

SIRIS, a new fast, ultra high dynamic, very low noise Infrared camera for Astrometry and Observation of Solar System Objects

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Keywords: High-Dynamic, Infrared, Low-noise, Non-Destructive-Readout, SWIR

Abstract

The presence of global oceans under the surface of Enceladus, Titan, Europa, Mimas (Lainey, 2024), Ganymede and perhaps Dione, Triton or Calisto make these objects privileged targets for the search of the life beyond our planet. Maintaining these oceans requires intense and perennial heating with the tidal effects, created by the interactions of the planets on each of these. This heating is difficult to quantify. Without a dedicated probe orbiting these moons, the only method for a global quantification of tidal heating involves the associated loss of orbital energy, i.e. measuring the position of these objects over long periods. This involves precise astrometric measurement surveys possible using the unique features of the SIRIS infrared camera. This document presents the first observations of SIRIS at the Pic du Midi Observatory, and results from the Jupiter, Saturn and Uranus systems.

Resumen

La presencia de océanos globales bajo la superficie de Encélado, Titan, Europa, Mimas (Lainey, 2024), Ganimedes y quizás Dione, Tritón o Calisto hacen de estos objetos objetivos privilegiados para la búsqueda de vida más allá de nuestro planeta. El mantenimiento de estos océanos requiere un calentamiento intenso y perenne con los efectos de marea (tidal effects), creados por las interacciones de los planetas sobre cada uno de estos objetos. Es difícil cuantificar este calentamiento. Sin una sonda dedicada que orbite estas lunas, el único método para una cuantificación global del calentamiento por mareas implica la pérdida asociada de energía orbital, es decir, medir la posición de estos objetos durante largos periodos. Se trata de realizar estudios astrométricos precisos gracias a las características únicas de la cámara infrarroja SIRIS. Este documento presenta las primeras observaciones de SIRIS en el Observatorio Pic du Midi, y los resultados obtenidos para los sistemas de Júpiter, Saturno y Urano.

1. Introduction

Imaging techniques are constantly pushed further in all fields and represent a rapidly evolving sector of instrumental development. In astronomy, imaging techniques are put to the test to detect very weak signals coming from low or high background noise, but also sometimes very high signals with increasingly strong dynamic range requirements. In recent decades, wavelength needs in astronomy exceeded the visible, extending to high energies, but also to the infrared and

near infrared. SWIR¹ wavelength range is highly strategic for scientific, industrial, medical, military applications, etc. Building on solid experience gained in the design of ultra-low-noise visible imaging systems and an active collaboration with a French manufacturer and designer of SWIR image detectors², we have completely designed a new “fast” SWIR camera based on a CMOS InGaAs hybrid FPA³. This detector was originally intended for industrial

¹Short Wave Infra-Red, from 0.9-1.7 μm .

²NIT - New Imaging Technologies.

³Focal Plane Array, i.e. image sensor.



Figure 1. SIRIS camera, marketed by Lytid SAS.

applications, but thanks to innovative controls and new readout methods, it has become fully usable for low-light scientific applications. This camera achieves the highest useful dynamic range and the lowest readout noise ever achieved in this wavelength range. This new imaging system, marketed by Lytid, is the SIRIS camera (Short InfraRed Imaging System, Figure 1).

This system makes it possible to exploit all its advanced features to gain in signal-to-noise ratio, resolution, and optimized acquisition time. Thanks to a close collaboration with the Midi-Pyrénées Observatory (OMP) and the Paris Observatory, we were able to optimize and test the camera and its SWIR detector on a telescope, the T1m of the Pic du Midi Observatory, located at an altitude of 3000 meters, renowned for its image quality and low infrared background. This system, equipped with its specific SWIR sensor, is presented below, illustrated by all its recent results obtained on the T1m telescope of the Pic du Midi.

2. SWIR InGaAs sensor and the first SIRIS prototype

For the last two decades, huge progress has been made in the field of visible detectors, based on silicon material, especially in CMOS technology. Nevertheless, this semiconductor material determines their range of detection in the visible and does not allow them to have a sensitivity that exceeds with enough quantum efficiency the micron of wavelength, making them almost completely transparent to the infrared. A technological solution solved this problem: hybridization of the traditional CMOS circuits, used as a charge accumulation and read-out circuit. This hybridization is done between the ROIC⁴ and an infrared-sensitive surface, here InGaAs via Indium bumps connecting each pixel of the CMOS circuit to the SWIR sensitive surface. Despite all the recent developments in SWIR, the FPA have very high thermal and read noise, which limits their use for weak signals. Their dynamic

range remains subject to the classical capacities of the CMOS circuit. We propose, with the SIRIS imaging system, to answer these different issues with a new SWIR camera, which offers the highest useful dynamic range and the lowest read noise ever achieved in this wavelength range.

A first version of the infrared camera with a resolution of 640 by 512 pixels has been entirely developed and realized⁵ at the LPENS⁶ around a hybrid infrared sensor from the NIT company. This camera allows to investigate and validate the solutions to reach high dynamics, low noise, and recently fast frame rates. Scientific results have already been obtained with this sensor, either at LPENS on an experiment of SWIR-Terahertz mixing wave via quantum cascade laser (QCL), or at Pic du Midi on the T1m Telescope, managed by OMP, in the study of asteroids. It still in a preliminary way on the Saturn system (Figure 6), Uranus system, Jupiter inner satellites (Figure 4), and results on the ground and atmospheric layers of Venus as shown in (Figure 5). In Biology and Biophysics, research groups are highly interested in using this camera. For example, a recent and very promising application (in results and value) in a new method of noninvasive control / diagnosis of tumors in vivo via photoluminescence of proteins functionalized with “quantum dots”. This first camera was also the tool to develop two new processes, one on adaptive optics and another on High Dynamic Range (HDR) reconstruction of images allowing to file the corresponding patents (Darson, 2017; Darson, 2018).

The detector used and designed by NIT is able to detect very strong signals and intrinsically have a logarithmic response to the incident photon flux. The “Magic” CMOS pixel technology patented by NIT allows this sensor to reach more than 120 dB of instantaneous operational dynamic range (Ni, 2011). Because when using this high HDR technology, saturation never occurs and it is possible to observe on the same image overexposed regions as well as underexposed regions (Darson, 2018). Aside from the linear/logarithmic mode, SIRIS can be read out by the very classical linear CTIA mode, under different pixel gains.

NDRO⁷ capability is another very interesting feature implemented in SIRIS. This read-out mode allowed by the full control of the clocking resources outside the detector has permitted to read the accumulated charges during an exposure (i.e. before a reset sequence), in concordance with the maximum read-out speed, without destroying them and as many times as desired. In association with NDRO, we proceed with very efficient read-out noise reduction such as Fowler sampling, described below. To detect low signals, we need to accumulate the incident photons. This operation can only be carried out with a FPA that is sufficiently cooled to eliminate the dark signal with its associated noise, which prevents this last one from accumulating in the place of the useful one. For SIRIS, we use a cryocooler in association

⁵Electronics, firmware, software and mechanics.

⁶Laboratoire de Physique de l'Ecole Normale Supérieure.

⁷Non-Destructive Read Out.

⁴Read Output Integrated Circuit.

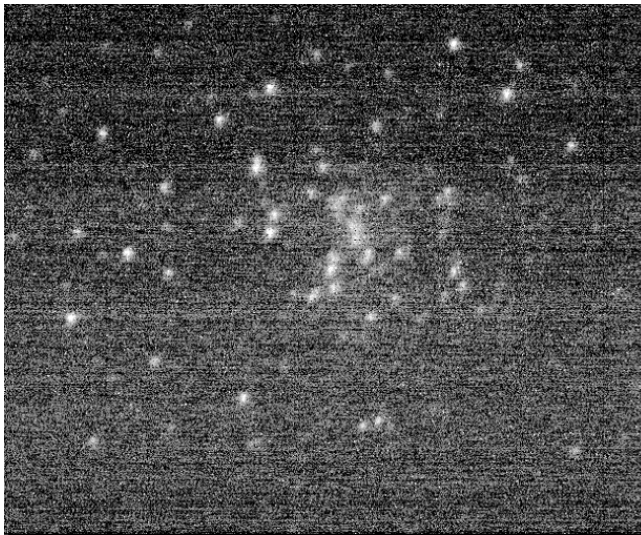


Figure 2. M15 1s exposure, 12th July 2022 23:00 UTC, classical mode with single readout at the end of exposure (J Band).

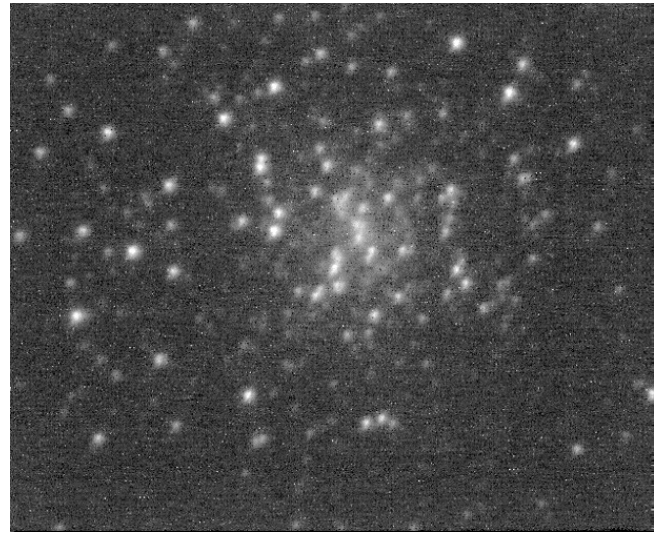


Figure 3. M15 1s exposure, 12th July 2022 23:00 UTC, same exposure as Figure 2, but taking into account the 100 NDRO, in the Fowler sampling reduction.

with an active vibration cancellation system, which assure vibrations under $1\mu\text{m}$ on the cold finger. With this cooling system, the working temperature can be set from ambient temperature to 70K.

3. First astronomical observation and results

For all the next observations and results, the CTIA mode⁸ has been used, even if ultra-high dynamic range images were present, thanks to our new uHDRTM method and the use of NDRO described in (Darson, 2017b ; Darson, 2018). When an exposure is longer than twice the time requested for an image readout (indeed, the time to perform an NDRO is exactly that of a sensor array reading), the proceeding with NDRO makes full sense, and it opens the way towards a lot of processing to improve the signal. In the linear region, we propose to use NDRO to improve the image dynamic range, first, for the detection of low signals with an optimized acquisition time, and, on the other hand, for the high illuminations with an “on the fly” selection algorithm of pixels still in their linear part before their saturation. The logarithmic part, with the logarithmic data “compression” of the response function, cannot provide the same accuracy (even with logarithmic sampling). Therefore, it makes sense to use the linear part of the sensor response function. We use NDRO to obtain multi-reading of the image in a single exposure, and by this multi-exposure approach, perform HDR with our uHDRTM process. In addition of this very HDR feature, we use at the same time classical NDRO processing, like Fowler sampling or FUR/SUTR⁹ (Garnett, 1993). We have been able to reduce the readout noise at very low levels (under 5 e^-) even if the FPA has intrinsically a “high” readout noise of 80 e^- , with its higher usable gain at low working temperatures.

⁸Full linear mode, as opposed to the linear/logarithmic mode.

⁹Follow-up the Ramp, sample-up the Ramp.

All of the astronomical observations were performed at the Pic du Midi Observatory in the French Pyrenees. The SIRIS camera has been installed on the Nasmyth focal plane of the T1m telescope, which has a focal length of 17 m. With the SWIR sensor and its 15 μm pixel pitch, the sky sampling is $0.18''$ per pixel and a field of view of 1.94 by $1.55'$. Among many results obtained over a few weeks of observation sessions during several years of development, we present some of them to show either low-noise performances or ultrahigh dynamic range acquisitions. Figures 2 and 3 come from the same exposure of 1 s. The detector has been cooled at 140 K, so the dark signal as well as its associated noise are completely negligible. Only readout noise and photon noise¹⁰ are included in the final total noise.

Figure 4 shows the capabilities of SIRIS on the inner satellites of Jupiter. The detector has been cooled down to 130 K, and the seeing conditions were particularly good during image acquisition (around $0,6''$). We have stacked 40 sequences of 500 NDRO each (2.5 s exposure time i.e. 5 s between two NDRO). A Fowler noise reduction with 100 samples has been set on these NDRO sequences. The resulting total integration time is 80 s. A manual equalization was performed on the Jupiter halo for a better visualization of its natural satellite Metis.

4. Conclusion

The camera described here is a unique instrument, which, in the SWIR range, allows detection of both weak and very strong signals, with numerous processing and optimizations possible thanks to the use of fast NDROs. There are many interests for a camera like SIRIS on a telescope like T1m especially for studies and surveys of Solar System Objects like Near Earth objects.

¹⁰Associated with the sum of all incident signals on the detector.

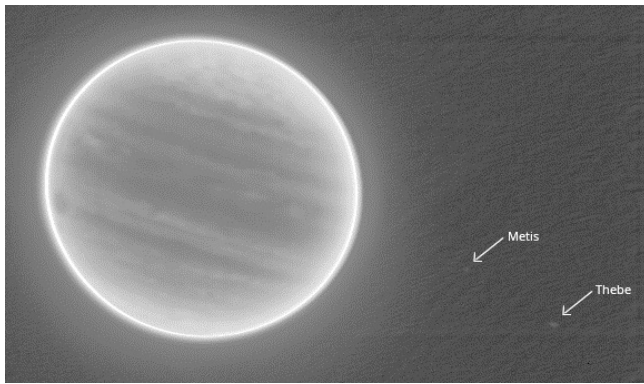


Figure 4. Jupiter (Magnitude -2.86), Thebe (Magnitude 15.52) and Metis (Magnitude 17.32) on the same image. Acquisitions made the 13th October 2023 at 00:19 UTC.



Figure 5. Venus with 1275 nm and 50 nm of FWHM filters. The displaying levels are stretched on these two HDR images to see the dark side of Venus. Acquisitions were made on 13th October 2023 between 5:00 UTC and 5:20 UTC.

Astrometric observations of the small objects in Saturn or Jupiter systems, in a high-contrast environment (planet versus satellite), are well suited to SIRIS camera with its quasi-unlimited dynamic (either logarithmic and/or linear response, thanks to uHDR™ process) and very low noise. Together with existing observations, these data for the period 2023-2033 will be fundamental and sufficient to obtain a reliable result on the tidal effects of the giant planets's icy-moons.

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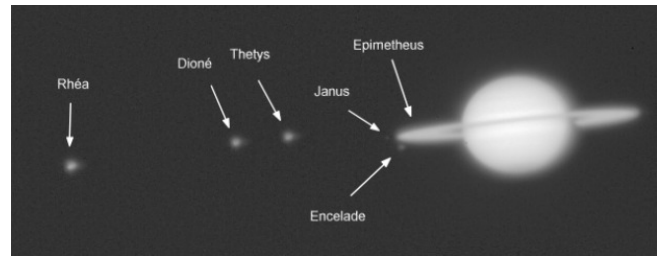


Figure 6. Saturn and inner Satellites in J band. One exposure of 20 s with 4000 NDRO and uHDR™. Acquisition made the 28th June 2025 at 3:10 UTC.

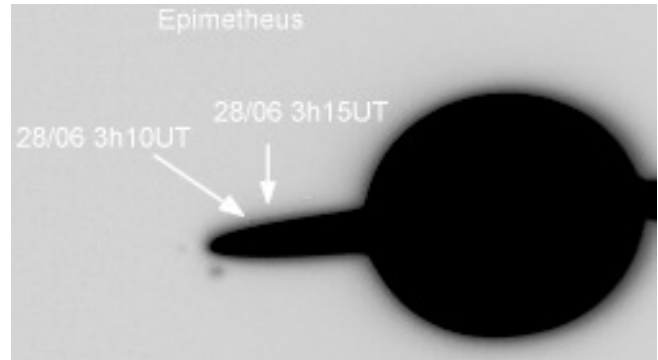


Figure 7. Superposition of two exposures were taken the 28th June 2025: the first was taken at 3:10 UTC and the second at 3:15 UTC (with the same set-up as Figure 4).

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Potential scientific applications of cart (Chinese Argentina Radio-Telescope)

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Keywords: *Radio telescope, Space geodesy, Astrophysics and space exploration*

Abstract

The potential scientific applications of the 40 m-diameter CART (Chinese Argentine Radio Telescope), which will be installed at the high-altitude Carlos Ulrrico Cesco Station of OAFA (Félix Aguilar Astronomical Observatory) in San Juan, Argentina, are presented in this contribution. CART will strengthen the geodetic techniques of the international network (VLBI, LLR, SLR, GNSS, and DORIS), becoming one of the few high-precision facilities in the Southern Hemisphere and improving coverage for studies of Earth's dynamics. After a rigorous site-selection process and modular assembly of its components, the project is 80 % complete, with commissioning scheduled for 2026.

Resumen

Se presentan las potenciales aplicaciones científicas del radiotelescopio CART (Chinese Argentine Radio Telescope) de 40 m de diámetro, que se instalará en la estación de altura Carlos Ulrrico Cesco del OAFA (Observatorio Astronómico Félix Aguilar) en San Juan, Argentina. CART reforzará las técnicas geodésicas de la red internacional (VLBI, LLR, SLR, GNSS y DORIS), convirtiéndose en una de las pocas instalaciones de alta precisión en el Hemisferio Sur y mejorando la cobertura para el estudio de la dinámica terrestre. Tras un riguroso proceso de selección de sitio y ensamblaje de sus componentes, el proyecto alcanza un 80 % de avance, con puesta en marcha prevista para 2026.

1. Background and Partnership for the CART Project

Building on the existing relationship, which has been in place for 30 years, both the National University of San Juan and the Chinese Academy of Sciences, through their respective research institutes (Félix Aguilar Astronomical Observatory and National Astronomical Observatories of China), have expressed their desire to expand the existing agreement to other areas of astronomy and related sciences that have a significant impact on the current global environment. To this end, both institutions have signed an agreement that provides for the implementation of a 40-meter diameter radio telescope in the province of San Juan.

Due to the high millimeter precision currently required for terrestrial and celestial studies such as polar motion, tectonic motion, Earth's orientation parameters, precession,

nutration, time, relativity, etc, the international body that leads all these studies (the International Earth Rotation and Reference System Service, [IERS](#)), currently uses these five space technologies: a) Very Long Baseline Interferometry (VLBI) that operate with radio telescopes, b) Lunar Laser Ranging (LLR) with laser stations towards the Moon, c) Satellite Laser Ranging (SLR), d) Global Navigation Satellite Systems (GNSS) -which includes the North American GPS, European GALILEO, Chinese BEIDOU, Russian GLONASS and other local systems from India and Japan- and, e) Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS).

The OAFA currently has three of these technologies in operation. With the installation and operation of the 40-meter Chinese-Argentine CART radio telescope (Fig. 1), it will now have four space-based geodetic techniques and become one of the most important stations in the Southern Hemisphere.



Figure 1. CART radio telescope to be installed on the Carlos Ulrrico Cesco Station belonging to the Oafa.

CART will be able to integrate into existing international networks, a situation that would position the Oafa, and therefore the National University of San Juan, as one of the few observatories in the world with a Satellite Laser Telescope, a GNSS station, a DORIS beacon, and a Radio Telescope capable of conducting long-baseline interferometric observations. The completion of the highly specialized work expected will be of great benefit not only to astronomy but also to geophysics and geodesy.

It should be noted that the implementation of an instrument like CART in the Southern Hemisphere is extremely convenient, as instruments of this type are few and far between in the southern region of our planet. The radiotelescope was entirely manufactured in China following proprietary technical developments. Once its construction was completed, the instrument was subjected to numerous adjustment tests. Once this stage was completed, the telescope was disassembled into large pieces and transported to San Juan for final installation.

Since 2009, the Oafa geodesy team has been working on campaigns to survey potential suitable terrain, characterize sites, and identify the largest number of options, especially those with low electromagnetic noise measurements. More than a dozen sites were evaluated throughout the province. Geophysical campaigns were also carried out in conjunction with the Volponi Seismological Institute, and geological surveys were carried out with teams from the Faculty of Exact, Physical, and Natural Sciences. The selected site corresponds to an area within the Oafa terri-

tory at the Carlos Ulrrico Cesco station, in the Calingasta department, in the south of the province of San Juan.

The project is currently 80% complete, and the instrument commissioning period is expected to begin next year (2026).

2. Potential Scientific Objectives of the CART

CART was originally designed for tasks related to space geodesy. The potential scientific objectives were later expanded to include astrophysics, planetary sciences, and deep space exploration (Podestá et al., 2025). The following list shows CART's future objectives:

1. Establishment and maintenance of ICRF, ITRF, and SIRGAS.
2. Link between the radio frameworks and frameworks established in other wavelengths.
3. Determination of EOPs.
4. Geodynamics studies of the crust of the Earth. Tectonic movements.
5. Study of radio and variation of structure.
6. Research of AGN redshift.
7. Observations of X-ray binaries, supernovae, and novae wrap.
8. Study activities of solar objects, e.g. planets and asteroids
9. Study the feedback of expanding HII regions.
10. Investigate the circumstellar medium around evolved stars.
11. Timing observations of pulsars
12. Research of interstellar masers
13. Polarization of galaxy clusters
14. Contribute to space exploration, participating in the chinese lunar exploration program

The installation of CART in Argentina will contribute to improving the global coverage of the radio telescope network and, consequently, to the determination of astrogeodetic parameters in our hemisphere and, in particular, in the American continent.

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The astronomical plate digitization at SHAO

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Keywords: *Astrometry, Methods: observational, instrumentation: detectors, techniques: image processing*

Abstract

The digitization of historical astronomical plates is essential for preserving century-long observations. This work presents the development and application of the specialized digitizers at the Shanghai Astronomical Observatory (SHAO), including technical details, international collaborations and scientific applications on plates.

Resumen

La digitalización de placas astronómicas históricas es esencial para preservar observaciones centenarias. Este trabajo presenta el desarrollo y la aplicación de los digitalizadores especializados del Observatorio Astronómico de Shanghai (SHAO), incluyendo detalles técnicos, colaboraciones internacionales y aplicaciones científicas en placas.

1. Introduction

Before the 1990s, astronomers used glass plates to record celestial bodies for over a century. These non-reproducible records are invaluable for studying long-term phenomena. However, degradation such as mildew and delamination has threatened their preservation. Samples of astronomical plates taken by SHAO are shown in Fig. 1. To address this, and according to the International Astronomical Union (IAU) in Resolution B3 of its 24th General Assembly in 2000, SHAO established a dedicated Plate Laboratory in 2009, initiating a national effort to rescue and digitize Chinese astronomical plates. By the end of 2012, about 30,000 plates from all Chinese observatories were transferred to SHAO's Plates Digitization Laboratory (PD-Lab).

We began by performing performance tests on conventional commercial scanners. The results showed poor positioning repeatability in the scanning direction, poor illumination uniformity, and relatively high distortion. We then concluded that a specialized digitizer for astronomical plates was required for micrometer-level scanning accuracy.

2. Development of Plate Digitizers at SHAO

2.1. First Digitizer (2013–2017)

We naturally began by drawing inspiration from existing scientific digitizing machines. In 2011–2012, our PD-Lab team members visited the DASCH digitizer at Harvard College Observatory (Simcoe, R. J., et al., 2006) and the DAMIAN digitizer at the Royal Observatory of Belgium (de Cuyper, J.-P., Winter, L., 2006), where we gained a wealth of knowledge about the operating principle and development of specialized digitizers.

Then, with the support from Chinese Ministry of Science and Technology and in collaboration with Nishimura Co. (Japan), SHAO developed its first dedicated plate digitizer (Fig. 2). The system, based on mechanical guide rails, included a telecentric lens, high-resolution camera, LED illumination, and a mobile platform mounted on granite.

The digitizer uses the line scanning method. For a large plate, after several strip scans (28 mm wide and less than 300 mm long), all the strip images are assembled to form a complete image. With this machine, we completed the digitization of 30,000 Chinese astronomical plates.



Figure 1. Examples of astronomical plates taken by SHAO.



Figure 2. The first digitizer at SHAO.

Our astronomical plate digitization work was fully recognized by the Shanghai government, which authorized our laboratory to provide high-precision digitization

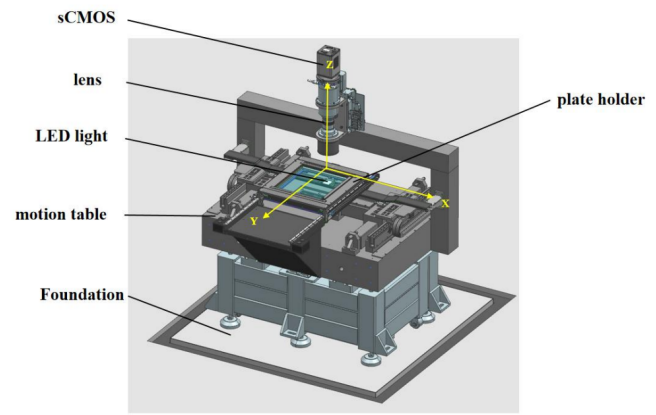


Figure 3. New generations of plate digitizers at SHAO.

services for other fields such as surveying and cartography, medicine, and biology.

2.2. New Digitizers (2019–2024)

In 2019, SHAO began developing a new digitizer based on air-bearing guide rails. Components included a high-precision sCMOS camera, air-bearing motion table, vibration-isolated foundation, electropneumatic plate holder, and fine-tuned camera alignment unit (Fig. 3). This new plate digitizer has a stable base and is built on a strong concrete isolated foundation to be isolated from vibrations and avoid vibrations from the outside.

Regarding the air-bearing motion table, we use a laser interferometer to check the accuracy and a marble square ruler to check the orthogonality.

After the table arrived, we carried out fine-tuning and performance tests to ensure that the table can meet the following requirements:

- Short-term positioning repeatability: $<0.1 \mu\text{m}$,
- Straightness and flatness: $<0.3 \mu\text{m}$,
- Pitch/yaw: $<1.0''$,
- Orthogonality of 2 motion axes: $<2.0''$.

Regarding the electro-pneumatic plate holder, we adopted the electric and pneumatic operation mode in order to:

- Load and unload plates of different sizes up to $320 \times 320 \text{ mm}^2$,
- Keep the plate stable during the scanning process.

We also worked on fine-tuning the camera rotation, to align the camera's axes with those of the motion table. A fine-tuning mechanism was installed, allowing for precise camera rotation. The angular resolution of the adjustment is approximately 1.4 arc-seconds.

The development of the first new digitizer was completed at the end of 2020, as shown in the Fig. 4. Concerning the operation mode, this new digitizer uses a block scanning step-and-stare method. A $300 \times 300 \text{ mm}^2$ plate is digitized in 210 seconds, generating 1.45 GB of 16-bit FITS data



Figure 4. The first new digitizer at SHAO.

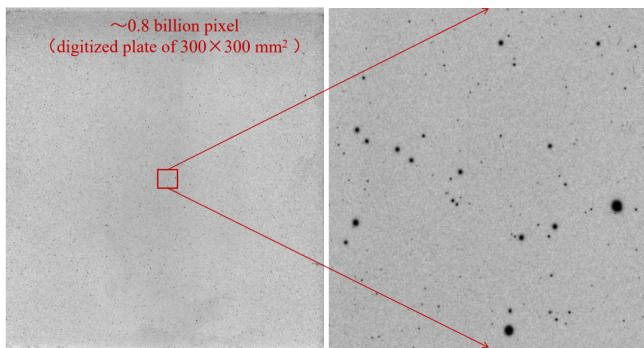


Figure 5. Example of star images on a plate digitized by the new generation SHAO's machine. At this digitized plate of 300×300 mm² we have ~ 0.8 billion pixels.

Table 1. Main parameters of the old and the new generation plate digitizers at SHAO

Parameter	First Digitizer	New Digitizer
Scanning mode	Line scanning	Block scanning
Optical resolution	2540 DPI	2309 DPI
Positioning precision	1.0 μ m	0.3 μ m
Photometric precision	0.02mag	0.01mag
Dynamic range	3.0 OD	3.9 OD
Max scanning area	300mm $\times$ 300mm	320mm $\times$ 320mm
Scanning time	620 s (300mm ²)	210 s (300mm ²)
Image format	16-bit FITS	16-bit FITS

with sub-micron positioning precision. An example of star images on a plate digitized by the new generation SHAO's machine is shown in the Fig. 5.

The main difference on parameters between the old and the new plate digitizers of SHAO are summarised in Tab. 1.

