remote sensing

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New Astronomical Observatory Design for the Detection and Tracking of Satellite Objects: The Satellite Robotic Observatory (SRO)

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Abstract: Robotic Astronomical Observatories (RAOs) have provided very good results in different research projects in astrophysics/astronomy. Their applications in the detection, tracking, and identification of near-Earth objects have contributed to the identification of potentially dangerous objects for our security, such as near-Earth Objects (NEOs), near-Earth Asteroids (NEAs), meteors, and comets, whose trajectory changes can cause an impact on our planet. If advances in astrometry techniques (measuring the position and trajectory of Earth-orbiting objects) and photometry (variation in light curves) are considered together with the new sensors that work in the optical and near-infrared spectral ranges, a new observatory system that allows for the detection of nearby satellite objects in different spectral ranges and with better-defined optics can be developed. The present paper describes the design of a new observatory applied to the surveillance and tracking of satellites and other debris objects, the Satellite Robotic Observatory (SRO). Starting from general constraints from astronomy observatories, the design process has been determined, considering the main objectives, the necessary sensors, and several technical improvements that have contributed to a final configuration proposed for the SRO. The result is the design of a portable observatory model that can host at least two sensors to track and monitor satellite objects simultaneously.

Keywords: astronomical observatory; space debris; orbit determination; satellite tracking; space surveillance

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1. Introduction

The study of objects close to our planet (such as near-Earth objects (NEOs), near-Earth asteroids (NEAs), satellites, and comets) and the physical phenomena associated with their entry into the Earth's atmosphere began in the 1860s with the observations of A.S. Herschel [1]. Since the late 19th century, photographic techniques have been used to observe meteors [2]. From the 1950s onwards, the study of the emission spectra produced in the atmospheric entry process of these natural objects began [3]. Furthermore, it can be mentioned that several new video techniques have been developed to study these phenomena within the last half century [4–7].

In contrast to photographic image captures, video techniques have allowed for the recording of relatively faint meteors [5], so celestial objects with an apparent visual magnitude range of 3 ± 1 can be captured [8]. The light emitted by meteors during the ablation process in the Earth's atmosphere makes it possible to study, from at least two stations, their trajectory, the radiant of origin, and the orbit of their progenitor in the solar system [9]. These studies are known as astrometry, where the variation in the object's position is measured, and photometry, where the variation in its light curve is studied.

Astronomical observatories protect the optical equipment and sensors housed within them and allow for a configuration that allows them to work autonomously [10] or remotely. In recent decades, Robotic Astronomical Observatories (RAOs) have evolved significantly [11]. In some cases, this evolution has produced reduced-size RAOs when the equipment and sensors are small (wide-field and short-focal telescopes) [12,13]. Reducing the size of the RAO reduces the cost and infrastructure required for it to operate effectively. This new generation of small RAOs has led to significant advances in numerous research projects, such as the early detection of potentially hazardous near-Earth objects and asteroids, the study of meteors and meteorites, and even the detection of supernovae and gamma-ray bursts [14–16]. These research works have been developed, thanks to the possibility of having several RAOs in different geographical locations, which is a considerable advantage, having a greater number of hours of observation and monitoring of these phenomena.

The investigation of minor solar system bodies and near-Earth objects has traditionally been performed with very bright, short focal length, wide-angle optical systems [17,18]. The objective has been to capture images of a wide region of the firmament to detect meteoroids and other objects coming from asteroids whose orbit and trajectory were unknown [19]. These optical devices and sensors have been located in astronomical observatories whose technical characteristics prevented the inclusion of additional optical systems (Figure 1). The traditional RAO has always had a dome on its roof, so only one telescope could be installed. This very limited configuration does not allow for additional equipment, since the observation window of the dome only allows working with a single optic and sensor. With regard to instrumentation, it should be mentioned that optical devices and sensors for capturing images of natural objects close to our planet are becoming increasingly common in ground-based space observatories [20,21]. CCD (Charge-coupled Device) sensors for capturing space images in the optical and near-infrared ranges have played a prominent role in comparison to alternative and newer technology represented by CMOS (Complementary Metal–Oxide–Semiconductor) image sensors, due to their heritage and their higher quality images (better fill factor and dynamic range values). Nevertheless, CMOS image sensors have become more and more popular in the last few years, as they are less complex and offer faster processing speed and lower power consumption [22,23].

