IRNSS Orbit Determination and Broadcast Ephemeris Assessment

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BIOGRAPHIES

Oliver Montenbruck is head of the GNSS Technology and Navigation Group at DLR's German Space Operations Center, Oberpfaffenhofen. His current research activities comprise spaceborne GNSS receiver technology, autonomous navigation systems, spacecraft formation flying and precise orbit determination as well as new constellations and multi-GNSS processing. Oliver Montenbruck presently chairs the GNSS Working Group of the International GNSS Service and coordinates the performance of the MGEX Multi-GNSS Experiment. He authored numerous technical papers and various textbooks related to his fields of work.

Peter Steigenberger is scientific staff member at DLR's German Space Operations Center (GSOC) in Oberpfaffenhofen. His research interests focus on GNSS data analysis, in particular precise orbit and clock determination of GNSS satellites. A special focus are the evolving navigation systems Galileo, BeiDou, and QZSS.

Stuart Riley is Director of Engineering at Trimble Navigation, where he has worked on the last five generations of Trimble's precision GNSS baseband chip. He now manages a multi-discipline product development team as well as the core GNSS baseband team. His current research interests include improving GNSS performance in harsh environments, along with optimizing the GNSS receiver architecture especially for the newer GNSS signals. Prior to joining Trimble in 1995, Stuart completed an Electronic Engineering PhD in the field of GNSS at the University of Leeds in the UK. After he graduated he was a Research Fellow at the University on an ESA funded project to develop a prototype GNSS receiver for space applications.

ABSTRACT

The Indian Regional Navigation Satellite System (IRNSS) is an emerging satellite based navigation system offering an independent positioning and timing service over India and neighboring regions. Based on satellite laser ranging data collected by selected stations of the International Laser Ranging Service (ILRS) precise orbits have been determined for the first pair of inclined geosynchronous satellites (IRNSS-1A/B). These orbits are used to assess the quality of the IRNSS navigation messages. A Signal-in-Space Range Error (SISRE) at the five meter level is confirmed, which is consistent with the accuracy assessment given in the message itself. Even though the current 3 satellite constellation does not yet support standalone navigation, the results offer a first indication of the navigation quality that can be expected by future users in the area.

INTRODUCTION

The Indian Regional Navigation Satellite System (IRNSS) is an independent navigation system that will be made up of seven satellites in inclined geosynchronous orbit (IGSO) and geostationary Earth orbit (GEO) [1]. Its primary service area will cover the Indian sub-continent and extend by about 1500 km around its political borders. A much larger secondary service area extends from 30° to 130° east longitude and 30°S to 50°N latitude [2],[3].

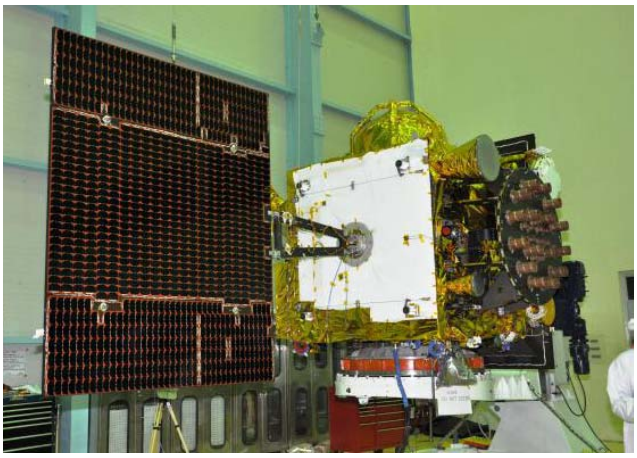

Figure 1 IRNSS-1B satellite in clean room at the Sriharikota launch site (image credit: ISRO).

The first two IGSO satellites (IRNSS-1A/B) were launched in the summer of 2013 and 2014, respectively. The spacecraft shown in Fig. 1 have a body size of about 1.5 x 1.5 x 1.5 m^3, and a total mass of 1400 kg at lift-off (including 800 kg of fuel). Their navigation payload includes redundant Rubidium Atomic Frequency Standards [3], L/S-band transmitters and a corresponding antenna. For validation purposes, the satellites are, furthermore, equipped with a laser retroreflector array (LRA, [5]).

At an orbital period of one sidereal day and inclinations of 27.5° and 30.8° the ground tracks of IRNSS-1A/B describe a figure-of-eight centered around 55°E longitude (Fig. 2). A first GEO satellite (IRNSS-1C; 83°E) was added to the constellation in October 2014 but has not yet been considered in the present study.

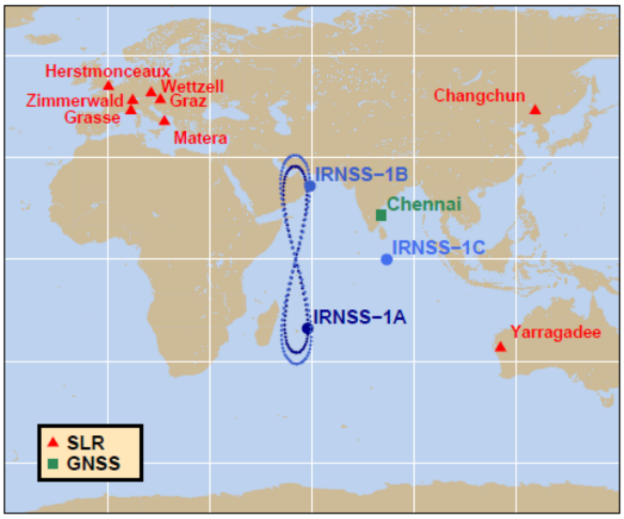

Figure 2 Ground tracks of IRNSS-1A/B on Oct. 20, 2014 and orbital location of IRNSS-1C. Furthermore, the location of ILRS stations contributing satellite laser ranging of the IRNSS satellites and the location of the IRNSS capable multi-GNSS receiver used in this study are indicated by the respective markers.