3. International Cooperations

In response to the call of the IAU, SHAO has carried out international cooperation in the digitization of astronomical plates with multiple institutions using

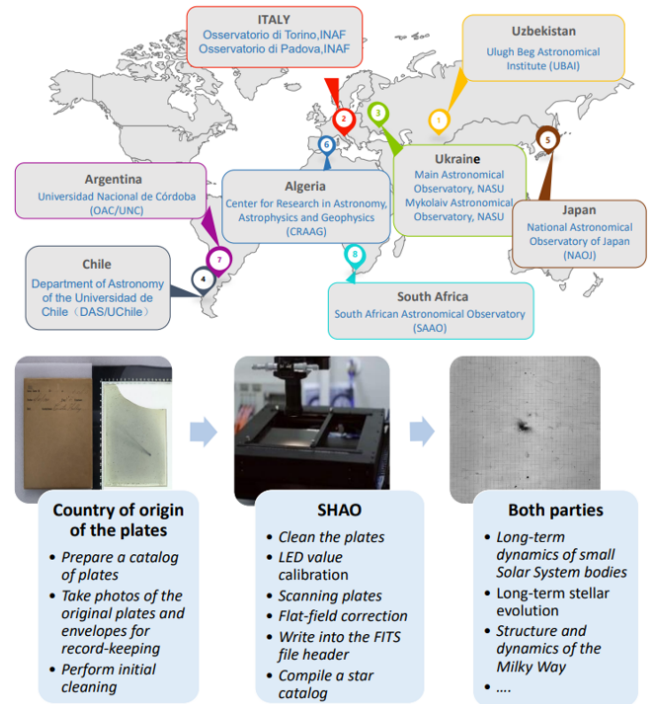


Figure 6. Top: International institutions currently engaged in collaborative projects. **Bottom:** Steps of bilateral collaboration with SHAO.

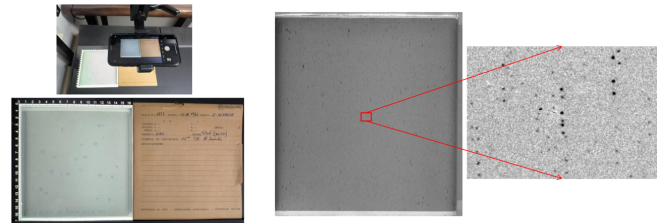


Figure 7. Recording the original information on the Chilean plates and envelopes (left), then digitization to obtain high-precision images from those plates (right).

the high-precision digitizers. Fig. 6 depicts the main institutions currently engaged in collaborative projects as well as the steps of bilateral collaboration with SHAO.

A collaboration is also underway with the University of Chile, where 6,012 plates from its observatory have arrived at SHAO. Digitization and processing of the data from these plates are in progress. We record the original information on the plates and envelopes, then use the new digitizer to obtain high-precision images from plates (Fig. 7).

4. Scientific Application on Astronomical plates

For Chinese astronomical plates, astrometric and photometric calibrations were conducted, with data made available through the China Virtual Observatory (<https://nadc.china-vo.org/data/data/legacyplateedr/f/>; Shang et al., 2024). This batch of data contains

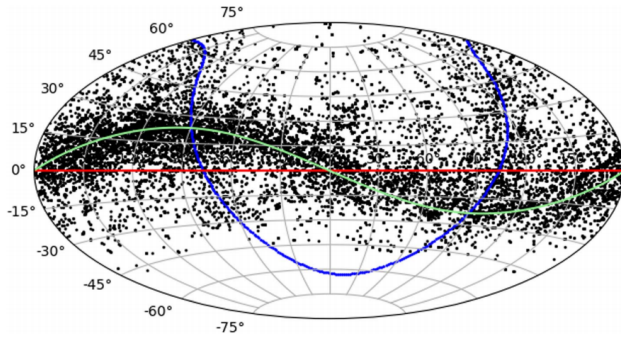


Figure 8. Distribution of the pointings of Chinese plates. The red line refers to the equator, the green line to the ecliptic, and the blue line to the galactic equator.

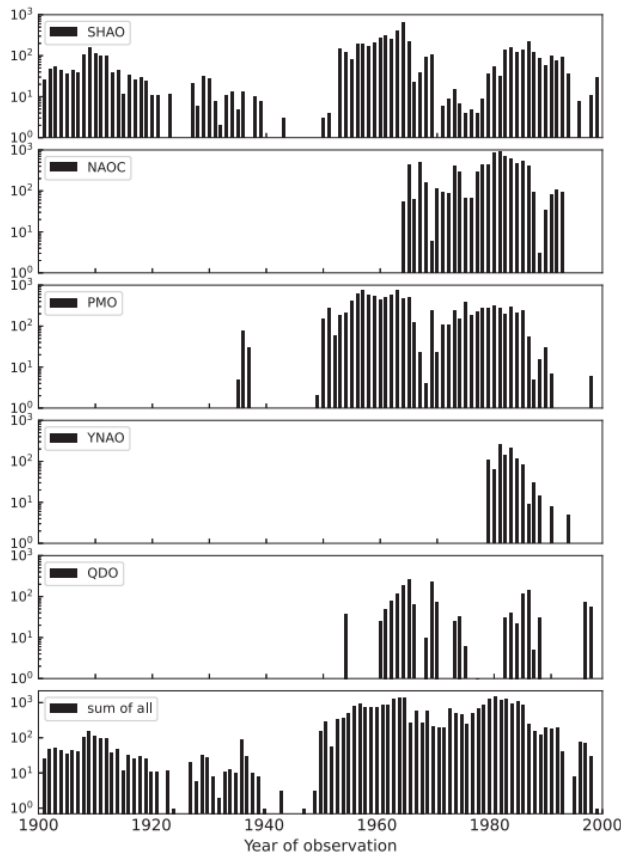


Figure 9. Distribution of the quantities of astronomical plates from each station over time.

observations from 9 telescopes at five stations, namely, National Astronomical Observatory (NAOC), Shanghai Astronomical Observatory (SHAO), Purple Mountain Observatory (PMO), Yunnan Astronomical Observatory (YAO), and Qingdao Observatory (QDO), and spans the period from 1901 to 1998. Fig. 8 illustrates the distribution

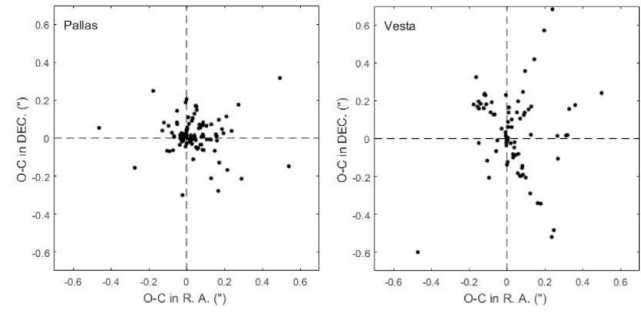


Figure 10. (OC)s in R.A. versus (OC)s in DEC.

of the pointings of the plates, and Fig. 9 shows the distribution of the quantities of plates from each station over time.

In addition, Chinese and Uzbek researchers collaborated to carry out the new reduction of the plates of Pallas and Vesta. Based on Gaia DR2 catalog, we obtained the asteroids astrometric results, with a precision of $0.1''$ to $0.2''$ (Wang et al., 2023). Fig. 10 shows the (OC) in right ascension versus (OC) in declination for Pallas and Vesta, where O represents the astrometric results from the plates reduction, and C represents the theoretical positions derived from the JPL Horizons System.

5. Conclusion

The plate digitization efforts at SHAO have advanced both in technology and in collaboration, preserving irreplaceable observational heritage while providing high-precision data for astronomical research.

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VLBI and reference systems: accuracy, evolution and scientific applications

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Abstract

In this paper, we focus on astrometry and geodesy applications of VLBI. We revisit some fundamentals of VLBI, present the role of the International VLBI Service for Geodesy and Astrometry (IVS), and examine VLBI's contributions to materializing the celestial and terrestrial reference frame. Moreover, we emphasize VLBI's ability to provide all five Earth Orientation Parameters (EOP), the only technique that can provide Universal Time (UT1). Lastly, we discuss current challenges, such as the uneven distribution of antennas, and prospects, including the VLBI Global Observing System (VGOS) and K-band VLBI.

Resumen

En este artículo, nos enfocamos en las aplicaciones astrométricas y geodésicas de VLBI. Revisamos algunos fundamentos de VLBI, presentamos el papel del Servicio Internacional de VLBI para Geodesia y Astrometría (IVS), y examinamos las contribuciones de VLBI para materializar los marcos de referencia celeste y terrestre. Además, destacamos la capacidad de la VLBI para proporcionar los cinco Parámetros de Orientación Terrestre (EOP), siendo la única técnica que puede proporcionar el Tiempo Universal **1, se puede omitir el 1? No, ver respuesta detallada** (TU1). Por último, discutimos los retos actuales, como la distribución desigual de antenas, y las perspectivas, incluyendo el Sistema de Observación Global de VLBI (VGOS) y VLBI en banda K.

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1. General

The Very Long Baseline Interferometry (VLBI) stands as a foundational space-geodetic technique, crucial for materializing the International Celestial Reference System (ICRS) through precise coordinates of extragalactic celestial objects emitting radio waves, but also contributes to the materialization of the International Terrestrial Reference System (ITRS), determining precise coordinates on Earth. Besides, this technique can determine the five Earth Orientation Parameters (EOP). Recalling that, we refer to EOP as the extended set formed by the Earth Rotation Parameters (ERP), **the variations of the Earth's rotation angular velocity expressed as (UT1 -UTC), the polar motion (x_p, y_p)**, and the Celestial Pole Offsets (CPO) **denoted as dX and dY. The whole set** links celestial and terrestrial reference frames. **sugiero implementar**

una frase que permita hacer una transición al tema de los radiotelescopios. Following, we will go into depth on the VLBI system. Each network antenna is a radio telescope, designed to collect radio wavelength radiation from celestial objects and convert these faint signals into electrical impulses, however due to diffraction, individual radio telescopes were limited in resolving small structures. The limit on its angular resolution depends on the antenna size and wavelength. Thus, increasing the resolution of the radio telescope would necessitate antennas stretching for kilometers in diameter due to the significantly longer wavelengths of radio waves compared to visible light. Interferometric arrays are commonly used to solve this problem. Combining signals from multiple long, spatially separated antennas, VLBI effectively simulates a much larger telescope, dramatically enhancing angular resolution. The need

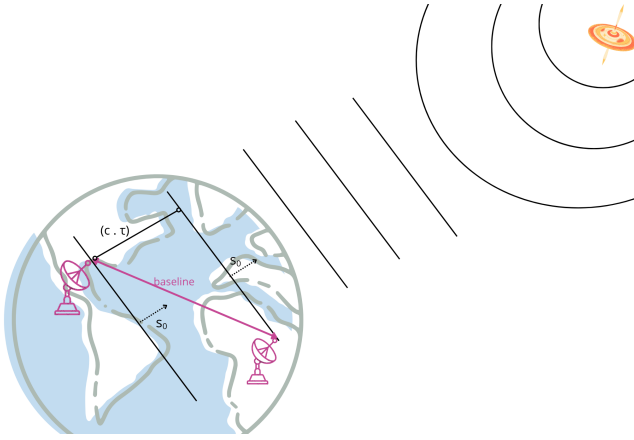


Figure 1. Basic scheme of VLBI functioning.

for physical connections between telescopes constrained early interferometers. However, a significant technological leap occurred with the advent of independent signal recorders and high-precision frequency standards, such as atomic clocks (nowadays, hydrogen masers), which enabled the synchronization of observations across vast distances without physical links. Nowadays, after more than 40 years of operational VLBI, this technique can achieve delay measurements precise to a few picoseconds and determine the relative positions of the antennas to a few millimeters and the quasar positions to fractions of a milliarcsecond (Schuh & Behrend, 2012).

In § 2, we present the basics of the VLBI technique. In § 3, we discuss the structure and relevance of the International VLBI Service for geodesy and astrometry. In § 4, we present the VLBI applications emphasizing the essential role of the technique for astrometry and geodesy. In particular, in § 4.1, we show the VLBI's contribution to materializing the celestial and terrestrial reference systems and determining the Earth Orientation Parameters. In § 5, we briefly expose the VLBI's challenges and prospects for the near future.

2. Fundamentals of VLBI

We briefly introduce the basics of the technique, its operating principles, and the main characteristics of the observed objects.

2.1. Operating Principles

The fundamental observable in VLBI is the difference in arrival times, or delay, of a signal originating from an extragalactic radio source as received by two or more radio antennas. When a signal reaches two stations, say 1 and 2, at times t_1 and t_2 , the observed delay time is $\tau = t_2 - t_1$. This delay is geometrically related to the baseline vector connecting the two antennas ($\vec{b}$) and the direction of the radio source, represented by the unit vector $\vec{s}_0$ (see Fig.1).

Thus, following Schuh & Behrend (2012),

$$\tau = -\frac{\vec{b} \cdot \vec{s}_0}{c}$$

The process of obtaining this delay involves several critical steps, such as scheduling. It refers to creating a sequence of observations (scans) that best uses the available observing time, balancing sky coverage, observation frequency, and the slewing time.

A unique feature of VLBI for geodesy is the use of subnetting, which involves arrays of stations observing more than one radio source at the same time.

In Legacy VLBI systems, signal reception occurs at S (2.2-2.4 GHz) and X (8.2-8.9 GHz) frequency bands. Upon reception, the signal is down-converted to a few hundred MHz using a locally generated reference signal. The data is then digitally recorded and precisely timed by the station's atomic clocks. Subsequently, these recorded data are transferred to a correlator, where the signals from different radio telescopes are cross-correlated. This correlation process yields key VLBI observables: phase, group delay (the derivative of phase across the frequency channels), and phase rate (the time derivative of phase) (Nothnagel et al., 2018).

The observed delay (τ) is a composite of several contributing factors, encompassing geometric delay (τ_g),

$$\tau = \tau_g + \tau_{ab} + \tau_{clk} + \tau_{inst} + \tau_{trop} + \tau_{iono} + \tau_{rel} \quad (1)$$

where the contributions are: diurnal aberration (τ_{ab}), clock synchronization errors (τ_{clk}), instrumental delays (τ_{inst}), atmospheric propagation delays (tropospheric τ_{trop} ; ionospheric τ_{iono}), and relativistic corrections (τ_{rel}) (Schuh & Behrend, 2012).

For the astrometric VLBI, all terms corrupting τ_g , must be coped as follows: τ_{ab} , and τ_{rel} are estimated from Physicss models; τ_{inst} is calibrated, τ_{clk} and τ_{trop} estimated by modeling using local input parameters and least squares, and most of τ_{iono} is eliminated by using a linear combination of the double frequency (Cannon, 1999).

2.2. Characteristics of Observed Radio Sources

Astrometric VLBI primarily observes Active Galactic Nuclei (AGN), including quasars, which are extragalactic radio sources located billions of light-years away. These sources are characterized by extremely weak signals upon reaching Earth and the absence of detectable proper motions (assumed to be null). That last characteristic enables VLBI to be a tool for materializing the kinematical inertial celestial reference system (Kovalevsky & Mueller, 1989; Fernández et al., 2023). Historically, the VLBI observed radio sources are assumed to be point-like sources. However, the assumption is not always accurate. The “structure index” **Structure Index** (SI), which quantifies the median source structure effect over the u-v plane, defines the astrometric quality of a source. Following Charlot (1990) and Fey & Charlot (1997), sources can range from point-like (Index 1) to solved (Index 2), extended (Index 3), or very extended (Index 4). The structure of a source is crucial, as changes in its morphology over time can, due to structure evolution, lead to position instabilities,

impacting the accuracy of VLBI materialization of the celestial reference system.

3. International VLBI Service for Geodesy and Astrometry

The International VLBI Service for Geodesy and Astrometry (IVS) is a technique-specific service created in 1999 under the umbrella of the IAG (International Association of Geodesy), and recognized as a service of the IAU (International Astronomical Union) in 2000 (Schuh & Behrend, 2012). IVS is a scientific and technical international collaboration that involves the operation and support of all the VLBI components. It is in charge of coordinating the observing programs, setting the performance standards for stations, establishing conventions for data formats, and giving recommendations for data analysis software and product delivery. Besides the directing board, associate members and coordinators, the IVSs structure is formed by the VLBI radio telescopes that form the global network, 3 operation centers coordinating the activities of the network, 7 correlators, 31 analysis centers producing products, 5 data centers distributing these products, and centers devoted to the developing of new technology applied to VLBI (see <https://ivscc.gsfc.nasa.gov/>).

IVS Data Centers provide not only VLBI data as input of the dedicated software, but also products. In particular, as in Schuh & Behrend (2012, Table 1), IVS provides the full set of EOP (see § 4.1) with 1-day resolution and different accuracies depending on the parameter, realizations of the terrestrial reference frame with stations coordinates (x, y, z) accurate to 5 mm, and the celestial reference frame with source coordinates (α, δ) accurate to $0.2 - 0.3 \text{ mas}$.

The IVS also works to integrate VLBI into the Global Geodetic Observing System (GGOS), a fundamental global framework that includes various geodetic observing techniques and data products to monitor and understand the Earth system. GGOS is an initiative by the IAG with the primary objectives to achieve an accuracy of 1 mm and a stability of 0.1 mm/year for coordinate determination (Schuh & Behrend, 2012).

As of 2025, the IVS network has expanded to 37 ground stations, with a significant concentration of antennas in the Northern Hemisphere (76%). This geographical bias in the antennas' distribution is due to several factors, including economic and geopolitical motivations. In § 4.1.2 we will see the direct consequences of this fact in the materialization of the celestial reference system.

4. VLBI applications

VLBI's applications extend across various scientific disciplines, including astrophysics, astronautics, astrometry, and geodesy. This technique gives the precise determination of extragalactic radio source coordinates and contributes to relativistic and cosmological models.

In cosmology, VLBI is instrumental in studying the structure and environment of black holes, observing transient phenomena, and testing fundamental theories of gravity, especially under extreme conditions. It also aids in constraining cosmological parameters such as the Hubble constant and dark matter density (Titov, 2017; Titov et al., 2018).

In astronautics, especially for space missions, VLBI provides critical support for precise navigation and tracking, ensuring high-quality spacecraft positioning for precise maneuvers, exemplified by missions like Voyager, Cassini, Rosetta, and New Horizons. It is also essential for mission planning, contributing to orbit determination, optimizing trajectories, and guaranteeing that spacecraft reach their intended destinations (Gimenez, 2005). Finally, VLBI helps to synchronize atomic clocks aboard spacecraft and at Earth-based tracking stations.

4.1. VLBI in astrometry and geodesy

Although the contribution of VLBI in other disciplines is very important, as we saw in previous paragraphs, its main contribution is in astrometry and geodesy.

VLBI plays a unique role in establishing and maintaining both celestial and terrestrial fundamental reference systems. Moreover, reference systems materialized through VLBI have implications for several practical applications. These frameworks are indispensable not only for accurate positioning needed by different scientific applications, but also for maintaining other techniques such as the Global Navigation Satellite Systems (GNSS).

Besides, VLBI is the only technique in astrometry and space geodesy capable of providing the five EOP, and it is unique in providing Universal Time (UT1). The Earth Orientation Parameters refer to five quantities that link the celestial and terrestrial reference frames: polar motion (x_p, y_p), (UT1-UTC), and the celestial pole offsets. This set enables the monitoring of Earth's movements in space and variations in its rotation. Thus, the transition from celestial to terrestrial reference frames, and vice versa, is made through a sequence of rotations involving the complete set of EOP (see more details in Fernández et al. (2023)).

To maintain their relevance, both terrestrial and celestial reference frames must continue to be refined and rigorously maintained to address current and emerging challenges.

4.1.1. Brief historical overview

The first VLBI successful *long-baseline* experiment was in 1966-67. This pioneering effort involved two radio telescopes separated by 218 km, which recorded signals from Jupiter on magnetic tape for later cross-correlation. Despite the strong Jupiter signal, this experiment successfully detected interference fringes and estimated Jupiter's radio source size (Brown et al., 1968).

Throughout the 1970s and 1980s, VLBI became a fundamental tool to monitor Earth's orientation variations and tectonic plate movements. During this period, source positions were measured with an accuracy of approximately

and between optical (Gaia Celestial Reference Frame 2) and radio positions ($\sim 22\%$ of sources), suggesting the influence of unknown source structures (Charlot et al., 2020).

Charlot et al. (2020) discussed how the limited distribution of antennas in the Southern Hemisphere resulted in a higher noise floor for sources south of -40° declination compared to those further north ($44 \mu\text{as}$ vs $25 \mu\text{as}$ for right ascension and $47 \mu\text{as}$ vs $29 \mu\text{as}$ for declination). Moreover, the effects of an uneven VLBI antenna distribution are also noticeable from Charlot et al. (2020, Fig. 6), where the scarce southern observations are evident at first glance.

As of January 1, 2022, and following the resolution B3 of the XXXI IAU General Assembly in 2022, the ICRS is fundamentally realized by combining the ICRF3 for the radio domain and the Gaia-CRF3 for the optical domain (IAU, 2021).

4.1.3. Terrestrial Reference Frame

VLBI also contributes to the materialization of the International Terrestrial Reference System, in other words, with the construction of the International Terrestrial Reference Frame (ITRF), which defines stable and accurate coordinates of points on or near the Earth's surface, as well as their velocities.

The ITRF results from the combination of the four main space geodetic techniques: Global Navigation Satellite Systems (GNSS), Satellite Laser Ranging (SLR), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) and VLBI, where VLBI is the only one that contributes to both materializations of the terrestrial and the celestial reference system.

The last realization, the ITRF2020, followed the same computation procedure as its predecessor (ITRF2014) by using as input time series of station positions and EOP estimated from the four aforementioned techniques. Nevertheless, this solution introduced new computation strategies refining the estimation of annual and semi-annual terms and post-seismic deformation (PSD) models for stations (Altamimi et al., 2022).

VLBI contributed to ITRF2020 not only with station positions but also by refining the EOP time series. Girdiuk et al. (2022) reported a significant improvement in consistency of EOPs derived from the new VLBI Global Observing System (VGOS) sessions (see § 5.1) with those from traditional S/X sessions. This alignment addresses previous offsets in operational EOP products, enhancing the overall quality and reliability of the data. The consistent performance of the new PSD model, even for stations affected by severe discontinuities, highlights VLBI's capacity to deliver high-quality products essential for global reference frame maintenance.

4.1.4. VLBI and Space Ties

The data combination is a significant challenge because the ITRF relies on combining data from the four techniques (VLBI, GNSS, SLR, and DORIS). Current practices involve

ground-based local ties at co-location sites to determine differential coordinates between instrument reference points. However, this method has limitations, with residual discrepancies of approximately 5 mm for 70% of local ties and 10 mm for the remaining 30%, far from the desired sub-millimeter accuracy. To address these inaccuracies, a proposed solution involves *Space Ties* through missions like GENESIS or GRITTS.

The GENESIS mission, scheduled for launch in 2027 as part of the European Space Agency (ESA)'s FutureNAV program, aims to be an orbiting reference point equipped with all four space geodetic techniques at an altitude of 6000 km. This mission is expected to solve inconsistencies between techniques and enhance ITRF accuracy and stability. An additional benefit is the precise modeling of non-gravitational forces, such as solar radiation pressure, due to highly accurate orbital tracking (Delva et al., 2023).

The GENESIS mission's instrumentation is designed to facilitate in-orbit combination and co-location of techniques. It will include an array of passive SLR retroreflectors (and potentially an active laser for time transfer between ground stations), a VLBI transmitter serving as a common target for VLBI stations, a DORIS receiver, and two GNSS receivers, one for redundancy (Delva et al., 2023).

Another proposed mission is GRITSS (Geodetic Reference Instrument Transponder for Small Satellites). This mission is an initiative from the US National Aeronautics and Space Administration (NASA). GRITSS will upconvert received GNSS signals and transmit them to a VGOS station. This unique approach requires only a single VLBI antenna to measure the time-of-flight (τ_{sv}) observable. Tracking τ_{sv} through multiple passes will allow for the derivation of a VLBI position which is fundamentally tied to the GNSS coded signals (Merkowitz et al., 2024; Beaudoin et al., 2025).

5. Present, challenges, and future of VLBI

The future of VLBI is marked by exciting advancements and ongoing challenges. We will focus on the VGOS system and VLBI on K-band (24 GHz).

5.1. VLBI Global Observing System (VGOS)

Legacy S/X telescopes are aging antennas, with low slew, and all of them with different infrastructure (Niel et al., 2005; Petrachenko et al., 2012). The advancements in technology and geodetic products demand the improvement in the telescope's velocity and sensitivity with the aim of accomplishing the goals of GGOS. This is the reason for VGOS. It aims to realize improvements that optimize the performance of the VLBI antennas, featuring faster slewing speeds, broader bandwidths, and increased sensitivity to enhance geodetic and astrometric measurements. To meet these requirements, VGOS has addressed numerous areas, ranging from technical restrictions caused by aging S/X (legacy) antennas to

Table 1. Main differences between the Legacy and VGOS systems

	Legacy S/X system	VGOS system	Benefit
Antena size	5 - 10 m dish	12 - 13 m dish	Reduced cost
Slew Speed	~ 20 - 200 deg/min	≥ 360 deg/min	More observations for troposphere
Sensitivity	~ 200 - 15,000 SEFD	≤ 2,500 SEFD	More homogeneous
Frequency Range	S/X band (two bands)	~ 2 - 14 GHz (four bands)	Increased sensitivity & data precision
Recording Rate	128, 256, 512 Mbps	8, 16, 32 Gps	Increased sensitivity
Data Transfer	usually e-transfer, some ship disks	e-transfer, ship disks when required	
Signal Processing	analog /digital	digital	Stable instrumentation

improving the network geometry. Nevertheless, the distribution of VGOS antennas is still far from being homogeneous (see Figure 2), with only a few stations planned in the southern hemisphere.

This new generation of VLBI radio telescopes started operations in 2020, making the Onsala twin telescopes the first. Currently, VGOS has 16 operational radio telescopes, including the Onsala and Wettzell twin telescopes. The number of VGOS sessions has also increased, with 5 DUT1 sessions and one 24-hour session per week for EOP, station, and source coordinates determination.

Table 1 summarizes the main characteristics of the VGOS system with respect to Legacy as exposed in Behrend et al. (2019).

5.1.1. VGOS gains and challenges

Currently, VGOS networks provide better station coordinates and UT1-UTC accuracy with respect to Legacy. It makes routine radio source imaging possible and improves the sky coverage by a factor of 2 to 3 with respect to previous technology.

On the other hand, VGOS does not yet have global coverage, and EOP determinations are still at the Legacy level, except for UT1-UTC. The low number of stations does not allow redundancy when some stations are down. But even in that situation, due to the high observation rate, the amount of raw data is huge and has the risk of increased RFI (radio frequency interference), due to new satellite megaconstellations.

Regarding the terrestrial and celestial reference frames, source structure is still a limiting factor for the goal of 1 mm in station position and 30 μ s accuracy for source coordinates.

5.1.2. VGOS in South America

If we analyze the distribution map of VGOS stations (Fig. 2), we appreciate that there is no VGOS in South America, and currently, there is only one operative Legacy.

In the recent work of Gomez et al. (2024), a study of different scenarios was presented, involving fictitious VGOS stations in the southern hemisphere, particularly in South America, and they conclude that including two

or more southern stations has a positive impact on all EOP determinations, not only in DUT1. The networks proposed also show an improvement in source coordinates. Additionally, as the authors proposed, a station in a location like Malargüe (western Argentina) could help improve baselines' global eastwest (E-W) distribution. Finally, the authors agreed with Petrachenko et al. (2012), concluding that a larger and more uniform northsouth global distribution of stations will reduce the coupling between troposphere gradients, height of the stations, and source declinations, improving then the celestial reference frame quality.

5.2. K-band VLBI: Pushing the boundaries

As shown in § 4.1.2, a significant subset of the sources in ICRF3 were observed at K-band, resulting from over a decade of global collaboration involving multiple K-band sessions conducted in astro-geodetic mode. These sessions were carried out by using networks such as the European VLBI Network (EVN), the Very Long Baseline Array (VLBA), and the Korean VLBI Network (KVN), among others.

The motivation behind these efforts lies in the increasing degradation of S/X-band observations due to radio frequency interference (RFI) a problem that has worsened with the deployment of satellite mega-constellations, which now even affect the VGOS frequency bands. In contrast, K-band observations offer several advantages (de Witt et al., 2023):

- Reduced plasma effects near the Sun (as the plasma delay is inversely proportional to the square of the frequency, $1/f^2$), allowing more accurate observations closer to the Sun.
- Less scattering in the galactic plane makes it feasible to observe sources in regions challenging at lower frequencies.
- Greater availability of compact calibrator sources is essential for differential astrometry.
- Reduced core shift in radio sources, improving the stability of source positions.

- Higher angular resolution (by a factor of ~ 3 compared to S/X), enhancing source imaging quality and aiding in the precise estimation of source coordinates and their long-term stability.

These benefits make K-band a powerful tool for improving the accuracy and robustness of the celestial reference frame, especially in an era where traditional frequency bands face increasing observational challenges.

