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Geodesy and Space situational awareness: How geodetic ground infrastructure enables navigation

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Abstract

Geodesy, the science of measuring and understanding the Earth's shape, orientation, and gravitational field, plays a crucial role in the field of spacecraft navigation and space situational awareness. As the number of spacecraft constellations increase, the integration of geodetic techniques with navigation systems has become essential to ensure precise trajectory planning, positioning, and orbit determination. This presentation explores the fundamental links between geodesy and space navigation and space situational awareness, examining how geodetic infrastructure is key to positioning in space and on earth. Key areas of focus include the use of geodetic reference frames, global navigation systems (like GPS) and Earth orientation parameters.

Two examples using Very long base Interferometry and Satellite Laser ranging will be presented to explain the contribution of global geodetic observatory systems to the parameters required for navigation and their role in determining accurate satellite orbits and in tracking variations in the Earth's center of mass. We will discuss how these techniques contribute to the definition of the reference frames required for navigation and to the increasing demands on accuracy for positioning. Additionally, we will explain how these techniques offer unique data required for navigation and their strengths. By unveiling the not-so evident link between terrestrial geodetic infrastructure and satellite operations, we aim to highlight why this infrastructure is essential for space navigation, collision avoidance and to improve our ability to provide more accurate positioning standards. The presentation concludes by explaining why Global Navigation Satellite Systems like GPS aren't sufficient to define these parameters and the challenges posed by an increasing number of satellites in space, signal interference and aging ground infrastructure.

Keywords: PNT, navigation, geodesy, orbits, VLBI, SLR, GNSS

1. Introduction

Geodesy is the science of measuring the Earth's size, shape, orientation, gravitational field, and their variations over time using geodetic techniques. These techniques rely on a global network of observatories that conduct Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Global Navigation Satellite Systems (GNSS), and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) measurements. The time-dependent data products generated from each technique are subsequently integrated to determine the reference that all observations systems use to determine changes in position over time. Together, these observatories and their associated analysis centers form a critical global geodetic infrastructure, essential for the operation of spacecraft orbiting the Earth and beyond.

As a society, our needs for precise and efficient positioning and navigation of objects are enabled by geodetic reference systems and their realization: geodetic reference frames. The International Terrestrial Reference System and Frame (ITRF) [1] is the globally adopted standard for spatial referencing and links directly with WGS84, the standard used by GPS. The ITRF is created and maintained using a worldwide network of geodetic observatories, where fundamental geodetic observations are used to define, realize, and maintain the frame. These observatories produce geodetic data

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essential for defining the ITRF, measuring Earth Orientation Parameters (EOP – see Fig.1), and determining precise satellite orbits [2].

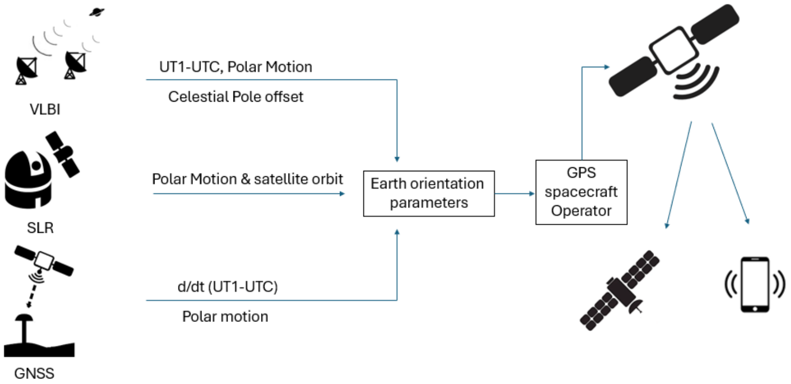

Figure 1: Geodetic techniques used for Position, Navigation and Timing

The ITRF is a fundamental component of modern space navigation. As a highly precise global reference frame, it provides the spatial foundation for positioning, satellite orbit determination, and interplanetary navigation. Its accuracy and stability enable the precise synchronization of spaceborne and terrestrial navigation systems, ensuring reliable satellite-based positioning and navigation. Current challenges in satellite positioning and space science are pushing the limits of the ITRF. The most demanding scientific research requires the reference frame to be accurate to 1 mm and stable to 0.1 mm change per year [3], which is an order of magnitude more precise than the signal to be monitored.

