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# Feasibility of a National Space Debris Monitoring Center in Brazil: Site Selection and Sensor Technology Assessment

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## Abstract

Space debris has become a persistent operational hazard, especially in low Earth orbit (LEO), where a single fragmentation event can release thousands of trackable fragments. Countries with mature space programs rely on dedicated Space Surveillance and Tracking (SST) infrastructure to catalogue these objects and support collision avoidance, whereas Brazil has no such center and depends on foreign data to protect its own satellites. This paper assesses the feasibility of establishing a national Space Debris Monitoring Center in Brazil, using the University of Brasília as the reference case. The ground-based SST capabilities of the European, US and Japanese space agencies, of selected universities and of existing Brazilian initiatives are first reviewed. A reference operator focused on objects of 10 cm and larger in LEO is then defined, and five Brazilian cities with existing space activities (Alcântara, Natal, São José dos Campos, Brasília and Cuiabá) are compared through a Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis based on climate, weathering of equipment, technological infrastructure, logistics and the potential for institutional coordination and funding. Brasília offers the most balanced combination of academic infrastructure, access to government and funding bodies, logistics and favorable dry-season observing conditions. A comparison of radar, optical and laser-based sensors in terms of precision, coverage, environmental dependence, detection capability and cost indicates that a monostatic radar is the most suitable primary sensor, as its operation does not depend on weather, daylight or the urban light pollution that affects the selected site.


## 1 Introduction

The launch of Sputnik 1 from the Baikonur Cosmodrome in 1957 opened the Space Age and, with it, a technological race in which access to orbit quickly became a matter of geopolitical weight [1]. Over the following decades, satellites took on a central role in global communications, navigation and Earth observation, and the number of objects placed in orbit grew at an accelerating pace. That growth came at a cost. Every mission leaves something behind, whether a spent upper stage, a satellite that has reached the end of its life or small fragments released during operations, and the accumulated mass of these objects is now a concern shared by the scientific community and by the space market as a whole [2].

The operational consequences are already well documented. In 1996, the crew of Space Shuttle Endeavour had to perform an emergency maneuver to avoid a piece of debris during mission STS-72 [3]. In 2009, the collision between the active Iridium 33 and the defunct Cosmos 2251 produced the first catastrophic breakup involving two intact satellites [4]. Seven years later, a small fragment struck one of the solar arrays of the European Space Agency's (ESA) Copernicus Sentinel-1A and caused visible damage [5]. The hazard also reaches the ground: when the Soviet nuclear-powered satellite Cosmos 954 re-entered in 1978, it scattered radioactive debris over Canadian territory [6].

Active removal of debris remains technically demanding and costly. For that reason, the short- and medium-term response adopted by space agencies, companies and universities has focused on prevention, that is, on detecting, tracking and cataloguing objects so that operators of active satellites can plan collision avoidance maneuvers in time. This activity sits within what is known as Space Situational Awareness (SSA). Countries with established space programs operate observatories and dedicated offices that feed tracking data to satellite control centers. Emerging space nations such as Brazil, on the other hand, do not have a center devoted to monitoring the orbital environment and must rely on cooperation with other countries to ensure the safety of their own missions.

This paper addresses that gap by assessing the feasibility of installing a Space Debris Monitoring Center (CMD) in Brazil. The analysis covers strategic, technical and operational aspects and seeks to answer two questions: where in the country such a center would be best located, and which sensor technology would best serve its mission. The University of Brasília (UnB) is used as the reference institution throughout the study. The work stems from a two-year research effort in SSA carried out during the first author's undergraduate studies, part of which was presented at the International Astronautical Congress in 2022 [2].

The remainder of the paper is organized as follows. Section 2 reviews the debris problem, the regulatory framework and the components of SSA. Section 3 describes the ground-based Space Surveillance and Tracking (SST) infrastructure operated by

ESA, the US National Aeronautics and Space Administration (NASA) and the Japan Aerospace Exploration Agency (JAXA), the contribution of universities to this field and the current Brazilian capabilities. Section 4 presents the method, including the reference operator profile and the selection criteria. Sections <link rid="Sec16">5</link> and 6 report the site assessment and the technology assessment, respectively. Section 7 discusses the results and their limitations, and Section 8 concludes the paper with directions for future work.

## 2 Space debris and the space situational awareness framework

# 2.1 The debris population and the Kessler syndrome

ESA defines space debris as all non-functional, human-made objects in orbit [7]. The category includes inactive satellites, abandoned spacecraft, discarded launch vehicle stages and the small fragments released during routine operations [8]. Because these objects can no longer be controlled, they represent the main publicly recognized threat to active satellites, and agencies and companies around the world try to keep track of them through dedicated centers and observatories. Catalogued and estimated objects are usually grouped by size. Table 1 summarizes the estimates published by ESA with data from September 2024.

Table 1
Estimated number of debris objects in Earth orbit by size [9]

| Size range | Estimated number of objects |
|---|---|
| Larger than 10 cm | ~ 40,500 |
| Between 1 cm and 10 cm | ~ 1,100,000 |
| Smaller than 1 cm | ~ 130,000,000 |

Collisions between active and inactive objects range in outcome from minor damage to the complete destruction of the bodies involved. When a breakup occurs, the resulting fragments form clouds that raise the probability of further collisions, a feedback mechanism described by Kessler and Cour-Palais [10] and later known as the Kessler syndrome. In its original formulation, the theory predicted that the crowding of low Earth orbit (LEO) would lead to an exponential increase in the debris flux, with direct consequences for the safety of space operations. Kessler et al. [11] later pointed out that, from around the year 2000 onward, LEO would itself become a major source of small debris, raising the probability of random collisions to critical levels.

The prediction did not take long to materialize. In July 1996, the French microsatellite Cerise was struck by a fragment of an Ariane upper stage that had been in orbit for ten years, in the first publicly known collision between an operational spacecraft and a catalogued piece of debris [12]. The impact severed the satellite's gravity-gradient stabilization boom and changed its attitude, rotational energy and angular momentum; at the time of impact, the fragment was moving at more than 50,000 km/h relative to the satellite [13]. The most severe accidental collision recorded to date took place on 10 February 2009, when the non-functional Russian communications satellite Cosmos 2251, of about 900 kg, struck the commercial Iridium 33, of roughly 560 kg, at about 790 km of altitude. The almost perpendicular impact, at a relative speed close to 36,000 km/h, produced more than two thousand catalogued fragments and many thousands of smaller pieces [4]. More than fifteen years later, debris from that event still requires constant surveillance. Deliberate destructions by ground-launched anti-satellite (ASAT) missiles have added even larger debris clouds. Table 2 lists the events that, for their consequences to the present day, are most often cited in the literature.

