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Advances in Satellite Ranging Methods Towards Precise Orbit Determination

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ABSTRACT

Accuracy in the satellite positioning is crucial for maintaining integrity and functionality, especially in safety-critical services of communication, navigation, and imaging applications. Perturbations in space affect the accuracy of satellite orbits. This paper discusses the satellite ranging methods, viz. ground-based tracking, onboard GNSS receivers, and inter-satellite links for satellite orbit determination. Accuracies achieved using the individual and combination of ranging methods have been analysed in this paper for the satellites in different orbits. The study reveals that the satellites in low earth orbit increasingly depend on onboard GNSS receivers supported by ISL for better accuracy and to reduce dependency on the ground-based tracking. Satellites in the medium-earth orbits rely predominantly on one-way CDMA ranging, supported by ISL to improve autonomy and accuracy. Satellites in geo-synchronous orbits and beyond utilise either passive or ground-based RF ranging. Advances in the Space Service Volume simulations in effectively utilising the GNSS applications in space are discussed. The paper analyses the accuracy levels and improvements in using hybrid ranging techniques across all orbits to optimize satellite positioning, emphasising the importance of continuity and autonomy in satellite operations.

Keywords: Satellite navigation systems; Radio position measurement; Satellite tracking; Global positioning system; Satellite applications

NOMENCLATURE

φ	: Latitude
λ	: Longitude
BDS	: BeiDou navigation satellite system
CDMA	: Code division multiple access
DOP	: Dilution of Precision
DORIS	: Doppler orbitography and radio-positioning integrated by satellite
LEO	: Low earth orbit
GEO	: Geostationary earth orbit
GNSS	: Global navigation satellite system
GPS	: Global positioning system
GRACE	: Gravity recovery and climate experiment
GOCE	: Gravity-field and ocean circulation explorer
GSO	: Geo synchronous orbit
ICG	: International committee on GNSS
ITU	: International telecommunication union
MEO	: Medium earth orbit
NavIC	: Navigation with Indian constellation
PNT	: Positioning, navigation and timing
PRISMA	: Prototype research instruments and space mission technology advancement
PROBA-3	: Project for on-board autonomy-3
QZSS	: Quasi-Zenith satellite system
RF	: Radio frequency
SLR	: Satellite laser ranging
SoL	: Safety of life
SSV	: Space service volume
TDOA	: Time difference of arrival
TOPEX	: Topography experiment
TSV	: Terrestrial service volume
UERE	: User equivalent range error
UNOOSA	: United Nations Office for Outer Space Affairs

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1. INTRODUCTION

Satellites are placed in distinct orbits to meet their mission objectives and applications. While an ideal satellite orbit follows a Keplerian conic path around a perfectly spherical and homogeneous central body, factors such as nonspherical Earth, Sun and Moon, space objects, space events and thruster operations contribute to the satellite's orbit change. Space systems conduct regular orbital estimations and corrections to counter orbital change. This paper focuses on prevailing satellite positioning methods in earth-oriented orbits, namely, low earth orbit, medium earth orbit, geosynchronous orbits and highly elliptical orbit. The paper reviews primary research papers and key research studies during 2008-2024 on current satellite ranging methods, orbital accuracy levels and trends. The paper is structured as follows. Section I introduces the need for precise satellite position and literature survey. Section 2 covers various satellite ranging methods. Section 3 provides the impact of satellite orbit accuracy on applications. Section 4 is on the achieved ranging accuracies and trends. Section 5 presents the advances in satellite ranging and tracking.

Section 6 provides the findings of the study and Section 7 gives the conclusion.

2. SATELLITE RANGING METHODS

In the geodetic coordinate system, the position of an object near Earth is expressed in terms of latitude (φ), longitude (λ) and height or altitude (h) (Fig 1). The orbit of a satellite is expressed in six cartesian coordinates supported by correction parameters. Ranging is the process of measuring the slant range using the antenna's look angles - Azimuth and Elevation, to deduce the satellite's orbital parameters. The slant range is the distance between the earth-station antenna and the satellite and is primarily determined through the following methods.

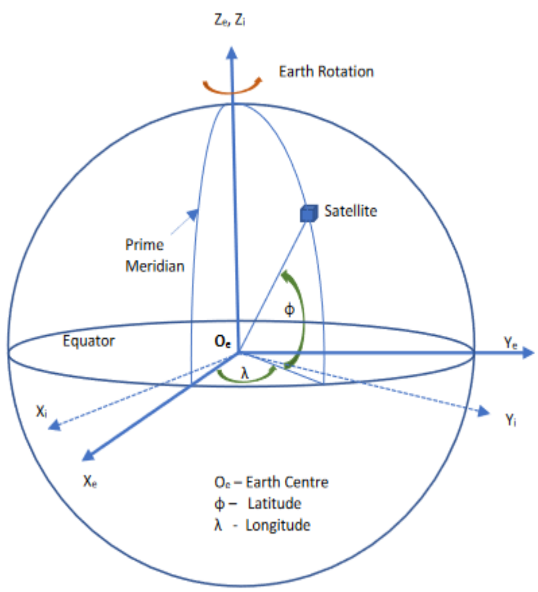

Figure 1. Satellite position representation.