5.2.1. Achievements and future prospects

The coordinated efforts of the K-band VLBI community now organized under The K-band Astro2geo VLBI Project, which also explores Ka- and Q-band observations have led to significant achievements. These include the determination of station positions for non-geodetic telescopes operating at K-band (Gomez et al., 2020), the estimation of radio source positions (Charlot et al., 2020), the determination of Earth Orientation Parameters (Krasna et al., 2022), and the development of a catalog of calibrator sources (Jung, 2018; Xu et al., 2024).

Although these are important accomplishments, the goal remains to produce and disseminate standard geodetic and astrometric products, similar to those currently delivered by the IVS for Legacy and VGOS systems. This means: the regular delivery of observation files, routine determination of station coordinates, an increase in the number and frequency of sessions dedicated to EOP, together with the rise of source images on existing databases.

Preparations for ICRF4 are already underway. As part of this global effort, a series of ten approved K-band global sessions is currently being conducted within the European VLBI Network (EVN), in collaboration with the VLBA and the Australia Telescope National Facility (ATNF).

6. Conclusions

VLBI is a fundamental tool in astrometry and geodesy. It is essential for materializing the celestial reference frame, very important for maintaining and refining the terrestrial reference frame, and the only one capable of providing the five EOP, enabling thus to monitor Earth's movements in space and the variations in its rotation. For more than 40 years, VLBI has been indispensable in realizing the ICRS. This work achieved maximum accuracy and axis stability in the ICRF3, the first multi-frequency realization, and the first one that could estimate the aberrational effect, named as galactocentric acceleration. However, challenges remain, notably the limitations imposed by uneven antenna distribution, which affects the quality of observations in the Southern Hemisphere.

The ongoing transition to VGOS is critical for meeting the goals of the GGOS by enhancing network performance. Additionally, using K-band VLBI mitigates challenges related to RFI and source structure, offering higher angular resolution and improving stability. These advancements highlight the importance of VLBI in providing the precise

measurements required for reference frame maintenance and Earth orientation studies.

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Evaluations of the Earth's Rotation Speed using SLR techniques and EOP analysis

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Keywords: SLR technique, Space geodesy, Earth orientation parameters (EOP)

Abstract

The Earth's rotation speed can be characterised by the length-of-day (LOD), defined as the difference between Universal Time (UT1) and Coordinated Universal Time (UTC). From this parameter, it is possible to compute variations in the Earth's angular speed. In this study, we present the results of an analysis of data obtained from **SLR (Satellite Laser Ranging)** observations of the International Laser Ranging Service (ILRS), processed at weekly intervals between 2010 and 2025. Processing the Normal Points enabled the construction of a continuous LOD time series, onto which mathematical models were applied to assess the evolution of the angular speed. A phase of acceleration in the rotation manifested as a negative trend in the LOD values is observed, followed by an apparent stabilisation. These results underscore the importance of maintaining continuous geodetic observations for the study of Earth's rotational dynamics.

Resumen

La velocidad de rotación de la Tierra puede caracterizarse mediante la duración del día (LOD), definida como la diferencia entre el tiempo universal (UT1) y el tiempo coordinado (UTC). A partir de esta magnitud es posible calcular variaciones en la velocidad angular terrestre. En este trabajo se presentan resultados del análisis de datos obtenidos mediante observaciones SLR (**Satellite Laser Ranging**) del **International Laser Ranging Service (ILRS)**, procesadas en intervalos semanales entre 2010 y 2025. El tratamiento de los Normal Points permitió construir una serie temporal continua de LOD, sobre la cual se aplicaron modelos matemáticos para obtener la evolución de la velocidad angular. Se observa una fase de aceleración en la rotación, representada por una pendiente negativa en los valores de LOD, seguida de una aparente estabilización. Estos resultados refuerzan la importancia de mantener observaciones geodésicas continuas para el estudio de la dinámica de la rotación terrestre.

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1. Introduction

Earth's rotation undergoes temporal variations that can be detected with great precision thanks to modern geodetic techniques. Among these variations, the **LOD** represents the difference between the actual duration of the day and its nominal value of 86,400 seconds. This quantity is directly sensitive to changes in the distribution of mass on and within the planet, as well as to dynamic processes that affect the Earth system's angular momentum.

The study of LOD, together with the calculation of the angular speed of Earth's rotation, constitutes a fundamental

tool for monitoring geodynamic phenomena such as the exchange of angular momentum between the lithosphere, the atmosphere, and the core, as well as for detecting climate-related signals, such as oscillations linked to the El Niño phenomenon or mass redistribution due to glacier melting (Gross, 2007). In addition, LOD variations have practical applications in satellite navigation, synchronization of atomic clocks, and orbital prediction models.

In this context, the use of data obtained through **SLR** techniques allows for the estimation of Earth orientation

parameters (EOP), including LOD, with high temporal and spatial resolution. Normal Points, as fundamental SLR observables, provide critical information for refining the orbits of satellites equipped with retroreflectors, from which parameters such as UT1UTC and, consequently, LOD are derived.

This paper presents a detailed analysis of the LOD values and the angular speed of Earth's rotation calculated from SLR data between 2010 and 2025, with special emphasis on the acceleration trend observed in the rotation and the subsequent transition to an apparent stabilization. The main objective is to characterize this temporal evolution and to highlight the importance of continuous observations for the study of Earth dynamics.

2. Methodology

2.1. SLR Observation Techniques

SLR techniques consists of emitting laser pulses from a ground station toward artificial satellites equipped with optical retroreflectors. These pulses travel to the satellite and are reflected back to the station, where the round-trip travel time is measured with high precision. From this measurement, the station-satellite distance is calculated with millimeter-level accuracy.

The set of these measurements, organized into orbital arcs, is temporally averaged to produce an observable known as the Normal Point (NP). These NPs form the foundation of the geodetic data used to determine the Earth orientation parameters (EOP), including the UT1UTC parameter, from which the Length of Day (LOD) is derived.

2.2. Data used and calculation of Earth's Rotation Speed

Data from 2010 through early 2025 were used, obtained from the **ILRS** and accessed via NASA's Crustal Dynamics Data Information System portal ([CDDIS, 2024](#)). The extracted parameters were:

- Observation date (day, month, year)
- UT1UTC
- Derived LOD
- Polar coordinates x and y
- Standard deviation

Earth's angular speed, $\omega(t)$, was calculated from the LOD values (originally obtained in milliseconds and then converted to seconds) using the following expression:

$$\omega(t) = \frac{86400}{86400 + LOD_s} * \omega_0, \quad (1)$$

where ω_0 is the nominal angular speed of the Earth, with a constant value of $2.921151463 \times 10^{-6} \text{ rad s}^{-1}$. This formula yields ω in radians per second.

2.3. Smoothing and Series Modeling

To highlight the underlying trend in the evolution of LOD and $\omega(t)$, a one-dimensional Kalman filter was applied ([Duckworth et al., 2025](#)), considering the dynamics of

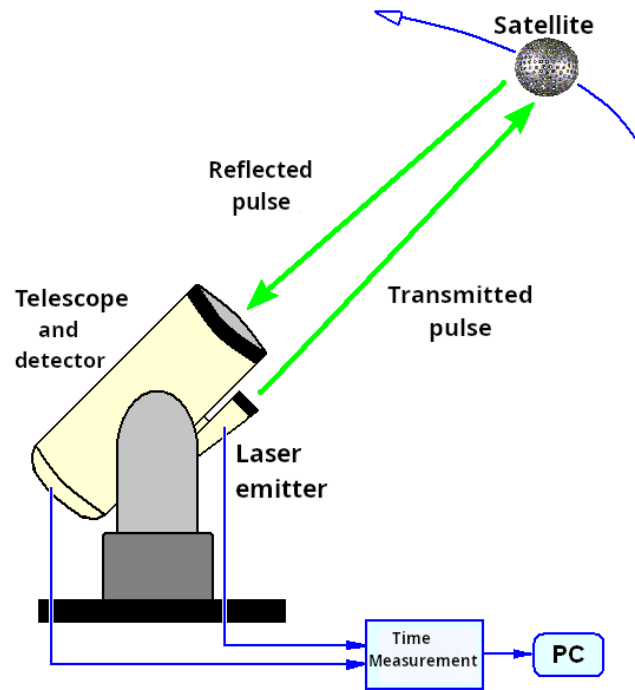


Figure 1. Schematic diagram showing the operation of the SLR technique. Obtained from [Pacheco \(2012\)](#).

a system with noisy observations and linear temporal evolution. This filter is a recursive mathematical algorithm that enables the estimation of the state of a dynamic system from incomplete, noisy, or time-sparse observations. The resulting model clearly visualizes the acceleration and stabilization phases in Earth's rotation speed.

3. Results

The temporal evolution of **LOD** exhibits both secular and seasonal variations, as shown in Fig. 2. In the early years, an upward trend in LOD is observed, reaching peaks above 1.3 ms around 2016. **It is worth noting that the absolute minimum in LOD occurs in July 2015 and coincides with the onset of a significant El Niño episode, characterized by the intensification of Westerly Wind Bursts (WWB) over the tropical Pacific. This phenomenon contributed to the redistribution of atmospheric and oceanic masses, influencing the Earth systems angular momentum and marking the beginning of the subsequent phase of rotational acceleration (Chen et al., 2017).** From that point onward, a sustained decrease continues until approximately 2021, reflecting a net acceleration in Earth's rotation. Subsequently, LOD values tend to stabilize, fluctuating around zero and even taking on negative values. From these LOD values, the angular speed of Earth's rotation, $\omega(t)$, was calculated; its inverse variation relative to LOD is clearly seen in Fig. 2. In this figure, one can observe how

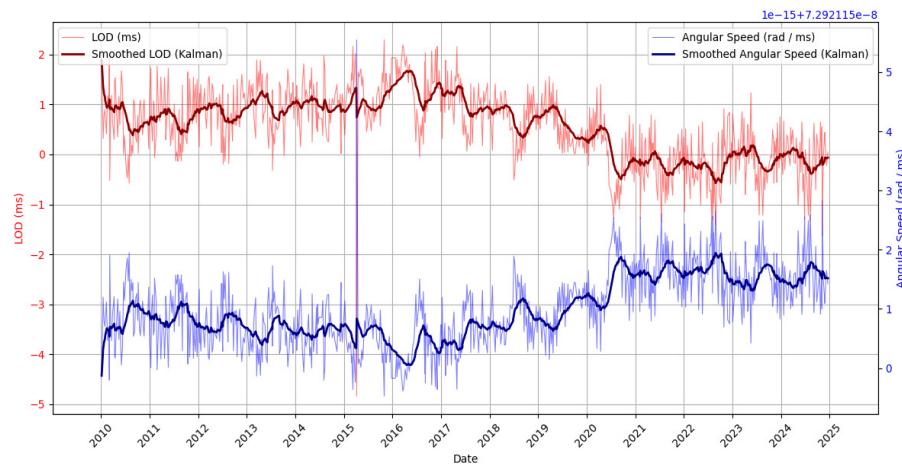


Figure 2. LOD and Angular Speed with Kalman Filter. **It is worth noting that the red and blue vertical lines mark the absolute minimum in LOD and maximum in angular velocity, respectively, on July 4, 2015. This date coincides with an intense WWB associated with the onset of the 2015/2016 El Niño event.**

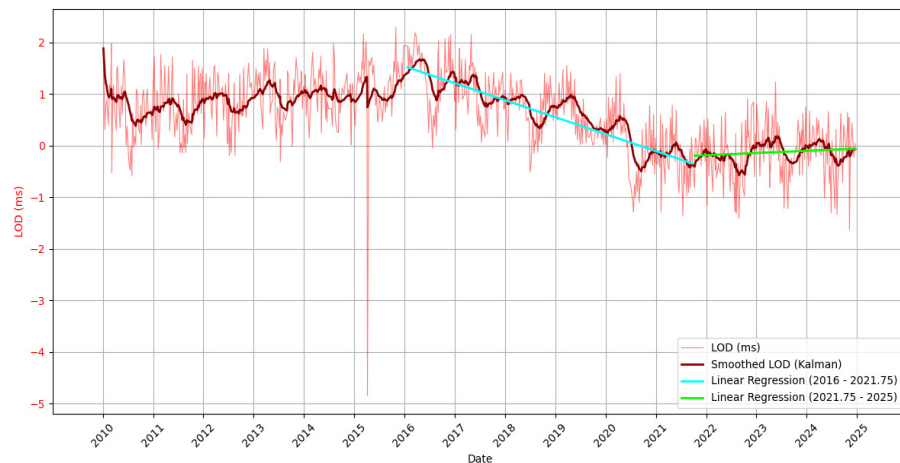


Figure 3. Linear Regression and Filtered LOD.

angular speed increases when LOD decreases, and remains more stable in recent years.

To highlight long-term trends and reduce the effect of noise in the series, a Kalman filter was applied to both the LOD and angular speed values. The filtering produced a smoothed version of both variables, represented by a bold line in Fig. 2. In the case of LOD, the filter clearly emphasizes the transition between the acceleration phase (with decreasing LOD) and the subsequent quasi-stationary phase, which begins to manifest around late 2021 (approximately 2021.75). The same pattern is preserved in the smoothed ω series, with an initial growth phase followed by a period of stability. Fig. 2 shows both filtered curves on the same plot, allowing simultaneous visualization of the dynamic changes in Earth's rotation.

To quantify the observed changes, a linear regression fit was performed on two specific segments of the filtered LOD series. In the first interval, corresponding to the acceleration period between 2016 and mid-2021 (approx.

2021.75), the calculated slope was 0.3289 ms/year; in the second interval, spanning from 2021.75 to early 2025 and associated with the stabilization stage, the slope was +0.0420 ms/year. These results, shown in Fig. 3 as straight lines fitted to the smoothed curve, confirm a substantial change in Earth's rotational dynamics. The slope reversal does not present as an abrupt break, but as a gradual transition reflected by the continuous evolution of the curve.

Finally, annual average LOD values from 2010 to 2024 were calculated to reduce the influence of intra-annual variability. These averages, presented in Table 1, display an evolution consistent with the trends detected in the previous analyses: a sustained increase until 2016, followed by a gradual decline leading to negative values from 2021 onwards. The lowest value is recorded in 2022, with an average of -0.2565 ms, while subsequent years show a slight recovery. This statistical analysis reinforces the

Table 1

Year	Average LOD (ms)
2010	0.670464
2011	0.765532
2012	0.847226
2013	1.001297
2014	0.968963
2015	1.137704
2016	1.341599
2017	1.013341
2018	0.693958
2019	0.547999
2020	0.002136
2021	-0.178198
2022	-0.256577
2023	-0.052903
2024	-0.097165

physical interpretation of an acceleration process in Earth's rotation, followed by a phase of apparent stabilization.

4. Conclusions

- **The most pronounced minimum in the LOD plots recorded on July 4, 2015 corresponds to a peak in rotational speed and coincides with the onset of the El Niño event, a natural climatic phenomenon caused by anomalous warming of the Pacific Ocean.**
- From mid-2010 to mid-2016, the LOD curve rises, indicating a slower rotation rate. This trend may be attributed to global warming, since the redistribution of mass and energy on Earth directly affects its rotation speed.
- The annual peaks and troughs align with seasonal transitions.
- From mid-2016 onward, the curve exhibits a marked LOD maximum (velocity minimum), followed by a steady decline in LOD over approximately five years, with a slope of about 0.33 ms/year.
- In 2021, 2022, 2023, and 2024, the shortest days since the 1930s were recorded ranging from 2 to 30 milliseconds. Research suggests these changes result from the combined effects of factors such as the dynamics of Earth's molten core and the movements of its oceans and atmosphere.

- In recent years, the computed trend has exhibited a period of relative stability, which may result from decoupling between Earth's core and mantle. Several seismic studies indicate that the core may be rotating more slowly, potentially accounting for the stability observed in the data (Yang & Song, 2023).
- Although variations in Earth's rotation can be measured with millisecond precision, pinpointing the exact mechanisms driving its episodes of acceleration and deceleration remains challenging. This underscores the need for sustained, ongoing research in this field.

5. Future Goals

A primary future objective is to use the CART radio telescope to determine the Earth Orientation Parameters (EOP) associated with the phenomena of precession and nutation (Podestá et al., 2025). In this context, the resumption of data acquisition from the OAFA SLR station is also anticipated, enabled by the imminent replacement of its oscillator. This will **enable the comparison of results and the development of predictive models based on machine learning techniques such as Random Forest, AdaBoost, XGBoost, or deep neural networks intended to improve both the understanding and forecasting of Earth's rotational dynamics.**

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Space situational awareness and the Falcon Telescope network

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Keywords: *telescopes*

Abstract

The Center for Space Situational Awareness Research (CSSAR) in the Department of Physics and Meteorology (DFPM) at the United States Air Force Academy (USAFA) developed and operates the Falcon Telescope Network (FTN) a low-cost, commercial-off-the-shelf, network of small telescopes for the purpose of conducting education and research in non-resolvable space object identification (NRSOI). The FTN currently consists of 12 observatories across the world; seven sites in Colorado, one in Pennsylvania, two in Australia, and one each in Chile and Germany. As we enter the second decade of operating the FTN, there is a need to upgrade and modernize, increase the reliability of the system, and enable the latest observation techniques. The FTN upgrade program includes a larger format CMOS camera, dual filter wheels, a direct-drive mount, an all-sky imager, and a redundant weather station. The dual filter wheels have photometric filters (Kron-Cousin and Sloan), transmission gratings (100- and 200-grooves per millimeter), and both linear and circular polarization filters. In addition to single filter measurements, the dual filter wheels allow us to collect double filter measurements such as polarized spectra. We present more details of the FTN upgrades and provide examples of the different NRSOI research capable with the FTN.

Resumen

El Centro de Investigación para la Concienciación Situacional Espacial (CSSAR) del Departamento de Física y Meteorología (DFPM) de la Academia de la Fuerza Aérea de los Estados Unidos (USAFA) desarrolló y opera la Red de Telescopios Falcon (FTN), una red de pequeños telescopios de bajo coste y disponibles en el mercado con el fin de llevar a cabo actividades educativas y de investigación en la identificación de objetos espaciales no resolubles (NRSOI). La FTN consta actualmente de 12 observatorios en todo el mundo: siete en Colorado, uno en Pensilvania, dos en Australia, uno en Chile y otro en Alemania. Al entrar en la segunda década de funcionamiento de la FTN, es necesario actualizarla y modernizarla, aumentar la fiabilidad del sistema y habilitar las últimas técnicas de observación. El programa de actualización de la FTN incluye una cámara CMOS de mayor formato, ruedas de filtro dobles, una montura de accionamiento directo, un generador de imágenes de todo el cielo y una estación meteorológica redundante. Las ruedas de filtro dobles tienen filtros fotométricos (Kron-Cousin y Sloan), redes de transmisión (100 y 200 líneas por milímetro) y filtros de polarización lineal y circular. Además de las mediciones con un solo filtro, las ruedas de filtro dobles nos permiten recopilar mediciones con doble filtro, como espectros polarizados. Presentamos más detalles de las actualizaciones del FTN y ofrecemos ejemplos de las diferentes investigaciones que el NRSOI puede realizar con el FTN.

Table 1. The Falcon Network

Education or Research Institute		Telescope location, city, state	Country	Longitude (East)	Latitude	Elevation (m)
USAF (campus)	Academy	USAFA, CO	USA	255.12	39.01	2212
USAF (Farish)	Academy	Woodland Park, CO	USA	255.01	39.01	2790
MITRE Corporation		Yoder, CO	USA	255.80	38.89	1961
Colorado University	Mesa	Grand Junction, CO	USA	251.76	39.96	1380
Fort Lewis College		Durango, CO	USA	252.13	37.27	1880
Northeastern Junior College		Sterling, CO	USA	256.80	40.65	1177
Otero Junior College		La Junta, CO	USA	256.46	37.97	1221
Penn State University		State College, PA	USA	282.12	40.86	317
Universidad de La Serena		Vicuña	Chile	289.32	-29.99	1139
University of South Wales		Canberra	Australia	149.17	-35.29	600
University of Western Australia (Perth)		Gingin	Australia	115.71	-31-36	18
Technische Universität at Braunschweig		Braunschweig	Germany	10.55	52.28	73

1. Introduction

The United States Air Force Academy (USAFA), through its Department of Physics and Meteorology, began designing and developing a global network of small aperture robotic telescopes in 2012, devoted to studying artificial satellites and celestial objects of the near universe, named the Falcon Telescope Network (FTN). Led by the Center for Space Situational Awareness Research (CSSAR), the FTN project was conceived as a network of telescopes capable of performing simultaneous observations of an object, from different locations across the globe, and with the ability to be controlled remotely from anywhere or programmed for autonomous operation in all phases of data acquisition. The current distribution of telescope nodes of the FTN, located in North America, South America, Europe and Australia, is detailed in Table 1.

Around the turn of the century, as more countries developed their space capabilities, a new term, space situational awareness (SSA) was created. SSA is defined as “The requisite foundational, current, and predictive knowledge and characterization of space objects and the operational environment upon which space operations depend including physical, virtual, information, and human dimensions as well as all factors, activities, and events of all entities conducting, or preparing to conduct, space operations” (Space Operations, 2020).

In the past, because of its space assets, the United States enjoyed an asymmetric advantage when conducting military operations. Fast forward to today, where civil

agencies and commercial companies have joined the space race, the space environment has become more congested, competitive, and contested. Coupled with the creation of the United States Space Force (USSF) in 2019, space domain awareness (SDA) became the new paradigm. SDA encompasses the effective identification, characterization and understanding of any factor associated with the space domain that could affect space operations and thereby impact the security, safety, economy, or environment of our Nation. SSA is a subset of SDA, providing situational awareness and object intelligence in the physical domain of space.

In short, SSA attempts to answer the question “what happened?” whereas SDA attempts to answer the question “is it a threat or non-threat?”.

2. The Space Environment

The space catalog is maintained by the USSF Space Surveillance Network (SSN) and as of 12 July 2025, consists of the following objects:

- Space catalog: 48,500 space objects¹
 - 12,300 active payloads
 - 18,500 pieces of orbital debris
 - 17,700 analyst objects

The first two sub-bullets add up to 30,800 objects that we know of its origin. The 17,700 analyst objects are objects

¹<https://www.space-track.org/auth/login>.

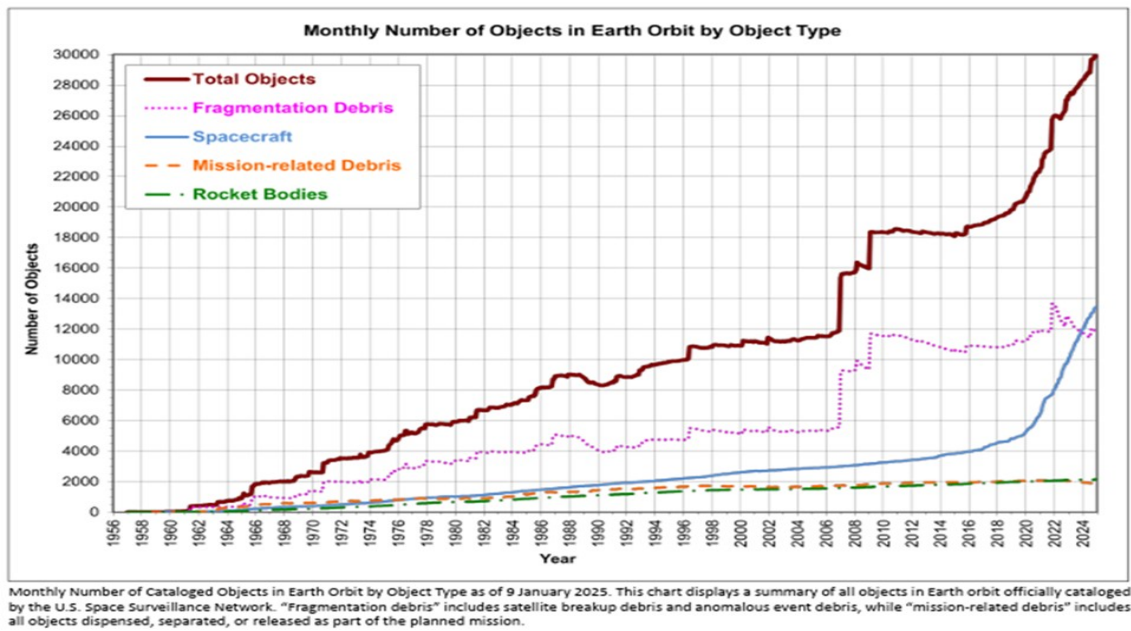


Figure 1. Number of cataloged objects in Earth orbit according to Cowardin et al. (2025).

that do not have a known origin but are routinely tracked by the USSF SSN. NASA also keeps track of the growth of the space catalogue as can be seen in Fig. 1. Two significant events happened in 2007 and 2009. In 2007, China shot down one of its own satellites demonstrating its anti-satellite (ASAT) weapon system, while in 2009, there was a collision between an operational Iridium satellite and a Russian upper-stage rocket body. Unfortunately, the target for the Chinese ASAT test had a high enough altitude such that very little of the debris cloud was able to decay due to increase satellite drag when the Earth's upper atmosphere expands. Since 2016, the growth in the space catalog is attributed primarily to commercial companies, such as SpaceX launching mega-constellations of communication satellites in low-earth orbits.

3. Falcon Telescope Network

The Center for Space Situational Awareness Research in the Department of Physics and Meteorology developed the global Falcon Telescope Network (Chun et al., 2018). Table 1 outlines the twelve Falcon telescopes that make up the FTN.

After a decade of operations, the FTN is currently undergoing an equipment upgrade (Chun et al., 2024). Whereas the telescope at each FTN node remains the same, most everything else of the system is being upgraded. This includes a new telescope mount and drive, sensor, filter wheel arrangement and selection of filters. Additionally, improved weather sensors and all-sky cameras are being added to each node to further enhance remote operations and automation. Below is a list of upgraded hardware

components for each FTN node. An example of an upgraded Falcon telescope is shown in Fig. 2, while the array of the existing observatories is shown in Fig. 3.

- Telescope: Officina Stellare 20-inch, f/8.1 Ritchey-Chrétien
- Telescope Mount: Planewave L-500 Direct-Drive Mount
- Sensor: Atik APX60-Industrial Charge-Coupled Device (CCD)
 - 9568 × 6380 pixels
 - 3.76 × 3.76 micron pixels
 - Full Frame 40.9 × 31.1mm FPA
 - 2.5FPS 16-bit Full Frame
 - 160FPS at 9600 × 100
 - FOV: 30' × 20'
- Redundant Weather Sensors
 - Boltwood II Cloud Sensor
 - Lunático Cloud Watcher
- Alcor Omea 3C All-Sky Imager
- Diffraction Limited AFW-10-50SQ Filter Wheels
 - Two per site with dual adapter (No filter, single filter, double filter measurement options)
 - 10 square slots per wheel
 - 50mm Square Filters
 - * Kron-Cousins: B, V, R, I
 - * Sloan: g', r', i', z'
 - * Diffraction gratings (100 & 200 gpm)mm
 - * Polarization filters
 - Linear (0°, 45°, 90°, 135°)

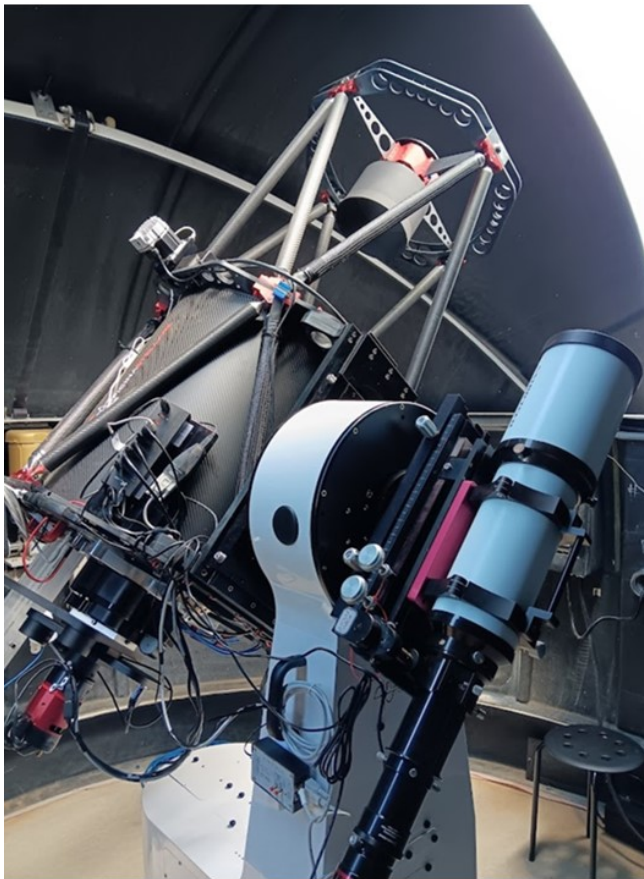


Figure 2. Upgraded Falcon Telescope.