Even though a public Interface Control Document (ICD) describing the freely accessible Standard Positioning Service (SPS) was only released in Sep. 2014 [6], key signal properties could already be identified shortly after the launch of IRNSS-1A through inspection with a high gain antenna [7]. In particular, the code generators of the open service signals could be revealed from an analysis of the observed chip sequence. This enabled development of a prototype receiver that has been used to track IRNSS-1A (and later -1B) for more than a year before the ICD release. At its location in Chennai, India, the station has full and continuous visibility of the entire IRNSS constellation (Fig. 2).

Other than existing global and regional systems, IRNSS uses only one signal frequency (L5, 115·10.23 MHz = 1176.45 MHz) in the common L-Band, while an S-band frequency (243.6·10.23 MHz = 2492.028 MHz) has been selected for the second signal. In view of this frequency plan, existing multi-GNSS receiver hardware is essentially limited to tracking of a single open service signal in the L5 band. The same applies to the prototype receiver used in this study, which offers single-frequency L5 observations of IRNSS. Aside from collecting high-quality pseudorange, carrier phase and Doppler observations, the receiver already enabled the extraction and Viterbi decoding of the SPS navigation message using basic information of the envisaged message structure presented in [2]. Even though the full message contents could only be decoded after public release of the SPS ICD, the raw navigation frames were stored on a largely continuous basis since the start of receiver operation. This archive now enables a long-term monitoring of the IRNSS navigation message performance over most of the ongoing, pre-operational phase of IRNSS.

Due to the limited number of IRNSS-capable receivers available for this study and the additional restriction of single-frequency observations, it was not possible so far to determine the orbits (and clock offsets) of the IRNSS satellites using only GNSS observations. However, all IRNSS satellites are equipped with a laser retroreflector array, which enables highly accurate distance measurements based on the turn-around time of laser-pulses. Using SLR measurements collected by the International Laser Ranging Service (ILRS, [8]) on a routine basis since shortly after launch, the orbits of IRNSS-1A and -1B have been determined. These orbits can then be used for comparison with the received broadcast ephemerides.

Within the following sections, the orbit determination methodology is first described and the achieved accuracy is assessed through various types of self-consistency tests. Subsequently, the properties of the IRNSS navigation message are discussed and the information decoded from the raw navigation frames of the Chennai receiver is discussed. The contribution of ephemeris errors to the Signal-in-Space Range Error (SISRE) is assessed based on the SLR residuals relative to broadcast orbits as well as a 3D comparison of SLR and broadcast orbits. Finally, pseudorange observations from the Chennai receiver are compared to a precise point positioning solution for an independent SISRE characterization considering both orbit and clock errors. All analyses are based on observations of the IRNSS-1A/B satellites collected up to and including October 2014.

ORBIT DETERMINATION

SLR Tracking

Satellite laser ranging measurements of IRNSS-1A and IRNSS-1B have been collected by a total of 8 ILRS stations. As shown in Fig. 2, most of these stations are located in central Europe. They are complemented by a single station in Western Australia (Yarragadee), and, occasionally, a Chinese SLR station.

Table 1 SLR normal points collected by individual ILRS stations for IRNSS-1A (2013/09/17–2014/10/24) and IRNSS-1B (2014/05/09–2014/10/24).

Station	IRNSS-1A	IRNSS-1B
Changchun	55	2
Grasse	438	217
Graz	421	108
Herstmonceux	98	67
Matera	154	-
Wettzell	166	85
Yarragadee	501	210
Zimmerwald	450	256

While the overall observation geometry is not very favorable, it is still sufficient to determine the orbits of the IRNSS satellites without complementary data. Other than GNSS pseudorange or carrier phase observations, which measure the light-time by comparison of the transmitter and receiver clock, SLR is a two-way measurement system, which uses a single clock to determine the turn-around light time between transmission and reception of a laser pulse. As such, it does not involve an unknown clock difference and exhibits only very small, mm- to cm-level biases.

Over a one year time frame, some 2000 normal points have been obtained, where each normal point represents an average of multiple return echoes received within a 5 min time window (Table 1). Depending on the particular laser and timing system employed at a given station, individual high-rate measurements within a normal point exhibit a scatter of about 5-25 mm. A timeline showing the number of SLR normal points for each of the two spacecraft is shown in Fig. 3.

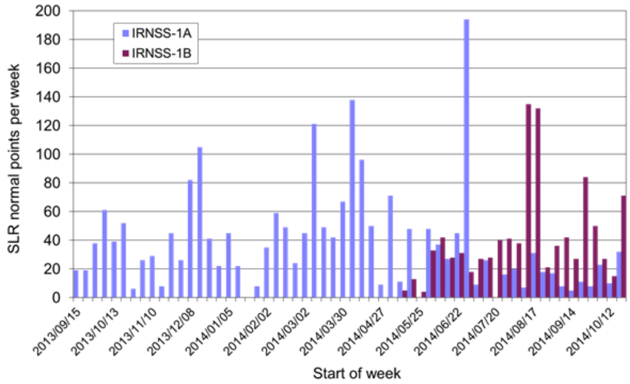

Figure 3 Number of weekly SLR normal points for IRNSS-1A and -1B (Sept. 2013 to Oct. 2014).