2.1 Ground-Based Satellite Ranging

Position estimation of satellites has mostly relied on radio tracking from the ground to determine the direction, angles, range, range rate and carrier phase of the target satellite. RF-based systems employ microwave measurements while optical systems use Laser signals[1]. The following are the prevailing satellite ranging methods.

- **Two-way tone-based ranging** is done in the S-band for LEO and the C-band for GEO for satellite tracking and orbit determination. The range of the satellite is computed by multiplying the number of full waves and the fraction wave with signal wavelength[2-3].
- **One-way CDMA ranging** is used with navigation satellites. A reference receiver receives the satellite signals with a time delay corresponding to the distance to the satellite and atmospheric effects, with the time delay multiplied by the speed of light yielding the satellite's pseudorange. To ensure accuracy in both range and orbit measurements, corrections are applied to compensate for the affecting errors, i.e., ionospheric, tropospheric errors, etc. A receiver capable of dual-frequency signal reception could be employed to rectify ionospheric errors[4].
- **TDOA method:** The satellite receives the signal initially transmitted by a stationary ground station and re-transmits it to the designated coverage area. Receivers intercept the re-transmitted signal. The time difference between the received signals by the two stations is directly correlated to the distance between the station and satellite[5].
- **Range-Doppler Technique:** The distance between the satellite and receiver is obtained by observing the highest Doppler frequency rate at the closest approach. TOPEX/Poseidon mission utilises the DORIS network working on this technique.
- **SLR:** SLR provides unambiguous range measurements with mm-level precision using laser pulses. GOCE and GRACE missions are supported by the SLR network[6].

2.2 Use of onboard GNSS Receivers

GNSS provides PNT services to users equipped with GNSS receivers which measure ranges based on the signals received from the visible GNSS satellites. By trilateration method, the receiver accurately computes its position by processing the signals sent by the GNSS satellites. GNSS systems currently operational are the GPS of the USA, the BDS of China, the Russian GLONASS, the European Union's Galileo, NavIC and Japan's QZSS. GPS, BDS, GLONASS and Galileo are global navigation systems whereas NavIC and QZSS are regional systems. GNSS user position accuracy is the product of DOP and UERE. UERE includes the errors related to Ephemeris, Clock, Ionosphere, Troposphere, Multipath and Receiver Noise.

2.3 Inter-Satellite Links (ISL)

ISL facilitates direct communication within the space segment, thus reducing dependency on the ground segment to relay the data. Inter-satellite ranging is the capability of determining the range and orbital parameters of a space system using signals from another space system. ISL operates either in RF or in the optical frequency band. ISL is used in formation flying missions such as GRACE. PRISMA and PROBA-3. GRACE was a twin-satellite mission for measuring Earth's gravity field changes to track water movement and ice mass changes. In PRISMA, GPS was used for its relative navigation between its main target satellites. PROBA-3 is a two-satellite mission used to demonstrate high-precision formation flying techniques.

3. IMPACT OF RANGING ACCURACY ON PAYLOAD AND APPLICATIONS

Satellite payload performance depends on stable and accurate satellite orbit and position. In SoL services, inaccuracies could lead to collisions and potential loss of human life. Bojanowski[7], *et al.* deal with the mitigation of orbital drift due to the J2 effect on the accuracy of climate data of a meteorological satellite. Orbital inaccuracies in communication satellites can lead to interference with neighbouring GEO satellites and unwanted RF power variations over the satellite service regions[2]. With multi-satellite LEO missions such as Starlink, OneWeb, etc., orbit accuracy maintenance plays a major role in avoiding collision at physical and RF levels and in formation flying to provide the services seamlessly. Centimetre-level imagery resolutions need the maintenance of precise LEO orbits. Accurate weather prediction imaging in multi-spectral bands from GEO needs maintenance of satellite stability and precisely in the orbital location allocated. Communication satellites with multi-beam transmissions are to keep position accurate to avoid efficient managing of spectrum with minimal interference.

Jian[8] examines the effect of pointing errors on the image quality of the space-borne video. Table 1 provides the typical GPS Pseudo-range Error Budget for a dual-frequency receiver. The contribution of Satellite orbit is 2.5 m with a total error of 3.4 m. Degradation in this orbital accuracy has a direct impact on the user. Hybrid orbital determination techniques can limit the satellite orbital error within 1 m which in turn reduces the user accuracy to 2.4-2.6 m. This will help in high-accuracy precision operations such as advanced formation flying, geodesy tasks, vehicle tracking, collision avoidance, military operations, imaging, and precise farming. With the increase in satellites in space and exploration of space for increased human space flights and plans of space tourism, the maintenance of precise orbit and position of the satellite is a necessity in almost all applications.