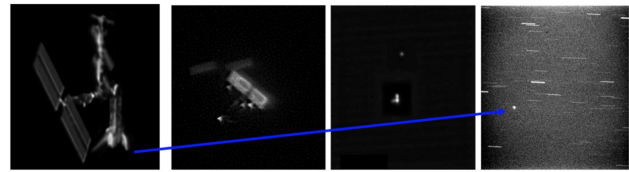


Figure 3. Existing Falcon telescope observatories.

- Circular (RHC, LHC)

4. Research using the Falcon Telescope Network

We use the FTN primarily to conduct simultaneous observations of unresolved satellites using multiple filters and telescopes. Fig. 4 illustrates what an unresolved satellite looks like. As the distance between the observer and the satellite increases or as the size of the satellite decreases, a resolved image such as depicted in the far-left panel of Fig. 4, can quickly become unresolved as shown in the far-right panel. Small telescopes such as the Falcon



Optical satellite imaging degrades with increasing distance and decreasing size

Figure 4. Optical satellite imaging degrades with increasing distance and decreasing size (Fulcoly et al., 2012).

telescopes are ideal for observing unresolved satellites. With the proper filters and gratings, we can measure the optical signatures of the unresolved satellite across the three fundamental properties of a photon: amplitude, wavelength, and polarization.

Broadband photometric filter measurements can be analyzed as a function of time and phase angle to ascertain the satellites attitude (stable vs. unstable), brightness (optical cross-section), and color index. Transmission gratings can be used to obtain a satellites spectral signature useful for identifying surface material properties. Finally, polarization filters can be used to identify surface materials and their scattering properties.

In addition to the equipment upgrade, the image reduction and processing pipeline has also been undergoing improvements (see Fig. 5)(Chun et al., 2024). This primarily involves converting to a Python-based code base with the goal of realizing the originally envisioned fully automated reduction, analysis, and archiving of results. This will include on-site scientific reduction (bias/dark subtraction for all images and flat field correction for photometric images), transfer to Cadet Space Operations Center (CSOC) for metrics extraction (e.g. photometric magnitudes for photometry and polarimetry, spectra for spectroscopy and spectropolarimetry), and archiving of results at CSOC for researcher access and analysis.

4.1. Photometry

Fig. 6 shows photometric data of DirecTV-10 taken during the 2013 vernal equinox. The equinoctial periods are usually when specular glints from a geostationary satellite can be observed from the surface of the earth. The x-axis is phase angle while the y-axis is absolute magnitude in the Johnson-Cousins blue filter (blue data points) and red filter (red data points). The color index (B-R) for two regions of interest is shown between 40°-50° phase angle and around 0° phase angle. Smaller values of B-R imply that the optical measurement is bluer. There is a clear glint at or near the 0° phase angle as seen in the sharp peak in both filters. The fact that the color index shifted to smaller wavelengths (i.e., became bluer) led to the determination that the solar panels were the source of this main glint. However, some ambiguity remained because the B and R measurements were not taken simultaneously.

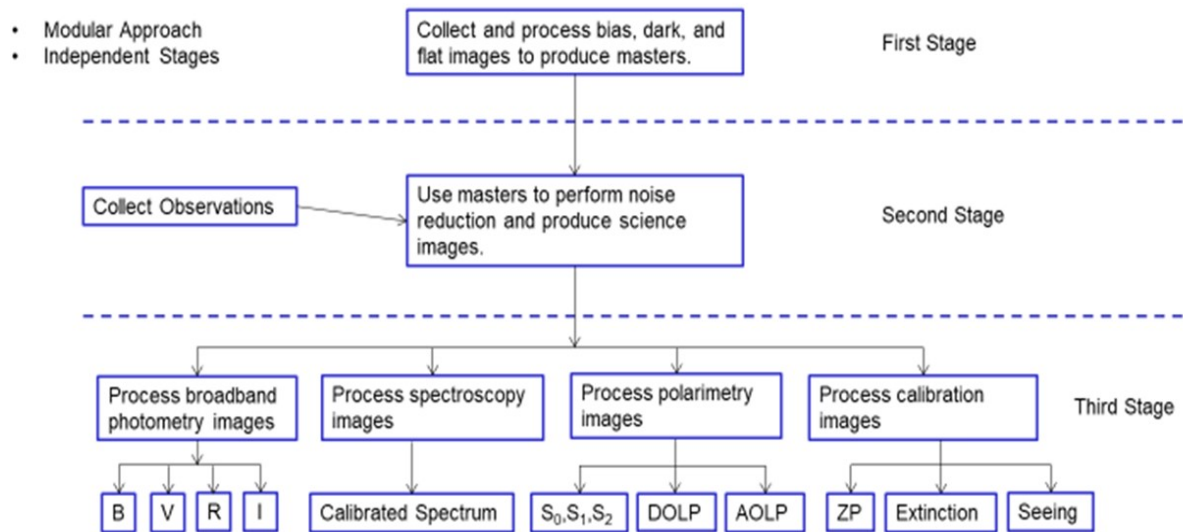


Figure 5. FTNs image reduction/processing pipeline.

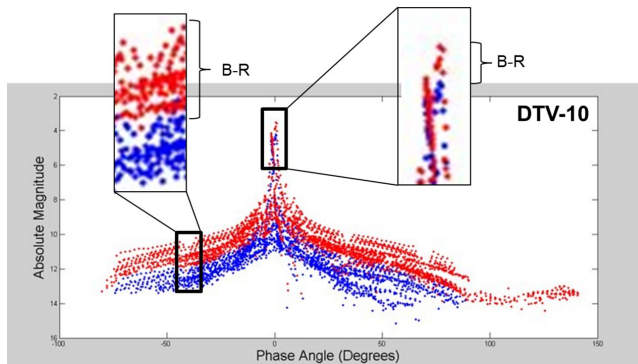


Figure 6. Photometric data of DirectTV-10 taken during the 2013 vernal equinox.

4.2. Slitless spectroscopy

Using transmission gratings, one can obtain spectral signatures of multiple sources visible within an image (Dunsmore et al., 2016; Tippetts et al., 2015). Fig. 7 below is an example of a slitless spectroscopy image of two geostationary satellites, Wildblue-1 and Anik-F2. Since we are tracking the satellites, the stars in the background are streaking through the image. Regardless of whether we track the satellites or the stars, we can usually observe both the zero-order and the first-order. Processing of slitless spectroscopy images such as these requires a pixel-to-wavelength conversion of the extracted first-order. Extinction and solar analog calibration stars can also be applied to satellite spectra to account for different airmasses and solar features.

Fig. 8 shows the spectral signature of Wildblue-1 (left panel) and DirecTV-12 (right panel). For both plots, the x-axis is wavelength from 400-1000 nm, the y-axis is time in seconds from the 1st image, and the z-axis is Flux in

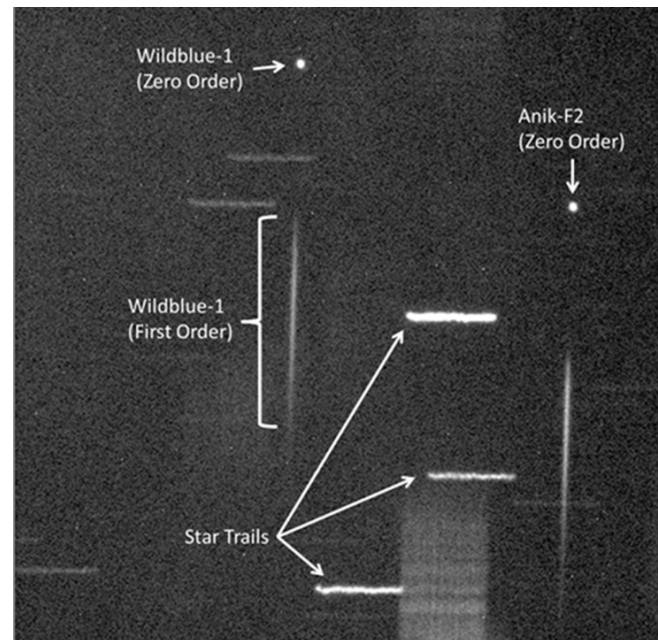


Figure 7. An example image using a transmission grating of geostationary communication satellites Wildblue-1 and Anik-F2. The telescope is tracking the satellites resulting in star streaks. Both the zero-order and first-order are observed for all sources in the image.

counts/sec. The black vertical trace is the wavelength associated with the peak in a satellites spectra. Around the 2,500 second mark for Wildblue-1 and between 1,500-2,500 seconds for DirecTV-12, the black trace shifts to shorter wavelengths indicating that the satellite spectra becomes bluer. These results are the definitive proof that the solar panels are the source of main glint (Dunsmore et al., 2016). DirecTV-12 exhibits two solar panel glints

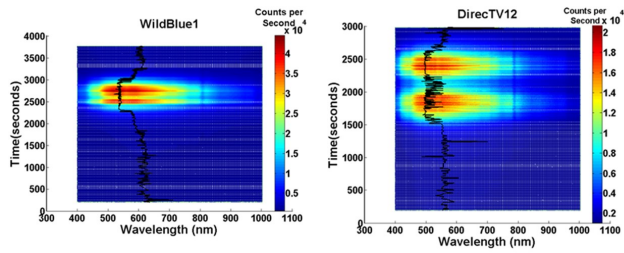


Figure 8. Spectral signatures of Wildblue-1 (left plot) and DirecTV-12 (right plot).

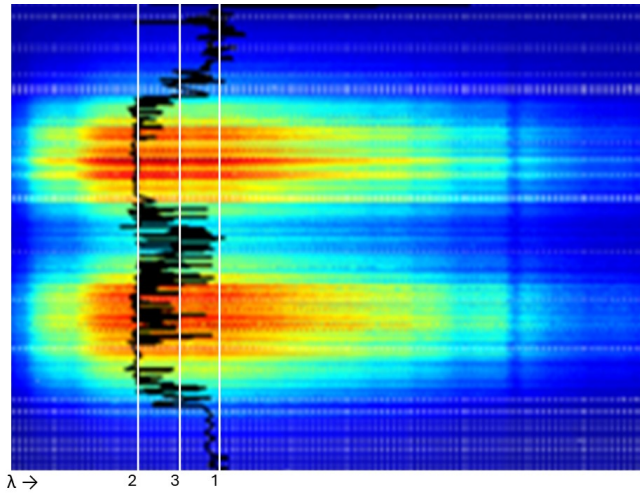


Figure 9. Zoomed in view of the spectral signature of DirecTV-12 from Fig. 7.

as opposed to a single glint seen from Wildblue-1. The double glint indicates that the two solar panel wings on DirecTV-12 are not aligned to one another and in fact have an east-west offset. This could be due to a power management configuration or a torque dampening configuration. Another feature seen in the spectral signature is the occurrence of micro-glints on top of the main glint begging the question whether the solar panels were the source of the micro-glints.

To investigate the source of the micro-glints, we zoom into the double-glint plot of DirecTV-12. There appears to be three baselines as seen in Fig. 9. Baseline 1 corresponds to the wavelength of the max-flux baseline before and after the two main glints. This is the solar reflectance off the satellite. Baseline 2 corresponds to the wavelength of the max-flux baseline during the two main glints which has been established that the source of the two main glints are the solar panels. Something associated with the solar panels or some other part of the satellite is producing the micro-glints. However, regardless of the source of the micro-glints, the main glint baseline is maintained indicating that the source of the two main glints is the same. Finally, baseline 3, which corresponds to the wavelength of the max-flux baseline between the two main glints, appears to be a distinctly new baseline associated with another surface

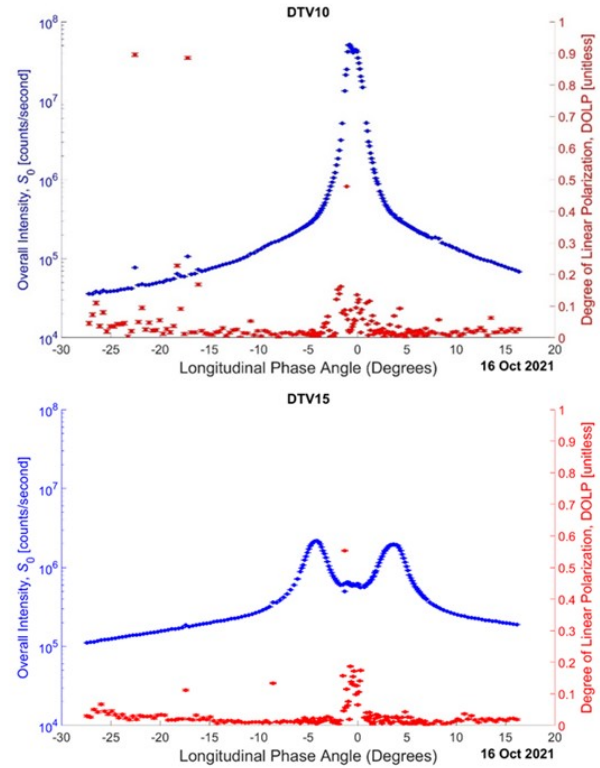


Figure 10. Linear polarization signatures of DirecTV-10 (top graph) and DirecTV-15 (bottom graph).

of the satellite. Micro-glints clearly exist on top of the new baseline. To further investigate the source of the micro-glints, we developed a new measurement capability for the Falcon telescopes: linear polarization.

4.3. Polarimetry

Fig. 10 shows linear polarization data for two GEO satellites, DirecTV-10 (top plot) and DirecTV-15 (bottom plot). These data were taken the same night, 16 Oct 2021, and in fact both GEOs were in the same image frame. The x-axis is longitudinal phase angle, while the left y-axis is intensity, S_0 (blue data points), and the right y-axis is the Degree of Linear Polarization, DOLP (red data points). DirecTV-10 glinted just once that night, whereas DirecTV-15 glinted twice. There are clearly micro-glints (blue data points) on top of the single main glint for DirecTV-10 which appear to correspond to polarization glints as seen in the DOLP (red data points). For DirecTV-15, the micro-glints do not appear embedded within the two main glints, but rather in the saddle between the two glints. The saddle between the two main glints are also where the polarization glints exist. We believe that this is direct evidence that the spacecraft bus and payloads are the source of micro-glints. Solar panels are uniform and mostly featureless resulting in a smooth transition of DOLP across the minimum phase angle, whereas the spacecraft bus and payload configuration are nothing but non-uniform (Eastman et al., 2024).

5. Summary

Over the past decade, the FTN has been operated and managed by the Center for Space Situational Awareness Research in the Department of Physics and Meteorology at the United States Air Force Academy with its educational and industry partners. Each observatory is an exact replica of the others and has been optimized to study low-altitude artificial satellites, to identify and characterize geosynchronous satellites based on simultaneous observations from different latitudes of the world, and to study astronomical sources in the nearby universe. Located on 4 continents, the FTN has provided world class data on man-made satellites and astronomical objects for a variety of purposes. Currently, the FTN is undergoing an equipment upgrade to both improve its performance and add new capabilities. The details of this upgrade were provided in this paper and will enable the FTN to continue contributing to SSA research and educational outreach into the future.

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Astrometric comparison of optical and telemetric observations of the geostationary satellite VENESAT-1 during the COVID-19 pandemic

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Keywords: *Geostationary satellite, Venesat-1, optical observations, telemetry observations, Stock method, Tepui function*

Abstract

During the operational period of the geostationary satellite VENESAT-1, a collaborative partnership was established between two Venezuelan institutions: The Centro de Investigaciones de Astronomía (CIDA) and the **Agencia Bolivariana para Actividades Espaciales** (ABAE). This collaboration led to the creation of a small astronomical observatory located at one of VENESAT-1's satellite tracking stations.

In February 2020, with the observatory fully operational and the potential coexistence of a future satellite within the same orbital slot under consideration, the first series of optical observations was conducted to bring a joint project to completion.

This work presents the reduction of data from four of those nights of observation, utilizing a model based on Stocks Method and the Tepui function, and compares the results with data provided by the satellites telemetric tracking antenna. Both sets of observations were acquired at the ABAE Satellite Ground **Tracking** Station Ground in **Baemari**.

Resumen

Durante el tiempo que el satélite Geoestacionario Venesat-1 estuvo operativo se creó un vínculo de colaboración entre las instituciones venezolanas, Centro de Investigaciones de Astronomía (CIDA) y Agencia Bolivariana para Actividades Espaciales (ABAE), que llevó a la creación de un pequeño observatorio astronómico situado en una de las estaciones de seguimiento satelital del Venesat-1.

En febrero de 2020, con el observatorio ya en pleno funcionamiento y ante la posibilidad de coexistencia en la misma ventana de un futuro nuevo satélite, se realizó la primera serie de observaciones ópticas, a fin de dar por concluido un proyecto conjunto.

Mostramos aquí la reducción de cuatro de esas noches de observación, haciendo uso del modelo basado en el Método de Stock y de la función Tepui, y su comparación con los datos aportados por la antena de seguimiento telemétrico. Ambos conjuntos de observaciones fueron obtenidos desde la Estación Terrena de Control Satelital del ABAE de **Baemari**.

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1. Introduction

On 28 October 2008, Venezuela's first geostationary satellite was launched from China. A few weeks **before** this event, Venezuelan personnel responsible **for the** ground-based tracking of the **satellite's** position and relocation maneuvers within the assigned window centered on the geostationary orbit visited the **Observatorio**

Astronómico Nacional (OAN), operated by the **Centro de Investigaciones de Astronomía** (CIDA). At that time, CIDA was still collaborating on a Spanish **state-funded** project aimed at evaluating the potential benefits of satellite tracking through optical means. This convergence of circumstances gave rise to a spirit of cooperation between CIDA and ABAE (Agencia Bolivariana para

Actividades Espaciales), leading to the creation of a joint initiative: the PASAVEN project (Posicionamiento **Astronómico** del SAtélite VENesat). The project focused on conducting optical observations from Venezuela's own Ground Tracking Stations located in Baemari and Luepa. The first astronomical observations were made from the Luepa Station in September 2011.

This collaboration was based on the experience gained by CIDA during its participation in the PASAGE project (Astrometric Positioning of the Geostationary Satellite) from 2004 to 2008, which explored the use of optical astrometry for positioning and orbit determination of a geostationary satellite (Montejo et al. 2011).

This project, led by ROA personnel (Real Instituto y Observatorio de la Armada) in San Fernando (Spain), also uses distance measurements obtained through the Two-Way Satellite Time and Frequency Transfer (TWSTFT) technique, which is used by the ROA Time Section in collaboration with other laboratories.

In our case, each **Ground Tracking Station** operated by ABAE was equipped with an antenna capable of determining **the distance of the antenna-satellite direction vector, through a method similar to TWSTFT, and its own orientation**. The system recorded one data point per second, with **distance** errors typically close to one meter, while **orientation errors** were more irregular, ranging from one to several arcseconds. The latter may be due to the fact that the orientation is derived directly from the antenna's alignment toward the point of optimal signal reception. This highlights the potential advantage of incorporating optical astrometry.

2. OPTICAL OBSERVATIONS OF THE GEOSTATIONARY SATELLITE VENESAT-1

Geostationary satellites occupy a privileged position in space, making them essential for applications such as telecommunications, meteorology, and navigation. A perfectly geostationary orbit, understood as a mathematical abstraction, would only be feasible in an ideal scenario, where a spacecraft orbited a perfectly symmetrical Earth, unaffected by any external forces other than Earth's central gravitational pull. Nevertheless, this theoretical approximation remains useful for describing the actual behavior of these satellites. Although additional forces, such as perturbations caused by the Moon, the Sun, and Earth's non-spherical shape, influence their motion, their magnitude is relatively small compared to the dominant gravitational force (Soop 1994).

If we select a rotating reference frame centered on the observation point and comoving with the satellite, these satellites appear as theoretically fixed points against a rotating sky. This simplifies the observation setup and makes it easily automatable.

In February 2020, the full operational readiness of the **Baemari** Astronomical Observatory was achieved. Located in El Sombrero, Guárico State, Venezuela, its

geographical coordinates are $66^{\circ}54'47''\text{W}$ and $9^{\circ}21'21''\text{N}$. This observatory offers a privileged location for optical monitoring of VENESAT-1, being just 200 meters from the satellite's tracking and control antenna. The nominal position assigned to the satellite was 78°W , within a 125 km orbital window. Considering the possibility of a future VENESAT-2 temporarily sharing this window with VENESAT-1, a series of observation nights was conducted to engage with this scenario. The new observatory is equipped with a Celestron Edge HD telescope of 35.56 cm aperture, focal length 3910 mm, mounted on an equatorial structure. It incorporates a FLI PL09000 CCD detector EQ $\sim 68\%$, with a resolution of 3072×3072 square pixels measuring $12\ \mu\text{m}$ per side, housed under a 3-meter dome.

In the present work, 8139 observations, each with an exposure time of 10 seconds, were processed from the **last** four nights of data acquisition: February 28 and 29, and March 1 and 2. These were the last observations conducted, as the satellite was unexpectedly retired to the geostationary graveyard due to antenna malfunctions. The exposures were taken without engaging the **sidereal tracking of the telescope** and contain two **different types of image**: the satellite, exhibiting radial symmetry; and stellar objects, appearing as streaks with lengths proportional to the exposure time ($10\text{ s} \sim 120$ pixels along the detectors x-axis) and widths determined by atmospheric seeing conditions.

3. Reduction and Processing of the VENESAT-1 Observational Data

The data reduction procedure was carried out following the steps outlined below:

1. Determination of detector regions containing images. To identify these regions, a column vector is constructed where each element represents the sum of counts from all pixels in its corresponding detector row. The resulting profile allows us to detect relative maxima formed solely by the aggregation of sky background pixels. A convolution is then applied over these rows of maxima, using a kernel whose width matches the number of pixels comprising a stellar trail. This process transforms stellar traces into pyramidal shapes and satellite signals into plateaus, thereby revealing the initial positions of both types of images.

2. To measure the satellite, a least squares fit of a radially symmetric function such as a Gaussian was sufficient. For the stellar trails, we apply the Tepui function, a mathematical tool developed at CIDA (Abad et al. 2004), based on the difference between two arctangent functions. This model depends on five parameters, one of which is the central point x_0 of the trail, associated with the UT time that corresponds to the midpoint of the exposure. The y_0 component is determined by performing a Gaussian fit on a transverse cut of the trail at the x_0 position.

3. **We selected UCAC5 as the reference catalog (Zacharias et al. 2017) aligned with the J2000.0 equinox, which will be automatically transferred to the observations during the reduction process.**

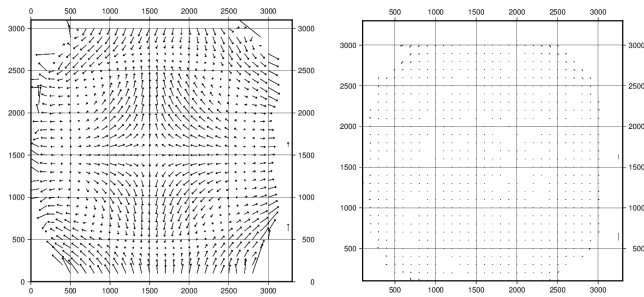


Figure 1. Vector representation of numerical distortion patterns: (Left) Pattern introduced in the observations. (Right) Final pattern after iterative corrections of (x, y) coordinates.

4. The reduction process will employ the Stock linear method (Stock, 1981) and its overlapping variant, incorporating the Sliding Polynomial (Stock & Abad 1988) to model overlap residuals whether between plates or between plates and catalogs (Abad, 1993).

5. Given the large number of exposures, partial solutions were generated from multiple subsets based on different criteria (regions from a single night or partial regions spanning all four nights) in order to assess whether the resulting distortion patterns were consistent across them. As a result, it was decided to work with 200 observations per night, corresponding to the satellites transit across the region in front of the Milky Way. These were used to derive distortion patterns expected to be common to all exposures. The patterns were then applied iteratively identifying, correcting the (x, y) measurements, recalculating the Stock solution, and repeating the determination until the residual pattern was fully eliminated. (Figure 1).

6. **An estimated internal error is derived based rms of the positional differences of each image in the overlapping observations to the average position. After the final reduction the associated internal errors are presented in Table 1**, where the residuals for each coordinate are distributed as a function of magnitude. The reported errors are approximately $0.1''$ in declination and slightly greater than $0.2''$ in right ascension, with a noticeable deterioration for fainter stars. This may be attributed to the reduced signal to noise ratio, particularly at the ends of the trails, as the analysis was conducted using unprocessed raw exposures without the benefit of calibration frames (flat, dark, and bias). It is also worth noting that the trails in the direction of right ascension exhibit significant length, approximately 120 pixels.

4. Astrometric and Telemetric Results: A Comparative Analysis

Satellite astrometry provides topocentric measurements of the **position of the satellite in equatorial coordinates, referring**, to the celestial reference system defined in this study by the J2000.0 equinox and the mean observation

Magnitude	$\sigma_{\alpha}('')$	$\sigma_{\delta}('')$	N_{stars}
8	0.013	0.08	260
9	0.015	0.09	1980
10	0.014	0.08	3511
11	0.018	0.09	6912
12	0.024	0.11	2426
Total error	0.018	0.09	15089

Final internal positional errors as a function of magnitude for the coordinates of the selected sample catalog.

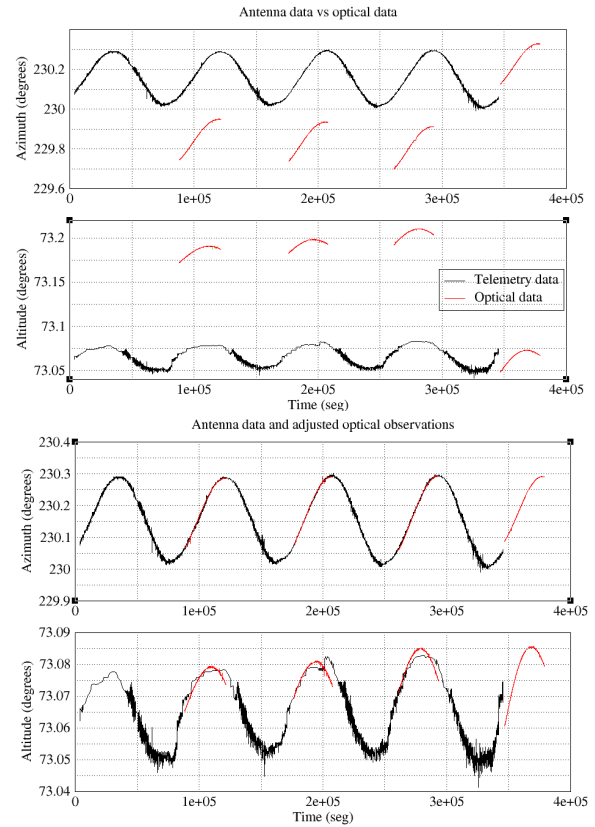


Figure 2. Time-series of Azimuth and altitude. (Top) Using the SOFA package at UT given by the computer of the telescope. (Bottom) Using the SOFA package at UT corrected by the ΔUT indicated by the operator.

epoch. To make these data operational and comparable with those obtained by the antenna at a specific moment, it is necessary to convert them to horizontal coordinates (azimuth and altitude), updated to the equinox and epoch corresponding to the instant of observation. For this purpose, the astrometric tools of the SOFA package (SOFA 2023) were used. From that point onward, both the antenna-derived coordinates and those obtained through astrometry are expressed in the same system and should coincide during periods of joint observation.

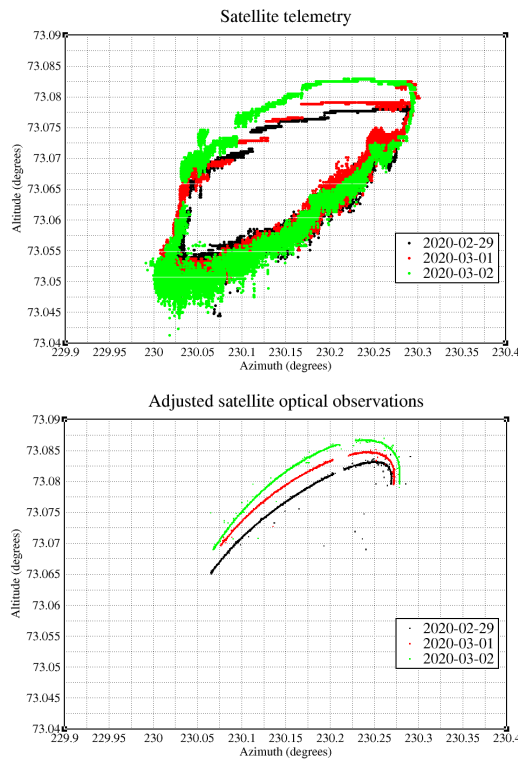


Figure 3. Azimuth vs Altitude for the **first three days of optical observation**: (Top) Telemetry data. (Bottom) Optical data.