Models

With an average of just a few normal points per day, SLR observations of IRNSS are fairly sparse compared to the GNSS observations that are most commonly used for precise orbit and clock determination of navigation satellite systems. A high-fidelity dynamic orbit model is therefore required to recover the motion of the satellites from observations over multiple revolutions.

Within this study, the gravitational forces of the Earth, Sun, and Moon as well as the dominant planetary perturbations are taken into account (Table 2). Solar radiation pressure (SRP) represents the largest non-gravitational perturbation and can induce orbit variations at the 100 m level over a revolution. Since detailed dimensions and optical properties of the IRNSS satellites are not publicly released, no a priori model is available to compute at least rough values of the SRP in the orbit computation. A purely empirical approach is therefore used, which describes the solar radiation pressure by a constant term and once-per-rev harmonics along three axes, aligned along the Sun direction (D), the solar panel rotation axis (Y) and the orthogonal (B) direction:

$$\boldsymbol{a}_{\mathrm{SRP}} = \begin{pmatrix} D_0 \\ Y_0 \\ B_0 \end{pmatrix} + \begin{pmatrix} D_c \\ Y_c \\ B_c \end{pmatrix} \cdot \cos(u) + \begin{pmatrix} D_s \\ Y_s \\ B_s \end{pmatrix} \cdot \sin(u) \quad . \qquad (1)$$

Here, u denotes the argument of latitude of the satellite, i.e. the orbit angle since the last passage of the ascending node. This parameterization has originally been introduced by the Center for Orbit Determination in Europe [9] and is hence known as the CODE model. It is particularly suitable for satellites performing yaw steering attitude control to keep the solar panel rotation axis perpendicular to the Sun-s/c-Earth plane. The model involves a total of 9 coefficients that may either be fixed to a priori values or adjusted within the orbit determination. For IRNSS an arc length of two weeks is employed and a subset of 5 parameters (3 constant terms and the 1/rev harmonics in B) is estimated. Different a priori constraints

Table 2 Models for SLR-based orbit determination of the IRNSS satellites as employed in the SLRORB software.

Orbit Model	
Earth gravity	GGM01 model 20 x 20
Third-body perturbations	Sun, Moon, Venus, Mars, Jupiter
Relativity	Post-newtonian approximation
Solar radiation pressure	Empirical CODE model, conic shadow model
Reference system transformations	Precession, nutation, Earth rotation, polar motion (IERS 1996)
Numerical Integration	Shampine-Gordon variable-order, variable stepsize multistep method
Measurement Model	
Observations	5-min normal points
LRA offset (IGS frame)	(–0.436, +0.528, +1.112) m
Spacecraft attitude	Yaw-steering
Troposphere	Mendes & Pavlis (IERS 2010)
Relativity	Space-time curvature
Station tides	Solid Earth and ocean tides
Estimation	
Estimation parameters	Epoch state vector Constant accelerations in DYB-frame, and 1/rev in B
A priori constraints	State vector: none D_0: 100±50 nm/s^2 Y_0, $B_{0/C/S}$: 0±1 nm/s^2
Data arc	14 days

are adopted for the dominant D_0 term (which amounts to roughly 85 nm/s^2 for the IRNSS satellites) and the other parameters (Table 2). The given arc length has been found to be a suitable compromise between the number of available SLR normal points (roughly 40 per week) and the degradation of the orbit modeling over extended arcs.

Due to the resonant nature of their geosynchronous orbit, the IRNSS-1A/B spacecraft experience a secular change of their semi-major axis. At the given sub-satellite longitude (55° East) the semi-major axis decreases at an average rate of $\dot{a} \approx -0.1\,\mathrm{km/d}$. Orbit maintenance maneuvers are therefore conducted roughly once per month, during which the semi-major axis is increased by roughly 3 km. As part of the SLR data analysis, maneuvers can typically be recognized from increased residuals of SLR observations with respect to the predicted a priori orbit. Approximate maneuver times can then be inferred from the intersection of independent orbit determinations considering only pre-or post-maneuver data. Maneuver epochs identified in the analysis period are collated in Table 3.

Table 3 Orbit maintenance maneuvers of the IRNSS-1A and -1B satellites

IRNSS-1A	IRNSS-1B
2014/09/25 06h	
2013/10/29 04h	
2013/12/02 13h	
2014/01/15 11h	
2014/02/24 04h	
2014/03/28 03h	
2014/04/29 15h	
2014/05/29 15h	2014/05/30 04h
2014/07/08 15h	2014/07/02 02h
2014/08/14 11h	2014/08/06 03h
2014/09/18 11h	2014/09/12 02h
2014/10/18 10h	2014/10/20 18h

Since the laser retro-reflector array of the IRNSS satellites exhibits an offset of about 0.7 m from the z-axis through the center-of-mass, the modelled station-to-LRA range depends also on the instantaneous orientation of the spacecraft. For use within this study an ideal yaw-steering with a nadir pointing +z-axis and a sunlit +x panel has been adopted in accord with IGS conventions for GPS and GLONASS satellites. The actual IRNSS attitude control differs slightly from the GPS-type yaw steering by pointing the +z-axis towards a fixed point (+83°E, +5°N) on the Indian subcontinent in order to maximize the received power in the primary service area (A.S. Ganeshan, priv. comm.). Due to late availability, this information could not yet be considered in the present study. Neglect of the antenna pointing bias and bias may introduce range modeling errors at the level of 5-10 cm, which are, however, considered to be acceptable in the current context.