Table 2
Collision and destruction events that generated space debris [11, 14–17]

| Date | Objects involved | Altitude | Fragments |
|---|---|---|---|
| 23 Dec 1991 | Cosmos 1934 and debris from Cosmos 926 | 980 km | 6 |
| 24 Jul 1996 | Cerise and an Ariane rocket fragment | 685 km | 3 |
| 11 Jan 2007 | Fengyun-1C and ASAT missile | 865 km | ~ 3,527 |
| 10 Feb 2009 | Iridium 33 and Cosmos 2251 | 790 km | ~ 2,378 |
| 27 Mar 2019 | Microsat-R and ASAT missile | 300 km | ~ 123 |
| 15 Nov 2021 | Cosmos 1408 and ASAT missile | 480 km | 1,402 |

The danger posed by these fragments comes less from their size than from their speed. Antennas, sensors, cameras and solar arrays are all exposed, and spacecraft designers resort to reinforced structures and shielding layers to protect them. Table 3 shows the kinetic energy carried by fragments of different sizes at an average relative speed of 10 km/s, typical of LEO. A 10 cm object at that speed carries about 70 MJ, an energy comparable to the detonation of more than 15 kg of TNT, which explains why such an impact is usually catastrophic. The robotic arm Canadarm2 of the International Space Station (ISS) offers a reminder that even small particles leave their mark: in 2021, a debris impact punctured its thermal blanket and damaged the boom underneath [18].

Table 3
Kinetic energy of debris fragments at a relative speed of 10 km/s. Kinetic energies from [19]; TNT equivalents computed with 4.184 MJ per kg of TNT

| Debris size | Kinetic energy (kJ) | TNT equivalent (kg) |
|---|---|---|
| 1 mm | 0.071 | 0.00002 |
| 3 mm | 1.91 | 0.0005 |
| 1 cm | 70.7 | 0.017 |
| 5 cm | 8,840 | 2.1 |
| 10 cm | 70,700 | 16.9 |

Current research on hypervelocity collisions concentrates on objects larger than 10 cm, and in particular on fragmentation characteristics such as the size distribution of the fragments, the resulting change in velocity (delta-V) and how both depend on the geometry and energy of the impact [20]. The destruction of Cosmos 1408 in November 2021 illustrates why these characteristics matter. The satellite was in an orbit inclined at 82.3°, while many Earth observation satellites occupy Sun-synchronous orbits inclined at about 97°. In the months that followed, the crossing between the debris cloud and those orbits produced recurring peaks of close approaches with active satellites [21].

## 2.2 Uncontrolled re-entries

Re-entry is the natural end of most objects in LEO, and in most cases it is harmless. According to Klinkrad et al. [22], about 100 tonnes of debris re-enter the atmosphere each year in an uncontrolled way, which corresponds to roughly two catalogued objects per day and two objects larger than 1 m² per week. Small and light objects burn up completely, but those with masses above about 100 kg have a high probability of reaching the ground and therefore pose a risk to people and infrastructure. For such objects, re-entry calls for continuous monitoring, prediction of the re-entry window and an assessment of the expected casualty risk.

Two historical cases show what is at stake. The US space station Skylab, about 30 m long and 75 tonnes in mass, re-entered on 11 July 1979 over the Indian Ocean and Western Australia, and fragments, including an oxygen tank, were recovered near

the town of Esperance a few days later [22, 23]. The Soviet station Salyut-7, docked to the Cosmos-1686 module in a composite of almost 40 tonnes, re-entered on 7 February 1991; its debris was expected to fall into the Pacific Ocean, but the station overshot the predicted area and pieces were found in Argentina [24]. Brazil has also been on the receiving end of such events: on 16 March 2022, a fragment of an object launched from the United States a few months earlier fell in a rural area of São Mateus do Sul, in the state of Paraná, although its re-entry had been expected over the ocean [25].

## 2.3 Regulatory context

The international regulation of space activities took shape in the 1960s, in response to the rapid progress of space exploration [26]. The Committee on the Peaceful Uses of Outer Space (COPUOS), created by the United Nations in 1959, became the forum in which the main space treaties were negotiated. The Outer Space Treaty of 1967 established that States bear international responsibility for their national space activities and banned nuclear weapons in space [27]. The Liability Convention of 1972 made States liable for damage caused by their space objects [28], and the Registration Convention of 1976 required them to register the objects they launch [29]. In recent years, COPUOS and the UN Office for Outer Space Affairs (UNOOSA) have turned their attention to debris, producing guidelines for the long-term sustainability of outer space activities that cover both the prevention of new debris and the management of existing objects [30]. The current agenda includes emerging challenges such as large satellite constellations and the commercial use of space.

At the national level, agencies such as the US Federal Aviation Administration (FAA) and the member states of ESA have their own rules for operators. Brazil is a party to the Liability and Registration Conventions, and on 31 July 2024 it enacted its General Law of Space Activities (Law No. 14,946), which establishes a comprehensive regulatory framework for the sector. Among other provisions, the law requires operators of satellites and other space objects to adopt measures to minimize the generation of debris and provides for supervision and enforcement mechanisms aligned with national and international norms [31]. Effective enforcement of such rules, however, depends on the ability to observe the orbital environment and to know, with adequate accuracy, where active and inactive objects are. This is precisely the role of SSA.

## 2.4 Space situational awareness and its segments

SSA is commonly described as the ability to view, understand and predict the physical location of natural and artificial objects in orbit in order to avoid collisions [32]. In practice, the concept covers the knowledge, characterization and tracking of space objects and of the environment in which they operate, and it is one component of the broader notion of Space Domain Awareness (SDA). ESA organizes SSA into three segments: Space Weather (SWE), Near-Earth Objects (NEO) and Space Surveillance and Tracking (SST) [33].