In Figure 2 (Top), we observe that this alignment does not occur. After consulting with Eng. C. Alvarado from **ABAE** indicated that there was a discrepancy of approximately 42 seconds between the clock of the computer used for the measurements and the reference UT time provided by the antenna. Figure 2 (Bottom) confirms this discrepancy after it is applied to the SOFA software.

By plotting azimuth versus altitude from the data, we obtain (Figure 3, Top) the daytime orbit of the satellite as recorded by the antenna, represented in three colors corresponding to different days. A significant dispersion in orientation is evident in this dataset, a pattern not observed in the astronomical measurements (Figure 3, Bottom). **In fact, this discrepancy is attributable** to the low error

values in the right ascension and declination provided by the optical instruments. Furthermore, we observe that the satellite orbit aligns more closely with the expected trajectory after accounting for the temporal correction.

Figure 3 graphically illustrates the improvement achieved by using astrometry over telemetry in orientation-related coordinate measurements.

5. Conclusions

The integration of optical observations with those provided by ABAE represents a significant improvement in the tracking of the geostationary satellite VENESAT-1. Residual errors on the order of a few tenths of an arcsecond in both declination and right ascension validate the robustness and quality of the optical data acquired from the new Baemari Astronomical Observatory.

Although this study may appear to mark the **end** of a collaborative cycle such as the PASAVEN project, it actually signifies the beginning of a new phase. Currently, the **Baemari Ground Tracking Station**, equipped with its new Astronomical Observatory, is fully capable of conducting geostationary monitoring by integrating both techniques should a new satellite VENESAT-2 be launched into orbit in the near future.

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Laplace plane: leadership and dynamics of orbiting space Debris

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Keywords: Space Debris, Leader, Spatial Statistical Distributions, Threshold distance

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The Laplace Plane ($\mathcal{LP}$) is characterized by the gravitational equilibrium between the Earth, the Moon, and the Sun, which enables high-altitude orbiters to maintain relatively stable orbits. This is particularly relevant for space debris, whose presence is notably increasing. At the same time, an increase in the amount of space debris has also been observed in the Geosynchronous Equatorial Orbit (GEO) region, where debris tends to remain stable over a specific area above the Earth's equator. Although collisions in this region are less frequent, several catastrophic events have been recorded in recent years, including incidents such as satellite explosions and the fragmentation of rocket bodies (R/B). These events have resulted in the creation of various debris clouds, such as Breeze-M DEB, Titan 3C Transtage DEB, Ekran-2 DEB, Atlas Centaur DEB, Telkom-1 DEB, and, more recently, Beidou and Intelsat 33E clouds. The aims of this paper are to analyze the distribution that characterizes the dynamics of debris located close to the $\mathcal{LP}$ at GEO altitude and to identify the potential leaders of each debris cloud, along with the objects grouped around them, named associates. To achieve this, the distances between different objects will be calculated, and a proximity threshold will be established. This will enable the identification of near or far relationships between them, contributing to a better understanding of the evolution of these debris in this region.

1. State of the art

The classical $\mathcal{LP}$, can be considered a frozen orbit or an equilibrium solution of the averaged dynamics arising from the quadrupole component of gravitational perturbations. Tremaine & Namouni (2009) and Rosengren et al. (2014) conducted analytical studies on the dynamics of this plane. The projection of the orbital pole of the $\mathcal{LP}$ lies in the

plane defined by $(i \cos \Omega) \times (i \sin \Omega)$, corresponding to the coordinates $(0, 7.4^\circ)$, where i is the inclination and Ω is the right ascension of the ascending node. Both elements determine the orientation of the orbital plane with respect to the equatorial reference frame. Figure 1 shows this projection, where cataloged space debris in the GEO region as of January 4, 2024, 00:00:00 UTC, is seen clustering around the $\mathcal{LP}$. Additionally, four known breakup events are highlighted in the same figure.

These fragments are distributed around the $\mathcal{LP}$ in regions of both higher and lower concentrations of cataloged objects. The cataloged objects for each debris cloud are represented by orange dots, blue squares, red boxes, and green hombuses, corresponding to Titan 3C Transtage DEB, Breeze-M DEB, Ekran-2 DEB, and Atlas Centaur DEB, respectively. In addition, these debris clouds include objects in highly elliptical orbits, resulting in large orbital eccentricities. Consequently, in the plot, they are located outside the $\mathcal{LP}$ region.

In terms of the orbital elements characterizing each fragments trajectory, we can analyze how these objects are spatially distributed. In particular, the eccentricity, e , as a function of the semi-major axis, a , in km, shows that the fragments are not only present in the GEO region but also extend into Low Earth Orbit (LEO), and Medium Earth Orbit (MEO) regions Lacruz & Casanova (2024).

Take into account that these orbital elements determine the shape of the orbit with respect to the equatorial reference frame. A key feature of their dynamical behavior is related to the orientation of each fragments orbital plane, which can be studied through the relationship between i and Ω . A more precise understanding of the dynamics exhibited by these fragments in the $\mathcal{LP}$ is shown in Figure 2, where their behavior is consistent with the long-period patterns obtained through numerical propagation in (Rosengren & Scheeres, 2013). This figure

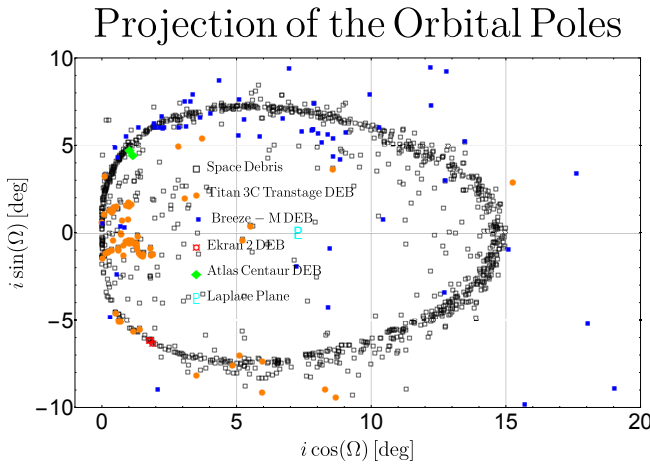


Figure 1. All space debris cataloged in GEO region, surrounding the $\mathcal{LP}$, where the orange dots, blue squares, red boxes, and green rhombuses are Titan 3C Transtage DEB, Breeze-M DEB, Ekran 2 DEB, and Atlas Centaur DEB, respectively.

shows a clear pattern of direct dependence between the two orbital elements. Similar to Figure 1, the cataloged objects classified as orbital debris in the GEO region are represented by black squares, along with the fragments from the four previously mentioned breakup events.

It is also observed that the maximum inclination is approximately 15 deg, which is consistent with the maximum inclination at which fragments are located in the GEO region. Fragments with an inclination significantly deviating from 15 degrees are classified as High Area-to-Mass Ratio (HARM). The behavior of these fragments has been described by Friesen et al. (1993) and Rosengren & Scheeres (2013).

We determine the correlation between the inclination and the right ascension of the ascending node through several mathematical expressions developed in this work. Specifically, we define this relationship using three nonlinear real functions, which represent a novel approach to characterizing the dynamics as, $\mathcal{LP}_1(\Omega(i))$, $\mathcal{LP}_2(\Omega(i))$, and $\mathcal{LP}_3(\Omega(i))$, such as:

$$\mathcal{LP}_1(\Omega(i)) = a_1 + a_2 \cos \Omega, \quad (1)$$

$$\mathcal{LP}_2(\Omega(i)) = b_1 + b_2 \cos(b_3 \Omega), \quad (2)$$

$$\mathcal{LP}_3(\Omega(i)) = 2 \tan^{-1}(c_1 \cos \Omega), \quad (3)$$

where the coefficient a_1 , a_2 , b_1 , b_2 , and b_3 , are calculated in an iterative process until the residuals of the fit are minimized toward zero. The three functions are fitted by optimizing a compromise between the overall distribution of fragments. Selection of the most suitable function is based on its ability to accurately represent the current catalog of fragments, as assessed through the distribution of residuals at each iteration. Key criteria include the residuals approximating a Gaussian distribution and the number of iterations required for convergence of the LevenbergMarquardt numerical method. Convergence is

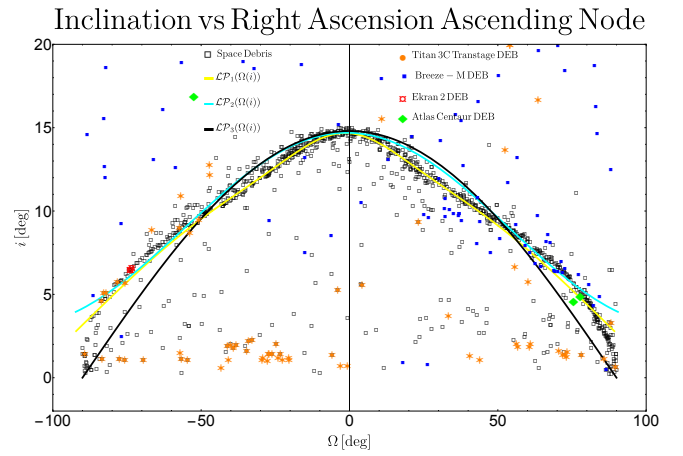


Figure 2. Distribution of the inclination i , in deg, as a function of the right ascension of the ascending node, Ω , in deg. All cataloged space debris in the GEO region surrounding the $\mathcal{LP}$, are shown, where the orange circles, blue squares, red boxes, and green rhombuses represent the Titan 3C Transtage DEB, Breeze-M DEB, Ekran 2 DEB, and Atlas Centaur DEB, respectively. The yellow, cyan, and black continuous curves represent the general behavior and the correlation between the two variables.

typically achieved after approximately 600 iterations, with $\mathcal{LP}_2(\Omega(i))$ yielding the lowest residual error, indicating the best fit. The value of the c_1 is obtained by $\cot^{-1}(7.4)$.

2. Identifying Leadership

To identify the leader objects and associated fragments within each cloud of space debris, a metric defined as the threshold distance ρ was applied. This metric is based on the distribution of the semi-major axis, a within each cloud and is implemented through the following steps: (1) Acquisition of orbital data using Two-Line Elements (TLEs) from <http://space-track.org>. (2) Orbital propagation using a perturbed orbital model that accurately represents the dynamics, specifically the *OrbitSat* tool (Abad & Lacruz, 2013). (3) Computation of the maximum of the minimum distances between each pair of discretized orbits (Lacruz & Casanova, 2024). (4) Application of the ρ to identify potential leader objects and their associated fragments.

2.1. Data

The orbital elements of each piece are obtained in the classical TLE format. These data are converted to classical orbital elements and the corresponding state vectors (position and velocity) along with their associated Julian Dates. For each object, its orbit is calculated from its six classical orbital elements over one orbital period.

2.2. Perturbed Orbits

Each orbit is propagated using a perturbed orbital model that accurately represents the relevant dynamical forces affecting space debris. Specifically, we use the *OrbitSat* tool, which incorporates perturbations such as Earth's oblateness, solar radiation pressure, and third-body

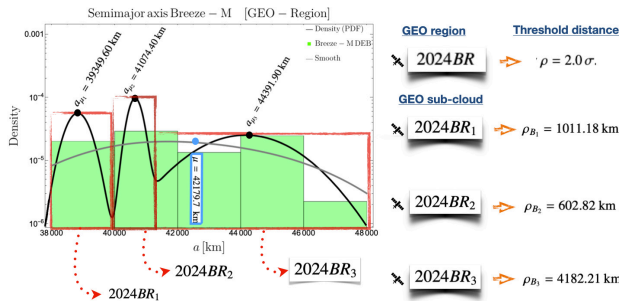


Figure 3. Distribution of the semimajor axis a , in km, for Breeze-M DEB. The histogram shows the subsets in GEO region. The grey curve correspond to the general tendency, while the black curve correspond to Probability Density Function (PDF) in each subset. This PDF is the Normal distribution.

gravitational effects to ensure precise trajectory predictions over time. This tool incorporates a set of fundamental parameters required to characterize the orbit at each given time instant. It uses C-based code implementing the Dormand-Prince 8th-order (dopri8) numerical integrator for orbit propagation.

2.3. Metric

After obtaining the ephemerides of each object over one orbital period which, in this case, corresponds to the Earth's rotation period due to their location in the GEO region we compute, for each pair of discretized orbits, the maximum of the minimum distances between their points, following the method described by [Lacruz & Casanova \(2024\)](#). Essentially, for each point on one orbit, we compare it with all points on the other orbit to find the minimum separation distance. Among all these minimum distances, the largest value is selected as a threshold reference between orbit pairs. This process is applied to all orbit pairs in the dataset.

2.4. Determining leaders

As a last step, to determine the leaders of each debris cloud, we establish a threshold distance based on the metric values obtained in the previous step. Using the distribution of the semi-major axis, we iteratively fit a density function via least squares to estimate measures of central tendency and dispersion. These parameters allow us to select an appropriate threshold distance according to the distribution characteristics. The fitted density function thus defines the overall distribution, providing a basis for identifying leader objects and their associated fragments.

2.5. Applications and Results

As an example of the previously described methodology, applying this process to the Breeze-M DEB cloud (40 pieces cataloged in GEO as of January 4, 2024, 00:00:00 UTC), we obtain the distribution of the semi-major axis, a , in kilometers, as shown in Figure 3. The histogram reveals several subsets at the GEO region. The central tendency and dispersion of each subset are derived using

Probability Density Functions (PDFs) applied to the data. The calculated values are then used to define $\rho = a_{\mu_i} + 2\sigma$ where the subscript i refers to the associated subset. The value 2σ has been chosen as a compromise based on the distribution function.

For this example, the set named 2024BR refers to all the data, is divided into the subsets 2024BR₁, 2024BR₂, and 2024BR₃, as shown in Figure 3. In the figure, we can see the different fits applied to each subset and the associated threshold distance values for each one, respectively. The general set 2024BR contains 4 leaders, each with 9 associated pieces, while for separate the subsets 2024BR₁ and 2024BR₂ contains 2 and 2 leaders, each with 1 and 1 associated pieces. The subset 2024BR₃ contains 3 leaders, the first has 9 associated pieces, while the other two have 8 each.

When comparing the different leaders obtained in each subset, the leaders identified in the complete set are preserved, and some new leaders appear in the subsets. This occurs because the process is more refined when applied to the subsets. Specifically, each leader in the SpaceTrack database is associated with its NORAD ID, and in this case, the identified leaders correspond to 39614, 40278, 41122, 41547 and 41548, respectively.

We were able to identify that the cloud has four leader pieces along with their corresponding associates. This suggests that if the leaders and their associates remain stable over time, and considering that all perturbing forces act on them similarly, they likely share a comparable Area-to-mass ratio (A/m). Therefore, by studying only the leader, we could estimate the A/m of its associates. This methodology can be extended to other debris clouds in the GEO region, as illustrated with the Breeze-M DEB cloud. Ultimately, we highlight that by analyzing the geometric characteristics of the fragments, it is possible to infer physical properties that enable more accurate modeling of the dynamics of these space debris objects.

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Astrometric parameters of the binary Asteroid (216) Kleopatra using joint speckle interferometry and classical photometry

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Keywords: *H II regions, ISM: Jets and outflows, Stars: Pre-main sequence, Stars: Mass loss*

Abstract

We present the astrometric characterization of the binary asteroid (216) Kleopatra by combining speckle interferometry and classical photometry. Our methodology enables the spatial resolution of asteroid satellites from ground-based observatories, using a semi-automated pipeline for image processing and orbit modeling. This work demonstrates the potential of applying high-resolution techniques, previously limited to binary stars, to multiple asteroid systems.

Resumen

Presentamos la caracterización astrométrica del asteroide binario (216) Kleopatra mediante una combinación de interferometría speckle y fotometría clásica. Nuestra metodología permite resolver espacialmente los satélites del sistema desde observatorios terrestres, utilizando una cadena de procesamiento semiautomatizada para el análisis de imágenes y el modelado orbital. Este trabajo demuestra la viabilidad de aplicar técnicas de alta resolución angular, previamente reservadas para sistemas estelares, al estudio de asteroides múltiples. Los parámetros astrométricos derivados son consistentes con valores previamente reportados en la literatura, y la fotometría complementaria permite recuperar el período de rotación y construir un modelo tridimensional del cuerpo principal.

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1. Introduction

The study of multiple asteroid systems (MASSs), including binaries and triples, has advanced significantly over the past few decades. Once considered rare or improbable, MASSs are now known to comprise a substantial fraction of the minor bodies in the Solar System, particularly within the main asteroid belt (Margot et al., 2015). These systems serve as natural laboratories for investigating fundamental processes related to planetary formation and collisional evolution.

Among their most valuable features is the preservation of dynamical quantities such as angular momentum, orbital eccentricities, and mass distributions, which can be used to infer their formation mechanisms whether via fission, capture, or large-scale impacts. Observational characterization of these parameters often requires

techniques with high angular resolution, such as space-based imaging, adaptive optics, or radar. However, these techniques are either costly or unavailable for wide surveys.

In this work, we propose a novel combination of speckle interferometry and classical photometry, performed simultaneously using mid-sized ground-based telescopes, to measure the astrometric parameters of the triple asteroid system (216) Kleopatra. The main component of this system exhibits a highly elongated, non-convex “dog-bone” shape, and is accompanied by two satellites: Alexhelios and Cleoselene. Previous studies using adaptive optics and radar have constrained the system’s orbital elements and bulk density (Marchis et al., 2008; Descamps et al., 2011).

Speckle interferometry has traditionally been used for the resolution of close stellar binaries, particularly in high-angular-resolution campaigns involving binary stars with

sub-arcsecond separations (Guerrero et al., 2018). Its use for the study of minor bodies, however, remains largely unexplored. This study applies Fourier-based analysis of speckle image cubes to resolve the companions of Kleopatra. Meanwhile, long-exposure photometry is used to derive rotational parameters and light curves, which feed into shape inversion algorithms for 3D modeling.

The synergy of these two techniques enables the robust identification of satellite signals and their orbital configuration. By correlating photometric features such as occultations and mutual events with astrometric data, we aim to provide an independent confirmation of Kleopatra's satellite system and demonstrate the broader applicability of this methodology to other MASs observable with 12 meter-class telescopes.

2. Methodology

2.1. Overview

The astrometric and photometric characterization of (216) Kleopatra was conducted through a coordinated observational campaign using the 2.1 m and 84 cm telescopes at the Observatorio Astronómico Nacional in Sierra de San Pedro Mártir (OAN-SPM), México. The campaign spanned from September 21 to 25, 2022, and aimed to extract precise positional and brightness information of Kleopatra and its satellites using two complementary techniques:

- **Speckle Interferometry** to spatially resolve the components of the system beyond atmospheric seeing limits.
- **Classical Photometry** to analyze brightness variations, determine rotational properties, and generate 3D models.

A semi-automated pipeline, the Asteroid Astrometric Parameter Calculator (AAPC), was developed in Python and Bash for efficient data processing, spectral analysis, and orbit fitting.

2.2. Speckle Image Acquisition and Processing

Fast-cadence speckle images were obtained with an EMCCD camera mounted on the 2.1 m telescope, using exposure times of 20 ms to freeze the atmospheric turbulence. For each target, we collected 20005000 short-exposure frames per observing run.

The reduction procedure included:

1. Frame Selection and Preprocessing: Dark subtraction.
2. Fourier Transform: Each frame was Fourier-transformed using Fast Fourier Transform (FFT) algorithms to derive the Power Spectrum (PS), as can be seen in Figure 1 a).
3. Averaging and Calibration: PS was averaged over the cube, and normalized using a reference PS from a calibration star.

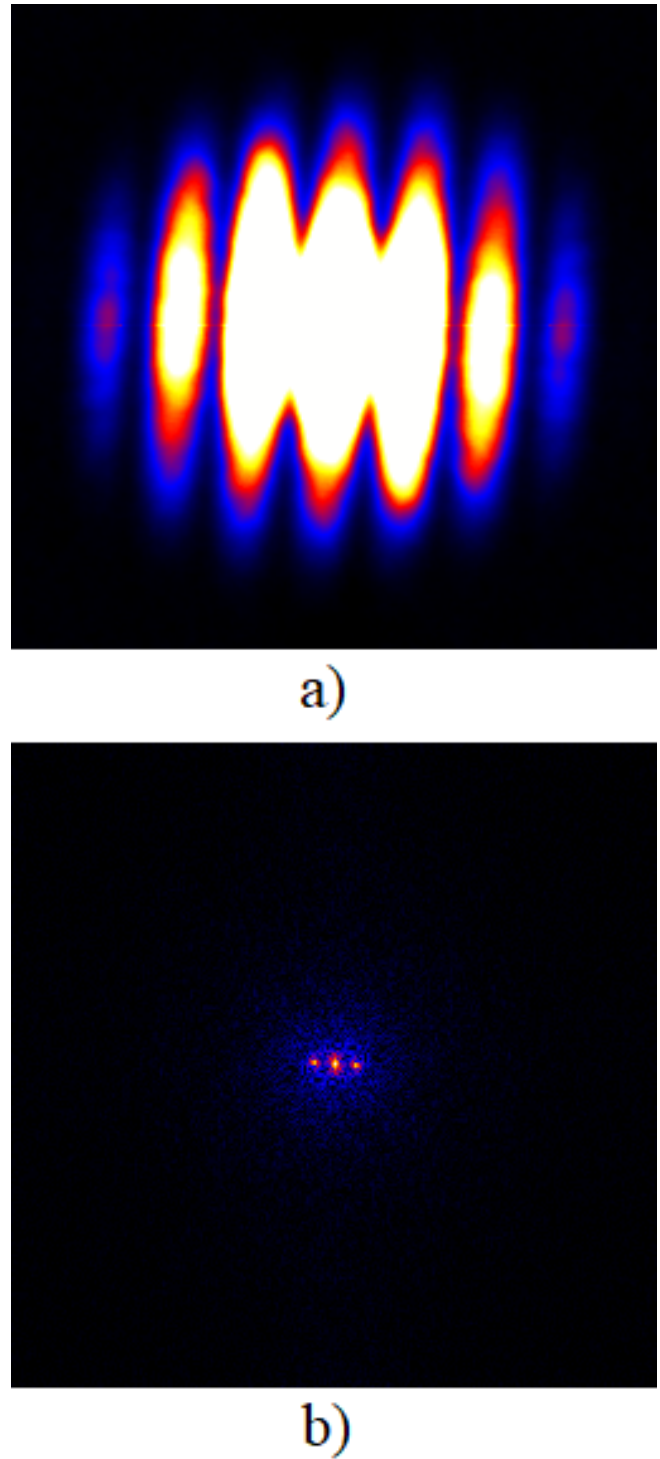


Figure 1. Example of a) the power spectrum and b) autocorrelation function of the binary star WDS09285+0903.

4. Autocorrelation Function (ACF): The inverse Fourier transform of the PS yielded the ACF shown in Figure 1 b), where satellite companions appeared as symmetric peaks.

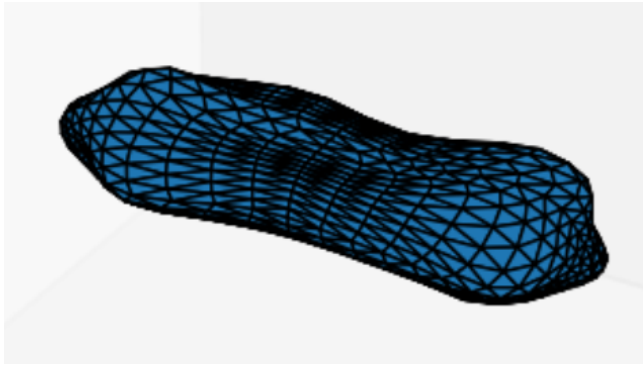


Figure 2. Reconstructed 3D shape model of Kleopatra using light curve inversion.

2.3. Photometric Reduction and Light Curve Analysis

Simultaneous long-exposure images were obtained with the 84 cm telescope using a broad R filter. The reduction steps included:

1. Calibration: Using dark, bias, and flat-field frames.
2. Aperture Photometry: Instrumental magnitudes were obtained using circular apertures centered on the asteroid.
3. Differential Photometry: A reference star in the field was used to correct for atmospheric extinction.
4. Light Curve Construction: Time series were assembled for each night to identify periodic modulations and eclipsing events.

The rotational period of the main body was determined using Lomb-Scargle periodograms and Fourier decomposition. We obtained a rotational period of 5.38 ± 0.01 h, consistent with literature.

2.4. 3D Shape Modeling

The light curves were inverted using the convex inversion technique developed by [Kaasalainen & Torppa \(2001\)](#). We used a dataset of seven light curves covering different aspect angles. Due to Kleopatras non-convex nature, the reconstruction required regularization and was cross-validated with the known adaptive-optics-derived shape model, as can be seen in Figure 2.

2.5. Orbit Modeling of the Satellites

Using the astrometric positions extracted from the ACF peaks across multiple epochs, we modeled the orbits of the two satellites. The fitting assumed Keplerian two-body motion around the system barycenter and yielded semi-major axes and orbital periods for both companions.

The derived orbital periods were:

- Alexhelios: 2.7375 ± 0.1095 days
- Cleoselene: 1.7885 ± 0.1460 days

These values are consistent with previous estimates obtained through adaptive optics and occultation timing.

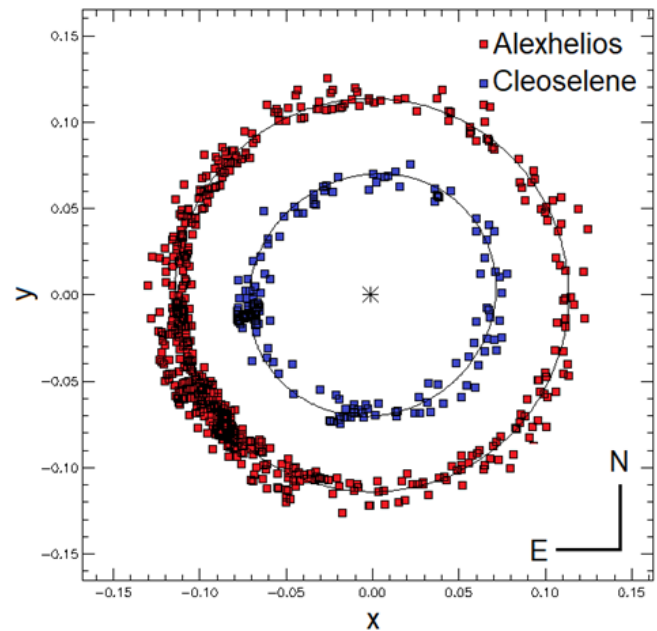


Figure 3. Orbital solutions for Alexhelios and Cleoselene.

In Figure 3 we show the orbital solutions for Alexhelios and Cleoselene.

3. Discussion

The results obtained from the application of speckle interferometry and classical photometry to the (216) Kleopatra system validate the feasibility of using ground-based mid-size telescopes for the astrometric characterization of multiple asteroid systems (MASS). Traditionally, such studies relied on space-based platforms or large-aperture adaptive optics systems. Our method provides a cost-effective alternative with sub-arcsecond resolution, using short-exposure imaging and Fourier analysis.

The angular separations derived from the autocorrelation functions (ACFs) were consistent across multiple nights and fell within the expected range of $0.08''$ to $0.14''$. When converted to physical distances, these correspond to 75120 km, in agreement with the orbital radii of Kleopatras satellites reported by [Descamps et al. \(2011\)](#). The reliability of these detections was further supported by the application of the “Shift and Add” method, which provided high-resolution composite images used to resolve the 180-degree ambiguity inherent in Fourier phase information.

Photometric observations yielded a rotational period of 5.38 ± 0.01 hours, consistent with earlier works (e.g., [Marchis et al. 2008](#)). Additionally, the observed light curve morphology and depth modulations support the presence of eclipsing or mutual occultation events, a hallmark of multiple systems viewed at favorable geometries.

The 3D shape inversion derived from the photometric time series reveals a bilobate structure similar to that

obtained via radar and adaptive optics. While the convex inversion technique has known limitations for strongly non-convex objects, our reconstructed model reproduces key features of Kleopatras known morphology.

The orbital periods of the satellites derived from our astrometric dataset are remarkably close to those obtained from space-based observations. This demonstrates that speckle interferometry, when coupled with sufficient cadence and temporal coverage, is capable of resolving complex orbital dynamics even for faint and compact systems.

Our approach highlights the complementarity of speckle interferometry and photometry:

- Speckle images provide high-angular-resolution information critical for astrometry and satellite detection.
- Photometric time series offer rotational and morphological constraints, and can independently verify binarity through light curve events.

Taken together, these methods enable a multi-modal analysis pipeline that can be generalized to other binary or multiple asteroid systems observable from Earth.

4. Conclusions

This work represents a pioneering effort to apply speckle interferometry to the astrometric study of an asteroid system, demonstrating several key outcomes:

1. We successfully resolved the two satellites of (216) Kleopatra using ground-based speckle interferometry and derived their angular separations and position angles.
2. The orbit modeling yielded periods (2.74 and 1.79 days) that match those obtained by space-based methods, validating the astrometric pipeline.
3. Classical photometry provided a precise rotation period for Kleopatra (5.38 h) and enabled the genera-

tion of a 3D shape model through light curve inversion.