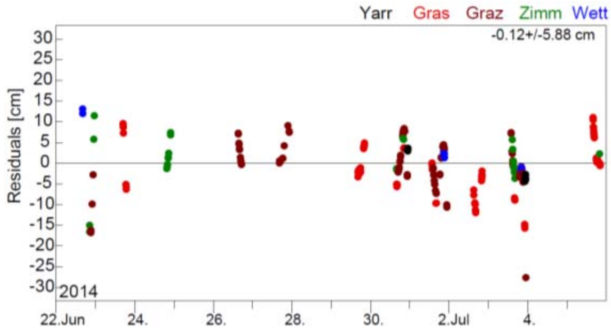

Figure 4 A sample set of post-fit SLR residuals for IRNSS-1A in a period of good SLR coverage. Colors identify data from individual SLR stations as listed in the header.

Results

For the chosen arc length (14 d) and adjustment parameters (state vector plus 5 empirical SRP model coefficients) post-fit SLR residuals at the few cm level (1-10 cm) are typically obtained (Fig. 4). While large residuals may indicate undetected bad data or orbit modeling deficiencies (e.g. small thruster activities) in the processing interval, extremely small residuals are often related to an insufficient number of observations for the given set of estimation parameters.

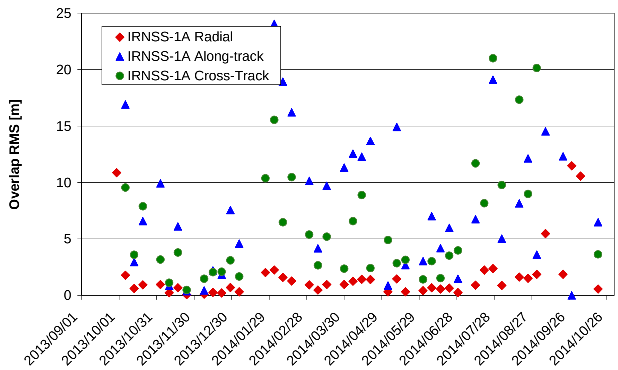

Figure 5 Consistency of consecutive 14 d SLR orbit determination results within the 7 d overlap interval for IRNSS-1A.

In the absence of external references, orbit overlaps have been used for the assessment of the orbit quality. To this end the entire data periods was processed in sliding batches of two weeks duration with a one week shift of the respective start epochs. Consecutive arcs thus exhibit a one week overlap, which provides a measure of the consistency of solutions using partly independent data. During maneuver-free periods and a representative SLR tracking coverage, a consistency of 2 m in radial direction, 15 m in along-track direction and 10 m in cross-track direction can typically be obtained (Fig. 5). Despite the high quality of SLR measurements, the achieved IRNSS orbit determination accuracy is about two orders of magnitude worse than the accuracy of individual observations. This reflects the impact of a very sparse overall tracking, a restricted distribution of tracking stations and potential deficiencies in the employed dynamical orbit model (e.g., radiation pressure and thruster activities).

For the further assessment of line-of-sight (LOS) ephemeris errors, the radial component is of primary relevance, though, since it is mostly parallel to the LOS. Along-track and cross-track errors, in contrast, contribute only a small fraction to the average range error. At geosynchronous altitudes this contribution amounts to roughly $1/11^{th}$ on average over the visibly surface of the Earth [10]. The errors of the SLR based orbit determination thus contribute a 2.5 m uncertainty to the (global) SISRE budget. While this is certainly much worse than common precise orbit products used for SISRE assessment of other GNSS constellations, it still enables a validation of the IRNSS broadcast ephemeris performance.

NAVIGATION MESSAGE

Overview

The IRNSS navigation message is structured into four subframes, each of which contains 262 bytes of data and takes 12 secs for transmission. The first two subframes provide the essential ephemeris data (i.e., orbit and clock information) and are repeated once every 48 s, while subframes 3 and 4 contain secondary data in a freely definable sequence. The secondary parameters include almanac and time system information but also differential correction and ionospheric grid data. Aside from a "normal" positioning service, IRNSS thus takes the complementary function of a satellite based augmentation system (SBAS). This is similar to BeiDou, except that all satellites (IGSOs and GEOs) of the IRNSS constellation can transmit the correction data, while this is only supported by the GEO satellites in BeiDou [11].

The IRNSS orbit and clock model is identical to that of GPS, which includes both the mathematical formulation and the associated physical constants (Earth gravitational coefficient, Earth rotation rate). Other than for BeiDou, the same algorithm and Keplerian elements set are used for both the IRNSS IGSO and GEO satellites. As discussed in [11]-[12], a tilted reference plane is used in BeiDou to cope with potential singularities in the orbit representation of the GEO satellites in view of their low inclination and a non-singular element set or Cartesian state vector representation is commonly considered to be more suitable for this type of orbits. Out of various possible options considered in pre-mission trade-off studies, the Keplerian elements representation has ultimately been adopted for IRNSS based on small upload requirements, the possibility to use a similar parameter set for almanac and ephemeris data and, finally, the communality with GPS [13]. It remains to be seen, whether the small inclination of the IRNSS GEO satellites affects the resulting ephemeris performance in an unfavorable manner.

