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Potential of Multi-constellation Global Navigation Satellite System in Indian Missile Test Range Applications

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ABSTRACT

In this paper, the potentials of using Global Navigation Satellite System (GNSS) techniques in the complex calibration procedure of the tracking sensors for missile test range applications have been presented. The frequently used tracking sensors in test range applications are- electro-optical tracking stations (EOTS) and tracking radars. Over the years, the EOTS are used as the reference for bias estimation of the radars. With the introduction of GPS in test range applications, especially the DGPS, the reference for bias estimation got shifted to DGPS from the EOTS. However, the achievable position solution accuracy is limited to the order of a few meters for DGPS, EOTS, and Radars. With the evolution of Multi-constellation GNSS and carrier-phase based measurement techniques in satellite navigation, achievable position solution accuracies may be improved to sub-meter level. New navigation techniques like real time kinematic (RTK) and precise point positioning have the potentials for use in the calibration procedures of the missile test ranges to the accuracies of centimeter-level. Moreover, because of the availability of a large number of navigation signals over the Indian region, multi-constellation GNSS receivers can enhance signal availability, reliability, and accuracies during the calibration of missile test ranges. Currently available compact, low-cost GNSS modules also offer the possibilities of using these for cost-effective, networked RTK for dynamic calibration of test ranges reducing cost and resource requirements.

Keywords: Test range; Calibration; Satellite navigation; GNSS; Tracking radar; EOTS

1. INTRODUCTION

In test ranges throughout the world, multiple auto-tracking sensors like electro-optical tracking stations (EOTS) and tracking radars are deployed at various geographical locations for generation of the trajectory of the missile under test (MUT). Also, these facilities provide tracking aid to radio-frequency telemetry stations with the help of which, the telemetry systems acquire the MUT for monitoring the telemetry health parameters including inertial navigation system (INS) data[1,2]. Thus, accurate testing of the missiles depends directly on the calibration of these tracking sensors so that the trajectories of the MUT generated by various tracking sensors do not provide erroneous or misleading results. Therefore, with every physical movement of any of the existing tracking stations, the new site needs to be surveyed accurately to find its latitude, longitude, and azimuth offset.

The EOTS are dual-axis auto-track system consisting of Infrared (IR)/ thermal cameras that are based on the principle of auto-track using image processing techniques[3]. More about the EOTS tracking algorithms and their error calculations may be found in the work by Sahu[4]. These are accurate trajectory generating sources compared to tracking radars operating in S and/ or C bands. Moreover, the EOTS stations are the only tracking sensors that provide the MUT trajectory information from the initial point of the flight. Because of the limited baseline distance between these EOTS stations, the error in the triangulated trajectory increases with the increasing distance of the target from the stations[5]. Poor weather conditions and low IR signature of the target limits the tracking distance of the target from the EOTS stations[6]. More details about the study of attenuation of the IR signature in the EOTS bands have been done by Dey[7], *et. al.* The complete tracking process of the MUT in the Indian test range may be subdivided into three phases, which are presented in the subsequent sections. In the tracking era before the introduction of GPS, the accuracy and effectiveness of the methods were limited. Initiation of GPS operation, the removal of Selective Availability from the GPS signals, subsequent initiation of other global and regional satellite-based navigation systems, and introduction of various positioning techniques enhanced the scope of using global navigation satellite system (GNSS) for various high-precision applications including those for the test ranges:

This paper discusses the potentials of using current GNSS based positioning techniques for enhancement of capabilities of position-based requirements of the missile test ranges. The advantages of the current multi constellation, multi-signal, global and regional satellite systems have been presented in the text. Discussion on the currently used GNSS based positioning techniques- code and carriers phase based measurements, multi-frequency single point positioning (SPP/ SPS), precise

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point positioning (PPP), differential GNSS (DGNSS) and real time kinematic (RTK) towards achieving precise and reliable position solution quality has been presented with real-time experimental results to provide the conceptual idea of the applicability of the techniques for better calibration process in test ranges vis-à-vis the existing techniques.

An initial discussion on the current methods of tracking used in the test ranges is presented in Section 2 as the background for understanding the limitations of the current techniques and the scopes of using GNSS to augment the existing facilities. Section 3 sequentially presents the evolution of GNSS constellations, the GNSS based positioning techniques, the potentials of the compact, low-cost GNSS modules, and the advantages from the Indian region in accessing signals from all available GNSS constellations due to the geographical location. Finally, the promising opportunities of the Indian Regional Satellite based Navigation System (IRNSS/NavIC) in range applications has been discussed.

