fielding, bias and dark removal), then the astrometry and image analysis.

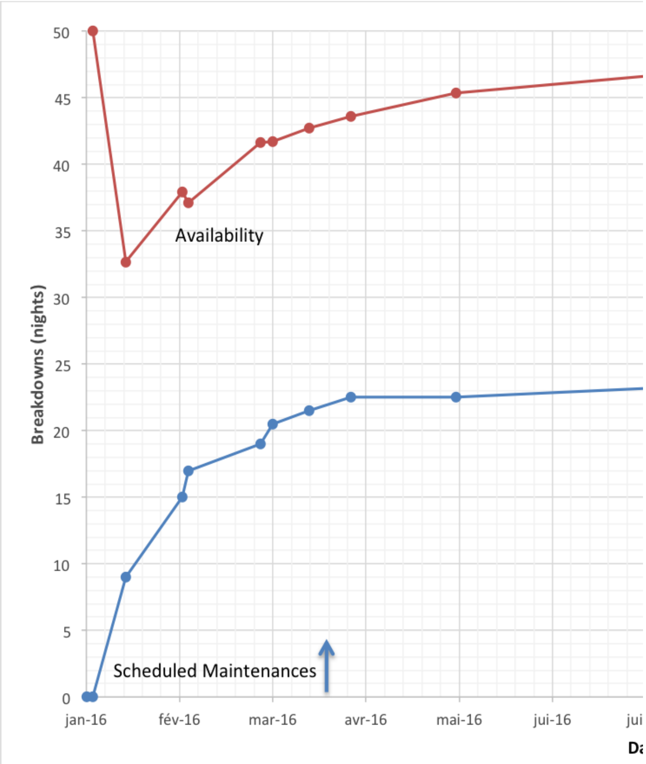

Figure 7: System efficiency statistics of TCA and TCH (see text): the overall efficiency increased to more than 90% after repair in January 2016. The various breakdown (instrumental, hardware or software), are shown together with their duration. The scheduled maintenance periods (March and September for TCA, November for TCH) are also shown with their duration (arrows), but are not taken into account for the computation of the system efficiency. Weather interruptions have not been taken into account.

For SST users, the basic steps are still handled by the GRENOUILLE, but then the image is passed to the newly developed TRITON image analysis package [16]. This software associates the measurements from an image and computes tracklets. Each tracklet are made from a series of measures that are consistently matched and has 4 parameters, 2 for the position (alpha, delta) and 2 for the speed (the derivatives of alpha and delta). As a first approximation, we suppose that the orbit is circular, and a first orbit is computed with 4 parameters. If this process is successful, then the detection is considered as valid.

Then TRITON passes the results of the image analysis and RSO search directly to the OSMOSE system at CNES, while the content of the local database is enriched and sent to CADOR through REPLICA. For practical reasons, images are saved on local disks, which are sent to the OHP physically twice a year.

For satellites in the GEO, the telescope follows the satellites (i.e. it does not move relative to the Earth, but the motors and encoders are active), and the stars are trailed for 10s (Fig. 5). For satellites moving relative to the Earth (HEO, MEO, GTO, etc.) the telescopes tracks the RSO (Fig. 6).

Given a mean of 400 images a night, about 3GB are generated each night at each telescope.

CNES scheduling and processing system: OSMOSE

The results of the local analysis by TRITON are sent to the OSMOSE database system in CNES, Toulouse. OSMOSE matches the different measurements of an object, then computes a precise orbits. It manages also the priorities for further observations of specific RSOs. On request from the CAESAR collision avoidance service an alert is prepared by the OSMOSE system and observations are scheduled with high priority and inserted in the CADOR database. OSMOSE uses as input the Spacetrack catalogue, as well as the results from TAROT and possibly other devices.

Finally OSMOSE publish a catalogue, which is used for internal tasks, and send to external users for SST related activities.

4 SYSTEM PERFORMANCE

General performance

Fig. 7 shows the overall performance of the system. The breakdowns are shown as a blue line for both TCA and

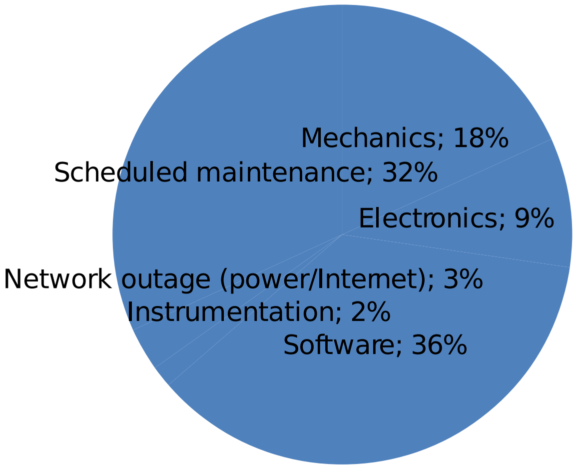

Figure 8: Relative fraction of the various causes of breakdown for TCA and TCH.