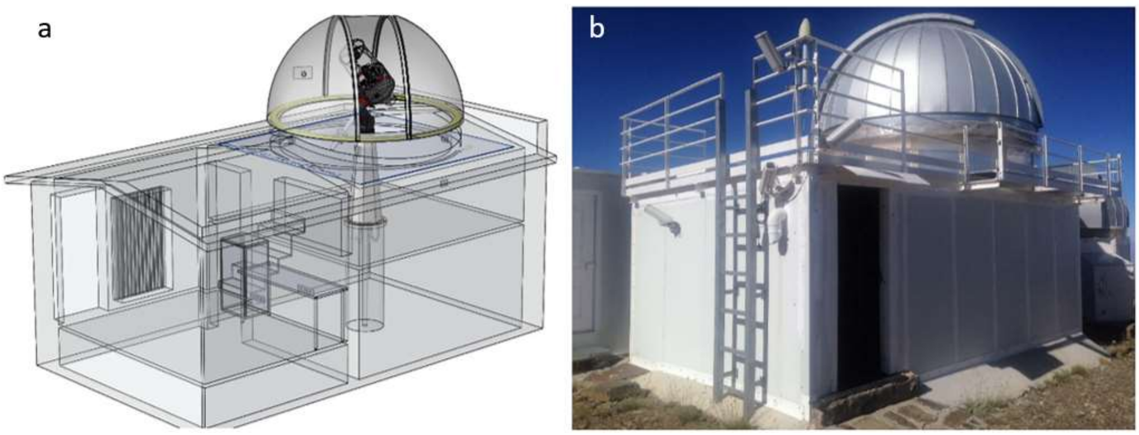

Figure 1. Classic design of an RAO for a telescope and dome (**a**). Image of an RAO at the Sierra Nevada Astronomical Observatory (**b**).

To accommodate several pieces of equipment with different optics and sensors, the RAO design needs to be modified [24]. A new model without a dome, with a retractable or roll-off canopy, provides a clear sky from the horizon to the zenith (Figure 2) without any obstacles or limitations, which is an important advantage when it is necessary to detect objects that are close to the horizon.

Figure 2. CESAR Astronomical Observatory. ESA-ESAC (Villafranca del Castillo-Madrid). RAO with open roll-off roof (**a**). S/C 12″ telescopes (each one on one of the two pillars displayed in the picture) at f/10 and two CCD cameras, Atik 314 L+ and Atik 4400 (**b**). RAO with closed roll-off roof (**c**).

With these systems, different images of the same object can be obtained, improving the accuracy of its orbit calculation and trajectory and even determining its parent object [19,25]. If at least two sensors with different optics are available, the RAO activities can be diversified and expanded. The combination of several optics and sensors allows for the capture of wide-field and even all-sky images to monitor phenomena in a wide region of the sky, and also the tracking of other celestial objects, with higher precision and lower apparent brightness.

In the present paper, the design of a new type of ground-based observatory, the Satellite Robotic Observatory (SRO), capable of tracking and monitoring a satellite in Earth's orbit, is described. With a reduced size and being able to be easily deployed, this observatory should be considered an evolution of the RAO to cover situations that require temporary observations from a specific location and/or lower cost of development.

The present paper studies the general design of an SRO from some initial constraints (Section 2) to the instrumentation it should comprise and the possible results (Section 3). A general discussion is also included in Section 3. Finally, the conclusions are summarized in Section 4.

2. Design Constraints and Methodology for the Design of a Satellite Robotic Observatory (SRO)

To design an observatory that can perform surveillance and tracking of Earth-orbiting objects at low/middle altitudes (that is, satellites and space debris), the following three fundamental issues should be taken into account:

- An effective design project must be developed according to the primary objectives for which the observatory is needed: tracking and surveillance;
- Selection of the optimal location and orientation, so that the telescopes and sensors can detect the objects of interest;
- Selection of the optical equipment, sensors, mounts, optical accessories, and software to obtain images and their processing provides the data of our interest, such as orbital parameters, for identification or light curves for characterization.

2.1. Development of a Satellite Robotic Observatory (SRO)

The premises stated above can be developed in three different phases (see Figure 3). In Phase 1, the objectives to be pursued must be defined, such as the detection, monitoring, and tracking of space debris and artificial satellites. Next, it must be specified how these activities will be developed, considering whether it is intended to work remotely or with human presence.