4. A modular and semi-automated pipeline (AAPC) was developed to combine speckle and photometric data for astrometric analysis of minor bodies.

Our results demonstrate that combining speckle interferometry and classical photometry is an effective and accessible method for studying asteroid multiplicity. This methodology is scalable and can be adapted for use in the astrometric and photometric monitoring of other suspected binary or multiple systems in the asteroid belt and near-Earth regions.

Future work will focus on increasing the temporal coverage of speckle observations, integrating additional photometric datasets (including occultation and Gaia DR3-based ephemerides), and refining the AAPC system for deployment in large-scale observing campaigns.

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Unveiling an overlooked structure behind the Coma Berenices open cluster

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Keywords: *Open Cluter, Star membership, Machine learning*

Abstract

In our initial attempt to identify new members of the Coma Berenices open cluster using Gaia DR3 astrometric and photometric data, we discovered a candidate stellar structure comprising approximately 500 stars beyond the nominal cluster. This structure initially appeared to meet the typical criteria of an open cluster, such as a coherent main sequence and reasonable age fitting. However, we later found that such detections may include false positives over densities created by clustering algorithms like HDBSCAN due to background noise and data border effects.

To address this issue, we developed a framework that combines the HDBSCAN algorithm with a spatial resampling technique. We generated 1000 resampled datasets by varying the region of the sky and background density conditions. Each was independently processed by HDBSCAN, and we computed a membership probability for each star based on its recurrence across runs. This probability metric enables us to distinguish between genuine stellar aggregates and spurious groupings.

We demonstrate that this method effectively filters out false detections that lack physical coherence such as spatial compactness or isochrone consistency while retaining real clusters. We validate the technique using the known Coma Berenices cluster and apply it to the newly identified structure, assessing its likelihood of being a bona fide open cluster.

Resumen

En un intento inicial por identificar nuevos miembros del cúmulo abierto Coma Berenices utilizando datos astrométricos y fotométricos de Gaia DR3, descubrimos una estructura estelar candidata compuesta por aproximadamente 500 estrellas, localizada más allá del cúmulo nominal. Esta estructura parecía inicialmente cumplir con los criterios típicos de un cúmulo abierto, como una secuencia principal coherente y un ajuste de edad razonable. Sin embargo, análisis posteriores revelaron que muchas de estas detecciones podrían ser falsos positivos sobre densidades generadas por algoritmos de agrupamiento como HDBSCAN debido al ruido de fondo y a efectos de borde en los datos.

Para abordar este problema, desarrollamos un marco estadístico que combina el algoritmo HDBSCAN con una técnica de remuestreo espacial. Generamos 1000 subconjuntos de datos modificando ligeramente la región del cielo y las condiciones de densidad de fondo. Cada subconjunto fue procesado de forma independiente con HDBSCAN, y calculamos una probabilidad de pertenencia para cada estrella en función de su recurrencia en las distintas ejecuciones. Esta métrica probabilística permite distinguir entre agrupaciones estelares genuinas y agrupaciones espurias.

Demostramos que este método filtra eficazmente detecciones falsas que carecen de coherencia física como la compacidad espacial o el ajuste de isócrona mientras conserva cúmulos reales. Validamos la técnica aplicándola al cúmulo Coma Berenices y evaluamos la probabilidad de que la estructura descubierta sea un cúmulo abierto genuino.

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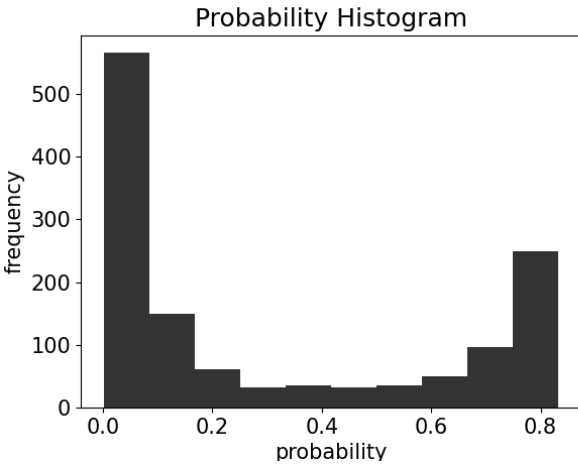


Figure 1. Probability distribution of stars initially identified as part of the Coma Berenices cluster. The histogram reveals two distinct peaks, indicating the presence of at least two separate stellar populations. This overlap led the initial clustering algorithm to incorrectly group them into a single cluster. Our resampling based method later disentangles these components by assigning membership probabilities that reflect their distinct parallactic separations.

1. General

The discovery and classification of open clusters in the Milky Way have been revolutionized by Gaia’s high precision astrometric data. Density based clustering algorithms like HDBSCAN have become key tools for identifying new stellar associations. However, they can also produce false positives, especially when applied to broad, non uniform sky regions.

In this study, we revisit a candidate stellar cluster detected beyond the well known Coma Berenices cluster. Our initial detection showed promising signs of cluster like behavior, but subsequent analysis raised doubts about its physical reality. This prompted us to investigate whether HDBSCAN might be identifying spurious structures caused by data edge effects or inhomogeneous background densities. An illustrative example is shown in Figure 1, where it becomes evident that the initial selection mistakenly combines two distinct parallax distributions into a single group, falsely interpreted as an extension of the Coma Berenices open cluster.

To address this, we introduce a robust statistical framework based on repeated HDBSCAN applications over resampled sky regions. This approach allows us to assign membership probabilities and validate the coherence of potential clusters more reliably.

The methodology consists of performing an 80% resampling of the dataset about 1000 times, in order to apply HDBSCAN to each subset. Then, by selecting a star as a member of a cluster, we count the number of times it belongs to a cluster to obtain a probability that allows us to determine whether it definitely belongs to a stellar

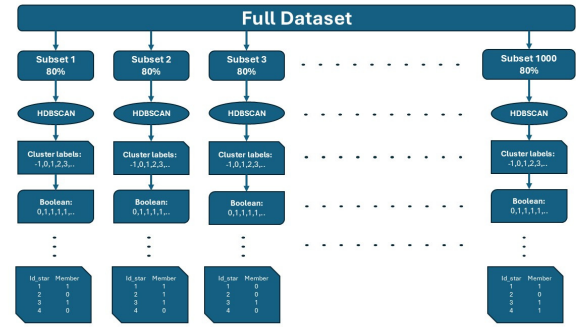


Figure 2. Graphical representation of the methodology implemented with HDBSCAN.

grouping or to the noise. An example of this methodology is shown in Figure 2.

2. Data and methods

2.1. Gaia DR3 Dataset

We use astrometric data from Gaia DR3, selecting stars within a 10 degree radius around the central equatorial coordinates (RA, Dec) = (193.5500°, +27.6261°). These coordinates encompass the region containing the Coma Berenices open cluster and its surroundings. To preserve the information of binary systems and avoid unnecessary filtering of complex stellar systems, we applied only a single quality constraint: a parallax signal to noise ratio condition of $\text{parallax_over_error} > 10$. No additional cuts (e.g., RUWE, photometric excess) were made in order to retain a comprehensive sample for clustering analysis.

2.2. Initial HDBSCAN Clustering

Our first application of HDBSCAN was performed using 3D feature space: proper motion in RA and Dec ($\mu_{\alpha*}, \mu_{\delta}$) and parallax (ϖ). We standardized the variables and used [min_samples = 20]. This run identified a candidate cluster of ~ 500 stars located beyond Coma Berenices.

2.3. Resampling Strategy

To test the robustness of the detection, we implemented a resampling approach. We created 1000 synthetic subsets by varying sky regions slightly (e.g., shifting coordinates, redefining boundaries). Each subset was analyzed with HDBSCAN using consistent parameters. For each star, we calculated the probability of being assigned to a cluster across all runs. Figure 3 displays the stars selected as cluster members after an initial noise removal step. Only stars with a membership probability greater than 0.5 were retained, effectively isolating the core of the Coma Berenices cluster. This selection mitigates the ambiguity illustrated in Figure 1, where multiple parallax components were initially blended.

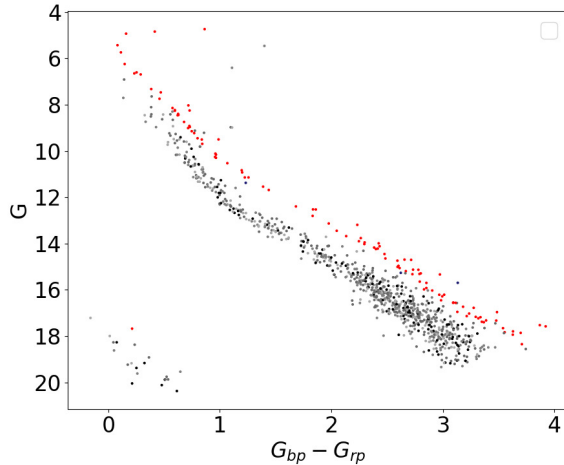


Figure 3. ColorMagnitude Diagram (CMD) based on Gaia photometry. The red points represent the selected members of the Coma Berenices open cluster. The grayscale points correspond to the initially discovered candidate cluster, with the shading intensity indicating the membership probability computed using our resampling based method.

3. Results

3.1. False Positive Filtering

We observed that many clusters identified in single run HDBSCAN outputs fail to exhibit coherent CMDs or spatial compactness. Figure 3 compares CMDs for structures with high and low membership probabilities. Similar structures have also been reported in previous studies, such as those by Cantat Gaudin et al. (2018) and Hunt & Reffert (2023). Therefore, this approach offers a robust methodology for assigning membership probabilities and performing an effective cleaning of spurious detections.

4. Discussion

Our findings highlight the risks of overinterpreting clustering results from single HDBSCAN runs. Many apparent structures are not gravitationally bound clusters but artefacts of local density fluctuations or algorithm sensitivity.

By introducing probabilistic membership through resampling, we provide a more statistically rigorous framework for cluster validation. This technique can be scaled to large surveys and helps ensure that reported cluster candidates meet both statistical and physical criteria.

Limitations include computational cost (1000 runs per region) and sensitivity to parameter tuning.

5. Conclusions

We present a method combining HDBSCAN with spatial resampling to reduce false positives in open cluster detection using Gaia data. Our key contributions are:

- A statistical framework to assign cluster membership probabilities.
- A filtering mechanism to exclude spurious detections.
- Validation using both known and candidate clusters.

This approach lays the groundwork for more robust cluster discovery pipelines in future large scale astrometric surveys.

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Speckle interferometry from the Ramon M^a Aller astronomical observatory: A review

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Keywords: *binaries: visual, techniques: interferometric*

Abstract

The Ramón María Aller Astronomical Observatory (OARMA) of the University of Santiago de Compostela (Galicia, Spain) has been a prestigious centre for the study of double and multiple stellar systems since Aller introduced their study almost 100 years ago. This paper first recalls the speckle interferometry technique discovered by Labeyrie in 1970, and then describes the development of the study of binary and multiple systems in Spain, continued by Docobo and collaborators. After innumerable campaigns of micrometric measurements in different telescopes, Docobo himself, together with Tamazian and Balega, made possible the acquisition of an ICCD camera at the beginning of this century, which was preferably used attached with the 1.5m and 3.5m telescopes at Calar Alto (Almería, Spain). A new eMCCD camera was tested at the Byurakan Astrophysical Observatory in Armenia. Speckle campaigns were also performed at the SAO-RAS (Russia) and Plato de Calern (France) observatories. The recent collaboration with R. Méndez's group opens the way to the southern hemisphere from Chile, specifically with the SOAR telescope.

Resumen

El Observatorio Astronómico Ramón María Aller (OARMA) de la Universidad de Santiago de Compostela (Galicia, España) es un centro de prestigio en el estudio de los sistemas estelares dobles y múltiples desde que Aller introdujera su estudio hace casi 100 años. En esta comunicación se recuerda en primer lugar el proceso speckle descubierto por Labeyrie en 1970, para luego describir el desarrollo del estudio de los sistemas binarios y múltiples en España, continuados por Docobo y colaboradores. Tras la realización de un sinfín de campañas de medidas micrométricas en distintos telescopios, el propio Docobo, junto con Tamazian y Balega, hicieron posible la adquisición de una cámara ICCD a comienzos de este siglo, la cual se utilizó preferentemente acoplada a los telescopios de 1.5m y 3.5m de Calar Alto (Almería, Spain). Una nueva cámara eMCCD se utilizó en el Byurakan Astrophysical Observatory de Armenia. Asimismo se realizaron campañas speckle en los observatorios de SAO-RAS (Rusia) y en el Plato de Calern (Francia). La reciente colaboración con el grupo de R. Méndez abrió desde Chile las puertas del hemisferio sur, concretamente con el telescopio SOAR.

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1. Introduction

Double stars, in particular visual binaries, are the most important source of data for the accurate calculation of stellar masses. French researcher, Antoine Labeyrie, first introduced a new technique of observation, called

speckle interferometry, one of the most useful tools for minimising the effects of atmospheric turbulence. This technique greatly improves both the accuracy and the limiting magnitude of the measured objects. For example,



Figure 1. Antoine Labeyrie

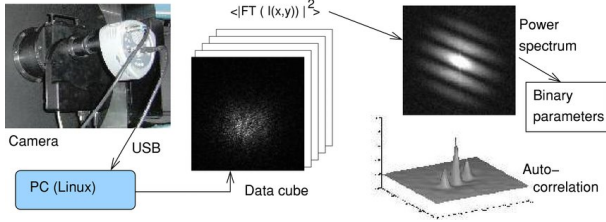


Figure 2. Schematic representation of data acquisition and processing. (Tokovinin, Mason & Hartkopf, 2010).

the Rayleigh resolution limit of 80 mas ($0''.08$) can be obtained in the case of a 1.5 m class telescope.

In this communication, we will present a review of the latest advances in this field and in particular observation campaigns, carried out by OARMA members, using the speckle interferometry technique.

In Section 2, we introduce the speckle interferometry technique. In section 3, we provide a description of the study of double stars in Spain, from its introduction by Ramón María Aller to date.

2. The speckle interferometry technique

The technique, called “Speckle Interferometry” was proposed by Antoine Labeyrie (Labeyrie, 1970) (See Figure 1) achieved the revival of interest in high-resolution optical astronomical imaging. The speckles have diameters essentially equal to the Airy disk. The minimum resolvable angle obtained from Speckle Interferometry has been found to agree very closely to the resolution set by the well-known Rayleigh criterion where the smallest resolvable separation of point sources, ρ , is given in radians by:

$$\rho = 1.22 \frac{\lambda}{D}, \quad (1)$$

where λ is the central wavelength of the observed passband and D is the telescope aperture. Since ρ for the largest telescopes is 0.02 arc-seconds, Speckle Interferometry was seen by Labeyrie as having strong potential for performing binary star astrometry.

The Figure 2 shows a schematic representation of data acquisition and processing. In this particular case, the camera software, developed by R. Cantarutti, works in a

Linux operating environment. Each night of observation a large amount of data cubes are taken which are processed with the Fourier transform and the Power Spectrum (PS) is obtained. When observing a double system near the diffraction limit of the telescope, interference fringes are seen. It is more practical, however, to detect companions in the autocorrelation functions calculated from the PS by means of the Fourier transform.

Yuri Balega was able to obtain resolutions of this order. With the 4.2m SOAR telescope in Chile, the theoretical separation limit is around $0''.03$, but Andrei Tokovinin even observed below it on exceptional seeing occasions. At the BAO in Armenia, the 2.6m telescope easily one can see below $0''.1$, as does the 2m telescope at Pic du Midi (France). The separating power of the Gemini telescopes is $0''.015$.

The first astronomical observations using Speckle Interferometry were presented by Gezari, Labeyrie, and Stachnik in 1972.

Labeyrie continued by publishing a series of articles with his collaborators. Bonneau & Labeyrie (1973) discussed the measurements of two close binary systems (α Orionis and α Cet).

From the late seventies on, the Speckle Interferometry technique became widespread and researchers from France, the U. S. A., the URSS, Great Britain Germany, and Australia began to conduct observations.

Especially Harold McAlister, creator of CHARA in the USA, and Yuri Balega in Russia (Maximov et al., 2003; McAlister, 1999, 2009), can be said to have been the pioneers in systematically applying this technique to binaries. Later, astronomers such as W. Hartkopf, B. Mason, A. Tokovinin, V. Orlov, M. Scardia, J. A. Docobo, etc., had extensive dedication to these topics (Docobo et al., 2023; Gómez et al., 2022; Mason et al., 2018, 2023; Méndez et al., 2025; Orlov, Voitsekovich, & Guerrero, 2012; Orlov, 2021; Prieur et al., 2024; Tokovinin et al., 2024; Tokovinin, 2025).

One of the applications of speckle interferometry is to try to resolve spectroscopic binaries, especially double-lined orbit. In fact, if both the visual orbit and the spectroscopic double-line orbit are available, it is possible to obtain the masses of the components with great precision. From the visual orbit the semi-major axis in arc seconds ($''$) and the inclination of the orbit in degrees are known; from the spectroscopic orbit $a \cdot \sin(i)$ in kilometres or astronomical units (au) is given. If we divide $a \sin(i)$ by the sine of the inclination of the visual orbit, we obtain a in ua. Finally, by dividing a'' by a , the called orbital parallax, π is obtained:

$$\pi_{orb} = \frac{a''}{a_{au}}. \quad (2)$$

This parallax is important in order to check the Hipparcos and/or Gaia parallaxes of binaries. Moreover, from visual orbit the sum of masses is given by means of the Third Law of Kepler, while from the spectroscopic double-line orbit the ratio of masses is provided and then the masses of the components, M_1 and M_2 , for separately are obtained in solar masses.



Figure 3. Top: From left to right, Professors Docobo, Balega, and Tamazian at the main dome of OARMA with the 0.62 m telescope. Bottom: OARMA staff with Andrei Tokovinin during his visit in Santiago de Compostela in October 2018.

3. The study of double stars in Spain

The Ramón María Aller Astronomical Observatory (OARMA) is a centre of international prestige in the study of double and multiple stars. This Observatory, founded by Father Aller 82 years ago, has specialised in this study since Aller introduced it in Spain, first at his private Observatory in Lalín (Galicia, Pontevedra), subsequently publishing several series of observations in the *Astronomische Nachrichten*. Ramón María Aller (1878 - 1966) gradually improved his Observatory until he bought the Steinheil refracting telescope in Germany in 1925 (See Figure 4), which is now in the Observatory of the University of Santiago de Compostela and which this year celebrates the 100th anniversary of this refractor. With this instrument, the professor Aller gave an improvement to his observations, in particular of double stars. He did not limit himself to the observation of double stars but extended his activities to calculation of the orbit of $\text{O}\Sigma 77$ (ADS 3082) in 1935 and that of $\Sigma 1932$ (ADS 9578) in 1939. These were the first calculations of double star orbits in Spain. When the observatory moved to the University of Santiago de Compostela in 1943, he not only continued his research work on binaries but he also created a group of researchers on the subject.

In the last decades, the Observatory achieved notoriety within the International Astronomical Union (IAU) thanks to the work carried out by Prof. Docobo and his collaborators: an original analytical method for the calculation of orbits (designed by J. A. Docobo), with which almost 700 orbits have been determined, numerous



Figure 4. The Steinheil refractor

publications in international journals, organization of international congresses, edition of the IAU Double Star Circular, direction of doctoral theses, observing campaigns in large telescopes in Europe, America and Asia, acquisition of state-of-the-art instrumentation.

In 1996, J. A. Docobo promoted an International Workshop on Binaries and Celestial Mechanics "*Visual Double Stars: Formation, Dynamics, and Evolutionary Tracks*" (supported by the IAU Commissions of Celestial Mechanics and Double and Multiple stars, see [De la Marcos et al. \(1997\)](#)) which was extraordinarily profitable for the Observatory since the worlds leading experts in these specialities attended.

The presence of Y. Y. Balega (Director of the Special Astrophysical Observatory, SAO, Russia) and his wife, I. Balega, at the above-mentioned workshop facilitated arrangements and with the support of V. S. Tamazian who was recently incorporated at OARMA, it was possible to establish a collaboration agreement with SAO for the construction of an ICCD camera.

In this way, OARMA was able in 1998 to obtain the first speckle camera from SAO-RAS (Russia), thanks to financing from the Xunta de Galicia. The following year, the camera reached Santiago de Compostela and was immediately used in initial astronomical observation campaigns when it was attached to the Calar Alto 1.52 m telescope. Professor Docobo, with other members of his research team and Y. Balega, published the first results ([Docobo et al., 2001](#)).

In the following years, a growing collaboration with SAO-RAS through joint observation campaigns using the Russian 6 m telescope took place which led to the publication of co-authored articles ([Docobo et al., 2006](#)). As part of this collaboration, the construction of a new eMCCD camera, a twin of the one they used ([Maksimov et](#)



Figure 5. Dr. Luca Piccotti (on the left) and Profesor José Ángel Docobo (on the right) with Profesor René Méndez during his research stay at OARMA in June - July 2025.

al., 2009), was also proposed and was eventually purchased with funding provided simultaneously by OARMA research projects funded by both the Spanish Ministry of Education and the Xunta of Galicia, respectively. This camera is used to measure the relative positions of binaries and the differences in magnitude between the components.

The new camera was first attached to the 2.6m Byurakan Astrophysical Observatory (BAO), thanks to a new agreement with this Armenian Observatory through N. Melikian. J. Gómez performed the first measurements and in the following years, another members of the time (Piccotti, Campo, and P. Couto) participated in several runs.

In recent years a growing collaboration with Professor René Méndez's team at the Universidad de Chile has made possible to obtain speckle measurements of visual binaries from both the northern and southern hemispheres.

Finally, thanks to the collaboration between personnel from the National Institute of Astrophysics (INAF) in Milan and astronomers of the University of Toulouse, it was possible to carry out several observation campaigns at the Observatoire de la Côte d'Azur (Calern site) (Scardia et al., 2019).

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Astrometric and photometric calibration of digitized old OAN photographic plates with GAIA DR3

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Photographic plates are unique historical records of the sky with significant scientific value. The National Astronomical Observatory (OAN), hosted by the Department of Astronomy (DAS) at Universidad de Chile, owns more than 17,000 astronomical plates dating from the early 20th century, obtained from major observatories such as CTIO and Cerro El Roble. Through an ongoing collaboration with the Shanghai Astronomical Observatory (SHAO), thousands of these plates have been digitized using high-precision scanners (Shang et al., 2024), enabling their subsequent analysis.

We present astrometric and photometric analysis methods based on a local approach. The astrometric calibration aims to accurately measure the coordinates of target objects at the plate epoch, while photometric calibration relates instrumental magnitudes to a standard system. For these purposes, we use GAIA DR3 (Gaia Collaboration et al., 2023) as a reference catalog due to the large number of sources and the precision in positions and proper motions.

The analysis consists of three main steps: (i) Preliminary astrometric solution with astrometry.net (Lang et al., 2012), (ii) Source detection and parameter extraction with Source Extractor (Bertin & Arnouts, 1996), and (iii) Cross-match with GAIA DR3 to identify reference stars. Their coordinates are then propagated to the plate epoch using proper motions.

The final astrometric calibration determines target coordinates (RA,DEC) from their pixel positions (x, y). To compare equatorial coordinates with pixel coordinates we first apply a gnomonic projection that transforms reference sky positions to a tangent plane (ξ, η). Then, a polynomial model is fitted to transform pixel coordinates to equatorial ones by minimizing positional differences (Eqs. (1)-(2)). The coefficients of the plate model account for

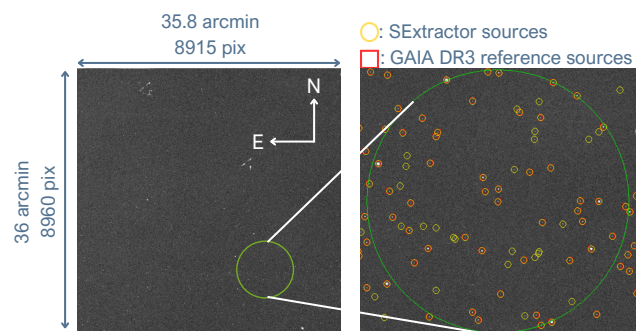


Figure 1. Local calibration scheme. Left panel: full size plate. Right panel: sub-plate containing 42 reference objects.

several optical effects, the order of the polynomial being a representation of the complexity of the corrections.

$$\xi - x = a_x x + b_x y + c_x + d_x x^2 + e_x xy + f_x y^2, \quad (1)$$

$$\eta - y = a_y x + b_y y + c_y + d_y y^2 + e_y xy + f_y x^2 \quad (2)$$

Large field of view plates typically use third-order models, but we apply a local approach, calibrating each target using only nearby reference objects within a small circular region (see Fig. 1). Due to the small field size, this approach allows the use of first or second order plate models.

After astrometric calibration has been performed, the residuals are evaluated as a measure of the accuracy of the fit. Figure 2 shows a scatter plot of the residuals in right ascension and declination as a result of the calibration of a sub-plate centered on a target object of the plate shown in Fig. 1. Low standard deviations of the residuals indicate good fits.

Photometric calibration is carried out in a similar way. The instrumental quantities calculated by SExtractor must be transformed to the GAIA DR3 photometric system, characterized by the G, RP and BP bands. Considering

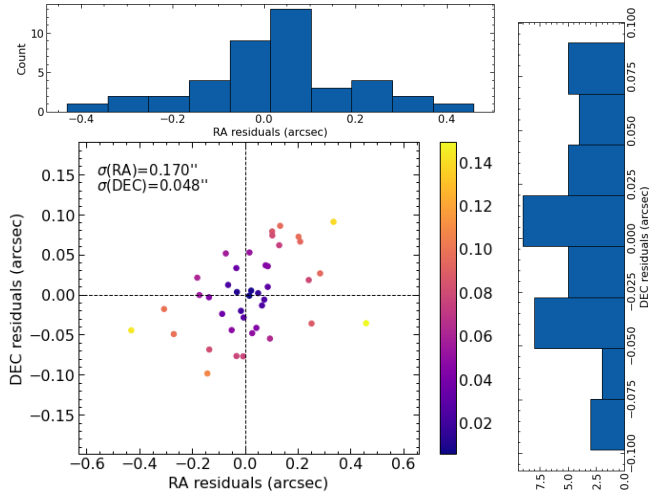


Figure 2. Dispersion of residuals along RA and DE for a single sub-plate after a second-order plate model reduction for astrometric calibration.

the emulsion type and filters used to observe the plate in Fig. 1, the GAIA G band is closest to the spectral response of the plate. A local approach is also considered in this procedure, whereby the closest reference sources up to a cutoff radius are used to determine the GAIA magnitude of a target object. Figure 3 shows that locally the relationship between plate magnitudes with GAIA magnitudes is linear, as opposed to a global fit where the best fit is achieved with a second order polynomial.

An interesting application of photographic plates relates to the study of binary stars, particularly those found in the Washington Double Star catalog (Mason et al., 2020). In one of our plates, observed on September 28, 1984 with the Irénée du Pont telescope at Las Campanas observatory, we found the binary system KPP1269 (see Fig. 4). Based on our local calibration method we were able to measure the coordinates of each component at the epoch of the plate to calculate the separation ρ and position angle θ of the binary system. Our coordinates and magnitude measurements remain within errors of 0.4'' and 0.3 mag respectively. Since the first measurement reported in the catalog is from 1994, our measurement now corresponds to the oldest data point of this binary system.

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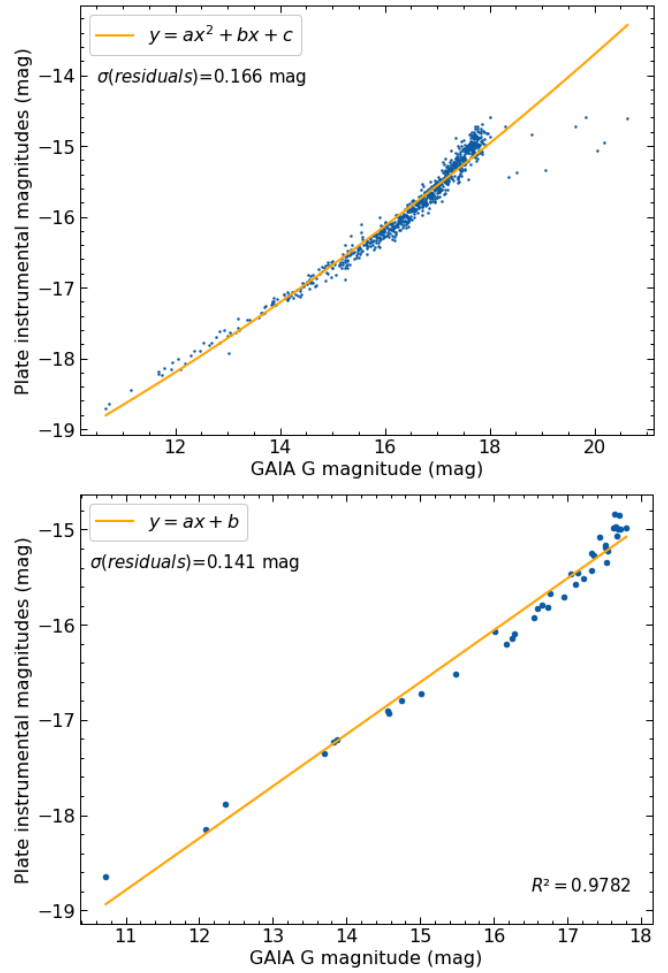


Figure 3. A full-plate photometric calibration (top) is best fit by a second-order polynomial, while a sub-plate calibration (bottom) is locally linear.