Fig. 7 shows the overall performance of the system. The breakdowns are shown as a blue line for both TCA and TCH. The total number of night losses for outage is 45 that convert to a mean of about 3 weeks per telescope.

In addition two periods of maintenance have been scheduled at TCA and one at TCH (the second took place in February 2017), adding 21 night lost, for a total of 66 nights, i.e. approximately 1 month per telescope or 18%.

The interruptions for weather are about 30% at TCA and 17% at TCH. This is less than the statistics given by the observatories, as TCA and TCH run as soon as the sky is clear (according to the weather monitor; there is only a minimum delay of 15 minutes between the closure of the roof and its re-opening, whatever the reason), and the limit for hygrometry is less stringent than that imposed on the other telescopes (90% for TCA and TCH, usually 80% in a typical observatory).

The reasons for failure are shown in Fig. 8. Beside the scheduled maintenance periods, the main reason is a crash or a bug in the software. The main mechanical problem has been a failure of the coupling of the TCH filter wheel: the breakdown lasted for 9 days, illustrating the difficulty to identify and fix a failure at a distance.

4.1.1 Image statistics

Between October 21st, 2016 and April 9th, 2017 16828 images have been acquired in the framework of the SST program for TRE, 18722 for TCH, and 29309 for TCA. The difference between the telescopes can be explained by several networking problems at TRE, as well as some hurricane alerts, and the preventive maintenance period of TCH, while the maintenance period of TCA occurred in September with a full mechanical adjustment, and the replacement of the PMAC automation board.

More details on the images taken are summarized in Fig. 9, and detailed for each telescope (TRE, TCA and TCH) in Fig 10-12.

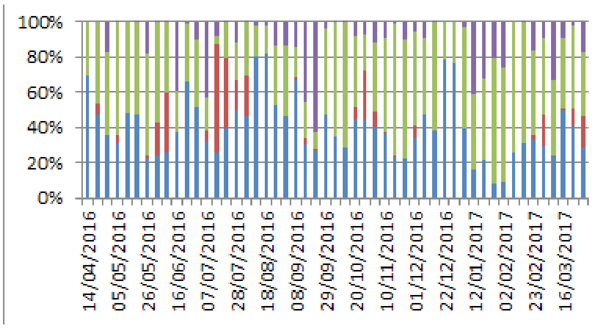

Figure 9: Weekly statistics of the relative fraction of images taken by TRA, TCA and TCH: blue, valid images; pink, failure; red, delayed; green, bad weather.

The precision for localization of a RSO in an image in 1 arcsec for TCA and TCH, 0.8 arcsec for TRE, corresponding to about a third of a pixel size on the sky.

Table 2: Number of images and number of measurements that lead to an orbital element circular with 4 elements (circular orbit hypothesis), for TCA, TCH, and TRE.

Instrument	Number of images	Number of measurements
TCA	21122	52773
TCH	28146	13095
TRE	43333	8353

Tab. 2 presents the statistics of the TAROT network for the 4 parameters (cf. section 3.2) measurements that lead to an orbit under circular hypothesis . Each image of TCA and TCH leads to about 2 – 2.5 measurements, while TRE, with its wide fov, produces about 5 measurements per image.

4.1.2 Support to the CAESAR collision assessment service

CAESAR is a public service run and provided by CNES to French and European satellites. Whenever there is a risk of collision in the GEO orbit, the CAESAR team sends high priority requests to the TAROT network telescopes via a dedicates interface and using operational procedures. The measures are used to improve the orbit of the debris and to better assess the risk level. Therefore the collision probability and the necessity of an avoidance manoeuver can be better assessed.

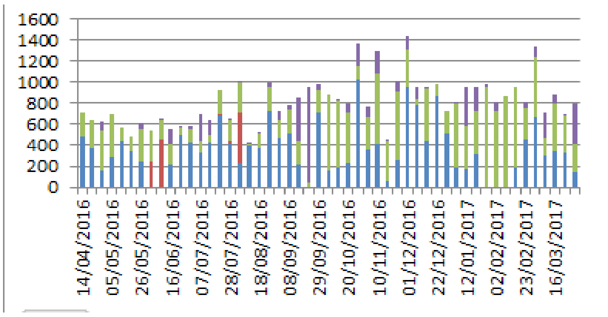

Figure 10: Same as Fig. 9, but for TCA only and absolute weekly numbers

4.1.3 Observation of the Ariane VA233 launch campaign (Galileo)

The TAROT network has observed the Ariane V launch VA 233 of four Galileo satellites from the Kourou Space Centre. An intensive observation campaign took place for all the telescopes of the network for a week. Fig. 13 shows the separation of the satellites from the EPS (Etage de Propulsion Supérieur – Upper Propulsion Stage) of Ariane. The four small dots are the Galileo satellites that have been released in pairs. The large dot is the EPS seen outgassing for the passivation (the "smoke" on the image), as required by the French Space Operation Act.