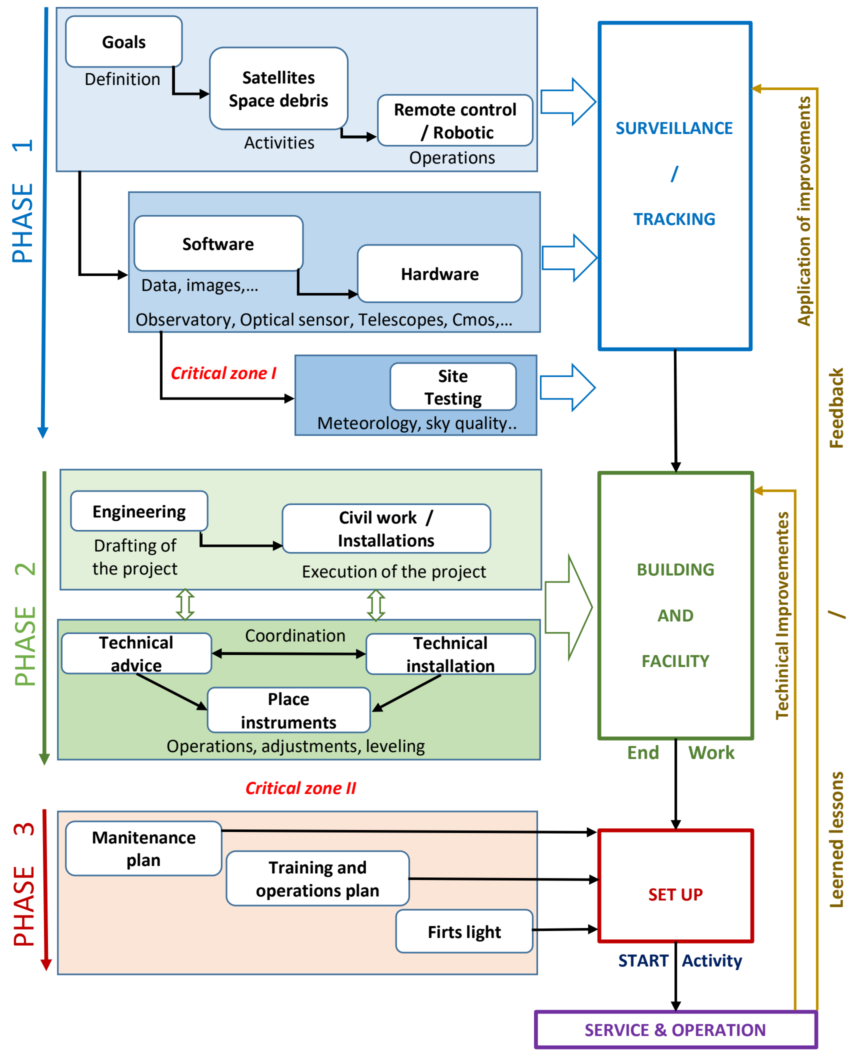

Figure 3. Sequential diagram of operations to design an SRO.

The initial objectives must give way to the selection of the required optical instrumentation, its mounts and movement systems, CCD and CMOS image sensors, and other auxiliary elements of measurement, optics, or image capture. It is also very important to detail the control systems of these devices, such as the necessary computer hardware and software that should provide the required information through the captured images.

It is important to bear in mind that all sensors and equipment of the SRO must be compatible with the systems present in the installations. Consideration should be given to the type of roof required (roll-off, folding roof, vault, etc.), Uninterruptible Power Supply (UPS), remote control systems, and the incorporation of a weather station, which can regulate and control the operation of the observatory in case of inclement weather [26].

Once these first steps have been completed, an important step follows, since all the initial technical premises must be incorporated into the data obtained from the site testing (see the following subsection) of the possible locations. The decision taken at this point will be fundamental for the correct operation of the SRO.

In Phase 2, it is necessary to address the needs of the SRO in terms of infrastructure and adaptations to civil works, which, once defined, will need to combine technical and scientific criteria to successfully address the second important step [27]. At this point, it is necessary to define the correct use and location of the optical systems and sensors. By sharing space within the same SRO, it is necessary to define how each piece of equipment will work, its correct location and orientation, and even establish a regime of priorities of use for surveillance and tracking of the objects to be selected.

In Phase 3, it is crucial to face the development of a detailed maintenance plan so that the SRO can operate normally and not suffer major breakdowns or shutdowns. It is also essential to establish a training and commissioning plan that guarantees and trains the personnel necessary for its operation.