Space weather refers to the conditions in the magnetosphere, ionosphere and thermosphere driven by the Sun and the solar wind, which can affect the performance and reliability of space-borne and ground-based systems or endanger property and human health [33, 34]. Solar storms, whether in the form of flares, coronal mass ejections or enhanced fluxes of energetic particles, can cause anomalies in satellite electronics, surface charging and premature degradation. On the ground, the geomagnetic storm of March 1989 caused the collapse of the Hydro-Québec power grid in Canada and left millions of people without electricity for more than nine hours, while satellites and communication systems suffered severe disruptions [35]. The NEO segment deals with comets and asteroids whose orbits bring them into the vicinity of the Earth. Its aims are to determine their present and future positions, estimate impact probabilities as early as possible and develop deflection techniques [36]. Asteroid 99942 Apophis, about 335 m in diameter and initially classified as a significant impact risk after its discovery in 2004, was later cleared for at least the next century once its orbit had been refined [37].

SST, the focus of this paper, comprises the technologies used to detect, catalogue and predict the motion of objects orbiting the Earth [38]. It supports launch and early orbit phase (LEOP) operations, collision avoidance and re-entry predictions, besides the monitoring of debris itself. SST data originally came from telescopes and radars placed at strategic locations around the world. As the number of missions grew and LEO became more crowded, demand for these data increased sharply, and dedicated centers linked to space agencies and universities were set up, followed more recently by private companies offering tracking services.

## 3 Ground-based SST infrastructure abroad and in Brazil

This section reviews the SST structures of ESA, NASA and JAXA, chosen for their pioneering role in the field and for their contribution to debris monitoring and mitigation strategies, followed by the contribution of universities and by the Brazilian initiatives to date. The aim is not an exhaustive inventory but a set of reference cases against which the Brazilian options can be judged.

# 3.1 ESA Space Debris Office

ESA's Space Debris Office, part of the European Space Operations Centre (ESOC) in Darmstadt, Germany, coordinates all of the agency's debris-related activities [39]. Its tasks include characterizing the debris environment through modeling and observation, analyzing impact risk, assessing collision risk and planning avoidance maneuvers, predicting re-entries and their associated risk, maintaining a database of space objects and producing reports that raise awareness of the problem. The underlying sensor network is made up of optical and radar systems distributed across Europe, complemented by observatories operated by international partners.

Two instruments illustrate the European approach. The first is the Optical Ground Station (OGS) at the Teide Observatory in Tenerife, Spain, whose 1 m Zeiss telescope surveys the region near the geostationary orbit (GEO) and can detect objects of 10 to 15 cm at that altitude [40]. Its observations revealed a number of fragmentation events in GEO far greater than expected, including the explosion of the Soviet satellite Ekran-2 in 1978 and the breakup of a US Titan IIIC transtage, which left about 24 fragments in the geostationary region [41]. The telescope can also perform photometric observations, which help to infer the thermal properties of fragments and, in turn, their origin [42]. The second instrument is the Tracking and Imaging Radar (TIRA), operated by the Fraunhofer Institute for High Frequency Physics and Radar Techniques (FHR) in Wachtberg, Germany. TIRA combines a narrow-band, high-power L-band tracking radar at 1.333 GHz with a wide-band Ku-band imaging radar at 16.7 GHz. Its 34 m antenna, weighing 240 tonnes and housed in a 47 m radome, can slew at 24°/s in azimuth and track objects as small as 2 cm at a range of 1,000 km [43, 44]. The system is used for precise orbit determination of debris, for imaging objects that have lost control, for supporting collision avoidance and for following uncontrolled re-entries, and its data are used by several space agencies.

# 3.2 NASA Orbital Debris Program Office

The NASA Orbital Debris Program Office (ODPO), created in 1979 at the Johnson Space Center in Houston, is the only US organization that coordinates research on orbital debris across the board [45]. Its responsibilities include developing and maintaining environment models and their uncertainties, conducting measurements to support those models, assisting NASA projects with Orbital Debris Assessment Reports (ODARs) and End of Mission Plans (EOMPs), supporting the Department of Defense in characterizing the environment and contributing to international mitigation guidelines in forums such as COPUOS, the Inter-Agency Space Debris Coordination Committee (IADC) and the International Organization for Standardization (ISO) [46].

Catalogue maintenance in the United States relies on the Space Surveillance Network (SSN), a set of more than 30 ground-based telescopes and radars and space-based sensors operated by the US military services. The SSN tracks objects of about 10 cm and larger in LEO and about 1 m and larger in GEO, but it cannot follow objects much smaller than 10 cm in low orbit. The ODPO fills part of that gap by characterizing statistically the population of objects too small to be catalogued but large enough to threaten operations, using ground-based sensors and the analysis of returned surfaces that reveal sub-millimeter impacts [45].

Three of its sensors are of particular interest here. The Meter Class Autonomous Telescope (MCAT), operated remotely on Ascension Island in the South Atlantic, collects metric and photometric data on both fast-moving LEO objects and slow-moving GEO objects. Its location near the Equator gives access to low-inclination orbits that are hard to observe from higher latitudes, while the low annual rainfall and the island's infrastructure favor continuous operation. The telescope has a 1.3 m primary mirror, slews at 4°/s with an acceleration of 10°/s², and its 7 m dome can move 18° in about two seconds, which

allows it to follow fast LEO passes [47, 48]. The Goldstone Orbital Debris Radar, part of the Deep Space Network facilities operated by the Jet Propulsion Laboratory in the Mojave Desert, has been used since 1993 to sample millimeter-sized debris in LEO. It works in a fixed, staring mode at X-band (8,560 MHz), with transmitter and receiver about 10 km apart, and can detect objects of 2 to 3 mm at altitudes up to 1,000 km; in 2016, about 46 hours of observation yielded 3,427 detections [49, 50]. Finally, the Haystack Ultrawideband Satellite Imaging Radar (HUSIR), installed in 2014 and operated by the Lincoln Laboratory of the Massachusetts Institute of Technology (MIT) in Tyngsborough, Massachusetts, has become the ODPO's main source of data on LEO debris between 5 mm and 10 cm [51]. Its 36.6 m antenna, inside a 46 m radome, operates at X-band around 10 GHz in a "beam park" mode, in which the antenna stays at a fixed elevation and counts the objects that cross the beam [52]. The price of this approach is that each object crosses the beam quickly, which limits the accuracy of the range measurement for individual fragments. Table 4 summarizes the HUSIR observation campaigns between 2020 and 2022.