2. THE PRESENT METHOD FOR MISSILE TRACKING (EOTS AND RADAR)

2.1 Initial Phase Tracking

Figure 1 depicts a typical range instrumentation configuration; the missile is launched from a launch pad and the placement of the range tracking instrument stations are distributed as shown in the Figure. In most of the cases, the auto-tracking stations are mobile and are suitably placed to have good coverage of the MUT trajectory. The EOTS systems sense the IR signature of the missile after launch and continue auto-track using the image processing techniques like co-relation or contrast algorithms. So, unlike the radars, they operate in passive mode by tracking the heat generated by the missiles by burning the fuel. Because of this, a single EOTS station cannot provide the trajectory of the MUT and theoretically requires a minimum of three stations to calculate the trajectory of the MUT using the triangulation principle as shown in Fig. 1. Therefore, its accuracy is defined in terms of small angles. It is to be noted here that more the number of EOTS systems deployed, better accuracy of the trajectory can be derived, though a more detailed analytical presentation is beyond the scope of this paper. The EOTS stations are placed in such a way that one station lies on the left side of the flight azimuth, one station to the right, and one directly behind the

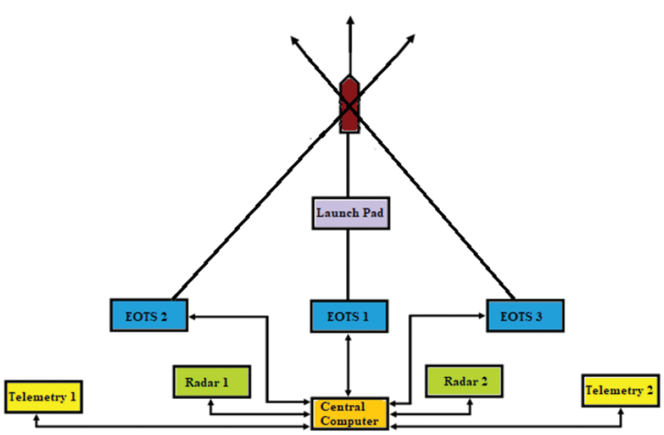


Figure 1. Test range instrumentation configuration.

MUT flight azimuth. This ensures good triangulation geometry for the initial phase of the missile trajectory. When the baseline distance between the EOTS stations becomes insignificant in comparison to the distance of the MUT from the stations, the tracking error increases for the EOTS triangulated trajectory[4]. During this time, the tracking radars placed on the left and right of the flight trajectory azimuth ensure better positional information of the MUT. However, it is to be noted that the radars operate in active mode by transmitting signals to the MUT and receive the reflected signal from the body of the missile called the skin mode tracking, generally used in case of short-range tracking. There is another tracking mode of the radars known as the beacon or transponder mode in which a transponder is fitted on-board the missile, the radar signal triggers the transponder and gets the downlink signal from the missile to carry out the auto-tracking process. This process of transponder fitment increases the range of tracking and is usually used in the cases of ballistic and cruise missile under test.

2.2 Mid Phase Tracking

The tracking radars utilize the principle of auto-track with the error generated based on the monopulse or conical-scan tracking principles[2]. These radars are unable to provide trajectory information from low elevations due to multipath and ground clutter and start providing the trajectory information above certain elevation angles. The radars take over from the EOTS systems and continue to provide the trajectory information of the MUT up to a large distance during the cruise phase as long as the line of sight is available or until limited by the radar RF link margin and the sensitivity of the receiver. In such a situation, a mid-phase radar is also placed suitably onboard a ship to pick up the tracking information when the initial tracking range of the radar is restricted by the curvature of the earth.

2.3 Reentry/Terminal Phase Tracking

The mid-phase radars continue to track the MUT till the terminal phase radars pick up the target. The splash point of the long-range MUT is again provided by the downrange EOTS stations by triangulation and by the downrange radars, both usually placed on ships as shown in Fig. 2. A continuous handshake is needed between the radars used during various phases and the EOTS systems for aiding of one system by the other. This becomes possible because of the precise calibration of the various sensors, which again depends on the accuracy of surveyed position locations of the systems and accurate dynamic calibration in the direction of flight azimuth.