Finally, relevant information might be obtained from the degree of agreement between the results and the objectives proposed at the beginning of the project. By analyzing these results within the frame of the initial objectives, new lessons will be learned, which will serve as feedback for future improvements and updates.

2.2. Site Testing

The correct operation of an astronomical observatory will depend on its location and orientation. Therefore, it is necessary to study the characteristics of the possible locations carefully, since the performance of the optics and sensors are affected by the one chosen. To this end, the meteorological characteristics and climatic conditions, altitude, and other technical elements such as the availability of a good electrical connection, data network, and good accessibility must be taken into account [28].

The evaluable parameters for determining the best location of an SRO are not as demanding as those for a common astronomical observatory. The focus should be on what can affect the astrometric determination of an object or the analysis of its light curves. If we take these assumptions into account, we can reduce the site test to the following parameters [29]:

- From a meteorological point of view, it is essential to look for a place with a very low index of relative humidity, cloudiness, rainfall, and little or moderate wind [30,31]. Regarding environmental values, very little or no light pollution and little environmental pollution (very little dust in suspension) are required, in addition to a good quality of sky brightness (not less than 19 mag/arcsec^2) [28].
- Regarding orography, it is recommended to look for a high place, if possible, above the thermal immersion layer [32], so that the sensors can work, in addition to the optical range, in the near infrared (between 3.400 and 10.000 Å). It is also very important to have the whole horizon clear, the most relevant area being a good south orientation, spanning from east to west. This will ensure good access to the geostationary ring at any time of the year [29].

3. Final Configuration of the Satellite Robotic Observatory (SRO)

To determine the trajectory of artificial satellites and other Earth's Resident Space Objects (RSOs), several image captures are necessary. For example, the trajectory of satellites in Low Earth Orbits (LEOs) can be determined with very short exposure times (less than one second) and wide-field optical lenses, but for more distant NEOs, characterized by lower apparent brightness, longer exposure times and smaller fields are required [21,27]. The combination of these techniques makes it possible to cover different areas of the firmament and allows a detailed study of the objects of interest, satellite constellations, and even space debris [33].

Optical equipment devoted to the imaging of RSOs and other NEOs comes in different configurations. They can be configured to image the whole sky, with fisheye optics (Figures 4 and 5), or to image a large star field, which can comprise several degrees of extension [32], when imaging objects in low orbits. In this case, the optics may be satisfied with a short-focal, wide-field objective. When the objective is to capture an image of a celestial object of lower brightness and a more distant orbit, a telescope with a smaller field of view and longer focal length will be selected. In Table 1, the equipment with its optics and sensors used to capture images of meteoroids and satellite objects from Figures 4 and 5 is described. In Figure 4, a meteor is shown during its entry into the Earth's atmosphere, becoming visible during its ablation process. On the other hand, the image of the trajectory of an artificial satellite can be observed in Figure 5.

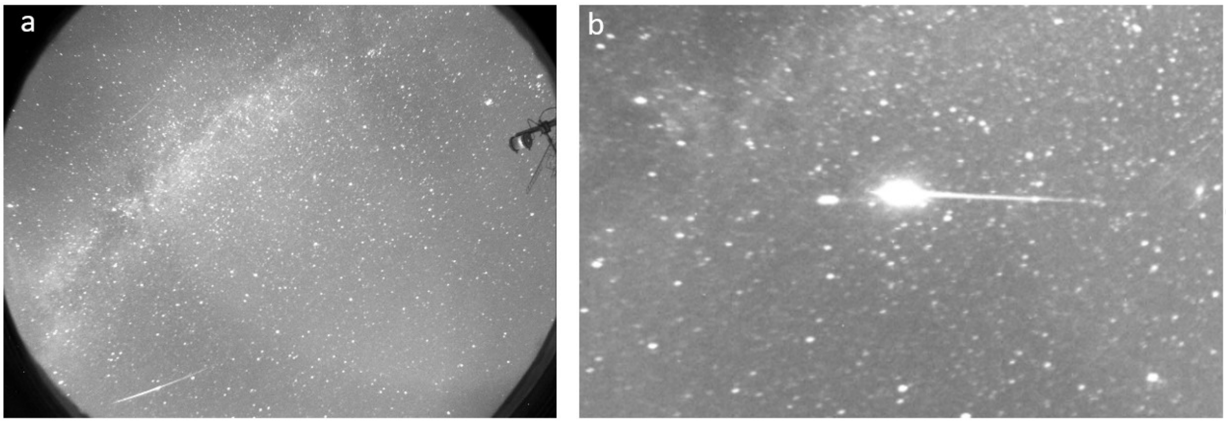

Figure 4. Image of a meteor during its entry into the Earth's atmosphere, captured with sensor 1 and 20″ exposure (**a**). Image of bolide (meteor with an apparent brightness magnitude greater than the planet Venus) captured with sensor 2 with a 30″ exposure (**b**).