Well distributed global geodetic infrastructure is a fundamental foundation for the use of all satellites in space. The ITRF enables positioning and navigation of satellites, regardless of their mission or intended application (e.g. communications, image acquisition, interferometry). The sections that follow will detail how key components of the ITRF contribute to spacecraft navigation and explain why GNSS alone cannot meet all positioning needs in space. The status of the global geodetic infrastructure is presented in the discussion.

2. The role of Geodetic infrastructure in navigation on earth and in space

Spacecraft navigation involves designing and implementing systems that guide, navigate, and control a spacecraft's movement. This includes determining position (orbit, clock, altitude) and velocity while executing maneuvers to maintain or adjust trajectories and avoid collisions. The efficient integration of geodetic infrastructure products into satellite operations is paramount for ensuring seamless control of orbiting satellites, such as allowing prediction of satellite orbits and clocks, which are required for real-time precise positioning services.

In 2024, the European Space Agency (ESA) reported that approximately 39,340 human-made objects are regularly tracked by space surveillance networks and maintained in their catalogs [4]. These objects include operational satellites, defunct spacecraft, spent rocket stages, and fragments resulting from collisions or disintegration events. The proliferation of space artifacts poses significant challenges for space operations, including the risk of collisions. This escalating situation underscores the importance of accurate orbit predictions.

Navigators must account for the constant motion of the spacecraft, the points on earth used as reference (the mission's ground segment), the earth and celestial bodies. The vast distances involved make precise navigation difficult, as even very small errors in the reference point can lead to significant deviations over time, especially if they accumulate, such as the variations in earth rotation every 24h cycle. The influence of forces due to various celestial bodies, including the earth and moon can alter a spacecraft's trajectory and require accurate calculations to ensure accurate navigation [5]. Wind and water load changes on Earth cause variations in the rate of rotation, which results in a small change in the length of day that cannot be predicted into the future with accuracy.

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Interplanetary navigation of spacecraft to planets, moons, comets, and asteroids within our solar system requires accurate ephemerides of the targeted solar system bodies [6] based on Doppler, range, VLBI, inter-planetary radar and optical measurements which are in turn used to model the external gravitational forces on the spacecraft. The spacecraft itself must be modelled for outgassing, reaction to solar radiation pressure and other effects. Geodetic techniques such as VLBI, GNSS, and SLR calibrate the position of the Earth based observing platforms. These models are then used to predict and control spacecraft trajectories based on advanced observing techniques used to estimate trajectory corrections for precise fly-bys, orbit insertions, and surface landings. Typically, data are obtained using very large radio antennas (34-m to 70-m) such as those of the Deep Space Network [7] to gather Doppler and Range for estimating radial position and velocity and VLBI for measuring angles in the plane of the sky. Moyer [8] documents the development of the models needed to relate spacecraft in a celestial frame to the position of the tracking stations in a terrestrial frame in order to estimate the spacecraft trajectory. More recently, the IERS has been tasked with keeping these models up to date [9] as well as collating Earth orientation (polar motion. UT1-UTC, nutation) from its member analysis centers. Typically, as spacecraft get farther and farther away, there is an increasing demand on the angular resolution of the tracking. Currently, the most demanding scenario is landing on Mars, requiring part-per-billion angular accuracy (1 nanoradian or 200 µas).

3. Earth Orientation Parameters

The Earth spins and wobbles in complex ways [10], causing the position of the poles to shift by millimeters over the course of a day and by meters over the course of a year. Melting icesheets and sea level changes also cause variations in the earth's rotation. The change in the rate of rotation causes a small change in the length of day. The motion of the rotation axis itself is described by polar motion and nutation. Polar motion refers to motion of the axis relative to fixed points on Earth's surface, while nutation refers to motion with respect to fixed objects in space. In addition, GNSS/GPS satellite orbits and Earth rotation variations need to be extrapolated into the near future for accurate real-time precise positioning, due to the very low latency required for real-time applications.