2.4 Calibration of the Test Ranges

Before the introduction of GPS, the survey of the station positions was done by optical theodolites for their latitude, longitude, and azimuth offset with respect to true north. In the Indian context, in the pre-GPS era, the EOTS systems were the references for the trajectory generation and the radars were calibrated with respect to the EOTS trajectory. During those days, the EOTS systems were calibrated using the concept of star calibration[6,8-9] using the pole star as the reference, and thus utilized a complex calibration procedure. The triangulated

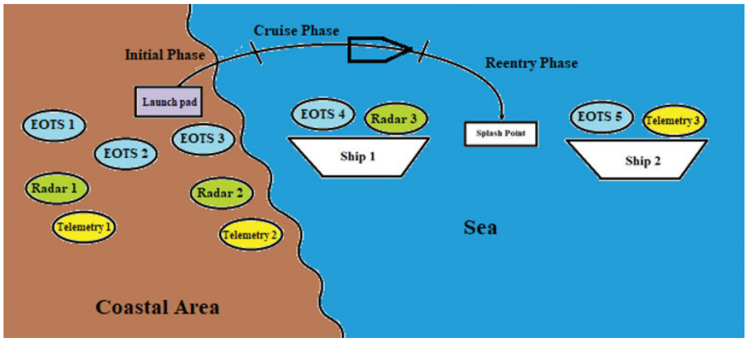
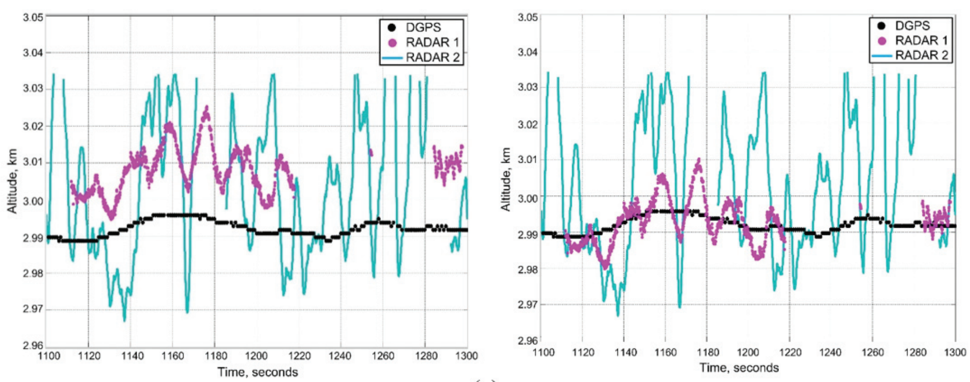


Figure 2. Total test range instrumentation configuration including down range (Not to scale).

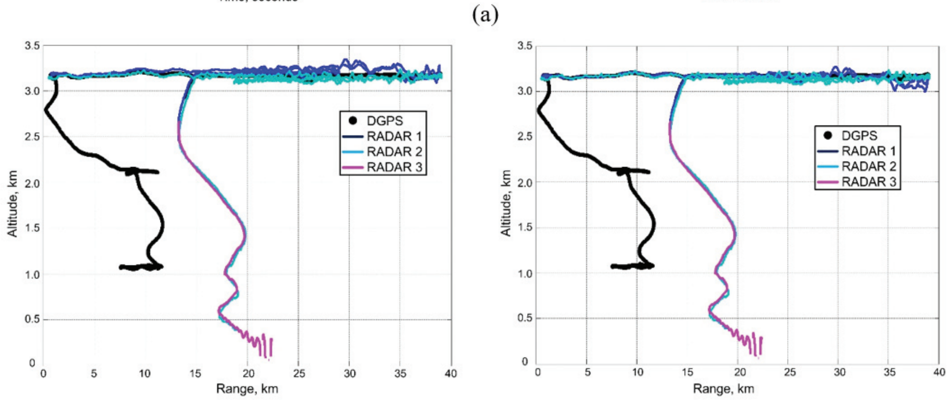
trajectory generated from these calibrated EOTS stations were considered to be the trajectory with an accuracy of the order of arcsecond of angle. The bias of the tracking radars was corrected at the central data processing computer with moving targets like aircraft/helicopter sorties with the EOTS trajectory as the reference during the pre-launch activity. Again, a bias validation sortie was done to verify the correctness of the calibration of the radar with respect to EOTS systems calculated through the previous helicopter/aircraft sortie.

In the 1990s, when GPS became operational, the use of GPS receivers inside the helicopter during the sortie was initiated for test ranges[10-11]. With the GPS as an additional source of trajectory, users started comparing this data with the accuracies of the sensors like EOTS and radars. In the Selective Availability (SA) prone GPS signal era, theoretical calculations suggested that survey-grade stand-alone GPS receivers could provide accuracies comparable to those of the tracking radars but less accurately than the EOTS systems[12]. However, after the removal of (SA) on 2 May 2000, and with the introduction of the differential GPS (DGPS) concept, there was additional improvement in the accuracy of the reference trajectory to the order of few meters for the calibration of the test ranges[13]. Thus, for the first time in the operations of test ranges, the DGPS positional accuracy was comparable or better than that of the traditional EOTS systems. So, the reference for the calibration process was changed from that of the EOTS to the DGPS. Currently, in most of the test ranges, the EOTS and radars are calibrated with respect to the DGPS reference[14]. In the case of DGPS, a GPS receiver operating from a precise pre-surveyed location serves as the "Base" and calculates the instantaneous errors w.r.t the reference location and transmits the error information. Within a limited geographical region, any GPS receiver (Rover) capable of receiving the error signals can use these values for instantaneous improvement of their location.