In accord with the common models, the contents and representation of IRNSS ephemeris parameters is also closely aligned with that of GPS. Differences include changes in the least significant bit (LSB) and/or field width of the mean motion difference, the harmonic correction terms, and the nodal rate (Table 4). Despite a somewhat lower resolution of some parameters, the overall discretization error is well below the typical accuracy of broadcast ephemerides and does not affect the achievable user range accuracy in a detrimental way.

Table 4 Scale factor (LSB) and field size (in bits) of IRNSS and GPS ephemeris parameters with different representation.

Parameter	IRNSS		GPS	
	LSB	Size	LSB	Size
Δn	2^{-41}	22	2^{-43}	16
C_{uc} , C_{us}	2^{-28}	15	2^{-29}	16
C_{ic} , C_{ic}	2^{-28}	15	2^{-29}	16
C_{rc} , C_{rs}	2^{-4}	15	2^{-5}	16
$\dot{\Omega}$	2^{-41}	22	2^{-41}	24

As a special feature, IRNSS offers the capability of "frequent updates", which are enabled by the permanent visibility of all IRNSS satellites from the spacecraft control facilities in Hassan and Bophal. While new ephemeris parameters are nominally uploaded once every two hours, a refresh interval down to 15 min is achieved during "frequent update" mode. The two modes can also be distinguished from the "Issue of Data Ephemeris and Clock" (IODEC) parameter provided in each ephemeris message [6]. While IODEC values of 0, 1,…, 11 signify "nominal" ephemeris sets (with associated reference epochs of 0^h, 2^h, …, 22^h), IODEC values of 160 to 254 are used to tag the "frequent" sets with epochs of approximately $(\text{IODEC}-160)\cdot 15^m$ after midnight. The frequent update mode is commonly employed in the vicinity of orbit correction maneuvers (see Table 3) and enables a continued use of the respective satellites without setting its navigation health status to invalid.

Orbit Comparison

Raw navigation frames of IRNSS-1A have been collected with the Trimble prototype receiver at Chennai, India, since fall 2013. While the navigation frames were populated with coarse ephemeris data at all times, a comparison with the SLR-based orbit determination results suggests that the routine generation and upload of accurate ephemeris data started only in mid-February, 2014.

A sample comparison for the full month of June 2014 is shown in Fig. 6. The time interval has been selected based on the continued recoding of navigation data at the Chennai station, an adequate coverage with SLR tracking and the absence of orbit correction maneuvers.

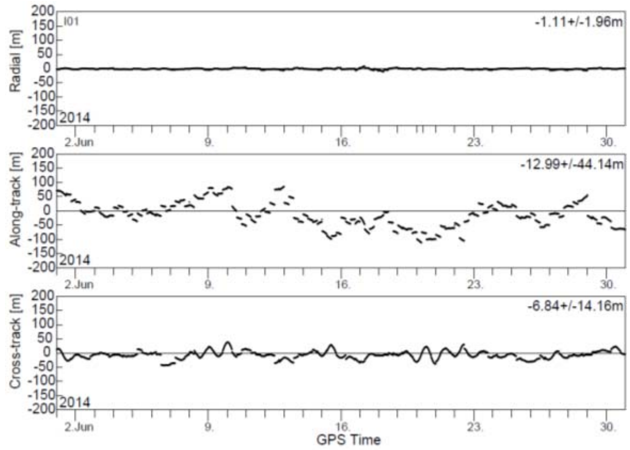

Figure 6 Comparison of IRNSS-1A broadcast orbits with SLR-based reference orbits for June 2014.

While a good consistency is obtained for the radial component, the cross-track and, most notably, the along-track component shows errors at the 10-50 m RMS level, which clearly exceed the reference orbit uncertainty. Even though only a small fraction of the latter components (roughly 9%) contributes to the global RMS user range error, the along-track error ultimately dominates the global orbit-only SISRE value of about 5 m. Similar values are obtained in other months with proper data coverage (Table 5).

Table 5 Orbit-only contribution of broadcast ephemeris uncertainties to the Signal-in-Space Range Error from comparison with SLR-based reference orbits. Values in brackets are based on incomplete data sets affected by extended data collection gaps.

Month	IRNSS-1A	IRNSS-1B
2014/03	(6.9 m)	
2014/04	(4.8 m)	
2014/05	7.9 m	20.4 m
2014/06	4.9 m	7.1 m
2014/07	4.6 m	3.6 m
2014/08	(3.4 m)	(8.1m)
2014/09	(5.2 m)	(8.9 m)
2014/10	5.7 m	15.2 m

For IRNSS-1B navigation data were made available soon after orbit injection even though the accuracy during the first month did not yet reach the normal performance. From June onwards an average orbit-only SISRE of about 8 m was obtained each month, which is somewhat lower than the performance of IRNSS-1A in the same period.

A noteworthy feature of the along-track error pattern, which can be recognized from Fig. 6, is the frequent occurrence of discontinuities. These may amount to several tens of meters and substantially exceed the otherwise smooth variation over time.

For further illustration, a zoomed version covering a time interval of only two days is shown in Fig. 7. Within this period, a new ephemeris set is transmitted once every two hours in accord with the nominal update scheme.

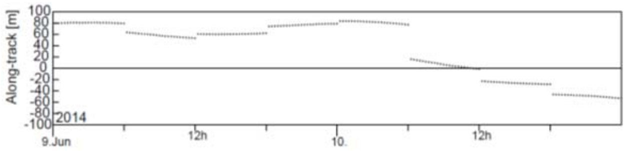

Figure 7 Short-term variation of broadcast ephemeris errors in along-track direction. Individual data points are separated by 15 min.