Table 1. Typical dual frequency GPS receiver error budget [Source: vectornav.com]

Source	Rms error (m)
Orbit	2.5
Satellite clock	2.0
Receiver noise	0.3
Ionospheric	0.5
Tropospheric	0.5
Multipath	1.0
Total	3.4

4. ACCURACIES OF SATELLITE IN DIFFERENT ORBITS

Ranging/orbital accuracies of satellites as realised by different ranging systems are tabulated in this section.

4.1 LEO

4.1.1 Ground-Based Tracking

- Traditional RF tone-based ranging: 20 - 80 m orbital accuracy using multiple stations depending on the stations' physical separation[9]
- Radio Interferometry: around 20 m orbital accuracy at an altitude of 1400 km[10]
- TDOA: 5 m (in-track) and 1 m (cross-track)[3]
- Doppler Tracking: Better than 100 m in Transit navigation system and 30-45 cm using DORIS[16]
- SLR: 3D RMS accuracy of about 5-10 mm[11].

4.1.2 On-Board GNSS Receiver

Real-time accuracy of 10-25 m 3D RMS accuracy in the Starlink constellation[12-13].

4.1.3 Inter Satellite Links

5 cm in PRISMA mission. GRACE, PRISMA and PROBA-3 missions use ISL for formation flying to meet the mission requirements[14-15].

4.1.4 Hybrid Techniques

1.66 - 3.16 cm using Hybrid DORIS and GPS solution[16-17].

4.2 MEO

4.2.1 Ground-Based Tracking

- Satellite Tone-based ranging: ~ 100 m. As ranging with the broadcast CDMA signals is available for the MEO satellites with better accuracy, tone-based ranging is generally not used.
- One-way CDMA ranging: An experiment by Geng[20]*, et al.* on BDS Satellites shows an accuracy of 6.7 m with the worldwide one-way CDMA ranging network.
- Doppler Tracking: Position accuracies of 1 m with DORIS[16].
- Satellite Laser Ranging: Bury[18]*, et al.* provide a multi-GNSS orbit solution using SLR on GLONASS, Galileo and BDS satellites. The orbital accuracies obtained are 3–4 cm (radial), 11–16 cm (along-track) and 15–27 cm (cross-track) with observed SLR data.

4.2.2 On-Board GNSS Receiver

With the development of GNSS-SSV, MEO satellites can utilise GNSS receivers with non-interfering GNSS signals if available for orbital determination. However, the use of GNSS signals for the MEO satellite's orbit determination has not been recorded to date.

4.2.3 ISL

GPS utilises wide beam ISL in UHF to provide autonomy for at least 180 days. ISL-aided GNSS one-way ranging would provide improvement in accuracy even with the reduced number of ground stations. The analysis of Yang[15]*, et al.* on BDS MEO satellite shows an accuracy of 19.8 cm with ISL ranging facility.

4.3 GEO/GSO

- **Ground-based tracking**
  - Tone-Based Ranging: ~1 km using a single station and ~100 m with multiple stations based on frequency of tones and number and wide baseline of ranging stations.
  - One-way CDMA ranging: 10-30 m. Ramakrishna[19]*, et al.* obtained a 10 m accuracy with a wide baseline.
  - Two-way CDMA ranging: 10-15m[19]
  - TDOA: 19 m (radial), 5 m (in-track) and 1 m (cross-track)[3].
  - SLR: 1.96 m BDS satellites orbit accuracy with several-day SLR data[18].
- **On-board GNSS Receiver:** 30-40 m[20-21].
- **ISL:** 28.4 cm for GSO and 30.9 cm for IGSO using sole ISL ranging[15].
- **Hybrid Techniques**: 20 m (3σ) or better in GOES-16, a US weather satellite[22].

4.4 HEO

4.4.1 Ground-Based Tracking

3.1 km in POLAR HEO spacecraft[23].