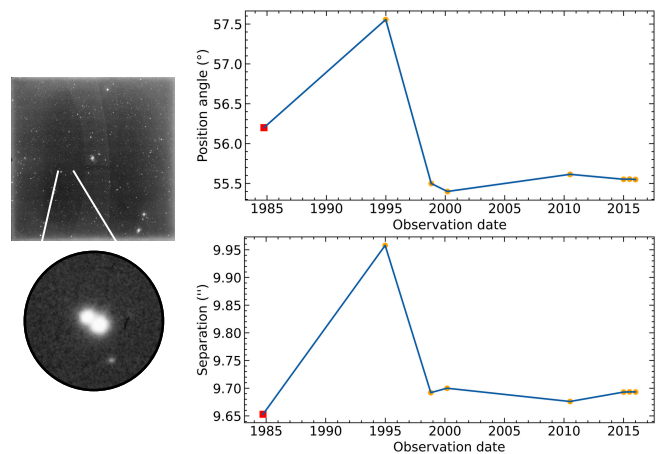


Figure 4. KPP1269 binary system in our plate (left) and historical observations for position angle and separation, including our new measurement (red square).

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Analysis of estimators and fundamental constraints in astrometry and photometry

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We review key theoretical foundations and estimation bounds for astrometry and photometry of celestial point sources observed on digital detector arrays. We review classical formulations of the Fisher Information and the associated Cramér-Rao Lower Bound (CRLB), emphasizing the impact of pixel size, PSF morphology, and background levels on estimator variance. This work highlights the conceptual and practical contributions of recent works and their influence on modern precision estimation.

1. Introduction

The estimation of brightness and position of point sources is a fundamental task in astronomical imaging. While improvements in sensor technology and image processing algorithms have greatly enhanced our measurement capabilities, it is essential to understand the theoretical limits that constrain the performance of any unbiased estimator. In this review, we explore such limits through the lens of statistical decision theory, primarily via the Fisher Information Matrix and the associated CRLBs.

2. Model and Likelihood Formulation

Let F denote the total source flux and B the background level. The intensity profile of a point source centered at x_c is given by:

$$F_{x_c}(x) = F \cdot \phi(x - x_c, \sigma), \quad (1)$$

where ϕ is the normalized PSF (typically Gaussian) and σ denotes its width. The expected count in pixel i is then:

$$\lambda_i(F, x_c) = F \cdot g_i(x_c) + B, \quad (2)$$

where $g_i(x_c)$ is the pixel response function (PRF), defined by:

$$g_i(x_c) = \int_{x_i - \Delta x/2}^{x_i + \Delta x/2} \phi(x - x_c, \sigma) dx, \quad (3)$$

and B is the background. Given a total of n pixels, each observation I_i follows a Poisson distribution:

$$I_i \sim \text{Poisson}(\lambda_i(F, x_c)), \quad (4)$$

leading to the likelihood function, with $\mathbf{I} = (I_1, \dots, I_n)$:

$$L(\mathbf{I}; F, x_c) = \prod_{i=1}^n \frac{\lambda_i(F, x_c)^{I_i} e^{-\lambda_i(F, x_c)}}{I_i!}. \quad (5)$$

3. Astrometric Bounds

The foundational analysis by Méndez et al. (2013) provides a closed-form expression for the CRLB in one-dimensional astrometry, under the assumption of known flux and background. For a source centered at x_c , the variance lower bound for any unbiased position estimator is given by:

$$\text{Var}(\hat{x}_c) \geq \left[\sum_{i=1}^n \frac{\left(\frac{\partial \lambda_i(F, x_c)}{\partial x_c} \right)^2}{\lambda_i(F, x_c)} \right]^{-1}, \quad (6)$$

where $\frac{\partial \lambda_i(F, x_c)}{\partial x_c} = F \cdot \frac{dg_i(x_c)}{dx_c}$. This reveals that astrometric precision improves with increased flux and sharper PSFs (small σ), while degrading under higher background B .

The analysis also shows that the shape and sampling of the PSF directly affect the Fisher Information. In particular, undersampled or aliased PSFs result in a poorer bound due to the reduced sensitivity of pixel counts to shifts in x_c .

4. Astrometric Analysis

A key starting point in the study of estimator performance is the work of Lobos et al. (2015), who analyze the least-squares (LS) estimator for astrometry. Despite its simplicity

and widespread use, they demonstrate that the LS estimator becomes suboptimal under high signal-to-noise conditions or in the presence of non-Gaussian PSFs. Notably, the LS estimator fails to attain the CRLB in many realistic scenarios, motivating the need for more robust alternatives.

Following this, [Espinosa et al. \(2018\)](#) formulate the estimation of x_c under a Poisson likelihood and study the performance of the maximum likelihood estimator (MLE). Their Theorem 3 proves that the MLE achieves the CRLB asymptotically, and under mild regularity conditions, it is minimax optimal and asymptotically efficient. Moreover, for sufficiently narrow PSFs and fine pixel resolution, the MLE outperforms alternative estimators such as centroiding or parabolic fits.

5. Photometric Bounds

Assuming x_c is known, [Vicuña et al. \(2024\)](#) derive the Fisher Information Matrix (FIM) for (F, B) as:

$$\mathcal{J}_\theta = \begin{bmatrix} \sum \frac{g_i^2(x_c)}{\lambda_i(F, x_c)} & \sum \frac{g_i(x_c)}{\lambda_i(F, x_c)} \\ \sum \frac{g_i(x_c)}{\lambda_i(F, x_c)} & \sum \frac{1}{\lambda_i(F, x_c)} \end{bmatrix} = \begin{bmatrix} \mathcal{J}_{1,1} & \mathcal{J}_{1,2} \\ \mathcal{J}_{1,2} & \mathcal{J}_{2,2} \end{bmatrix}, \quad (7)$$

with sums over $i = 1$ to n . This formulation includes off-diagonal terms, revealing statistical coupling between flux and background estimates due to their simultaneous inference. The CRLB for unbiased estimators $\hat{F}$ and $\hat{B}$ is:

$$\text{Var}(\hat{F}) \geq \frac{\mathcal{J}_{2,2}}{\mathcal{J}_{1,1}\mathcal{J}_{2,2} - \mathcal{J}_{1,2}^2}, \quad (8)$$

$$\text{Var}(\hat{B}) \geq \frac{\mathcal{J}_{1,1}}{\mathcal{J}_{1,1}\mathcal{J}_{2,2} - \mathcal{J}_{1,2}^2}. \quad (9)$$

Before introducing the photometric estimators, it is important to highlight a key structural feature of the estimation problem: the FIM for the joint estimation of source flux and background contains non-zero off-diagonal terms. These cross terms arise due to statistical coupling between the flux F and the background B , which are inferred simultaneously from the same pixel measurements. As a result, the estimators for F and B are not independent, and this interdependence affects the precision bounds of each component. This contrasts with simpler models where either F or B is assumed known, in which case the FIM becomes diagonal and the estimators decouple. The presence of these off-diagonal entries must therefore be accounted for when analyzing estimator performance and when designing optimal photometric strategies.

6. Photometric Analysis

The work of [Vicuña et al. \(2024\)](#) also investigates estimator design in the joint inference of source flux and background. Among the estimators analyzed are:

- **Naive Flux Estimator:** Computes the total flux by subtracting a background estimate from a fixed aperture sum. This is intuitive but sensitive to background fluctuations.
- **Joint Least Squares Estimator:** Simultaneously fits F and B by minimizing the Poisson negative log-likelihood. Shown to be near-optimal to the CRLB in many scenarios.
- **Aperture-Optimized Estimator:** Selects the aperture radius that minimizes the CRLB-based bound, adapting the estimator variance to the source SNR and PSF width.

These methods are evaluated in terms of variance and bias relative to the theoretical CRLB. The analysis shows that optimal performance is achieved only when the aperture and background estimation region are carefully matched to the PSF and noise conditions. The ability to tailor aperture photometry using Fisher-based guidance makes this framework adaptable to different observing conditions and detector characteristics.

7. Conclusions

This review illustrates the power of statistical methods in characterizing the limits of astronomical measurements. The Cramér-Rao Lower Bound provides a principled benchmark for evaluating estimator performance, and recent work has shown that estimators such as the maximum likelihood method can closely approach these limits under realistic conditions. By grounding instrument calibration and data analysis pipelines in statistical decision theory, astronomers can extract the most precise and unbiased information from their observations. Furthermore, understanding the structure of the Fisher Information reveals how measurement precision is affected by factors like PSF shape, pixel size, background level, and model coupling. These insights guide the development of optimal estimators and observational strategies in both astrometry and photometry.

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Exploring the nature of new radio sources identified in the ODIN survey in the vicinity of M42

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Keywords: *Extragalactic radio sources, Galactic radio sources, Radio galaxies, Radio source catalogs*

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Recently, large radio surveys that search to map the neutral hydrogen distribution in our galaxy have led to the discovery and identification of new radio sources, enabling us to assess the completeness of current catalogs. This was the case of the ODIN (Orion Dynamics of Ionized and neutral gas) survey (Soler et al., 2019), which focused on M42 and produced deep images of this region, allowing the identification and analysis of radio sources, most of which had not been catalogued and characterized before. In this work, we present preliminary results from the ODIN survey, focusing on the identification and analysis of 78 radio sources near M42. We provide detailed information about their physical and morphological characteristics, highlighting six double-lobed candidates that are likely to be extragalactic, more specifically, radio galaxies.

Understanding the physical nature of radio sources is essential for characterizing both galactic and extragalactic populations detected in large surveys. In this context, the ODIN survey provides observations at 1-2 GHz, a dataset and study that serves as a continuation for previous large-scales surveys such as THOR (The HI/OH/Recombination line survey of the Milky Way) (Bühr et al., 2016), which identified thousand of continuum sources across the northern Galactic plane.

The ODIN dataset used in this study comprises continuum observations at 1440, 1820, and 1950 MHz, obtained with the VLA in its D-configuration. The imaging process was made using the `tclean` task in CASA, with which we were able to obtain three mosaics with the synthesized beam ranging from $34.97'' \times 20.06''$ to $43.97'' \times 29.06''$, depending on the frequency.

For the identification of the sources, we used the automatic source detection algorithm `DAOSTARfinder`, which is designed to detect point-like sources in 2D images based on local maxima and morphological criteria and has proven effective in identifying compact structures in radio continuum images, especially dealing with noisy

backgrounds. After the identification, we performed a cross-matching with existing catalogs such as NVSS, PMN, and TXS to classify the uncatalogued and cataloged sources.

To estimate spectral indices, we extracted flux densities at the three frequencies and fitted a power-law model $F_\nu = c\nu^\alpha$ using a Bayesian approach implemented with the `emcee` sampler (Foreman-Mackey et al., 2021). In Fig. 1 we can see how this method provides posterior distributions for the spectral index α , allowing robust classification of the emission mechanism.

We based the morphological classification on the angular size and symmetry; structures with clear bipolar lobes and an angular separation of less than three times the beam size were interpreted as part of the same source and therefore flagged as double-lobed sources. The existence and reliability of these sources were confirmed by analyzing their appearance across all the frequencies and comparing them with the NVSS survey.

The results reveal a catalog of 78 radio sources, including both catalogued and uncatalogued objects. Cross-matching with existing catalogs revealed that out of the 78 sources, 45 of them had never been catalogued before, and 33 had been reported at least once.

For a subset of sources, the spectral indices calculations range from -0.9 to -0.2, consistent with synchrotron emission. The angular sizes of the detected sources allowed us to rule out the possibility of them being Galactic supernova remnants (SNRs), since none exhibit the large-scale diffuse emission or shell-like structures expected from this type of source. Similarly, we excluded H II regions as a possible explanation for their nature due to the absence of compact and high-brightness cores, thus confirming a mostly extragalactic source population.

Among the identified radio sources, six exhibit double-lobed morphologies, as shown in Fig. 2 at 1440 MHz, where their emission appeared more intense. These radio sources display well-defined bipolar lobes with symmetry

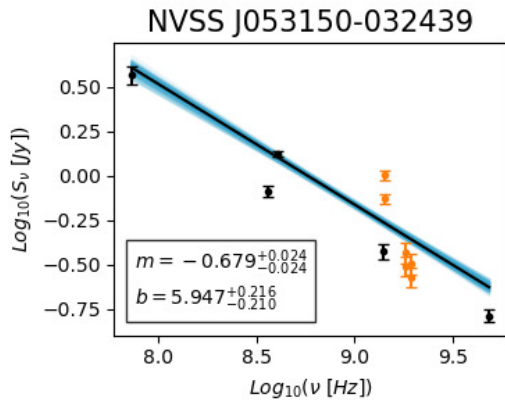


Figure 1. Spectral index estimation for a particular double-lobed source using *emcee* sampler (Bayesian approach). The orange points correspond to the integrated flux densities extracted from ODIN data, while the black points represent measurements from external catalogs. The blue-shaded lines show the family of power-law models possibly consistent with the data. The inset reports the best-fit spectral index (m) with its uncertainty.

and angular separation, features that are consistent with possible radio galaxy structures; for these cases, we verified that all of them were detected in the three ODIN bands, confirming the morphological consistency across frequencies and ruling out the possibility of them being noise or imaging artifacts. Moreover, comparison with NVSS maps at 1.4 GHz shows positional agreement within 5% relative error, validating the robustness of the detections.

Using the observed flux asymmetries between lobes and assuming mildly relativistic jet velocities, we obtained the inclination angles of the six double-lobed sources, with values between 30° and 40° , characteristic of radio galaxies. None of the sources displayed angles below 15° , ruling out strongly beamed sources like blazars. The absence of core dominance, the presence of concentrated hotspots, and the angular separations are coherent with those expected for radio galaxies at moderate redshifts (Miley, G., 1980). Therefore, taken together, the morphological features, positional confirmation, and inclination angles all support the conclusion that these double-lobed sources are extragalactic, strongly associated with radio galaxies.

As future work, this study may justify future deeper and higher resolution observations to determine the nature and evolutionary state of these possible radio galaxies through spectral index maps with high spatial resolution.

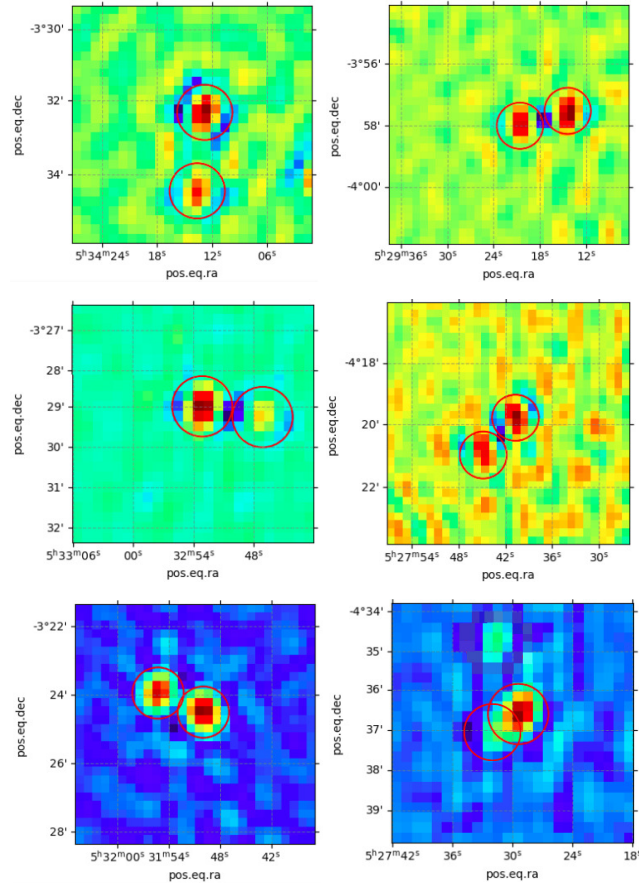


Figure 2. View of double-lobed radio sources at 1440 MHz. The bipolar structure and symmetry support their classification as possible radio galaxies.

Acknowledgments: We thank Dr. Juan Diego Soler for providing access to the ODIN data to develop this study.

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The plate digitizers at SHAO

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Since the first photograph of the Moon was taken in 1840, millions of photographic plates have been produced to capture various celestial objects at astronomical observatories around the world, continuing into the 2000s. Beyond their immense scientific value, these plates represent a significant astronomical heritage for all humanity, as recognized by the International Astronomical Union (IAU) in Resolution B3 of its 24th General Assembly in 2000. Since 2013, the Shanghai Astronomical Observatory (SHAO) has developed multiple plate digitizers. With these devices, SHAO is carrying out international cooperation to the preservation of the scientific heritage on astronomical plate digitization.

1. High-Precision Plate Digitizers at SHAO

Prior to the widespread adoption of CCD technology in astronomy, photographic plates served as the primary detection method for over a century. Recognizing the need to preserve these invaluable historical records, IAU has called for a global effort to digitize astronomical plates using advanced digitization technologies. **High-precision, high-speed specialized digitizers** have emerged as essential equipment for this crucial task.

During 2013-2016, SHAO collaborated with Japan's Nishimura Co., Ltd to develop China's first high-precision plate digitizer (Fig. 1). This instrument was subsequently used to complete the digitization of all nighttime-observation astronomical plates in China (Shang et al., 2024). Building on this success, Shanghai government identified broader applications for this high-precision scanning technology beyond astronomy. With sustained government support, our laboratory developed four sets of new-generation of plate digitizers based on air-bearing guide rails (Fig. 2). Table 1 compares the main technical parameters of the first and second generation of all the five sets of plate digitizer.

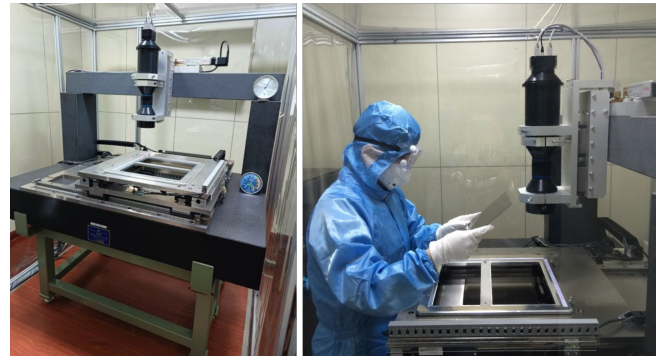


Figure 1. First high-precision astronomical plate digitizer based on mechanical guide rails.

2. Digitizer Application on International Cooperations

In response to the call of IAU, SHAO has carried out international cooperation in the digitization of astronomical plates with multiple astronomical institutions. Between 2016 and 2024, SHAO digitized plates from:

- Chinese Observatories (29,314 plates),
- Astrophysical Observatory of Torino, Italy (7,275 plates),
- Ulugh Beg Astronomical Institute, Uzbekistan (13,918 plates),
- National Astronomical Observatory, Japan (4,999 plates),
- University of Chile (6,012 plates, ongoing).

Figs. 3 depicts an example of the entire process photographic plates preservation, starting from packaging and transporting (in that case from Uzbekistan) to their reception in Shanghai, their storage in an archive room at controlled temperature ($\sim 20^\circ\text{C}$) and humidity ($\sim 50\%$),

Table 1. Main technical parameters of the five sets of plate digitizer.

Parameters	First digitizer	New Digitizers			
		Monochromatic Transmissive	Color Multifunctional	Large scanning range	Equipped with a film rolling unit
Scanning method	Line scanning	Block scanning	Block scanning	Block scanning	Block scanning
Optical resolution	2540 DPI	2309 DPI	3908 DPI	2309.6 DPI	11772.4 DPI
Positional precision	0.7 μm	0.3 μm	0.3 μm	0.3 μm	0.3 μm
Photometric precision	0.02 mag	0.01 mag	0.01 mag	0.01 mag	0.01 mag
Dynamic range	3.0 OD	3.9 OD	3.9 OD	3.9 OD	3.9 OD
Scanning range	300×300 mm	320×320 mm	320×320 mm	450×450 mm	350×350 mm
Scanning time	600 s	210 s	260 s	591 s	296.5 s
	(300 mm ²)	(300 mm ²)	(300 mm ²)	(450 mm ²)	(350 mm ²)
Image bits	16-bit B/W	16-bit B/W	16-bit B/W / 48-bit color	16-bit B/W	48-bit color

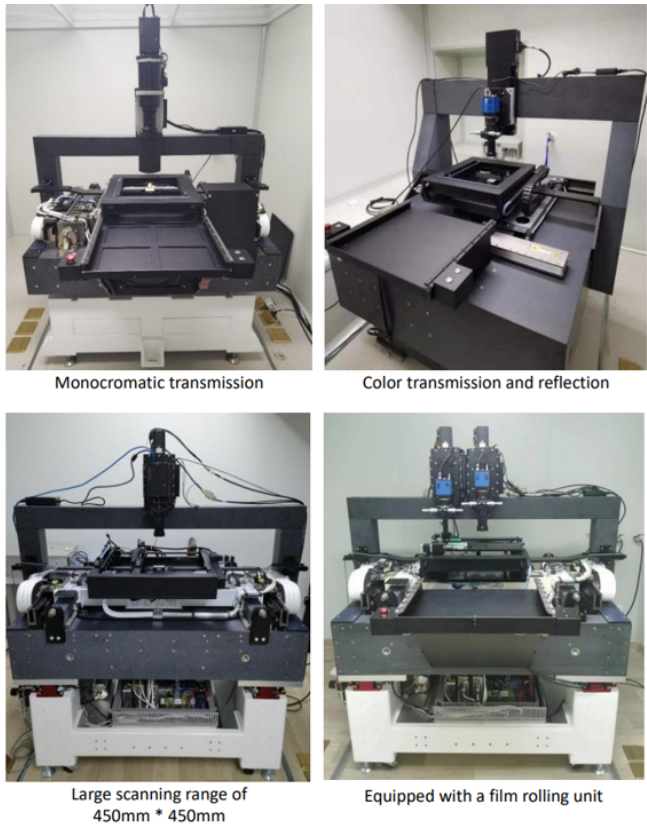


Figure 2. New high-precision digitizers.

their pre-digitization processing, digitization and then saving in digital form in a dedicated server.

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Figure 3. The entire process photographic plates preservation. a) packaging and transporting (in that case from Uzbekistan). b-c) Reception in Shanghai. d)Storage in an archive room at controlled temperature and humidity. e) Cleaning of the plate. f-g) Digitization. h) Saving in digital form in a dedicated server.

Determination of geodetic parameters for cart (chinese argentine radio-telescope)

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Keywords: VLBI, geodesy, radio telescopes, reference systems, ITRF, Southern Hemisphere

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“Félix Aguilar” Astronomical Observatory (OFA) from the National University of San Juan (UNSJ) and the National Astronomical Observatories (NAOC) of the Chinese Academy of Sciences (CAS), have maintained a close collaboration for more than 30 years in the discipline called “Astrometry”. Based on the excellent relationship between China and Argentina, both the UNSJ and the CAS through their respective research institutes have extended the agreement to other studies in astronomy and related sciences.

In this sense, both institutions have signed an agreement for the installation of a 40-meter diameter radio-telescope in San Juan, which will be the largest single dish in South America (Fig. 1). The working frequency will cover the range from 1 GHz to 50 GHz and although it will be mainly dedicated to the establishment and maintenance of the Celestial Reference Frames (ICRF) and Terrestrial Reference Frames (ITRF), research may also be carried out in cosmology, astrophysics, geodetic, geophysics and space navigation.

In this work we show all the tasks that have already been carried out, site search, geophysical, seismological, and geological studies of the possible installation sites of the radio telescope, and mainly the current geodesy tasks, precise auscultation of the CART basement for the control or tracking of ground settling and monitoring of the structure movement, taking into account that CART is located in an area of high seismic activity.

This will be the largest radio telescope in all South America, and in the near future will be operational using the VLBI technique and will be part of a global network whose main objective is to implement the International Terrestrial Reference Frame (ITRF).

The Positional Astronomy and Geodesy Area of the OFA is in charge of the CART project. This group has maintained for more than three decades



Figure 1. Digital rendering of the 40 m-diameter CART antenna.

agreements between the UNSJ and the Chinese Academy of Sciences, developing several projects of Astrometry, Astrogeodynamics and Space Geodesy.

Site Search. During the years 2009-2011, topographic survey campaigns in many areas of San Juan were done, to find the best CART place. Finally, in 2013, the CART site was selected at the EACUC (Carlos U. Cesco Astronomical Station), in the El Leoncito zone. The electromagnetic noise measurement campaign was subsequently carried out.

Precision Geodesy at the CART site. The general objective of this project consists of designing and executing Superior Geodesy tasks, for the installation of the CART antenna and the planning of the construction of a fundamental geodetic observatory. The first tasks were to enable access to the CART site and the materialization of network points in the area for plani-altimetric control of the base and future co-location with other geodetic techniques.

During the years 2015-2016, the Spatial Geodesy Group placed stakeouts of the new access road to the CART site,



Figure 2. Internal, intermediate and external networks for CART foundation monitoring.

and a topographical survey from the access to the EACUC station to the entrance to El Leoncito Park. Since 2017, precise positioning tasks of the CART center and its link to the national reference framework POSGAR 07 have been required.

Microgeodesic auscultation. The primary objective of the Microgeodesic auscultation works is the continuous monitoring of the structure of the CART base, in addition to the three-dimensional movement control of the site, considering that CART is located in an area of high seismic activity.

For this, it was necessary to develop the following stages:

- Design of monitoring networks (see Fig. 2).
- Demarcation of network points.
- Precision measurement of geodetic networks (see Figure 3).

Coordenadas Ajustadas G-K			
Punto	X (metros)	Y (metros)	Tipo de red
1	6482012.4382	2469357.8774	Red de apoyo
2	6481940.6900	2469421.8800	Red de apoyo
3	6481898.0763	2469372.5238	Red de apoyo
4	6481840.1185	2469246.5527	Red de apoyo
5	6481980.9714	2469296.7855	Red intermedia
6	6481992.4854	2469387.2744	Red intermedia
7	6481905.9627	2469416.3352	Red intermedia
8	6481846.3931	2469342.2426	Red intermedia
9	6481947.9761	2469351.8572	Red interna
10	6481961.2376	2469344.9002	Red interna
11	6481965.0809	2469345.8753	Red interna
12	6481973.1701	2469361.1930	Red interna
13	6481971.7860	2469364.9461	Red interna
14	6481958.5068	2469371.9271	Red interna
15	6481954.6188	2469370.9413	Red interna
16	6481946.5745	2469355.6478	Red interna
17	6481936.7753	2469601.6938	Red externa
18	6481668.1724	2469476.4302	Red externa
19	6481943.0800	2469200.0800	Red externa

Figure 3. Instruments used: Theodolite WILD T2, Distance meter WILD DI2002, GPS CHCNAV.

- Calculation of geodetic networks and temporal variations.
- Evaluation of the base center motion (ITRF linked).

Final remarks. The CART project will be integrated into the existing international VLBI geodetic networks. This global network of radio telescopes used for astrometric and geodetic purposes has approximately 40 operational instruments, most of which are concentrated in the Northern Hemisphere. The installation of CART in Argentina will not only contribute to improving the global coverage of this network, but also to determining astrogeodetic parameters in the southern region of our planet.

OAFA is part of the current International Terrestrial Reference Frame (ITRF 2020), hence the importance of the CART project for Argentine and South American geodesy.

Doris SJVC station. Update and geodetic applications

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Keywords: *space geodesy, co-location, reference systems, GNSS, SLR, DORIS*

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The DORIS (Doppler Orbitography and Radiopositioning Integrated Satellite) geodetic satellite technique is a global network composed of 60 strategically distributed antennas. In 2018, a DORIS beacon and antenna were installed at the Félix Aguilar Astronomical Observatory (San Juan, Argentina). After overcoming technical issues, the system was upgraded with advanced equipment in 2022, significantly improving the transmitted signal. This paper aims to present the characteristics of the DORIS technique, the installation and upgrade of the SJVC Station, and its results on Polar Motion.