At the given scale, a smooth and continuous orbit representation is evident over three consecutive 2 hour intervals, while larger discontinuities occur at integer multiples of 6 hours. Obviously, these discontinuities are related to uploads of new orbit information by the ground control center that occur at this interval. Following [14], the IRNSS broadcast ephemeris parameters are derived from a real-time orbit determination process but only updated at intervals of up to one day. The observed discontinuities suggest that the along-track motion can only be predicted with limited accuracy from the filtered orbit estimate and further refinement of the tracking and orbit determination would be required to achieve a broadcast ephemeris accuracy comparable to GNSS constellations in medium altitude Earth orbit (MEO). It must be emphasized, though, that the contribution of orbit determination/prediction errors to the broadcast SISRE appears compatible with the overall expectation of a 10-20 m positioning accuracy for the final IRNSS in the planned service regions, where PDOP values of about 3-4 can be achieved [14]. Furthermore, broadcast ephemeris errors can readily be mitigated in IRNSS by the transmission of differential correction data for users in the primary service area.

Line-of-Sight Range Error

For an independent verification of the SISRE assessment given above, a direct comparison of SLR observations with IRNSS broadcast orbits has been performed to assess the orbit contribution to the line-of-sight range error.

Table 6 Line-of-sight error (RMS) of IRNSS broadcast orbits based on SLR residuals.

Month	IRNSS-1A	IRNSS-1B
2014/03	6.3 m	
2014/04	5.5 m	
2014/05	4.1 m	2.5 m
2014/06	4.7 m	4.6 m
2014/07	3.7 m	5.7 m
2014/08	2.8 m	2.3 m
2014/09	7.6 m	7.0 m
2014/10	6.3 m	9.1 m

As shown in Table 6, the monthly root-mean-square SLR residuals are slightly smaller than the SISRE values inferred from the orbit comparison, but still amount to 3-5 m in most cases. While both methods are based on SLR observations, the residuals analysis is limited to a small set of stations in specific geographic regions and the sparse epochs with SLR tracking points. In contrast to this, the SISRE derived from the orbit comparison represents a global average and is potentially affected by a larger contribution of along-track and cross-track errors. Furthermore, errors of the SLR-based orbit determination itself map into the broadcast orbit assessment and cause a less favorable SISRE budget.

Clock Offset

The IRNSS satellites are equipped with redundant Rubidium oscillators as their primary frequency standards. Following diverse press statements [3],[16], the clocks are manufactured by Spectratime, Switzerland, which also provided similar clocks for the GIOVE and Galileo program. Up to four clocks are reported to be used in each spacecraft.

As illustrated in Fig. 8, the clock offset of IRNSS-1A and -1B remained within a limit of ±1 ms at all times. During the first six months of operation, a notable frequency drift can be observed on IRNSS-1A, which resulted in a quadratic variation of the clock offset. Even though the ephemeris format supports provision of a full second order clock polynomial, the a_{f2} has so far been set to zero at all times. Starting in March 2014, the frequency drift of IRNSS-1A was reversed and the clock offset is now gradually decreasing.

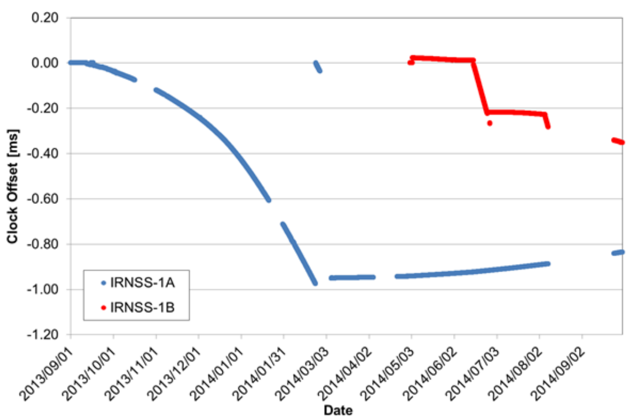

Figure 8 Clock offset variation of IRNSS-1A/B as reported in the broadcast navigation message. Data gaps are caused by non-availability of the employed test receiver in the respective periods.

On IRNSS-1B, the clock frequency was largely stable except for two short periods in June and August 2014, where a frequency offset of about 22 µs/day was encountered.

PPP Residuals

The SLR based analysis of IRNSS broadcast ephemerides is naturally restricted to the impact of orbit errors on the signal-in-space range error. To assess the combined contribution of orbit and clock errors, the residuals of IRNSS pseudorange and carrier phase observations with respect to a precise point positioning solution have been analyzed for the Chennai monitoring station.

Kinematic stations coordinates as well as epoch-wise receiver clock offsets and tropospheric zenith delays were first obtained for a one-week period in a precise point positioning (PPP) solution using dual-frequency GPS code and phase observations along with precise ephemerides. Based on these data, modelled pseudoranges for IRNSS-1A and -1B were computed using satellite coordinates and clock offsets from the IRNSS broadcast ephemerides. Since the test receiver is presently limited to L5 single frequency observations, ionospheric path delays have been corrected using vertical total electron content (VTEC) data from global ionosphere maps (GIMs) along with a single-layer mapping function. For a rigorous elimination of ionospheric path delays, the ionosphere-free Group and Phase Ionospheric Correction (GRAPHIC, [17]) combination

$$G_{\mathrm{L5}} = \frac{1}{2}\left(P_{\mathrm{L5}} + \varphi_{\mathrm{L5}}\right). \tag{2}$$

of the L5 code and phase observation has, furthermore, been formed.