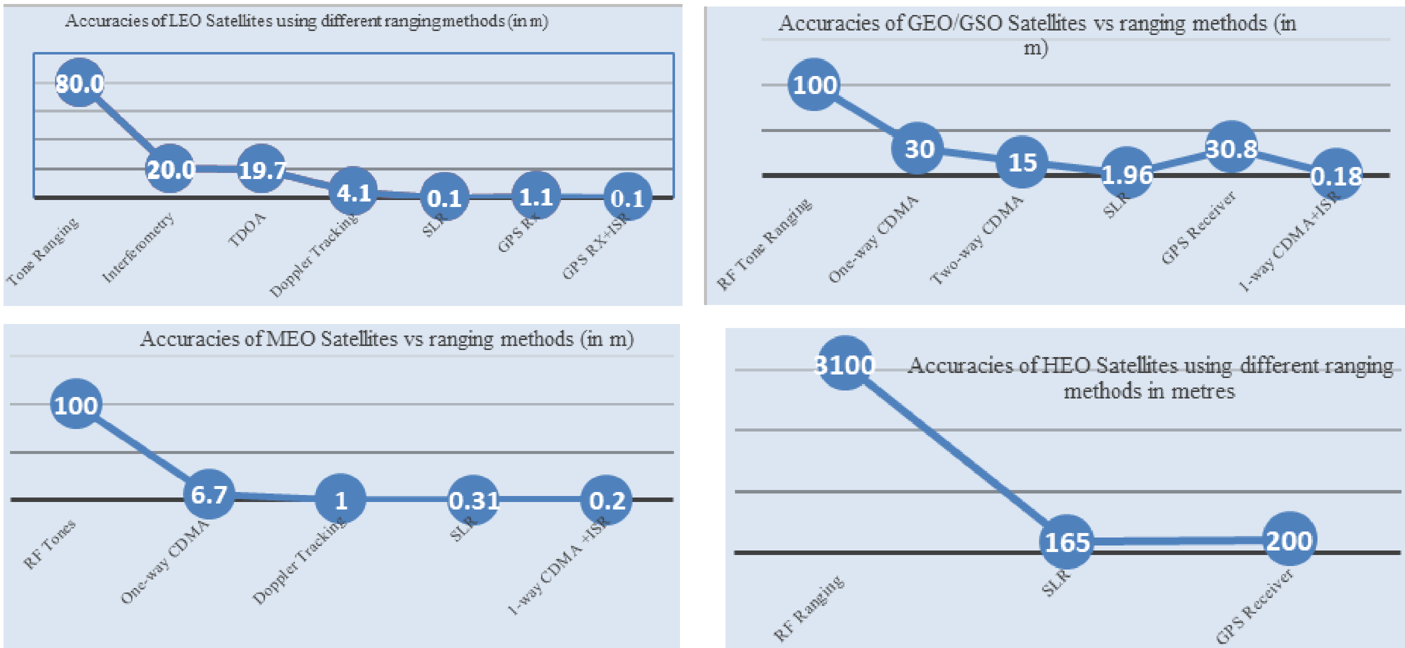

Figure 2. Accuracies of Earthbound Satellites using different ranging methods.

4.4.2 SLR

With sparse SLR measurements on Japan's QZS-1, the observed post-fit RMS residuals of the two-week-long arcs were 11.98 cm and 10.77 cm (with each arc bias estimation) and 2.40 cm and 3.60 cm (with biases estimation in every pass)[24].

4.4.3 Onboard GPS Receiver

Davis[23], *et al.* demonstrated for the highly elliptical orbit (558 km X 59258 km) of AMSAT-OSCAR-40 at 58,000 km, with sufficient amplification of the weak GPS signals, an accuracy of 3 km compared to the reference orbit accuracy of 100 km. Magnetospheric Multiscale Mission (MMS) space weather constellation in HEO has shown 165 m accuracy at 40 % of lunar distance with a GPS receiver.

Accuracies of earthbound satellites using different ranging methods are summarised in Fig 2.

5. ADVANCES AND TRENDS IN SATELLITE-RANGING METHODS

Advances and trends in ranging methods are reviewed comprehensively as follows.

Doppler frequency measurements contribute significantly to satellite position estimation. The maximum Doppler shift (Δf) is computed using the following Eqn.:

$$\Delta f = v/c \tag{1}$$

where, v is satellite velocity, f is signal frequency and c is the speed of light. Doppler frequency shifts observed in orbits at different altitudes are shown in Fig. 3.

5.1 Ground-Based Ranging

LEO and the near-perigee region of HEO take advantage of higher Doppler frequency to arrive at high-accuracy orbit estimates. GEO/SIGSO (Slightly Inclined GSO), HIGSO (Highly Inclined GSO) and HEO additionally use GNSS and ISL for better orbit determination. Zhao[25] presents precise orbit determination of the Haiyang-2A satellite using dual-frequency GPS and DORIS with validation using SLR. The study by Hyungjik[24], *et al.* on China's Compass GEO satellites with sparse SLR with Normal Points (NP) of 49 and 47 shows post-processed OD residuals of 8.81 cm and 12.00 cm respectively.

5.2 GNSS SSV Receivers

The availability of multiple satellites and different civil signals from different GNSS systems make GNSS-based satellite position determination a preferred method for avoiding global ground stations. GNSS service providers, in collaboration with the UNOOSA, have actively developed simulations of the SSV as shown in Fig. 4. SSV is divided into two regions, lower SSV between 3,000–8,000 km altitude and upper SSV between 8,000-36,000 km. Below 3000 km altitude service volume is known as TSV. This initiative aims to incorporate high-sensitivity GNSS receivers with advanced features suitable for use in space systems[26-27].