Table 4
HUSIR observation campaigns, 2020 to 2022 [51, 52]

| Year | Frequency (GHz) | Observation time (h) | Detections |
|---|---|---|---|
| 2020 | 10.0 | 166.2 | 2,388 |
| 2020 | 10.1 | 71.1 | 1,112 |
| 2021 | 10.0 | 71.15 | 1,222 |
| 2021 | 10.1 | 104.4 | 1,993 |
| 2022 | 10.1 | 417.7 | 6,154 |

The HUSIR case deserves emphasis because it shows how a university-hosted laboratory can become a cornerstone of a national SST capability.

## 3.3 JAXA Space Tracking and Communications Center

Japan's SSA network combines two observation sites in Okayama Prefecture, the Kamisaibara Spaceguard Center (KSGC) and the Bisei Spaceguard Center (BSGC), with the Space Tracking and Communications Center (STCC) at the Tsukuba Space Center, where data are processed, catalogued and shared with the global SSA community [53]. The STCC was originally responsible for tracking and controlling satellites, but as concern over orbital crowding grew, those functions were transferred to the departments that manage each mission and the center refocused on the observation, tracking, cataloguing and mitigation of debris [54].

The KSGC, built in 2004, was Japan's first experimental radar for debris observation. Its 3 m × 3 m L-band phased-array antenna is fixed at 45° of elevation, can steer between 15° and 75°, and covers up to 270° in azimuth. The radar detects objects of about 10 cm at 650 km, has a maximum range of 1,350 km and can track up to thirty objects simultaneously [55]. The BSGC, established in 1999, was the first Japanese center to use telescopes for debris tracking and is the country's main facility for NEO detection. It operates telescopes of 25 cm, 50 cm and 1 m aperture; the 50 cm instrument is used for LEO objects above about 300 km and the 1 m instrument for GEO, and the center has recorded a very large number of debris detections since its opening [56].

## 3.4 The role of universities

Universities contribute to SSA in ways that go beyond training engineers and scientists. Abroad, many of them host advanced tracking infrastructure. Besides MIT and HUSIR, the Advanced Instrumentation and Technology Centre (AITC) of the Australian National University (ANU), which built instruments for the Gemini, Subaru, Keck and Giant Magellan telescopes, has extended its work to SSA by applying adaptive optics to the tracking of debris and satellites in LEO and GEO [57]. Adaptive optics measures the wavefront distortions introduced by the atmosphere and corrects them in real time, so that the resolution of a ground-based telescope is no longer limited by seeing [58]. At ANU, this technique has been used to retrieve the altitude and shape of LEO objects with improved precision. In the United Kingdom, the Surrey Space Centre of the University of Surrey,

active in space research since 1979 and a pioneer of small satellites, led the RemoveDEBRIS mission. Deployed from the ISS in June 2018, it was the first active debris removal (ADR) demonstration to test capture technologies in orbit, releasing two CubeSats as targets for net and harpoon experiments and vision-based navigation [59].

In Brazil, universities and research institutes such as the National Institute for Space Research (INPE), the Aeronautics Institute of Technology (ITA) and several federal universities, including UnB, have successfully carried out space projects, especially in small satellite development, as in the SERPENS program conducted by UnB with the Brazilian Space Agency (AEB). Initiatives specifically devoted to SSA, however, remain modest.

## 3.5 Debris detection in Brazil

Although Brazil has no center dedicated exclusively to SSA, the country has contributed to the field through INPE and the Brazilian Air Force. INPE performs collision avoidance analyses and maneuvers for Brazilian satellites, while the Air Force, through the Alcântara Launch Center (CLA), the Barreira do Inferno Launch Center (CLBI) and the Space Operations Command (COPE), has been improving its tracking capabilities. In the observation segment, cooperation with the Russian State Corporation Roscosmos led to the installation, in 2017, of the PanEOS system at the Pico dos Dias Observatory (OPD) in Itajubá, Minas Gerais. PanEOS combines five telescopes, a main instrument of 75 cm aperture, two of 25 cm and two of 13.5 cm, each fitted with a scientific camera, and can observe between 500 and 800 debris objects per night in low, high and geostationary orbits. Pointing plans are generated in Russia, observations are made in Brazil and the data are sent back for processing and cataloguing, so access to the processed products depends on prior request [2]. This arrangement limits the system's contribution to the autonomous development of SSA expertise in the country. A different kind of milestone came in 2021, when the Air Force tracked a fragment of an Atlas-Centaur rocket with the BEAR radar at the CLBI, a C-band trajectography radar originally designed for rockets and missiles [60].

These efforts show that Brazil already has relevant infrastructure and know-how, but also that it lacks a national facility able to produce and own SST data on a routine basis. The experience of the countries discussed above suggests that close collaboration between government, academia and industry is a promising path toward that goal.

# 4 Method

The study combines two approaches. The first, applied in Sections 2 and 3, is a review of recent papers and reports from the main space conferences and agencies, with emphasis on SSA. The second, applied in Sections <link rid="Sec16">5</link> and 6, is a qualitative SWOT (Strengths, Weaknesses, Opportunities and Threats) analysis, used to compare candidate sites and, in adapted form, sensor technologies. Costs were deliberately left out of the scope, so the comparison concerns technical and strategic suitability rather than budget.

### 4.1 Reference operator

A feasibility study of this kind needs a clear statement of who will operate the center and for what purpose. A reference operator was therefore defined: a hypothetical, recently created government entity, here called the Brazilian Orbital Monitoring Company (EBMO, from the Portuguese), whose mission is to mitigate the risks posed by debris in LEO. Its objectives are to detect and track objects of 10 cm and larger in LEO, to provide accurate and up-to-date positions and trajectories, to compile these data in a database accessible to the government and to registered companies, to support the operational safety of Brazilian satellites such as those of the Amazônia and China–Brazil Earth Resources Satellite (CBERS) series, and to establish partnerships with foreign agencies and private companies for the exchange of data and technology. Its staff would include researchers from Brazilian universities and research institutes, aerospace engineers, data analysts and debris specialists. EBMO's administrative headquarters would be in the federal capital, but the location of its sensors and processing facilities is precisely what the site assessment is meant to determine. In doing so, the center would help reduce collision risk for Brazilian assets, protect national strategic interests in space and strengthen Brazil's role in global space governance in line with the COPUOS and UNOOSA guidelines.