These observations, performed by all the telescopes of the TAROT network, are not only a means to compute and verify the first orbits of the Galileo systems. They can also be used to assess the orbit of the EPS after it has been passivated, i.e. with no means of control, and to verify that the orbit is a long term parking orbit that complies with the French and international guidelines.

5 Conclusions and Perspectives

Perspectives

The TAROT network has become more and more reliable, with a MTBF around a month now (excluding bad weather), and a system efficiency around 90% for TCA and TCH. It is too soon to derive statistics for TRE since its upgrade in the La Réunion Island,

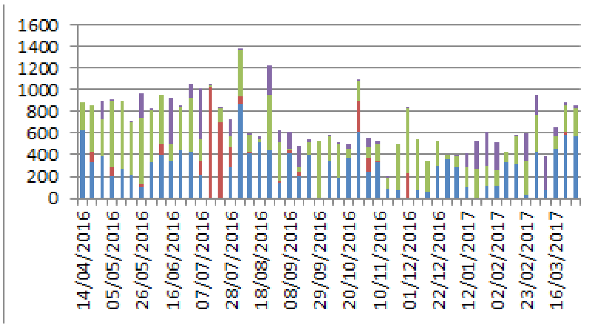

Figure 11: Same as Fig. 10, but TCH.

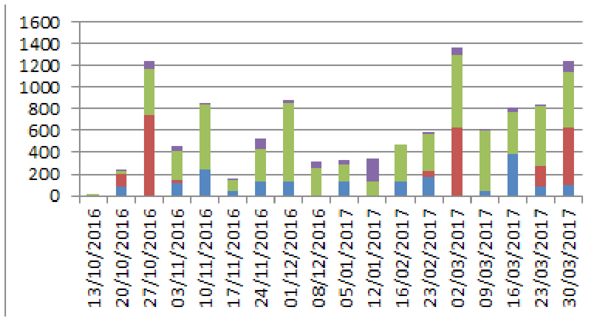

Figure 12: Same as Fig. 10 and 11, but for TRE.

but the first impression is that its reliability is on the same order as its brother telescopes.

The possible evolutions are:

- Enhance the reliability of the network, replacing all single points of failure by redundant hardware: we are working on that, however, some parts (e.g. motors, amplifier, camera) cannot be duplicated, though we have spare parts whenever possible.
- Enhance the reliability of the software chain and its security: we are currently engaged in a major effort.
- Enhance the efficiency of the existing system: we are working on that. As an example we are replacing the old ANDOR camera by BEX2 – DD cameras, and the Cousin filters with Sloan type filters; this enhance the overall quantum efficiency and the adequation of the filters to the camera response. We have recently implemented a new imaging software that is more robust and has better detection performance. We are also hunting all dead times in order to reduce them to a minimum, resulting in more reactivity and throughput of the system.
- Replace the existing telescopes / sensor combination with more sensitive one. This supposes to use larger telescopes, thought keeping the field of view. ZDK is already a response to this problem, and this 1m telescope provides sensitive observations of RSOs of known orbits. After the qualifying phase, we plan to replace TRE with a larger instrument, possibly on a higher site on the La Réunion Island. The replacement of TCA and TCH is not a priority, as these instruments have proven their qualities and the adequation of the optical/sensor combination to the problem of RSOs.
- Extend the network to new locations: this is important in order to follow the orbit of debris, and to be able to survey the launch and station-keeping manoeuvres of satellites, notably those

equipped with electrical propulsion. We are currently discussing the implementation of new instruments in new sites, among them Australia and French Polynesia.

- Develop new concepts to observe new orbits, especially LEO. The reader is referred to the accompanying paper on the MétaTélescope in this conference [17].

Figure 13: The Ariane V233 launch of four Galileo spacecrafts. The EPS is seen outgassing before passivation, and the four Galileo satellites are clearly seen and released by pairs (TRE image, CNRS – CNES).

Conclusions

Albeit started as a secondary objective of an astrophysical experiment, the TAROT telescopes have proven their efficiency in Space Surveillance and Tracking activities. Over the years the network has extended, and its reliability has importantly improved (>90% reliability).

About 40% of the observing time is now devoted to the observation of RSOs by TAROT, either as a survey task or in support to collision assessment activities, as part of the emerging European SST system.

We have developed a new mount concept that enables the observation of lower, i.e. faster from the observer point of view, orbits. The next steps will be the expansion of the network and the development of a new type of instrument for the observation of the LEO.

Acknowledgements

TCA and TCH have been built thanks to the support of the *Centre National de la Recherche Scientifique*, *Institut National des Sciences de l'Univers*, *Division Technique*. The *University of Western Australia Zadko Telescope* has been built thanks to the generous donation of James Zadko. The CNRS, the CNES, and the European Commission support the TAROT network.

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