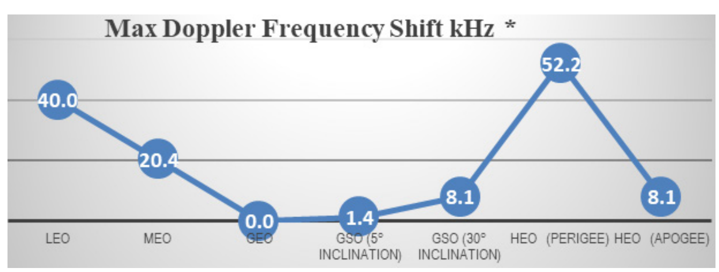

Figure 3. Typical doppler frequency shift observed in different types of orbits.

Simulations on GNSS SSV receivers by the GNSS operators under ITU provide the following advantages.

- Wider coverage with the use of onboard antenna sidelobes along with main lobe power
- Use of multiple GNSS systems to improve availability and DOP
- Highly sensitive receiver operation at the power levels of -175 to -185 dBW.

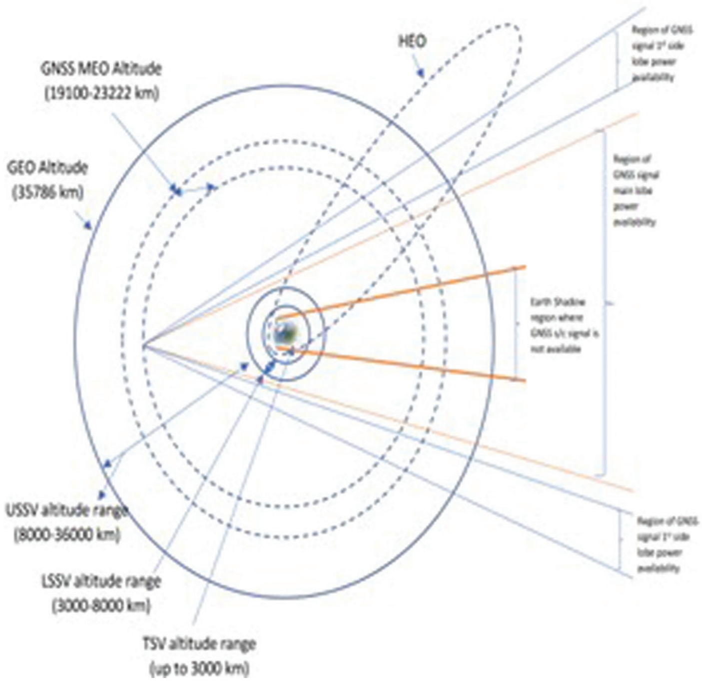

Figure 4. GNSS SSV.

The SSV receiver can receive signals from the GNSS satellite antenna main and side lobes. LEO satellites fully utilise space-borne receivers capitalising on the visibility of GNSS satellites, strong signal power and geometry coverage. The use of space-borne receivers in orbits higher than 20000 km altitude has begun relatively recently. Davis[23], *et al.* demonstrated the use of GPS receivers on AMSAT OSCAR-40 satellites to determine the orbit of a high-altitude spacecraft.

5.3 ISL

The use of ISL along with the regular orbit determination operations provides improvements to any orbit in terms of accuracy, robustness and autonomy.

The trends in improving the accuracies in orbits at various altitudes are presented in Table 2. The advances in the earthbound satellite orbits at different altitudes are presented as follows.

5.4 LEO

The visible duration of a LEO satellite to a ground location is ~16 minutes of its total 90 min orbit, hence, global ranging stations are necessary to get an accurate and complete orbit. With a GNSS receiver on board the LEO satellite, position measurement has become a very cost-effective and simple solution. The ISL in LEO supports data transfer, time-synchronization and formation flying. ISL-based ranging along with other on-board sensors and GNSS receivers, provides precise satellite orbit for rendezvous, docking and formation flying. Postprocessing of Starlink GNSS receiver carrier phase data provides 0.7 m 3D RMS accuracy[12-13]. Analysis of the GPS receiver data of the return trajectory of the STS shows that the Crew Return Vehicle and International Space Station (ISS) trajectory position accuracy is better than 40 m[29].