## 4.2 Selection criteria

Five criteria, grouped into technical and strategic factors, were used to compare the candidate sites.

The technical factors start with climate and weather. Heavy rain, strong winds, high humidity and frequent cloud cover can reduce both the efficiency of operations and the lifetime of equipment, and optical sensors in particular lose observing time and accuracy at cloudy sites. The second technical factor is weathering. Salt spray in coastal areas accelerates the corrosion of metallic and electronic components, forcing the use of stainless steel or special coatings [61]. High relative humidity, typical of tropical and coastal regions, favors oxidation, short circuits and the corrosion of external structures, and calls for sealants and dehumidification systems [62]. Large day-night temperature swings cause repeated expansion and contraction, which leads to fatigue and mechanical failures and degrades the stability of radars and telescopes that need a controlled environment to keep their accuracy. The third technical factor is the technological infrastructure: high-speed fiber networks, reliable power, data centers able to store and process large volumes of data, and the presence of universities, research centers and technology parks. Real-time analysis and data exchange with networks such as the SSN require robust connectivity, and a consolidated infrastructure shortens the time and cost of implementation. The MIT Lincoln Laboratory, which operates HUSIR, was placed at MIT in 1951 precisely because of the institution's technological base and today employs about 1,300 people, many of them MIT researchers and students [63, 64].

The strategic factors are logistics and the potential for institutional coordination and funding. Logistics covers access to the site, transport infrastructure for people and equipment, proximity to urban centers, ports and international airports, and ease of importing specialized components. A tracking center needs regular maintenance, upgrades and occasional replacement of precision parts, and it depends on the movement of national and foreign specialists for joint projects and training. The second strategic factor measures the ability of a location to build and sustain partnerships with public, private and academic institutions and to attract the continuous funding that research, maintenance and operation require, whether through the state research foundations (FAPs), federal agencies or companies in the space sector. A location with established links to these actors has a clear advantage in competitive calls, agreements and sponsorships, and is better placed to support international scientific cooperation through data exchange and joint development of tracking methods.

## 4.3 SWOT analysis and data sources

The SWOT matrix was chosen for its versatility and its ability to combine internal factors (strengths and weaknesses) with external ones (opportunities and threats). For a complex undertaking such as a national debris monitoring center, this combination helps to identify competitive advantages, structural limitations, strategic opportunities and risks in each region. Five cities with existing space-related activities or facilities were assessed: Alcântara (state of Maranhão), Natal (Rio Grande do Norte), São José dos Campos (São Paulo), Brasília (Federal District) and Cuiabá (Mato Grosso). Climatological averages of cloud cover and precipitation were taken from [65–69], light pollution was assessed with the Dark Site Finder map [70], and institutional and infrastructure information was drawn from official sources cited in Section 5. For the technology assessment in Section 6, the candidate sensors were compared against five criteria: precision, coverage, dependence on environmental conditions, detection capability and infrastructure and cost.

# 5 Site assessment

## 5.1 Alcântara

Alcântara, on the coast of Maranhão, is widely regarded as one of the most strategic places in the world for launch activities, since its proximity to the Equator allows launches to take advantage of the Earth's rotation. The Alcântara Launch Center (CLA), installed in 1983, has launch pads, a runway for large aircraft, and sensors and telemetry systems used to monitor and control launches [71]. The region has a humid tropical climate with well-separated rainy and dry seasons, which leaves a substantial window for observation [65], and its relative isolation from the state capital, São Luís, keeps light pollution low, a clear benefit for optical sensors [70]. The Federal University of Maranhão (UFMA), in São Luís, offers undergraduate and

graduate programs in aerospace engineering, belongs to the Northeast Aerospace Network (RNA) and has laboratories engaged in small satellite projects, which opens the way for academic collaboration.

These strengths are offset by important weaknesses. Although only a few kilometers away, São Luís is separated from Alcântara by the São Marcos Bay, and the only connections are by ferry or by air, which makes logistics expensive and slows the movement of the specialists and researchers that a monitoring center depends on. The town also lacks robust urban and technological infrastructure such as high-capacity fiber networks. Being on the coast, the CLA is exposed to salt spray and high humidity, which accelerate the wear of radars and metallic structures and raise maintenance costs. On the side of opportunities, the Technology Safeguards Agreement (AST) with the United States, in force since 2020, has strengthened Alcântara's international position; although designed for launch activities, it may also attract agencies and companies interested in cooperation on tracking, and a monitoring center would diversify the activities of the CLA and help consolidate it as a multifunctional technology hub. The main threat is the strong dependence on federal funding and international partnerships, both sensitive to political and economic instability.

## 5.2 Natal

Natal, capital of Rio Grande do Norte, also enjoys a favorable equatorial position. The Barreira do Inferno Launch Center (CLBI), in the neighboring municipality of Parnamirim, was founded in 1965 as the first launch base in South America [72]. Besides launching suborbital rockets, it is part of a chain of five telemetry stations along the equatorial region, together with Galliot (French Guiana), Ascension (South Atlantic), Libreville (Gabon) and Malindi (Kenya), which tracks rockets during their powered phase; the CLBI took part, for instance, in tracking the Ariane 5 launch that carried the James Webb Space Telescope [73]. As noted in Section 3.5, the CLBI's BEAR radar has already been used to track a debris object. Natal's humid tropical climate has defined rainy and dry periods [68], and the Federal University of Rio Grande do Norte (UFRN) runs a graduate program in aerospace engineering, also part of the RNA, with research in materials and collaborations with INPE, the Northeast Strategic Technologies Center (CETENE) and the launch centers [74].

The CLBI provides radars, communication equipment and a skilled technical team, and the equatorial location gives a privileged view of low-inclination LEO orbits. On the other hand, the center sits right on the seashore, where salt spray and humidity cause accelerated corrosion of sensors and equipment, and the growth of the city has raised light pollution to levels that significantly degrade optical observations [70]. The site offers opportunities for partnerships with foreign agencies and companies and for strengthening the space sector in the Northeast through the RNA. The threats are that the CLBI was designed for suborbital launches and basic tracking, so complex tracking projects would require substantial investment, and that, as in Alcântara, operations depend heavily on federal funds.