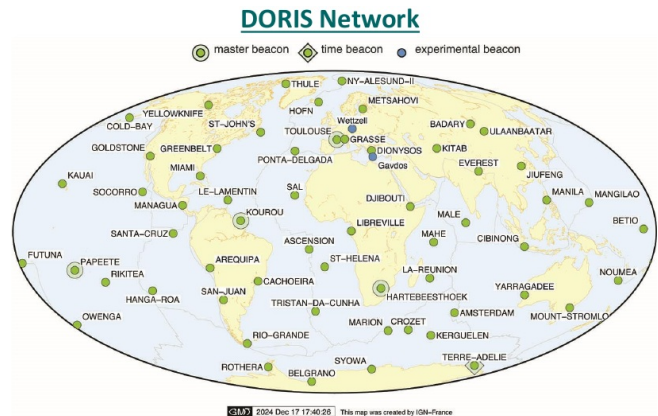


Figure 1. DORIS beacon and antenna installed at Oafa.

1. What is DORIS?

DORIS stands for Doppler Orbitography and Radiopositioning Integrated Satellite. It is a French technique that has been operational since 1990 at the initiative of the National Center for Spatial Studies (CNES) and National Geographic Institute of France (IGN). DORIS consists of a network of 60 beacons evenly distributed across the Earth's surface. Doris works in the opposite way to the Global Navigation Satellite System (GNSS), because the receivers are on board the satellites and receive the signal from the network of ground stations. This technique uses the Doppler effect, which consists of the frequency shift caused by the relative motion of the satellite with respect to the ground station. DORIS beacons transmit signals on two frequencies: one at 2 GHz for precise Doppler shift measurement and the other at 400 MHz for ionospheric delay correction. DORIS allows the precise determination of the orbits of artificial satellites. This geodetic technique also contributes to the determination and implementation of the International Terrestrial Reference Frame (ITRF) (Moreaux et al., 2020).

2. Components of the DORIS System

Ground stations are made up of two parts: a) Beacons: generate signals on both frequencies. b) Antennas: transmit signals to the satellites in orbit. Satellites: They carry on board the receivers that capture the signals emitted by ground stations. Satellite Control Center: They are responsible for monitoring them and making the necessary corrections to ensure proper operation. Computing Center (SSALTO): Its objective is to calculate the products derived from DORIS observations. The International Doris Data Center (IDS): Collects information and calculated products for publication. The IDS is part of the International Earth Rotation and Reference Systems Service (IERS, Moreaux et al., 2021). DORIS SJVC STATION: In 2014, the French IGN and the CNES decided to relocate the DORIS Ground Station that was located in Santiago, Chile. New selected location: Oafa (Figure 1). In 2017, the pedestal for the antenna and the beacon building were built (Saunier et al., 2016). In September 2018, the equipment arrived at the Oafa and was installed. Co-localization measurements were also performed. In June 2022, the fourth generation of DORIS beacon and antenna were installed. The biggest

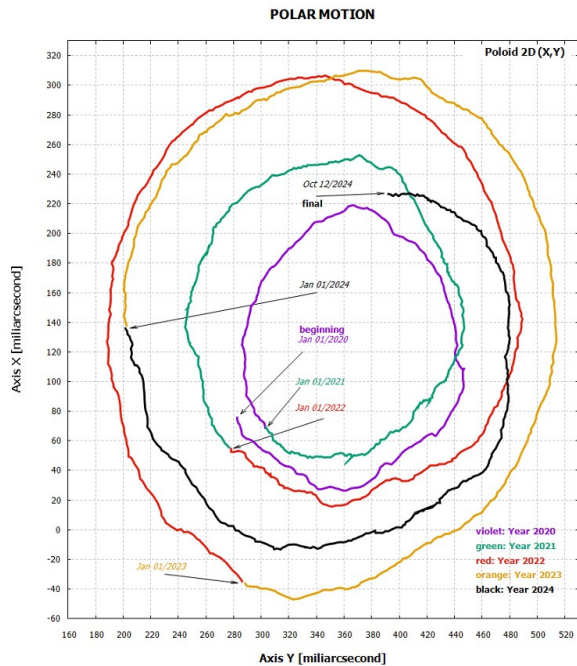


Figure 2. The graphs illustrate a variation in the poloid. In 2020, the curve amplitude was $X = 195$ mas, $Y = 165$ mas. In contrast, the 2023-2024 period exhibited a total amplitude of $X = 260$ mas, $Y = 327$ mas. Notably, the 2024 trend indicates a decline. Further investigation of this phenomenon will be conducted using new observational data.

change was the addition of an amplifier near the antenna to achieve stronger and more stable signals.

Based on data collected from the DORIS SJVC station between 2020 and 2024, two polar motion graphs were generated (Figures 2 and 3). The continuous graph was created using modified Julian date (MJD) values.

3. Conclusions

- 1. Since its installation, the DORIS SJVC Station has contributed to international services with its observations.

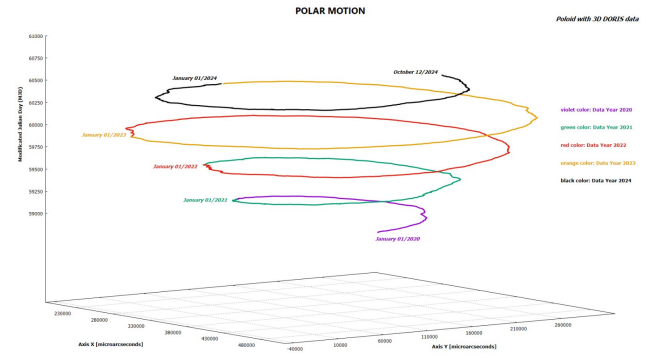


Figure 3. 3D perspective of the poloid.

- 2. From the Satellite Geodesy Group of the OAFA, we aim not only to be the host organization for this technique but also to process and produce our own publications based on the observations made.

Acknowledgements: We thank the French institutions IGN and CNES for working with us and choosing our institution.

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Inclusion of orthogonality in the method of reduction of astronomical observations with overlapping, devised by Dr. J. Stock in 1981

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Keywords: keyword 1, keyword 2, keyword 3, keyword 4, keyword 5

The Center for Astronomical Research Foundation (CIDA) was established nearly simultaneously with Venezuelas National Astronomical Observatory at Llano del Hato (OAN). Astronomer and astrometrists Dr. J. Stock was its principal architect and the first president of both the Foundation and the Observatory, which operated under its auspices. In 1981, Dr. Stock published his method for reducing photographic plates (Stock, 1981), based on projecting the measured (x, y) coordinates from the plates onto the celestial sphere to determine the rotational matrix solution that links these projected coordinates with the astronomical positions of stars found in the selected reference catalog. He also emphasized the importance of plate overlap, noting that overlapping stars can contribute to the solution of the plates that contain them, even if they are not part of the reference catalog. This scientific approach, combined with the fact that the OAN housed a 1-meter Schmidt telescope must be appreciated in the context of the period in which it was developed.

The observational reduction method that has traditionally prevailed and continues to dominate today operates on the plane and is based on the determination of standard coordinates, along with a polynomial development aimed at representing the distortions present in the observations. The Stock method generates linear solutions but does not account for these distortions, which must be identified and corrected to complete the procedure and render it a competent method.

The Schmidt Camera (1m), with a focal ratio of 3 and a location near the equator, highlighted the limitations of comprehensive, high quality, extensive reference catalogs (those spanning both hemispheres) and with sufficient depth, discarding bright reference stars due to saturation in projects requiring greater depth. An additional important feature was its lack of a flat focal plane. The plates had to be curved, matching the curvature of the mirror so

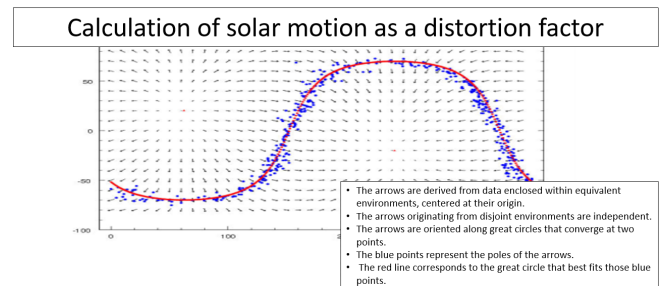


Figure 1. Calculation of solar motion using the proper motions from the Hipparcos catalog.

that the images appeared focused on the curved focal surface. After exposure, the plate had to return to its original flat state before undergoing the development process. What polynomial function could represent this phenomenon within the reduction procedure? This marked the beginning of a distinct line of astrometric research at CIDA, with several key works contributing to its development. It began with Stock & Abad (1988), which aimed to unify catalogs by reducing the systematic errors among them through the Sliding Polynomial function introduced in that study.

The use of overlap as an observational design strategy intended to replace polynomial functions with systematic numerical patterns is presented in the following three publications. Abad (1995), Abad (1993), and Vicente et al. (2007). The first addresses the lack of a defined function capable of representing the bending and unbending process of photographic plates in a Schmidt telescope. The second demonstrates the strength and potential of overlap by reducing 1260 plates covering the area assigned to the Paris Observatory in the Astrographic Catalog, using only 104 reference stars from the fundamental FK5 catalog. The

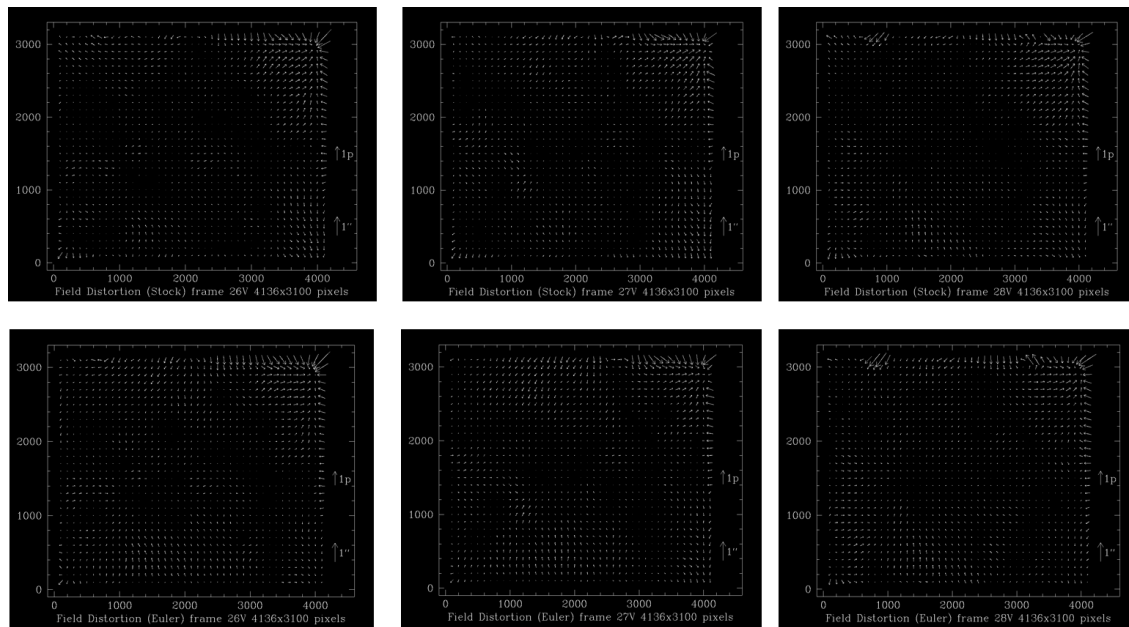


Figure 2. Comparison of distortion patterns for 3 exposures using (Top) Stocks method and (Bottom) Euler angles.

third publication presents a complex mixture of issues, including potential deformation and degradation effects that may have impacted approximately 400 plates from the San Fernando zone of the *Carte du ciel*, which remained stored in the same position for nearly 100 years.

It is also worth mentioning that the recovery of saturated stars as reference stars led to the design of the Tepui function, named for its similarity to this type of geological formation. This function has been used in its two-dimensional form for satellite observations (Montejo et al., 2011) and for tracking space debris (Lacruz et al., 2017).

The power of the Sliding Polynomial function is further highlighted by its application to galactic dynamics, for example, in the calculation of the Sun's motion using data from the Hipparcos catalog (Abad et al., 2003) (Figure 1).

Stocks method defines a matrix as the linear solution to the observation, whose nine elements are calculated using the least squares method from equations derived using three or more stars. This solution is not necessarily orthogonal, due to the nature of its derivation from observational data, although ideally it should be. We have attempted to calculate the rotation matrix using Euler angles and reconstruct it from them, in order to examine whether both solutions exhibit different distortion patterns.

We have worked with exposures taken using the Camera Schmidt and its new detector: the FujiFilm GFX 50R non-reflex camera (8256 × 6192 pixels, 5.6 × 5.6 μm), equipped with an RGB Bayer filter. Figure 2 illustrates the contrast between the patterns obtained from 3 of the 7 exposures (using the G filter as an example), and no significant differences in the patterns are observed.

The positive response to the use of systematic numerical patterns for the reduction of observations is evident. Our

goal was never to compete with the classical method, but rather to find solutions to specific problems encountered within our institution. The reduction of these new exposures from the Camera Schmidt has broadened our future outlook. The arrival of the GAIA catalog will produce an impact on the unification of methods. One example of this is that for many observations conducted with medium aperture telescopes, the majority of the stars will now serve as reference stars. This implies that, except for some particular cases, the overlapping design we had pursued no longer remains essential. Additionally, for the first time in our case, both the detector and the telescope meet the necessary requirements to perform the classical reduction, which uses standard coordinates and gnomonic projection. Perhaps we can now align with the majority approach and see whether the experience gained from processing and applying numerical distortion patterns can improve the solution even if only in some cases.

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Space Debris detection and tracking in astronomical images

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Keywords: *Space Debris, Detection, Tracking, Morphology in astronomical images*

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Advanced telescopic capabilities and wide-field observation campaigns can significantly contribute to the detection and monitoring of Space Debris (SD) populations. The main methodology involves performing astrometric reductions on astronomical images to determine the positions of detected SD and, combining these data with precise orbital models, to estimate their intrinsic geometric and physical features. This study aims to improve the understanding of SD behavior, thereby contributing to more effective mitigation strategies and safer orbital environments.

There are three main regions where space objects are located, among others: Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geosynchronous Equatorial Orbit (GEO). According to NASA, there are 39230 SD larger than a tennis ball, half a million with sizes of a marble or larger, up to 1 cm and approximately 130 million about one millimeter (ESA, 2025). Figure 1 shows the distribution of approximately 30000 cataloged objects as of January 1, 2024, at 00:00:00 UTC (<http://space-track.org>), displaying eccentricity, e , as a function of the semi-major axis, a , in km. Beyond their spatial distribution, these debris populations represent a significant challenge to the long-term sustainability of space operations. LEO, in particular, exhibits the highest density of debris due to frequent launches and satellite constellations, resulting in elevated collision probabilities. In contrast, MEO and GEO, while less populated, are critical for navigation and communication services, where even a single fragmentation event could have severe operational consequences. The figure includes the eight main sources of SD clouds, such as known breakup events: Iridium 33 DEB, Cosmos 1408 DEB, Cosmos 2251 DEB, and Fengyun-1C DEB located in LEO, as well as Breeze-M DEB, Atlas Centaur DEB, Ekran-2 DEB, and Titan 3C Transtage DEB in GEO.

Due to the orbital dynamics of each object, space debris appears as streaks in astronomical images, varying in orientation, brightness, and length. The length of each streak is proportional to the exposure time and the object's orbital velocity, while the brightness depends on the object's reflective area, allowing for morphological classification. To detect SD and determine the astronomical coordinates associated with each trail in astronomical images, a pipeline was developed based on GNU Astronomy Utilities Gnuastro 0.23 (Akhlaghi, 2024) that performs the process automatically. The pipeline essentially consists of creating a mask, detecting the trails, and verifying the final streaks. As a first step, initial detections are performed; subsequently, false detections are identified and removed by applying a threshold distance, which allows the extraction of a significant signal-to-noise ratio for the streaks. Figure 2 shows the results of the pipeline applied to four consecutive images containing trails that correspond to the same SD. The black points represent the stars in the field, while the blue, red, green, and yellow points represent the trail at different times. After the astrometric reductions which include measurement, identification, and coordinate transformation it is possible to determine positions with high precision (Lacruz et al., 2018) and perform a preliminary orbital determination (Abad & Lacruz, 2013).

As the results were calculated for each streak, approximately 20 coordinates (α_{t_i} , δ_{t_i}) were obtained at different time instants, t_i , distributed between the start and final exposure time. The histogram in the upper left shows the distribution of magnitudes calculated for each streak, with a mean value of 15.5 in the V band.

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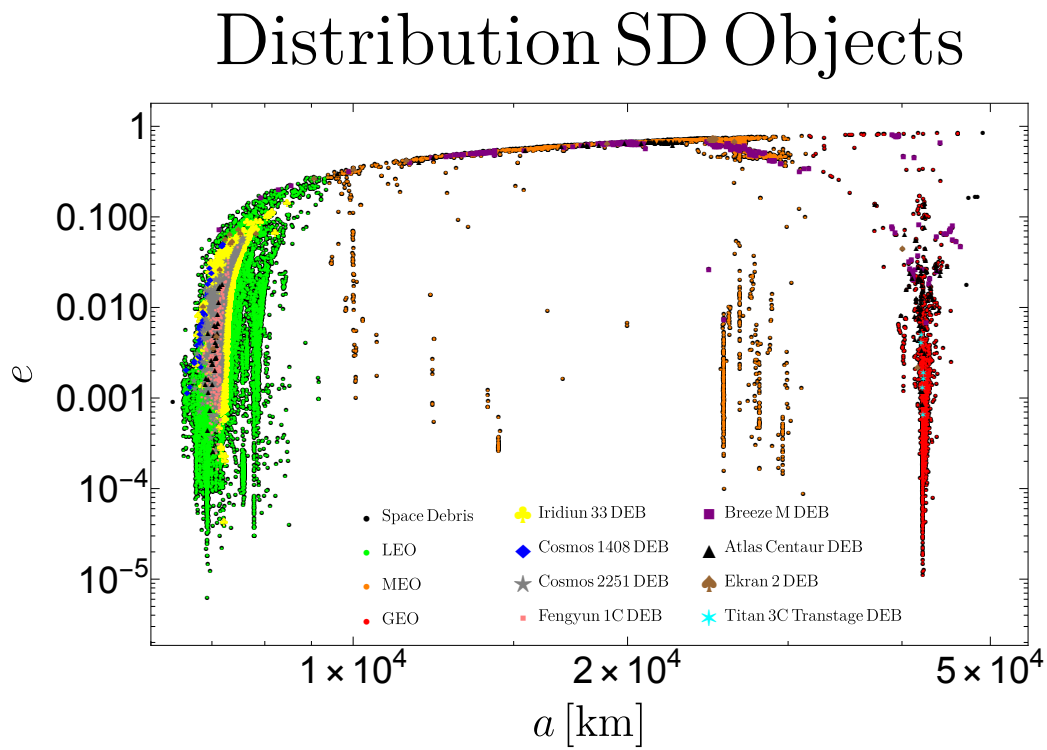


Figure 1. Distribution of eccentricity, e , as a function of semi-major axis, a , in km, of cataloged SD at January 1, 2024, at 00:00:00 UTC.

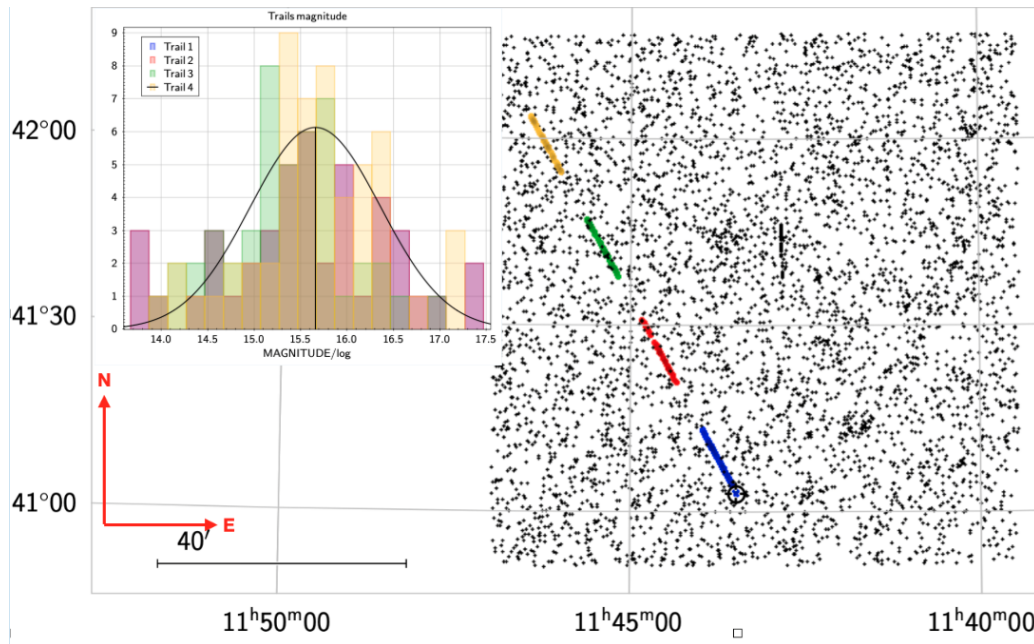


Figure 2. Right ascension, α , and declination, δ , of the trails were determined through the pipeline and astrometric reductions on four consecutive images. The mean magnitude in the V band was also calculated.

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ISON: an open international project and database on space Debris

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The exploration and research of near-Earth space has brought attention to potential threats, particularly the dangers posed by asteroids and the rise of technological space pollution known as space debris. To address these challenges, an international initiative known as the International Scientific Optical Network (ISON) was established. The National Astronomical Observatory in Tarija, Bolivia (Zalles, 2020), has been participating in the ISON network since 2009 with the Sigma Ori telescope, since 2016 with the Zeiss 600 AA telescope, and will soon include the new Tal 25 telescope (see Figure 1).

1. INTRODUCTION

The number of non-operational satellites, spent rocket stages, and fragments accompanying each launch has reached a critical point and poses a serious threat not only to manned orbital stations, spacecraft, and functioning satellites, but also to Earth's ecology. The ISON project began in 2004 with the goal of serving as an open repository of scientific data related to near-Earth objects. At its peak, the project included 33 observatories in 17 countries, operating 100 telescopes under the coordination of the Pulkovo Observatory and the Keldysh Institute of Applied Mathematics of the Russian Academy of Sciences. Currently, ISON conducts its research using approximately 50 optical telescopes located in 23 observatories across Europe, Asia, the Far East, Africa, and North and South America (Zalles et al., 2015) (see Figure 2). The network coordinates with the innovation company "ISON Ballistics-Service" (SIE ISON-BS) (Molotov et al., 2023), which operates 32 telescopes, observation scheduling centers, and databases focused on space debris and asteroids.



Figure 1. Above: Zeiss 60 AA telescope. Below left: Sigma-Ori 25 telescope. Below right: Tal 25 telescope.

2. SPACE DEBRIS DATABASE

The software system for space debris (SD) data collection and analysis relies on the open-source object-relational database management system PostgreSQL, operating under the Ubuntu 20.04 (LTS) operating system. The fundamental structure of the database is illustrated in Figure 3.

Two types of data, namely optical position measurements and orbit lists, are acquired on the server through FTP or SFTP protocols, after which a validation process takes place. The system supports multiple encodings to facilitate collaboration with international partners. Additionally,

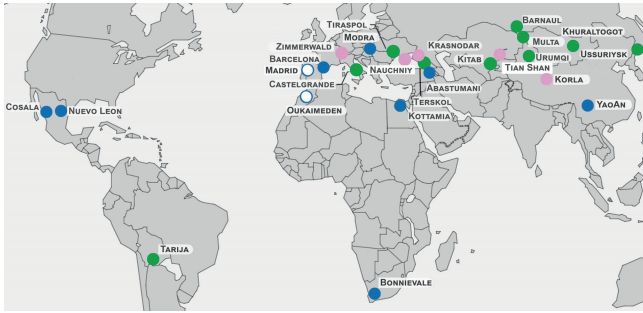


Figure 2. Approximately 50 optical telescopes located in 23 observatories.

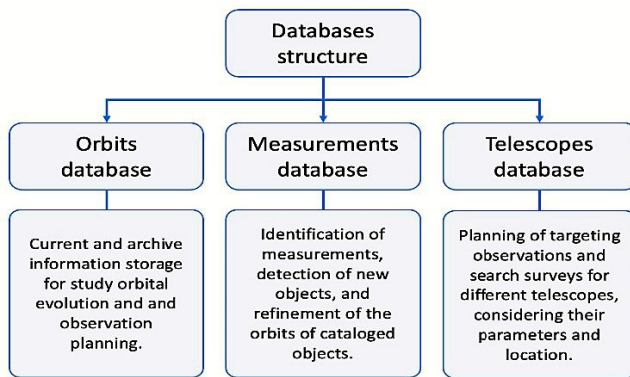


Figure 3. The main structure of the ISON database on SD.

source files can be uploaded in archive formats such as tar. Upon successful validation and identification of the data type, the information is directed to one of two processing pipelines, specifically tailored for measurements and orbits. In these pipelines, the data undergo parsing and are subsequently written to the database. The system operates with two distinct tables, namely “measurements” and “orbits”. In the event of errors detected during input validation, an automated system notifies the source, prompting them to rectify potential formatting issues or other errors. Comprehensive data on telescopes, including coordinates and technical parameters, are stored, encompassing all essential information for the automated observation planning subsystem. The structure of this subsystem is depicted in Figure 4.

The data processing software package has been created utilizing the free cross-platform framework .NET Core 6, enabling deployment on various x86 operating systems such as Linux, Windows, and Mac OS. The server's hardware infrastructure is built around an Intel Xeon E2697 v2 processor, boasting 12 cores and 24 threads, accompanied by 64 GB of RAM. The storage capacity of the server totals 12 TB, organized in a RAID 1 array, with the flexibility to expand if needed. As of September 1, 2023, the cumulative database comprises over 127 million entries, occupying

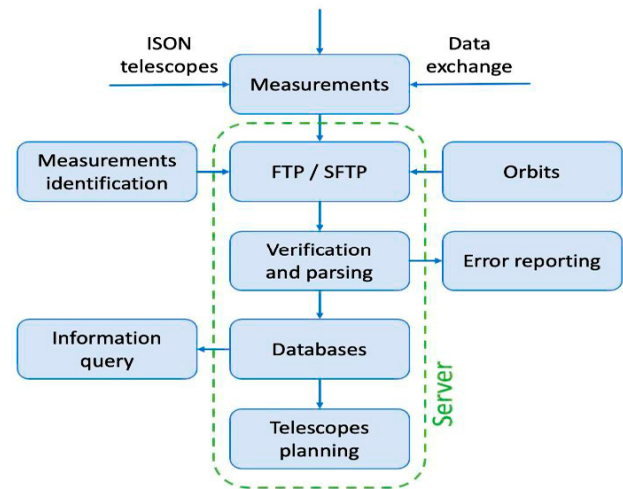


Figure 4. The overall scheme of the system.

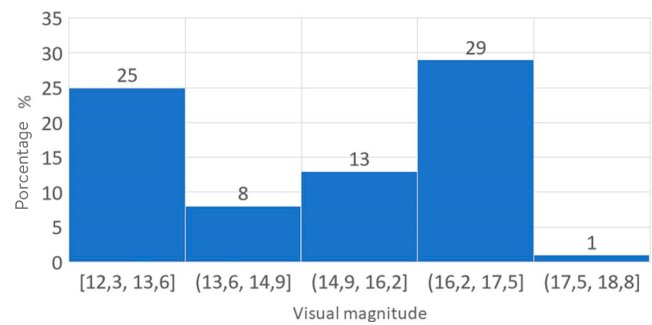


Figure 5. Distribution of these measurements, categorized by magnitudes.

more than 45 GB of disk space. This extensive dataset includes 96,333,409 measurements and 9,750,341 tracklets. The distribution of these measurements, categorized by magnitudes, is illustrated in Figure 5.

3. CONCLUSION

Currently, the ISON scientific cooperation consists of 53 telescopes at 27 observatories across Europe, Asia, the Far East, Africa and North & South America and carries out investigations of space debris and asteroids. ISON small survey telescopes cover all the GEO orbits and provide a significant contribution to the maintenance of the catalog accuracy for space objects brighter than 15.5m, which is important for the conjunction analysis procedure. Due to a 15-year series of the observations of space debris by ISON the knowledge about the space debris population at the GEO and HEO has reached a fundamentally new level. For more information on the database and additional information on collaboration opportunities please contact Molotov I. (im62@mail.ru). The project is in the process of developing an international exchange of space debris

data with interested institutions, resulting in a substantial increase in the volume of measurements within the ISON database, now reaching 40 million measurements. These ongoing efforts underscore ISON's commitment to advancing our understanding of near-Earth space and providing critical data for the safety and sustainability of space activities.

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