Table 2. Typical ranging accuracies of different satellite orbits (in metres)

LEO						
Tone Ranging	Interferometry	TDOA	Doppler Tracking	SLR	GPS Rx	GPS Rx+ ISR
80.0	20.0	19.7	4.1	0.05	1.1	0.1
MEO						
Tone Ranging	1-way CDMA	Doppler Tracking	SLR	1-way ranging +12 ISLs		
100	6.7	1.0	0.31	0.64		
GEO/GSO						
Tone Ranging	1-way CDMA	2-way CDMA	SLR	GPS Rx	1-way CDMA +ISR	
100	30	15	1.96	30.8	0.18	
HEO						
Tone Ranging	ISR			GNSS SSV Rx [35]		
3100	165			< 200		

5.5 MEO

Doppler-based ranging helps MEO satellites. Also, precise CDMA-based ranging with an orbital accuracy of 10 m is possible using the ranging signals broadcasted by the MEO satellites. Y. Yang[15] analyses the 3D orbit accuracy of BDS-3 satellites with 24 hr prediction as given in Table 3.

Table 3. MEO ranging accuracies with hybrid solution[15]

Ranging system	Accuracy in m
Regional stations (RS)	2.03
Global stations (GS)	0.93
RS+ISL	0.73
GS+ISL	0.56

By post-processing the receiver data, accuracies of the order of centimetres are achieved. The study by Montenbruck[29], *et al.* provides the MEO satellite orbital accuracies using IGS stations. 3D RMS values of 6-17 cm, 14-29 cm and 12-26 cm were obtained for GLONASS, Galileo and BDS MEO satellite orbits, respectively. There is no record of using ground-based two-way CDMA ranging in MEO satellites. Also, the use of GNSS receivers on board MEO satellites is yet to be explored.

5.6 GEO/GSO/IGSO

Communication satellites generally use tone-based ranging methods as the accuracy needs are not very stringent. Navigation satellites in GEO/GSO utilise CDMA-based ranging to meet the accuracy requirements. Montenbruck[30], *et al.* provide the GSO/IGSO satellite orbital accuracies through precise products as measured at IGS stations. 3D RMS values of 32-51 cm and 40-240 cm were obtained for BDS and QZSS satellite orbits, respectively. The experiments in Yang[15], *et al.* show an accuracy of ~88 cm for GEO and ~20 cm for IGSO with worldwide ground network-based precise products. An orbital accuracy of 17.9 cm for GEO and 12.8 cm for IGSO is achievable with worldwide CDMA stations and the ISL ranging. Fig. 5 shows the advantage of the GNSS-SSV receiver utilising several signals from multi-GNSS constellations with the use of onboard antennae main lobes for position estimation[26-27.] The number of visible satellites from any individual GNSS system ranges from 0 to 6 at GEO. With an interoperable GNSS SSV receiver onboard a GEO satellite,

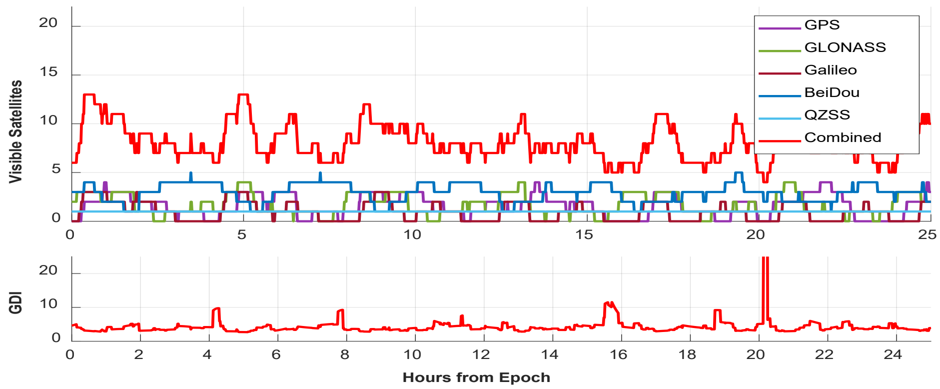

Figure 5. L1 navigation signal visibility for GEO at 240° [25].

the visibility of satellites contributing to position estimation increases to 8-14 and the accuracy achieved could be better than 20 m.

5.7 HEO

With widely variable Doppler frequency shift from 10-32 kHz, Doppler-based techniques are useful in determining the satellite position and orbit. GNSS SSV receivers onboard a HEO satellite improve orbital accuracy. Fig. 6 presents the number of visible GNSS satellites over an HEO mission altitude for 14 days. The number of visible satellites ranges from around 10 to more than 100 for the interoperable L1 band signal.

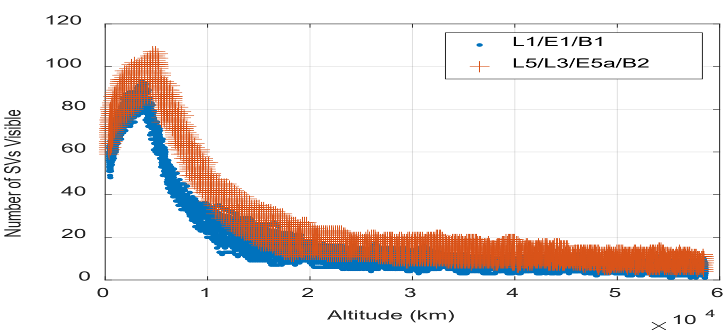

Figure 6. Visible GNSS satellites over HEO (Ref: ITU).