Figure 3 shows typical calibration processes of the test range tracking radars with respect to the DGPS using helicopter sortie. In Fig. 3(a), a helicopter with an on-board DGPS rover is flown following a predefined trajectory and the same helicopter is tracked by the radars. Considering the DGPS as the reference the EOTS and the radar plots are corrected at every point so that all the three matches throughout the trajectory. Thus, the bias can be positive or negative which are corrected at each point with respect to the DGPS. It is evident that after the bias correction with respect to the DGPS, there is closer matching between the tracking sensors[15].



(a)



(b)

Figure 3. Variation of target altitude with range of flight as detected by multiple radars before bias correction (left) and after bias correction (right) using DGPS system.

Figure 3(b) depicts the calibration of multiple radars with respect to DGPS during the helicopter flight. A helicopter sortie trajectory is being shown before and after bias correction of various tracking radars with respect to DGPS. Here, a portion of the flight trajectory is being shown where the ground range against altitude is plotted and close matching between the sensors after bias correction is witnessed. However, in all these plots the reference for the bias correction is taken to be the DGPS. So, the achievable precession and accuracy of DGPS limit the improvement of accuracy of the reference trajectory to an order of a few meters[14]. Over the last couple of decades, the initiation of many other navigation constellations and techniques for accuracy enhancement have been implemented; and therefore, opportunities have evolved to use satellite navigation signals towards achieving higher accuracy and precision more efficiently. The next section briefly describes the evolution of multiple constellations and revisits various GNSS based techniques for the improvement of solution qualities.

3. POTENTIAL OF GNSS IN RANGE APPLICATIONS

3.1 The Present Scenario

Experience in the efficient use of the GPS and associated advantages, need for self-reliance in strategic requirements and huge business potential paved the way for many other countries to develop their own satellite-based navigation system. GPS was fully operational since the early 1990s and gradually improved classes of satellites were deployed till early 2020 when the 4th civilian L1 Band signal was introduced[16-17]. Since 1982, the Russian counterpart, GLONASS started operation as an active alternative of GPS using FDMA signals in L-Band. GLONASS constellation gradually degraded due to the non-replenishment of satellites and became unusable since early 2000. Following a major replacement and revitalization plan, the constellation was regularly populated from 2004 and again in 2011, the constellation was declared operational[18]. The European system, Galileo, was deployed since 2011; the first Galileo-only 3d fix reported from India was obtained in 2013[19]. In December 2015, the system was declared fully operational. The Chinese system was first developed as a regional system, called the COMPASS and subsequently, Beidou deployment was initiated as a global system. Beidou is a combination of satellites placed in geostationary and Medium Earth Orbits (MEO) with regional and global coverages; it is declared to be fully operational in 2020[20]. Regional satellite-based navigation systems- Quasi-Zenith Satellite System (QZSS) developed by Japan began initial operation since November 2018 with satellites placed in highly elliptical orbits. The Indian system, Navigation with Indian Constellation (NavIC) is now complete with 7 satellites placed in Inclined Geosynchronous (IGSO) or Geostationary (GEO) orbits and the system started operation in 2017. As of end June 2020, 32 (31 operational) GPS[16], 27 (23 operational) GLONASS[21], 49 (35 operational) Beidou[22], 26 (22 operational) Galileo[23], 4 QZSS[24] and 7 (6 in operation) NavIC satellites[25] are in the respective space segments providing a system space volume of total 145 (121 operational) satellites. All the constellations together are put under the common generic of Global Navigation Satellite System (GNSS).

3.2 Types of Positioning Solutions Techniques in GNSS

The evolution of various global or regional GNSS constellations over the last two decades has transformed the positioning, navigation, and timing (PNT) technology unprecedently by introducing an unparalleled combination of precision, accuracy, convenience, and confidence. The capabilities of professional and amateur users have been boosted manifold through the adoption of GNSS positioning technology by enhancing the accuracy levels from a few meters to the sub-centimeter level for both the types of users. Positioning with carrier phase-based measurements has increased the accuracy in comparison to the code-based measurements. Various techniques like concurrent use of dual-frequency, ionospheric error-free standard positioning service (SPP/SPS), real time kinematic (RTK), and precise point positioning (PPP) have increased the level of accuracies and precision in both static and dynamic operations[26-28].