## 5.3 São José dos Campos

São José dos Campos, in the Paraíba Valley about 90 km from the city of São Paulo, is the main technological and aerospace hub of the country. It hosts INPE, the Department of Aerospace Science and Technology (DCTA) and ITA, as well as companies such as Embraer and Avibras clustered around the Technological Innovation Park (PIT). INPE was responsible for satellites such as SCD-1, in operation since the 1990s, and Amazônia-1, the first satellite designed, built and tested entirely in Brazil. The city is about 170 km from the Pico dos Dias Observatory, home of the PanEOS system. Logistics are excellent: Guarulhos International Airport, the largest in South America, is about 75 km away, and the port of Santos is within easy reach, which simplifies the transport of both people and large equipment.

The drawbacks are environmental. The region has a tropical climate with heavy rainfall, high humidity and overcast skies for most of the year [69], and its proximity to the São Paulo metropolitan area produces intense light pollution [70]. Both factors make optical tracking difficult and imprecise, and the humidity accelerates the wear of equipment. The opportunities lie in the city's attractiveness for international partnerships and in the aerospace cluster, which brings industry, academia and research centers together. The threats are the dependence of many projects on federal funds and the limits on urban expansion, since an already saturated infrastructure may hinder the construction of new laboratories or tracking stations in suitable areas.

## 5.4 Brasília

Brasília is the administrative and political capital of Brazil. Besides the three branches of the federal government and the ministries, it hosts bodies that are central to the Brazilian space program, such as AEB, which coordinates the National System for the Development of Space Activities (SINDAE), and COPE, the control center for Brazilian military satellites, as well as the funding agencies FINEP (Funding Authority for Studies and Projects) and CNPq (National Council for Scientific and Technological Development). The Federal District government adds its own research foundation, the Federal District Research Support Foundation (FAPDF) and several research and development centers. The city lies on the Central Plateau at about 1,100 m of altitude [75] and has a tropical savanna climate with two well-defined seasons. During the dry season, low cloud cover and reduced atmospheric interference provide a favorable observing window [66].

UnB hosts the Institute of Physics, responsible for the Luiz Cruls Astronomical Observatory, the Faculty of Technology and the Faculty of Science and Technology in Engineering (FCTE), where the aerospace engineering program started in 2012. Its faculty includes researchers trained at INPE, ITA and foreign institutions, with work on small satellites, such as SERPENS, and on propulsion, particularly electric propulsion. The university also has laboratories in space software and ground station systems, and since 2014 it has hosted a GLONASS monitoring station resulting from cooperation between Brazil and Russia, whose measurements are used to improve positioning signals and reduce errors [76]. Because the station's data are collected and processed in Brazil, UnB already has hands-on experience with the processing of space data that could be extended to debris tracking. The international airport offers good connections for researchers and small equipment and gives direct access to government bodies.

In SWOT terms, Brasília's strengths are the proximity to strategic government institutions, which eases political coordination and access to funding, the technological infrastructure and expertise of UnB, and its central position, which connects it to every region of the country. Its weaknesses are the light pollution of a densely urbanized and widely illuminated city, which would compromise optical sensors unless mitigated [70], and its distance from the coast, which complicates and increases the cost of transporting large equipment. The opportunities include calls for proposals from federal research and innovation bodies, the city's role as a center of diplomatic activity, which can attract partners with advanced SST infrastructure, and the training of qualified personnel by UnB. The threats are the high dependence on federal resources, vulnerable to budget cuts, and administrative bureaucracy, which can delay project approval and the release of funds.

## 5.5 Cuiabá

Cuiabá, capital of Mato Grosso, is close to the geodetic center of South America. It hosts the Cuiabá Tracking and Control Ground Station (ETC), part of INPE's Satellite Tracking and Control Center, which also includes a station in Alcântara and the Satellite Control Center in São José dos Campos, all connected by a dedicated communication network [77, 78]. The semi-humid tropical climate has well-defined seasons, high temperatures and low cloud cover for most of the year, which benefits the ground station [67], and light pollution and electromagnetic interference are relatively low compared with large urban centers [70]. These features, together with the existing tracking infrastructure, would facilitate integration with a debris monitoring center, and with suitable incentives the city could become a regional reference in tracking and remote sensing.

Cuiabá, however, lacks a consolidated aerospace cluster and significant investment in space research and development. It is far from the industrial centers of the sector and from seaports, which makes the maintenance and upgrading of equipment harder and raises operating costs, and the absence of specific government incentives for the region, together with competition from better-established sites, may prevent it from attracting the resources needed.

## 5.6 Comparative synthesis and site selection

Table 5 condenses the SWOT findings for the five cities.

Table 5
Summary of the SWOT analysis of the candidate sites

| City | Main strengths | Main weaknesses | Opportunities | Threats |
|---|---|---|---|---|
| Alcântara | CLA infrastructure; equatorial position; low light pollution | Access only by ferry or air; poor urban and fiber infrastructure; salt spray and humidity | AST agreement; diversification of CLA activities | Dependence on federal funds and foreign partners |
| Natal | CLBI radars and staff; equatorial position; UFRN | Seaside corrosion; high light pollution | International partnerships; growth of the RNA | CLBI designed for suborbital launches; dependence on federal funds |
| São José dos Campos | INPE, DCTA, ITA; aerospace cluster; excellent logistics | Frequent rain and cloud cover; intense light pollution; humidity | International partnerships; industrial cluster (PIT) | Dependence on federal funds; limited room for urban expansion |
| Brasília | Proximity to AEB, COPE and funding agencies; UnB infrastructure; national connectivity | Urban light pollution; distance from the coast | Federal research calls; diplomatic presence; training at UnB | Dependence on federal funds; bureaucracy |
| Cuiabá | INPE ground station; low cloud cover; low light pollution | No aerospace cluster; far from industry and ports | Expansion of tracking infrastructure | Lack of regional incentives; competition from established sites |

Alcântara and Natal share the advantages of active launch bases and an equatorial location, which favors the observation of certain orbits, but both suffer from salt spray and humidity and would require investment to modernize their tracking infrastructure; Alcântara, in addition, faces serious logistical constraints. São José dos Campos offers the strongest industrial and scientific ecosystem and the best logistics, yet its cloudy climate and light pollution undermine observing efficiency. Cuiabá combines a dry climate and an existing ground station with weak logistics and limited access to specialized personnel. Brasília's main disadvantage is its distance from the coast, while its dry season provides a long favorable observing window and its academic and institutional environment is the richest among the candidates in terms of access to decision-makers and funding.