6. FINDINGS

The key findings of this study are the following:

- LEO satellites are increasingly using GNSS receivers onboard with the advantage of improved accuracy levels and minimal ground-based tracking dependency. Sub-metre level accuracy is achieved with the sole use of a GNSS receiver. Accuracy could improve by post-processing of the data, carrier phase measurements and with the support of onboard sensors and RF systems. Simulations of SSV-based receivers promise highly precise accuracies for docking and rendezvous operations.
- Navigation satellites are general in MEO, and they use one-way CDMA ranging through navigation reference receivers. Simulations on ISL and results of working systems show that accurate satellite position will reduce UERE error at the user receiver resulting in better accuracies in satellite navigation applications. Also, by using different ranging systems together improvements in accuracy and autonomy could be achieved with less dependence on the global ground station support.
- Since GEO satellites exhibit very low Doppler frequency shifts of the order of 10-15 Hz, the Doppler-based ground tracking techniques are not useful for determining GEO orbits and SIGSO orbits with an inclination around 5 deg. HIGSO satellites with an inclination around 30 deg exhibit required Doppler frequency shift which enables the use of Doppler-based techniques to such orbits. GEO satellites depend on the ground-based RF tone ranging for communication and imaging payload operations. Inclined GSO satellites, if used for satellite-based navigation, depend on one-way CDMA ranging through ground-based navigation reference receivers. GNSS receivers onboard the GEO/LIGSO/LIGSO satellites could reduce ground-based tracking dependency. If these satellites are part of a navigation system, sufficient frequency separation of their own navigation signals from the onboard GNSS signals should be ensured to avoid interference among them. ISL with ranging capabilities could provide improvements in accuracy and autonomy with position data from onboard GNSS receiver data or ground-based ranging as the reference.
- HEO satellites generally depend on ground-based ranging. HEO satellites receive navigation signals over the limb of the Earth when the satellite is near apogee. At perigee, the operations are like those of the LEO. Effective use of GNSS receivers is being explored to provide improved orbital accuracies.
- Satellite systems are moving towards using hybrid ranging techniques, instead of depending on any single ranging method to optimise the satellite position estimation accuracy.

7. CONCLUSION

In this paper, three ranging methods viz., ground-based satellite tracking, onboard GNSS receivers and ranging through ISL of the earth-bound satellites have been studied. Primary research papers have been reviewed and collated for the latest trends and the advances in these methods to achieve enhanced satellite orbit accuracies. With the availability of multiple navigation signals in different navigation brands from many GNSS satellites, LEO satellites predominantly have started depending on GNSS receivers, replacing the ground-based ranging for orbit determination, and using ISL for data transfer and ISR providing autonomy, precise position, velocity and timing for formation flying, rendezvous and docking operations. MEO satellites predominantly use the CDMA ranging method supported by ISL for improved accuracy and autonomy. ICG and GNSS operators have made system-level developments and simulations of GNSS use for space service with enhanced coverage using antenna sidelobes. Simulations show more signals and satellite availability, hence, improving accuracy in satellite missions in all orbits. GEO, GSO, HEO satellites and other trajectories depend on hybrid ranging techniques based on the applications. Hybrid techniques have been utilised to get the benefits of each of the ranging methods for continuity, accuracy and autonomy. A hybrid solution for each orbit is unique, and optimal solutions must be worked out considering all influencing factors.