3.2.1 Single Point Positioning

GNSS technology has rapidly replaced most of the traditional surveying techniques and has provided a more flexible condition for 24 x 7 independent operation, without having a restriction on the separation between surveyed points[29]. In the case of the SPP technique, the 3-dimensional (3d) absolute coordinate of any point is determined using a stand-alone GNSS receiver at that point. The collected GNSS observations are contaminated by biases like the satellite and receiver clock errors, tropospheric and ionospheric delays, multipath, receiver clock bias and noises, and satellite geometry[30]. The highest achievable positional accuracy using single point position in the order of 2 to 3 meters using single-frequency, code-based measurements[31]. Accuracy enhancement may be done through the use of dual-frequency measurements, carrier phase-based measurements, averaging, correction models, and the use of multi-constellation signals.

3.2.2 Precise Point Positioning

The precise point positioning (PPP) technique was developed in the late nineties[32]. A high level of position accuracy using a solitary GNSS receiver is achieved through this method that removes or models the errors in GNSS systems. A PPP solution uses the GNSS satellite clock and orbit biases generated and disseminated from a globally distributed network of high-grade receivers within the International GNSS Service (IGS)[33-37]. After the calculation of the corrections, they are delivered to the user over the Internet or other electronic data dissemination services[38-39]. In static operation mode, PPP can provide accuracy up to several millimeters in the horizontal plane and to centimeter-level in the vertical direction[26]. A PPP solution requires an adequate convergence time to attain sub-meter accuracy by resolving the locally present biases like the atmospheric conditions, multipath environment, and satellite geometry[40]. The required convergence time and the achieved accuracy depend on the quality of the applied corrections to the solutions. Online complimentary or paid PPP position services from government and commercial agencies are now available, those accept appropriate data from the user over the internet and utilizes International GNSS Service (IGS) products to implement PPP and send back the results to the user. GPS PPP was implemented first and subsequently, GLONASS and GPS+GLONASS PPP implementations were initiated[41].A major limitation of the PPP technique is the required finite convergence time that may vary from a few to several minutes to get accurate ambiguity fixing.

3.2.3 Differential GNSS

A common technique to improve GNSS performance is differential GNSS (dGNSS). In dGNSS, the position coordinates of a reference GNSS receiver (called a Base) is determined very accurately using conventional survey methods[31-42]. The Base finds ranges of the visible GNSS satellites using the code-based positioning technique. The Base then calculates the instantaneous position solution from the satellite ranges and compares this instantaneous solution value with the pre-surveyed position. Differences (errors) between the instantaneous and surveyed positions are calculated those may be attributed largely to the associated atmospheric delay, satellite ephemeris, and clock errors[43]. The Base can send these errors using some wireless link to one or multiple remotely located user receivers (Rovers); the Rovers incorporate the received error values as corrections during their own position calculation to enhance the accuracy of the solution. dGNSS positioning, therefore, requires at least four common GNSS satellites in view and a data link between the Base and Rover(s). The Rover's absolute solution accuracy depends on the absolute accuracy of the Base position and the Base-Rover distance. dGNSS works well with up to a few kilometers of Base-to-Rover separations[26,41] so that both remain within a similar atmospheric condition and can have common satellite visibility.

3.2.4 Real-Time Kinematic (RTK)

In general, the initial GNSS positioning technique uses code-based positioning by correlating with and using the pseudorandom codes transmitted by at least four or more satellites to calculate the range of the individual satellite. From these ranges and knowing the exact position of the satellites from the transmitted data stream, the GNSS receiver calculates its position accurate to within a few meters[44-46]. For more demanding applications of higher accuracy requirements, RTK is a promising technique that uses carrier-phase based measurements that provides ranges (and therefore positions), those are more precise by an order of magnitude compared to those available using the code-based positioning methods[47].