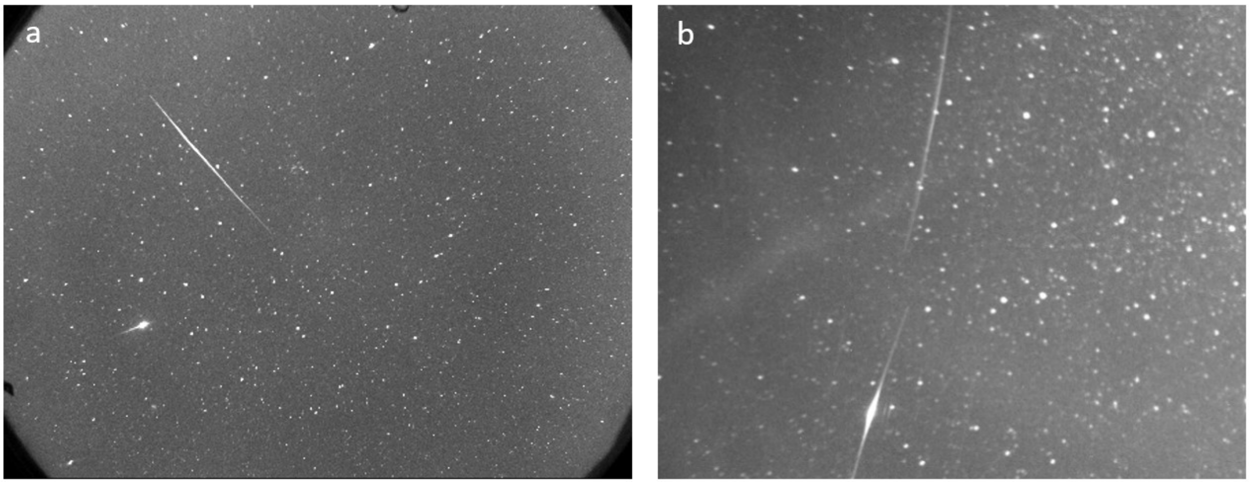

Figure 5. Image of the trajectory of an artificial satellite captured by sensor 1 with a 10″ exposure (**a**). Image of a satellite object and an Iridium captured by sensor 2 with an 8″ exposure (**b**).

Table 1. CCD monochrome devices (cameras) used for wide-field image acquisition (pictures from Figures 4–6).

CCD	Sensor	Resolution (Pixel)	Format (mm)
Atik 314 L+	Sony ICX 285 AL	1392 × 1040	10.2 × 8.3
Atik 11000	Kodak KAI 11002	4008 × 2672	37.25 × 25.7
CCD 1100	Teledyne e2V	4096 × 4112	61.4 × 61.7

Figure 6. Satellite traces captured with the Instituto de Astrofísica de Canarias IAC80 telescope, Smith–Cassegrain configuration, 82 cm field, with an exposure time of 3 s for each image.

Image download times range from 4.2 s for the Atik 314 L+ to 27 s for the Atik 11000. Although this second CCD camera is capable of capturing objects whose apparent brightness magnitude is greater than 16, the long download times make it difficult to continuously track satellite objects in low orbits. The pictures in Figure 6, provided by the CCD 1100 instrument on the IAC80 Telescope of the *Instituto de Astrofísica de Canarias* (IAC), belong to three different satellites, which cannot be identified for security reasons. These images have been obtained raw without any processing. The image quality is remarkable, and the trajectory of the satellite object can be perfectly identified. When using CMOS format sensors, download times are drastically reduced. They are very short and even less than a second when capturing a LEO satellite. Furthermore, they are much more sensitive to light, making it possible to manufacture smaller devices with better performance (a thorough comparison between CCD and CMOS image sensors for space observation can be found in [22,23]). Table 2 includes the characteristics of the CMOS cameras used to capture images of satellite objects from Figures 7 and 8.