Satellite motion is modeled in a non-rotating coordinate frame, whereas GNSS-derived positions are in an Earth-fixed and therefore rotating coordinate frame, the ITRF [1,11]. A transformation from the non-rotating International Celestial Reference Frame (ICRF) [12] to the ITRF is needed when using GNSS to position in the ITRF. Earth Orientation Parameters (EOPs) are used to define this transformation, accounting for precession, nutation, polar motion, and UT1-UTC relative to the ICRF [13].

3.1 VLBI Contributions to ITRF

Very Long Baseline Interferometry (VLBI) is a precise geodetic technique used to measure the time difference between the arrival of radio signals from distant quasars [14]. The basic principle of operation involves multiple radio telescopes, on a global scale, simultaneously observing a very distant radio source. Each telescope records the arrival time of the radio signal using highly precise atomic clocks. The recorded data from each telescope is later combined and correlated to determine the time differences between the signal arrivals. These time differences are used to calculate the precise distances to within a few millimeters between the telescopes' reference points. The EOPs are characterized by three angles slowly changing in the terrestrial Frame, the earth rotation around its pole (UT1-UTC), Polar Motion X and Y and two angles of the celestial pole which change slowly in the celestial frame: Nutation X and Y. VLBI is the only technique that measures all five of these angles and the only one that can measure the absolute angle of the earth's rotation around its pole. This makes spacecraft positioning and navigation inextricably dependent on VLBI. VLBI is also used to compute the ITRF scale, providing an independent estimate to that of SLR. The VLBI technique also used to measure differential angles (i.e. Delta Differential One Way Range or ΔDOR) [15] between spacecraft and quasars serving as known reference objects to determine the angular position (Right Ascension, Declination) of satellites and space probes on interplanetary missions.

3.2 SLR Contributions to ITRF

Satellite Laser Ranging [16,17] is a precise geodetic technique used to measure the distance between a ground-based laser station and a satellite equipped with retroreflectors. The basic principle of operation begins with a ground station that emits very narrow pulses of laser light towards a satellite. The satellite, equipped with retroreflectors, reflects the laser pulses back to the ground station. The ground station measures the roundtrip time it takes for the laser pulses to travel to the satellite and back. Using the speed of light, the round-trip time is converted into a precise distance measurement from the ground station to the satellite.

SLR is the most accurate technique for determining the origin of the ITRF, the earth’s center of mass and is a very important contribution to the estimate of scale. SLR is also an important spacecraft tracking tool, providing millimeter-level precision in distance measurements for satellite orbit determination, which makes it a unique tool for calibrating very precisely orbits of altimeters and radar satellites used for interferometric analysis, measurement of the earth’s gravity field, and tests of fundamental physics (i.e., general relativity).

SLR stands out as a ground based optical space geodetic technique which is less affected by the ionosphere than GNSS and has a remarkable observation accuracy. SLR plays a pivotal role in various domains, such as the determination and validation of the orbits of Global Navigation Satellite System (GNSS) and Low Earth Orbit (LEO) satellites [18] and the global geodetic parameters including scale [19] and geocenter motion [20].

SLR is the only space geodesy technique that operates in the optical region of the electromagnetic spectrum, reducing its susceptibility to range biases. In addition, SLR ranging is unaffected by transit through the Earth’s ionosphere, whereas longer wavelength techniques such as VLBI and GNSS must account for ionosphere refraction. SLR is, however, effected by weather (clouds) and the data needs to be corrected for changes (temperature and pressure) in the atmosphere.

3.3 GNSS Contributions to ITRF

GNSS’ most impactful contribution to the ITRF is that it provides universal access to the ITRF and helps densify the network of reference points resulting in more locations around the world being accurately positioned within the ITRF. GNSS also contributes to the definition of origin, scale and orientation.