Weighing these findings against the objectives of the reference operator, Brasília emerges as the most balanced option. The combination of UnB's academic and technological base, proximity to government and funding bodies, good air connectivity and favorable dry-season conditions provides the best environment to build and sustain the center. Its main technical weakness, urban light pollution, is a limitation for optical sensors in particular, and this point carries directly into the choice of technology discussed next.

## 6 Sensor technology assessment

# 6.1 Operational requirements

The performance of a monitoring center depends as much on its sensors as on its location. The reference operator aims to track objects of 10 cm and larger in LEO. This threshold reflects the severity of the threat, since, as shown in Table 3, an impact with a 10 cm fragment releases tens of megajoules and is almost always catastrophic, and also the fact that tracking objects of this size is considerably cheaper than characterizing the millimeter population. A second requirement is data quality: measurements with large uncertainties propagate into errors in orbit determination and collision probability estimates and, ultimately, into poor maneuver decisions. A third requirement is operational resilience, that is, the ability to work continuously with as few interruptions as possible. A good site reduces interruptions, but the choice of sensor has an equally strong influence on maintenance costs and on the continuity of operations.

# 6.2 Radar systems

Radars emit electromagnetic waves that are reflected by objects in orbit and return to a receiver, providing range, velocity and trajectory information. Their two main advantages for debris tracking are the ability to observe objects at different altitudes and the fact that they work regardless of weather or lighting conditions.

In a monostatic radar, the transmitter and receiver share the same antenna or are located very close to each other, a configuration also common in air traffic control and weather monitoring [79]. A high-frequency pulse, usually in the microwave range, is sent toward the target, and part of the energy is reflected back to the same site. For debris, the returned signal carries information on the size, shape and orientation of the object, and the Doppler shift caused by its motion gives its radial velocity, an essential input for collision probability calculations. Monostatic radars used for debris generally operate at L-band (1 to 2 GHz), C-band (4 to 8 GHz) or X-band (8 to 12 GHz); HUSIR operates at 10.1 GHz [50], and TIRA, which combines two monostatic radars, uses 1.333 GHz for tracking and 16.7 GHz for imaging [80]. The configuration is simple to operate, sensitive, offers wide coverage and relies on mature technology. Its limitations include lower angular resolution in mechanically steered systems, the risk of total loss of service if the transmitter or antenna fails, and greater susceptibility to interference.

In a bistatic radar, the transmitter and receiver are separated by distances that range from a few kilometers to hundreds of kilometers [79]. The principle is the same, but the reflected energy is collected at a remote receiver, which improves sensitivity, reduces ground clutter and increases resistance to interference. The angle formed at the target between the transmitter and receiver lines of sight, the bistatic angle, governs the performance of the system: small angles approach the sensitivity of a monostatic radar, while larger angles favor resolution [81]. The Goldstone radar, with its two antennas about 10 km apart, detects objects as small as 2.2 mm at 1,000 km [50], and the French GRAVES system detects LEO objects between 400 and 1,000 km of altitude using widely separated transmitter and receiver sites [81]. Bistatic systems for debris work in the ultra-high frequency (UHF) band (0.3 to 1 GHz) and in the L, S and X bands [79]. The price of these advantages is operational complexity: the separation between sites calls for more advanced processing algorithms and raises the costs of operation and maintenance compared with monostatic systems.

## 6.3 Optical telescopes

Optical telescopes complement radars. While radar excels at detecting small objects and measuring range, telescopes are essential for characterizing larger objects, particularly in higher orbits where radar coverage is less effective, and they provide information on rotation, shape and brightness variations. Only ground-based telescopes are considered here. They are usually grouped by aperture, the diameter of the primary optics that defines the instrument's light-gathering capacity [82].

Small-aperture telescopes, with primary optics up to about 1 m, are inexpensive, transportable and able to detect debris in LEO and GEO [83]. They collect sunlight reflected by the targets during the night and focus it on a charge-coupled device (CCD) or complementary metal-oxide-semiconductor (CMOS) detector, which records the position, brightness and motion of each object; determining an orbit requires sufficiently long observation arcs. Their low cost of construction, operation and maintenance is their main advantage, and they can be used both to discover new objects and to follow catalogued ones. The French TAROT network, with 25 cm telescopes at the Calern (France) and La Silla (Chile) observatories, an 18 cm telescope at Les Makes (Réunion) and a 1 m telescope at Gingin (Australia), is a successful example of their use for GEO and eccentric orbits [84]. Their limitations are reduced sensitivity, dependence on clear skies and stable weather, and the need for elaborate processing to distinguish debris from stars and active satellites, the last two being common to all optical sensors.

Medium-aperture telescopes, between 1 m and 2.5 m, combine part of the cost advantage of smaller instruments with higher sensitivity and resolution, and are effective in LEO, medium Earth orbit (MEO) and GEO. Examples are the 1 m telescope of ESA's OGS and the 1 m telescope of the Zimmerwald Observatory of the University of Bern, in Switzerland, which first tracked GEO objects and today also follows LEO debris [85, 86]. These instruments can be paired with laser ranging systems that measure the distance to the target with high accuracy. In exchange, they require more infrastructure and maintenance, especially with laser ranging, and they are less mobile than small telescopes.

Large-aperture telescopes, above 2.5 m, reach very high sensitivity and resolution across all orbital regimes, but they are expensive, complex to operate and generally devoted to astronomy, so their exclusive use for debris is rare. Some are equipped with adaptive optics, which corrects atmospheric distortions in real time [58]. The 3.6 m Telescopio Nazionale Galileo (TNG) in the Canary Islands, mainly an astronomical facility, has been used to observe NEOs and, on an experimental basis, space debris [87, 88]. Their narrow fields of view make them unsuitable for wide sky surveys.