In the images included in Figure 7, numerous traces corresponding to the trajectories of several satellite objects can be observed. The photograph has been formed by superimposing several long exposure images and the result clearly indicates the difficulty of obtaining sharp images of an object by this method. Looking at the image in detail, it is not advisable to capture images with long exposure times, due to the large number of satellite objects that exist at the present time.

Table 2. CMOS monochrome devices (cameras) used for wide-field image capture (pictures from Figures 7 and 8).

CMOS	Sensor	Resolution (Pixel)	Format (mm)
ZWO ASI071	Sony IMX 071	4944 × 3284	78 × 86.8
ZWO ASI183	Sony IMX 183	5496 × 3672	62 × 36

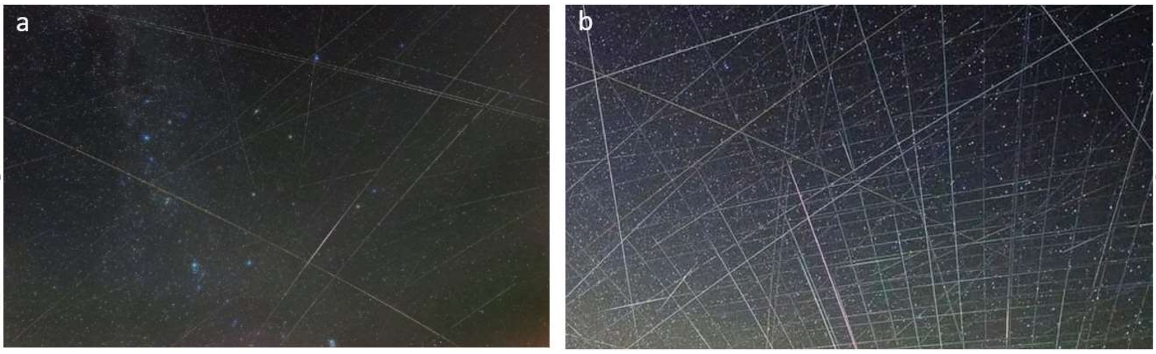

Figure 7. Composite photographs by stacking several 25″ exposure images, with a total integration time of 4 h 12′ (**a**) and 6 h 03′ (**b**). ZWO ASI 071MC Pro camera (sensor 1) and William Optics 80 mm f/4.8 refracting telescope.

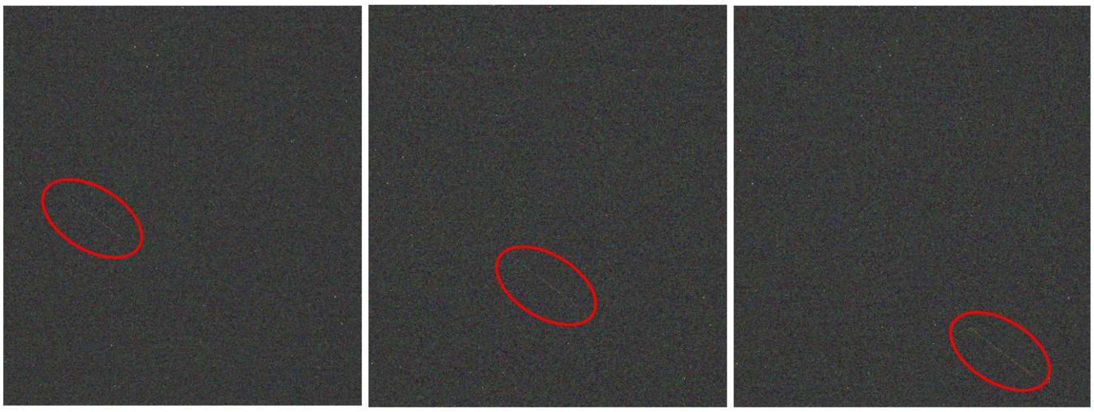

Figure 8. 1.5″ exposure image sequence of a LEO satellite. ZWO ASI 183 Monochrome (sensor 2) and 10″ S/C telescope at f/10 with altazimuth mount.

In the sequence of pictures shown in Figure 8, the traces of a LEO satellite, corresponding to the ONEweb constellation, can be seen. A very faint sky background can be seen, due to the short exposure time of each image. The optics used for these sensors have been two different models of telescopes. An apochromatic refractor of 80mm aperture at f/4.5 for sensor 1 and a 10″ Smith–Cassegrain at f/10 for sensor 2. These optics, together with their mounts are not very fast and limit the exposure times to capture images, especially of satellites in low orbits.