GNSS alone is not sufficient to define the ITRF due to its inability to separate the earth rotation angle (UT1-UTC) from the node of the satellite constellation, and the long-term stability required for defining such a reference system. To address these shortcomings, it is necessary to incorporate data from the different geodetic techniques (VLBI, SLR, and DORIS). These combined data sources provide a comprehensive understanding of Earth's movements, orientation, and geocenter, which are essential for defining the ITRF [1, 11, 21].

4. Discussion

As the number of applications dependent on satellite services continues to increase, the necessity for a robust, well maintained geodetic infrastructure becomes even more critical. This infrastructure provides essential parameters on a daily basis to all GNSS systems used for navigation (for guiding vehicles, automating agricultural practices, space navigation and precise timing dissemination). Despite being a vital tool in the support of operations that enhance livelihoods and drives large economic growth [22] its current state is far from ideal [23].

The ITRF enables GNSS systems to achieve centimeter-level precision in positioning by offering a stable reference frame that considers Earth's dynamic movements, including tectonic shifts. This unified reference frame allows various GNSS constellations to be integrated smoothly, enhancing overall positioning accuracy. Without ongoing daily updates to their orbits and clocks, GNSS satellite geolocations – indeed all satellite geolocations – would systematically degrade by several orders of magnitude.

The measurement of earth parameters requires data from multiple locations on earth (independent of political boundaries), just like weather. The components of this geodetic infrastructure are dispersed among various national governments, scientific agencies, and organizations. Each of these bodies has independent missions, budgets and priorities, and there is no clear chain of global responsibility and authority for maintaining, upgrading, and augmenting the global geodetic infrastructure on which we all rely. The global geodetic infrastructure has not been considered holistically like other services, such as those provided by the International Civil Aviation Organization, the World Meteorological Organization or the International Hydrographic Organization.

For this reason, VLBI and SLR instruments are not evenly distributed around the world which makes it hard to measure the Earth at the accuracies required for certain applications, such as monitoring sea-level rise. Furthermore, over 50% of the infrastructure we use today is severely aging or based on old technology. Most of the geodetic infrastructure is owned and operated by a mix of academic and scientific institutions and government agencies all around the world. Owning and operating this infrastructure is largely a voluntary commitment. As a result, nations can, and do, stop operating a site due to a lack of sustained funding and political support. This issue of in-kind contribution and non-binding agreements extends to the data analysis and the number of experts in this field is shrinking very rapidly [24]. Every new station is beneficial to the network: it enhances its geometry and/or redundancy (to allow maintenance and calibration). The more reliable the network solution is in terms of homogeneity (same precision of the network stations) and isotropy (same precision in all three coordinate components), the more robust the system and the more accurate its products.

A persistent issue with the SLR network is its inconsistent coverage and performance. Approximately 80% of the total number of SLR stations are in the northern hemisphere [25] and only about a third are in the western hemisphere [26]. Additionally, tracking can vary significantly between stations due to weather conditions and available staffing [27].

A robust geodetic system allows nations to maintain control over their own positioning services without an increasing reliance on foreign systems. Countries such as China and the European Union have developed their own independent navigation systems, BeiDou and Galileo, respectively, to strategically enhance the foundation of multiple economic activities [28]. The geodetic infrastructure's strength is rooted in its endurance, consistent performance, stability, resilience, precision, quick accessibility, and ability to meet new precision demands. Its fragility resides in aging components, lack of redundancy with single-point-of-failure designs, and ongoing fiscal pressures on operations and maintenance budgets and lack of long term-commitments for funding. The funding being allocated to the operation of the all the components of global geodetic infrastructure is estimated to be less than 0.05% of the revenue generated from GNSS and EO-based services [29].

Enhancing sovereignty through geodetic infrastructure is a strategic investment in national security, economic development, and scientific advancement. Nations that develop and maintain key geodetic infrastructure secure their position in the global technological and economic landscape of location-based services, minerals and space exploration. As geopolitical and economic challenges evolve, geodesy will continue to play a vital role in current and emerging technologies such as those used in space exploration.

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