The basic concept of RTK lies in the methods of reducing and removing common errors for a Base-Rover pair. Conceptually, the receiver resolves the cycle ambiguity, then the number of carrier cycles between the satellite and the Rover is calculated; the satellite range is then calculated by multiplying this number of carrier cycles by the carrier wavelength[48]. The ranges thus calculated still contains errors from the space segment sources like satellite clock and ephemerides, the contribution from the atmosphere in the form of ionospheric and tropospheric delays[45], and local errors. To eliminate or minimize these errors and to use the advantage of the precise carrier-phase based measurements, RTK measurements are wirelessly transmitted from the Base to the Rover. Rovers determine their position using suitable algorithms that incorporate ambiguity resolution and differential corrections. Like dGNSS, the solution accuracy achievable at the RTK rover depends on the Base-Rover distance and the quality of the differential corrections. Again, the quality of the corrections depends on the accuracy of the Base location survey and the correctness of the Base station's satellite observations. Here, site selection for the Base antenna is an important criterion for minimizing the local errors arising due to environmental conditions such as interference and multipath. Quality of the Base and Rover hardware also plays a major role[26,41,49-52]. The achievable accuracy level using RTK is to the order of few centimeters.

For comparison, results of the achievable accuracy and/or precision based on the experiments carried out at GNSS Laboratory, The University of Burdwan, India (GLB) are now presented in Table 1. A reference point (RP) is created at GLB using a survey-grade GNSS receiver (Leica GR50) and a geodetic choke ring antenna (Leica AR25). Using dual-frequency GPS RINEX data for 24 h on 01 December 2019, the PPP position solution is calculated using AUSPOS online PPP service provided by Geoscience Australia[53]. For the open-sky SPP solution, GPS NMEA data is collected using a Javad Delta G3T survey-grade receiver with the same antenna at the RP for 24 hours @1Hz during 10-11 January 2020. 2d and 3d precision parameters in terms of Distance Root Means Square (2DRMS), Circle of Error Probable (CEP), Spherical Error Probable (SEP) and Mean Radial Spherical Error (MRSE) are computed using the following equations as mention in Santra[54], *et al.* and the results are shown in Table 1 along with the average

Table 1. Precision and accuracy comparison of SPP, PPP and short-baseline RTK solutions in open sky condition from GLB, India

Method	Open Sky SPP		Short Baseline RTK[55]	PPP using AUSPOS[53] 24 hrs GPS RINEX data @ 1Hz
Precision Parameters (m)	2DRMS:	2.8139	0.2678	(Position Uncertainty, m, 95% confidence)
	CEP	1.1304	0.1081	Latitude (North): 0.006
	SEP	1.6270	0.1469	Longitude (East):0.004
	MSRE	1.9203	0.1689	Altitude (Up): 0.018
Accuracy w.r.t the RP (m)	2d Offset: 3.1807		-	
	3d Offset: 3.8371		-	

offset values w.r.t the reference location.

$$2DRMS = 2\sqrt{\sigma_x^2 + \sigma_y^2} \tag{1}$$

$$CEP = 0.62\sigma_y + 0.56\sigma_x ; \quad provided\ that \frac{\sigma_y}{\sigma_x} \succ 0.3 \tag{2}$$

$$SEP = 0.51\left(\sigma_x + \sigma_y + \sigma_z\right) \tag{3}$$

$$MRSE = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} \tag{4}$$

A short-baseline RTK experiment was performed with the same geodetic receiver and antenna as the Base and an uBLOX M8T compact GNSS module with the commercial antenna as the Rover during 17 November 2018[55]. The results are also shown in Table 1.

3.3 Satellite Based Augmentation System

To provide differential GPS/GNSS service over a large area and to reduce the cost, satellite based augmentation system (SBAS) is used. SBAS systems consist of the reference, control, and uplink stations, and one or more geosynchronous satellite(s). The geosynchronous satellites receive correction messages from the reference station network and retransmit these error values over a large geographical area which is used by the rovers for improvement of the solution quality using a similar technique of DGPS. Different countries have implemented their own SBAS-wide area augmentation system (WAAS) by the USA, European Geostationary Navigation Overlay Service (EGNOS) by Europe, Multi-functional Satellite Augmentation System (MSAS) by Japan and GPS Aided GEO Augmented Navigation (GAGAN). Various systems- Satellite Navigation Augmentation System (SNAS) from China, Wide Area Differential Global Positioning System (WADGPS) from South Korea and System for Differential Corrections and Monitoring (SDCM) are under development. GAGAN is an SBAS system that supports aviation users within the Indian airspace. GAGAN consists of 3 geostationary satellites, 15 reference stations scattered over India, 3 uplink stations, and 2 control centers. GAGAN's operation is compatible with other SBAS systems like WAAS, EGNOS, and MSAS[56-58].

Other evolving and upcoming GNSS features like new civilian signals such as GPS L2C and L5 with new CNAV messages, GLONASS L3 CDMA, BeiDou B1C, B2a, B2b are expected to bring in the new scope of improving the GNSS performance globally. The accuracy of the navigation message parameters is under continual improvement to help the overall error budget in a single point and for relative positioning. Better accessibility of satellites and improvement of satellite geometry due to a larger number of available satellites, better tracking stability of receiver electronics, higher precession and faster initialization enabled by new signals, higher accuracy of broadcast ephemerides and clocks pave the improvement in space and ground control segments in the recent years. These factors enhance the scopes for accuracy and precision of solutions from sub-meter to sub-centimeter in various applications including those for the test range applications.