The resulting residuals between observed and modelled pseudoranges exhibit a mean offset of about 90 m (Fig. 9). This value comprises the difference of the respective time systems (IRNSS broadcast time scale vs. GPS precise ephemeris time scale) as well as a receiver specific differential code bias between GPS L1/L2 and IRNSS L5 observations. In the absence of external information, the two contributions cannot be separated in a mixed constellation positioning and will typically be lumped into a combined intersystem bias (ISB, [18]) that is adjusted along with station coordinates, receiver clock offsets and, optionally, other estimation parameters.

Clock offset values in the IRNSS broadcast ephemerides are referred to a ionosphere-free combination of S-band and L5 observations. Single-frequency users must therefore consider the timing group delay parameter (TGD) to correct for satellite-specific differential code biases between the two frequencies. More specifically, the differential code bias between L5 single-frequency pseudoranges and the S/L5 ionosphere-free combination amounts to

$$\mathrm{DCB}_{\mathrm{L5\text{-}IF(S,L5)}} = \left(\frac{f_{\mathrm{S}}}{f_{\mathrm{L5}}}\right)^2 \cdot \mathrm{TGD} \approx 4.5 \cdot \mathrm{TGD}\,, \tag{3}$$

were f_{S} and f_{L5} denotes the respective signal frequencies of S-band and L5 observations. In addition, inter-signal-corrections (ISCs) are required to translate between regulated service (RS) signals and signals of the standard positioning service (SPS). While broadcast clock offsets where originally planned to be referred to RS observations [19], they can in fact be used directly by SPS users

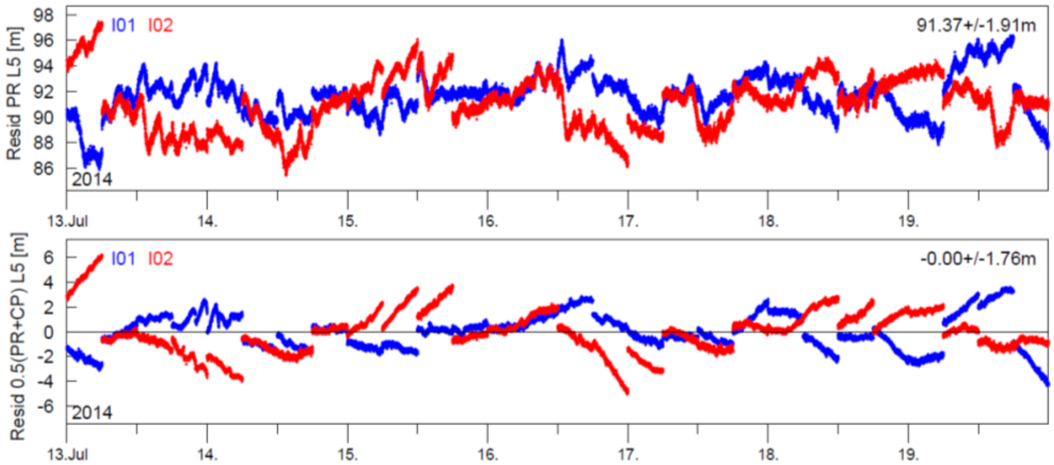

Figure 9 Residuals of GIM-corrected L5 pseudoranges (top) and GRAPHIC observations (bottom) relative to a GPS-only precise point positioning solution and IRNSS broadcast ephemerides for GPS week 1801 (13-20 July 2014). Blue and red colors refer to IRNSS-1A (PRN I01) and -1B (PRN I02), respectively.

without a need for further ISCs according to the current SPS ICD [6].

Table 7 Broadcast TGD parameters for IRNSS-1A and IRNSS-1B.

From	IRNSS-1A [ns]	IRNSS-1B [ns]
2013/09/01	-4.66	
2013/09/03	-4.13	
2013/09/04	-4.66	
2013/09/05	-4.13	
2014/05/05		9.31
2014/07/09	-5.59	8.38

Broadcast TGD parameters for IRNSS-1A and -1B amount to roughly -5 ns and +9 ns, respectively, which translates into corrections of -7 m and +12 m for the modelled L5 pseudoranges. However, a much better consistency of IRNSS-1A and -1B observations was in fact obtained *without* applying any TGD correction in the L5 single-frequency data processing. This is evidenced by Fig. 9, which shows the uncorrected pseudorange residuals of the two spacecraft. These exhibit a highly consistent mean value, whereas a 19 m difference would be obtained when applying the broadcast TGDs. It is unclear, at present, how to interpret this empirical finding.

The pseudorange residuals shown in Fig. 9 (top) exhibit a standard deviation of about 2 m, which provides an independent SISRE estimate covering both orbit and clock errors but may include residual ionospheric path delays due to imperfections of the GIM-based correction. In fact, a slightly smaller standard deviation is obtained from the GRAPHIC analysis (Fig. 9, bottom), which evidences a fairly smooth growth of the line-of-sight error within the 6 hourly updated intervals.

Overall, the GNSS-based SISRE estimate is well below the SISRE(orb) values of ~5 m that have previously been derived from the SLR observations. It may be noted, though, that the employed GNSS receiver is located well within the primary service area and the region covered by the IRNSS monitoring network. Here, the impact of IRNSS orbit determination errors on the line-of-sight range is typically minimized. The SLR stations, in contrast are located far off the service region where broadcast orbit errors result in larger projected orbit errors. For comparison with the above values, the User Range Accuracy (URA) transmitted in the period of interest ranges from 4-8 m.