## 6.4 High-power laser systems

Among emerging technologies, which also include machine learning for data processing, laser systems have attracted attention since the 1990s as a complement to traditional sensors [89]. Laser ranging measures the round-trip time of highly focused light pulses reflected by the target. Because these pulses have much shorter wavelengths than radar signals, they provide very precise range measurements and a high update rate, and they can reach objects smaller than those detected by many conventional radars, particularly at higher altitudes. The OGS and the Zimmerwald Observatory use laser systems to complement their telescopes. At the Mount Stromlo Observatory of ANU in Australia, a laser guide star creates an artificial reference star used to measure atmospheric distortion and feed the adaptive optics that sharpen debris tracking [90, 91]. The drawbacks are high implementation and operating costs, strict regulation, since laser beams can endanger aviation and the optical sensors of operational satellites, and the same dependence on clear skies as optical systems.

## 6.5 Comparative assessment

Table 6 compares the four families of sensors against the criteria defined in Section 4.3.

Table 6
Qualitative comparison of SST sensor technologies for the reference operator

| Technology | Precision | Coverage | Environmental dependence | Detection capability | Infrastructure and cost |
|---|---|---|---|---|---|
| Monostatic radar | High for position and velocity | Wide, set by transmitter power and receiver sensitivity | None for weather or daylight | Good for small objects in LEO | High |
| Bistatic radar | High; geometry adds viewing angles | Wider, through separated receivers | None for weather or daylight | Very good, down to millimeter sizes | Very high; multiple sites and complex processing |
| Optical telescopes | Good astrometry; strong characterization | Strongest in high orbits | Clear, dark skies required | Limited by aperture and site conditions | Low (small) to very high (large) |
| High-power laser | Very high range accuracy | Narrow; requires prior pointing | Clear skies required; strict regulation | Very good | Very high |

Monostatic radars offer high precision in determining the position and velocity of debris, are well suited to small objects in LEO, can cover a wide area depending on their power and sensitivity, and work day and night in any weather. Their downside is the infrastructure they require and the corresponding installation and maintenance costs. Bistatic radars share these advantages and can extend coverage and improve accuracy by observing targets from different angles, but the need for installations at separate sites adds complexity and cost. Small and medium optical telescopes are affordable and provide detailed characterization, making them good complements to radar, while large telescopes offer outstanding resolution at a much higher price; all of them, however, depend on favorable weather and dark skies. Laser systems promise the highest measurement accuracy, but their cost, safety regulations and dependence on atmospheric conditions make them unsuitable as the primary sensor of a first national center.

On balance, the monostatic radar is the most suitable primary technology for the CMD. It meets the precision and coverage needed for objects of 10 cm and larger in LEO and, above all, its independence from weather and lighting removes the main

technical weakness identified for Brasília: the UnB observatory, the most natural place to host the equipment, lies close to the urban area and is affected by light pollution. Although installation and maintenance costs are high, the robustness and operational reliability of the monostatic radar make it the most viable option for a center that must track continuously and with minimal interruption.

# 7 Discussion

The two parts of the assessment reinforce each other. The site analysis favored Brasília mainly for strategic reasons, namely access to policy-makers, funding agencies and a university with relevant expertise, while recognizing that the city is not the best place in Brazil to observe the sky with optical instruments. The technology analysis, in turn, points to a sensor whose performance does not depend on dark or clear skies. Taken together, the results suggest that the best configuration for a first Brazilian center is not the one that maximizes observing conditions but the one that places a weather-independent sensor where institutional support, qualified staff and data processing capacity are strongest. The cases of HUSIR at MIT and of the SSA work at ANU show that this model, in which a university hosts and operates national tracking assets in partnership with government, is both viable and productive, and UnB's experience with the GLONASS station indicates that part of the necessary competence already exists locally.

A radar-based center in Brasília would not exclude other sites or sensors. Equatorial locations such as Alcântara and Natal keep a genuine advantage for observing low-inclination orbits, as the choice of Ascension Island for MCAT illustrates, and darker, drier sites such as Cuiabá would be natural candidates for optical telescopes that characterize objects and extend coverage to higher orbits. A national network in which the central facility in Brasília processes and shares data from complementary sensors elsewhere in the country would follow the logic adopted by JAXA, whose observation sites feed a single processing center at Tsukuba. Such a network would also reduce the dependence on foreign data that currently limits arrangements like PanEOS.

The study has limitations that should be kept in mind when reading its conclusions. The SWOT analysis is qualitative, and the relative weight of the criteria reflects the authors' judgment rather than a formal multi-criteria scoring. The reference operator is hypothetical, and a different mission, for instance one focused on GEO or on millimeter-sized debris, could lead to a different site and sensor. Climatic conditions were assessed from long-term averages rather than from site-specific measurements of seeing or usable observing hours. Finally, costs were deliberately excluded, even though they are likely to weigh heavily in any real decision, especially for a radar of the class recommended here.

# 8 Conclusions

This paper assessed the feasibility of a national Space Debris Monitoring Center in Brazil. The review of the debris problem showed that the growth of fragment populations, driven by accidental collisions and destructive tests, makes the ability to detect, track and catalogue orbital objects a basic requirement for safe space operations, and that the United States, Europe and Japan meet this requirement with combinations of radars, optical sensors and, increasingly, laser systems. Brazil still depends heavily on foreign data, despite meaningful initiatives such as PanEOS and the use of the BEAR radar for debris tracking.

For a reference operator focused on objects of 10 cm and larger in LEO, the SWOT comparison of five Brazilian cities identified Brasília as the most balanced location, thanks to the infrastructure and expertise of the University of Brasília, the proximity of government and funding bodies, good connectivity and favorable dry-season conditions. Among the available technologies, the monostatic radar stood out as the most suitable primary sensor, owing to its precision in determining position and velocity, its coverage of LEO and its independence from weather and lighting, which offsets the light pollution that limits optical observation at the selected site.

A center of this kind would reduce Brazil's dependence on external data, improve the safety of national missions and strengthen the country's voice in global space governance, while stimulating research, training specialists and supporting the

national space industry. Future work should address a detailed financial analysis covering acquisition, installation, maintenance and operating costs, including possible funding through public-private partnerships and calls from CNPq, FINEP and FAPDF; the structural and logistical requirements for building and operating the center, including safety specifications for the selected technology; and the technical and institutional arrangements needed to integrate the center into global debris monitoring networks.

## Declarations

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**Author contributions** L.F.A.O. conceived the study, carried out the review and the analyses and wrote the manuscript. W.R.S. supervised the work and reviewed the manuscript.

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