3.4 Low-cost, Compact, Multi-GNSS Modules

The availability of compact, cost, and power efficient, multi-GNSS enabled modules brought an important change in the GNSS hardware scenario. With a cost between 100-1000 USD and weighing within 100 grams, the modules are now being used for various positioning applications[55,59-62] in single point positioning and predominantly for RTK purposes providing moderate to high precision. Many manufacturers have introduced such modules in the market and more such products are expected to be introduced shortly. Dual frequency enabled, compact receivers are enhancing the scope of more precise SPP. For compact form factor, cost and power efficiency, multi-frequency operation, and ease of integration with other electronic subsystems, these modules have ample potential for test-range applications.

3.5 Multi-GNSS and the Indian advantage

India is favorably located within the Asia-Oceania region that has the advantage of simultaneously receiving signals from all global and regional GNSS constellations, and therefore has the potential for effective utilization of this Multi-GNSS signal environment. As of now, any GNSS hardware capable to track all GNSS constellations can use around 50 GNSS satellite signals simultaneously from India as shown in Fig. 4. This multi-constellation signal in space (SiS) volume is providing the Indian GNSS user community the benefits of redundancy, system-independence, better satellite geometry[63], and higher accuracy in comparison to stand-alone operation[64] for SPP, PPP, and RTK operation. From the strategic viewpoint, the multi-constellation would bring enhanced confidence in using GNSS for various applications. The associated issues in multi-GNSS hybrid operation are the inter-system biases, the difference in coordinate systems, and reference time frames for individual constellations. Many works have been done on the harmonization of multi-constellation operation, but more efforts are needed towards efficiently exploiting the advantages of the multi-constellation environment[65-67].

NavIC, the Indian regional indigenous navigation system provides extra advantages over the Indian region specifically from self-reliance in strategic applications. Operating from GEO and IGSO, the NavIC constellation provides satellite visibility from high elevation angles to counter the time and location-specific GNSS visibility problem during some parts of the day towards seamless and enhanced accuracy positioning[68-69]. Standalone NavIC SPP provides <5 m position solution accuracy as obtained from GLB under stand-alone, open sky operation of the ISRO-developed IRNSS-GPS-SBAS (IGS) receiver[69-70] and in future, differential NavIC (dNavIC) operation is expected to enhance the solution capability of NavIC. Similar to the DGPS base stations[71], NavIC Range and Integrity monitoring stations and properly designed permanent NavIC Base stations may be established at suitable locations near the test ranges to the dNavIC operation. The other associated differentiator in the case of NavIC is the provision of the S-band signal. S-band signals provide better 2dimensional (2d) solution precision in comparison to the L band operation[69] and this would enhance the resilience of the navigation system against the threats of jamming and spoofing, an important attribute for strategic