SUMMARY AND CONCLUSIONS

An initial assessment of broadcast ephemeris errors for the first IRNSS satellites in inclined geosynchronous orbit has been performed using satellite laser ranging tracking and GNSS data collected with a first IRNSS prototype receiver. The analysis indicates a signal-in-space range error at a level of several meters, which is large consistent with the user range accuracy assessment in the broadcast navigation message and compatible with the planned positioning performance in the IRNSS services areas. However, the analysis is severely limited by the unfavorable regional and temporal distribution of SLR observations, which does not presently enable a highly accurate orbit determination. Likewise, the availability of only a single reference station and the limitation to single-frequency observation is a major obstacle for IRNSS performance monitoring.

It is unclear at present, when dual-frequency IRNSS receivers will become available for geodetic applications and when a sufficiently large network of monitoring stations can be deployed. Active contributions of research organizations in India and neighboring countries to the Multi-GNSS Experiment (MGEX, [20]) of the International GNSS Service (IGS) are strongly encouraged to promote this new navigation system, to increase its acceptance and to exploit the potential benefits of its unique design.

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REFERENCES

[1] Ganeshan A. S., Rathnakara S. C., Gupta R., Jain A. K. (2005) “Indian Regional Navigation Satellite System (IRNSS) Concept”, ISRO Satellite Center Journal of Spacecraft Technology, 15(2):19-23.

[2] Ganeshan A.S. (2012) “Overview of GNSS and Indian Navigation Program”, GNSS User Meeting, 23 Feb. 2012, ISRO Satellite Center, Bangalore.

[3] Saikiran B., Vikram V. (2013) “IRNSS Architecture and Applications”, KIET Int. J. of Comm. & Electron., 1(3):21-27.

[4] Malette L.A., Rochat P., White J. (2008) “An Introduction to Satellite Based Atomic Frequency Standards”, Aerospace Conference, Big Sky, Montana, 1-8 March 2008. DOI 10.1109/AERO.2008.4526366.

[5] IRNSS-1/B/C Retroreflector Array Characteristics; http://ilrs.gsfc.nasa.gov/missions/satellite_missions/current_missions/irna_reflector.html.

[6] ISRO (2014) “IRNSS Signal In Space ICD for Standard Positioning Service”, v. 1.0, June 2014, ISRO-IRNSS-ICD-SPS-1.0, Indian Space Research Organization, Bangalore.

[7] Thoelert S., Montenbruck O., Meurer M. (2014) “IRNSS-1A: signal and clock characterization of the Indian regional navigation system”, GPS Solutions 18(1): 147-152, DOI 10.1007/s10291-013-0351-7.

[8] Pearlman M.R., Degnan J.J., Bosworth J.M. (2002) “The International Laser Ranging Service”, Advances in Space Research 30(2):135-143, DOI 10.1016/S0273-1177(02)00277-6.

[9] Springer T., Beutler G., Rothacher M. (1999) “A new solar radiation pressure model for GPS satellites”, GPS Solutions 2(3):50–62.

[10] Montenbruck O. Steigenberger P., Hauschild A. (2014) “Broadcast versus Precise Ephemerides: a Multi-GNSS Perspective”, GPS Solutions, DOI 10.1007/s10291-014-0390-8.

[11] Montenbruck O., Steigenberger P. (2013) “The BeiDou Navigation Message”, Journal of Global Positioning Systems 12(1):1-12, DOI 10.5081/jgps.12.1.1.

[12] Du L., Zhang Z., Zhang J., Liu L. Guo R., He F (2015) “An 18-element GEO broadcast ephemeris based on non-singular elements”, GPS Solutions 19(1): 49-59, DOI 10.1007/s10291-014-0364-x.

[13] Neetha T., Kartik A., Ratnakar S. C., Ganeshan A S. (2011) “The IRNSS Navigation Message”, Journal of Spacecraft Technology 21(1):41-51.

[14] Sarma A. D., Sultana Q., Srinivas V. S. (2010) “Augmentation of Indian Regional Navigation Satellite System to Improve Dilution of Precision”, Journal of Navigation, 63(2):313-321.

[15] Rajaram B., Mula P., Rathnakara S. C. (2012) “Improved Orbit Determination Accuracy of IRNSS Satellite Using Combined Filter Smoother Method”, IAC-12-B2.6.5, 63rd Intl. Astron. Congress, Naples, Italy.

[16] http://www.elektronikbranche.de/Nachrichten/SpectraTime-bestueckt-das-IRNSS-mit-Rubidium-Atomuhren-Der-franzoesische-Anbieter-von-Navigationssystemen-erha-339.html.

[17] Yunck T.P. (1996) “Orbit Determination”; in: Parkinson B.W., Spilker J.J. (eds.); “Global Positioning System: Theory and Applications”. AIAA Publications, Washington DC.

[18] Montenbruck O., Hauschild A. (2013) “Code Biases in Multi-GNSS Point Positioning”, Proc. ION International Technical Meeting 2013, 28-30 Jan. 2013, San Diego, pp. 616-628.

[19] Majithiya P., Khatri K., Hota J.K. (2011) “Indian Regional Navigation Satellite System - Correction Parameters for Timing Group Delays”, Inside GNSS 6(1):40-46.

[20] Montenbruck O., Steigenberger P., Khachikyan R., Weber G., Langley R.B., Mervart L., Hugentobler U. (2014) “IGS-MGEX: Preparing the Ground for Multi-Constellation GNSS Science”, InsideGNSS 9(1):42-49.