REFERENCES

1. Pratt, T. & Jeremy, E. Allnutt. Satellite communications. 3rd ed., Wiley, 2019. ISBN-10: 1119482178. doi: 10.1002/9781119482178.
2. Pocha, J.J. An introduction to mission design for geostationary satellites. *Kluwer*, 1987. doi: 10.1007/978-94-017-7625-0
3. Ibrahim, ÖZ, Yilmaz, Ü.C. & Güler, Ü. TDOA based tracking measurement for GEO satellites orbit determination: evaluation for the satellite operators. *Eskişehir Tech. Univ. J. Sci. Technol. A - Appl. Sci. Engin.*, 2022. doi: 10.18038/estubtda.923711
4. Bock, H.; Jäggi, A.; Dach, R.; Schaer, S. & Beutler, G. GPS single-frequency orbit determination for low earth-orbiting satellites. *Adv. Space Res.*, **43**(5), 2008, 783–791. doi: 10.1016/j.asr.2008.01.016
5. Marzioli, P.; Santoni, F. & Piergentili, F. Evaluation of Time Difference of Arrival (TDOA) networks performance for launcher vehicles and spacecraft tracking. *Aerospace*, MDPI, 2020. doi: 10.3390/aerospace7030079
6. Appleby, G. Current trends in satellite laser ranging. AGU Fall Meeting Abstracts, 2010.
7. Bojanowski, J.S. & Jan, P.M. Deselecting effects of orbital drift of polar-orbiting satellites on accuracy and trends of climate data records of cloud fractional cover. Remote Sensing Centre, Institute of Geodesy and Cartography, Poland, 2020.
8. Jian, L. Study on pointing accuracy effect on image quality of space-borne video SAR. *In* IOP Conf. Ser.: Mater Sci Eng, 2019.
9. Sakamoto, Y. & Nishio, M. Orbit determination using radio interferometer of small-diameter antennas for LEO Satellites. IEEE Transacti. *Aerospace and Electron. Syst.*, 2011.
10. Yunck, T.P. Orbit determination. In Global Positioning System: Theory and Applications, **2**, 1996.
11. Sosnica, K. Satellite laser ranging to low earth orbiters: Orbit and network validation. *J. Geodesy*, 2018.
12. Selvan, K.; Siemuri, A.; Kuusniemi, H. & Välisuo, P. A review on precise orbit determination of various LEO satellites. University of Vaasa, Finland, 2021.
13. Chuang, S.; Zhang, Y. & Li, Z. Revisit the performance of doppler positioning with LEO satellites. Beihang University, Research Square, 2022.
14. Shiarifi, M. Satellite to satellite tracking in the space-wise approach. Institute of Geodesy, University of Stuttgart, 2006.
15. Yang, Y.; Yang, Y.; Hu, X.; Chen, J.; Guo, R.; Tang, C.; Zhou, S.; Zhao, L. & Xu, J. Inter-satellite link enhanced orbit determination for BeiDou-3. *J. Navigation*, 2019.
16. Stepanek P.; Gurtner, J.M.; Malyr, J.P. & Cristian, F.R. Satellite laser ranging validation of DORIS and GPS precise orbits. *Remote Sensing*, 2020.
17. Couhert A. & Bock H. Towards the 1 cm/s Orbit determination for low-earth orbiters. *Adv. in Space Res.*, 2015.
18. Bury, G.; Sośnica, K. & Zajdel, R. Multi-GNSS orbit determination using satellite laser ranging. *J. Geodesy*, 2018, **93**(12), 2447–2463.
19. Ramakrishna, B.N.; Mishra, P.; Subramanya, G.T.; Sharda, V. & Sen, Gupta A., A long baseline tracking network for improved NavIC orbit determination. Indian Academy of Sciences, 2023.
20. Geng, T.; Su, X. & Zhao, Q. MEO and HEO satellites orbit determination based on GNSS onboard receiver. *In* China Satellite Navigation Conference (CSNC), 2012.
21. Kim, G.; Kim, C. & Kee, C. Coarse initial orbit determination for a geostationary satellite using single-Epoch GPS measurements. *Sensors*, 2015.
22. Ashman, B.W.; Bauer, F.H.; Parker, J.J.K. & Donaldson, J.E. GPS operations in high earth orbit: Recent experiences and future opportunities. Goddard Space Flight Center NASA, 2018.
23. Davis, G.; Moreau, M.; Carpenter, R. & Bauer F. GPS-based Navigation and orbit determination for the AMSAT AO-40 Satellite. NASA Goddard Space Flight Center AIAA ,2001.
24. Oh Hyungjik. orbit determination of high-earth-orbit satellites by satellite laser ranging. *J. Astronomy and Space Sci.* ,2017.
25. Zhao, G.; Zhou, X.H. & Wu, B. Precise orbit determination of Haiyang-2 using satellite laser ranging. *Chinese Sci. Bulletin*, 2012, **58**.
26. ICG-ITU WG B, UNOOSA .The inter-operable GNSS Space Service Volume (SSV) simulations booklet 1 .0 for GNSS standard for space users, 2018.
27. ICG-ITU WG B, UNOOSA .The inter-operable GNSS Space Service Volume (SSV) simulations booklet 2 .0 for GNSS standard for space users, 2021.
28. Chen, P.; Jian, Z. & Xiucong, S. Real-time kinematic positioning of LEO satellites using a single-frequency GPS receiver. *GPS Solutions*, 2017, **21**.
29. Gomez, S.F. GPS on International Space Station (ISS) and Crew Return Vehicle (CRV). NASA JSC ,2001.
30. Montenbruck, O.; Steigenberger, P.; Prange; Deng, Z.;

Zhao, Q.; Perosanz, F.; Romero, I.; Noll, C.; Stürze, A. Weber, G.; Schmid, R.; MacLeod, K. & Schaer, S.The multi-GNSS experiment (MGEX) of the international GNSS service (IGS) achievements, prospects and challenges. *Adv. Space Res.*, 2017, **59**.

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