As satellite objects have very different orbits and depending on their height and size, different sensors and optics should be used to capture images accurately. The detection of satellite objects, the tracking, the determination of their orbital parameters, or the study of their light curve, will depend on whether space surveillance, tracking, or characterization of these objects is intended [7]. In any case, at least two types of sensors and optics, which can be complementary, should be available in an SRO. It is very important to have wide-field imaging, where objects in MEO (Medium Earth Orbit) and LEO orbits can be detected and tracked, and at the same time, have sufficient capability to accurately track other objects. These two systems can perform surveillance and tracking tasks together [34].

The best-performing optics for a wide field of view are configured with an Astrograph, which is a wide-field telescope with a very short focal length (between f/2 and f/3). For follow-up work, a telescope with a smaller field and a focal length between f/5 and f/8 is recommended. This gives greater accuracy and range, as well as being able to detect fainter objects. CMOS cameras seem to obtain as good results and performance as CCD cameras. It can be appreciated in a certain way by comparing images from Figures 5 and 6 (CCD) and Figure 7 (CMOS). As mentioned, CMOS cameras have very fast times (while a discharge camera cannot capture images), better sensitivity, and even lower noise because their operating temperature can be much lower [35,36]. Additionally, it can be said that a CCD camera (2048 × 2048 pixel sensor) installed on the 130 cm diameter International Liquid Mirror Telescope can detect Resident Space Objects (RSOs) up to 50 cm in diameter at an altitude of 1000 km [37], while a CMOS camera installed on an 18 cm diameter telescope has been shown to be able to detect 10 cm objects in LEO orbits [38]. It should also be pointed out that these figures are close to the present limits for image detection with optical sensors [39].

Optical equipment and sensors must be installed in an SRO that can guarantee their safety and proper operation in the event of inclement weather. It shall allow two or more pieces of equipment to operate simultaneously inside the SRO. For this purpose, the SRO must be completely open and have a clear horizon in any direction (Figure 9). It must also have an autonomous, safe, and efficient control system, allowing for automatic and remote operation.

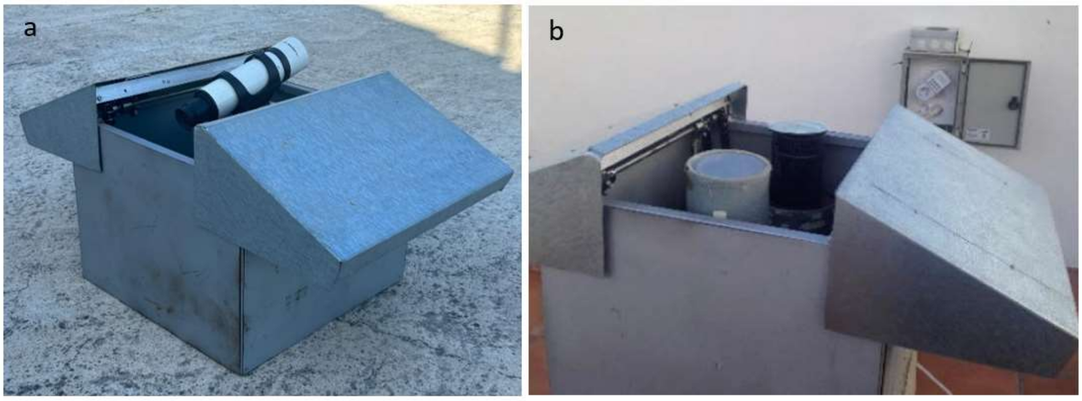

Figure 9. Prototype of an SRO, capable of housing a refracting telescope (**left**) or two wide-field and all-sky objectives (**a**). The optical systems of this SRO integrate sensors that allow capturing images of artificial satellites in different types of orbits (**b**).

The SRO proposed in Figure 9 has been tested as a prototype and has given excellent results (the final dimensions of the SRO should be similar to those of a 10-foot shipping container). After implementing some design improvements and corrections for synchronized opening and closing of the roof, it has been completed with a new control system, so that the SRO can close at dawn and open its roof at dusk, based on a photometer whose threshold is at 12 magnitudes of apparent sky brightness [24]. This value marks the beginning of nighttime activity and its end with the arrival of dawn. In this way, the equipment is protected from the sun's rays during the day.