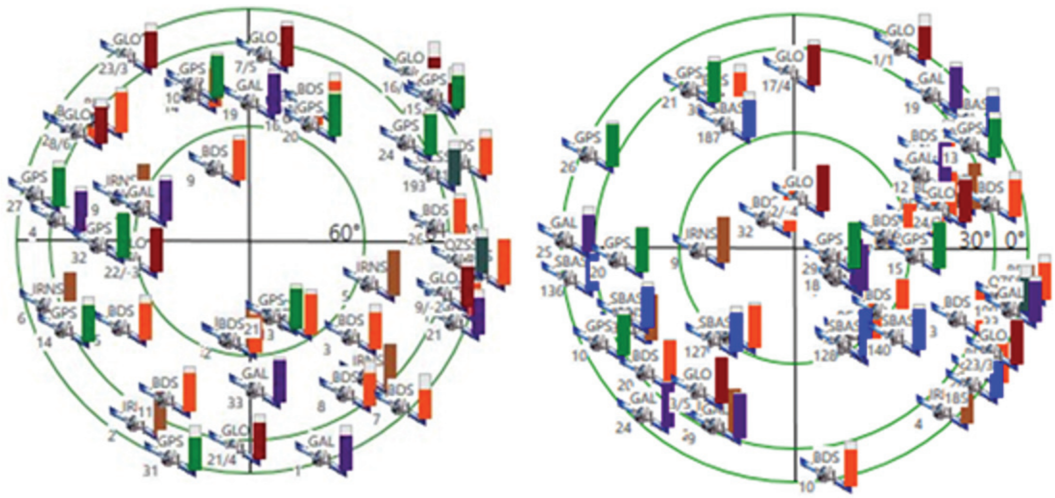


Figure 4. Typical skyplot screenshot from GNSS receiver operating in multi-GNSS from India. All global and regional satellites (GPS+GLONASS+Galileo+Beidou+NavIC+QZSS) are being tracked by a survey-grade receiver. From Burdwan, Eastern India; total 48 satellites in view, 46 used for the solution, 4 December 2019, 10:15 IST(Left). From Surat, Western India; total 54 satellites in view, 45 used for the solution, 23 June 2019, 18:11 IST(Right).

applications including the test-range requirements. The illegal, cheap, commercial GPS jammers and spoofers are found to operate over the L band; as of now, NavIC being the only system using S-band, and in-band jammer and spoofers are not commercially available protecting the operation in this band. But, the design of smart antenna, signal processing techniques, and signal authentication methods towards NavIC secured service would be a few of the open topics for research in cases of strategic and law enforcement applications.

Given the changing scenario of GNSS constellations, ever-improving positioning techniques, availability of low-cost and compact hardware, GNSS may be used effectively for strategic applications especially for the different phases of tracking in range applications. During the initial phase, the precision location of the EOTs plays a major role in the triangulation accuracy. As the EOTS are placed on static points, the EOT locations can be estimated to the accuracy of the centimeter-level by use of GNSS PPP. Data of sufficient period from a dual-frequency GPS/GNSS receiver from the location may be post-processed using standard GNSS data processing software to obtain sub-meter accuracy, or depending on the permitted strategic restrictions, the data may be uploaded to online data processing services to get 3d PPP solution accuracy to the order of few centimeters. SPP using survey-grade dual-frequency receivers may provide an order of 3m precision; nearly similar accuracy may be obtained using dual-frequency compact GNSS modules to save for cost, size, and power requirement; standalone SPP NavIC L5 operation can provide precision less than 5 m[55]. Therefore, in the initial tracking phase, GNSS/NavIC, or a combination may provide a higher accuracy level of precision for placement of the EOTS in achieving higher tracking precision of the missiles. In cases of the pre-launch helicopter-based surveys, RTK based positioning of the sorties may be useful by the creation of a base station at the launch location. Using the Radio Technical Commission for Maritime (RTCM) data streamed from the base to the helicopter (the Rover) through a dedicated radio frequency link, the precise location of the helicopter may be estimated with higher precision. Satellite-based augmentation system (SBAS) data, specially GAGAN, may also be used to carry out GPS-based differential operation, in terms of the strategic requirements.

In both the cases of the mid and terminal phase tracking, GNSS may support for providing accurate positioning of the ships carrying EOTS and radars through SPP more efficiently and precisely than the conventional methods. Over the maritime environment around India, a large number of satellite signals from multiple GNSS constellations would support redundancy, system independence, excellent satellite geometry, and enhanced solution accuracy in comparison to the single-constellation operations. GNSS can play an important role in the calibration of the sensors in terms of precise positioning and seamless availability.

4. CONCLUSIONS

In a multi-constellation GNSS signal environment, specifically in and around India, GNSS/NavIC may bring in several benefits for strategic applications including those for test-range purposes. The associated advantages are higher position accuracy, less manpower or resource requirement leading to economic implementation and time efficiency. All these may support repetitive calibrations for the sensors towards enhanced confidence within the same cost and time. With the availability of compact, low-cost GNSS modules and powerful UAVs and drones, it would also be interesting to explore the capabilities of drones and UAVs for pre-flight calibration instead of the helicopters once again saving cost and manpower. With the operation of NavIC and an achievable standalone accuracy limit of less than 5 m, specifically for the strategic applications, standalone NavIC may be used to serve many requirements in a self-reliance manner. In the future, differential NavIC operation would bring in improved quality of solution benefitting such applications. As of now, the concurrent operation of multiple GNSS systems ensures redundancy and system independence. Each of these systems has developed a large commercial userbase, and therefore, in a competitive scenario, the system operators are engaged in providing the best possible service quality to the users and in continuous development of the systems. Therefore, the advantages of the existing GNSS systems can be exploited for enhanced efficiency for test range applications. Future works in this aspect may be to explore the capabilities of GNSS to provide high accuracy, high-rate relative positioning in dynamic platforms like a helicopter landing on moving vessels, differential NavIC with higher precision for self-reliance in strategic applications, and use of low-cost RTK for accuracy enhancements of UAV or drone-based positioning applications.

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