The SRO incorporates a complete weather station. In case of wind speed above 40 km/h and/or relative humidity above 70%, the SRO acts on the sensors and telescopes to put them on "standby", while closing the roof to protect the equipment. When weather conditions improve, the SRO reopens its roof and returns the sensors to normal activity (Figure 10). Image captures are downloaded to a hard disk and transferred via fiber optics to the remote operator. The SRO computer integrates all sensor and telescope systems via ASCOM protocol. With these data, it is possible to track and classify RSOs [40,41] and determine their orbit parameters [42], and even their attitude [43].

Finally, while it is true that tracking RSOs is generally better in orbiting observatories than in ground-based observatories (space-based telescopes can track smaller objects [44], and they are less affected by inaccuracy caused by meteorological conditions [42]), the proposed SRO offers some significant advantages. It can be moved as an industrial container and placed wherever it is most convenient, with networking also being possible.

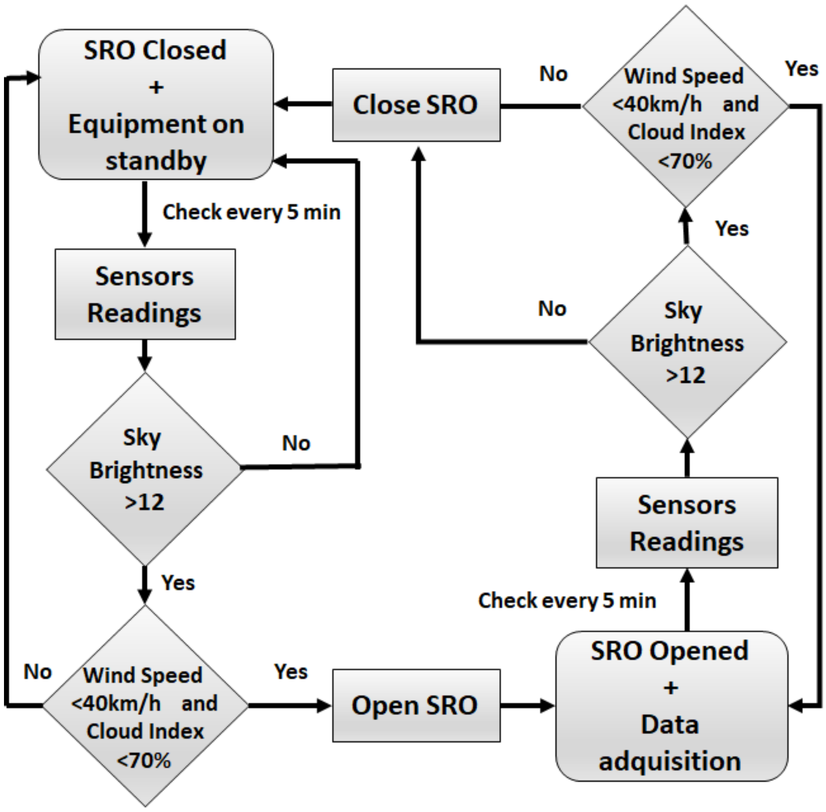

Figure 10. Sequential diagram of SRO operation (see also Figure 9).

4. Conclusions

In this paper, the design of a Satellite Robotic Observatory (SRO) for the detection, surveillance, and tracking of satellite objects has been presented and described. It is derived from the well-known configurations of Robotic Astronomical Observatories (RAOs). The SRO integrates two or more sensors with different optics and capabilities, allowing us to have a complete system to detect, identify, and perform tracking and space surveillance on any type of satellite object in different orbits and differences in brightness and sizes. The incorporation of wide-field and short-focal optics on fast mounts allows effective tracking and continuous tracking of any object. In both cases, CMOS sensors have been chosen because of their better performance than CCDs.

The SRO described in this paper has a simple and easy-to-operate design. Among the characteristics of the proposed SROs, it is possible to underline the following ones:

- They are modular and have standard dimensions;
- These new observatory models are designed with a robust structure, which allows transport operations to be carried out without affecting the equipment inside;
- They are easy to transport and move. Therefore, the possibility of networking operations is possible;
- The configuration allows future expansions so that two or more modules can be connected without affecting the previously established configurations or equipment.
- The cost is reduced when compared with a standard RAO.

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