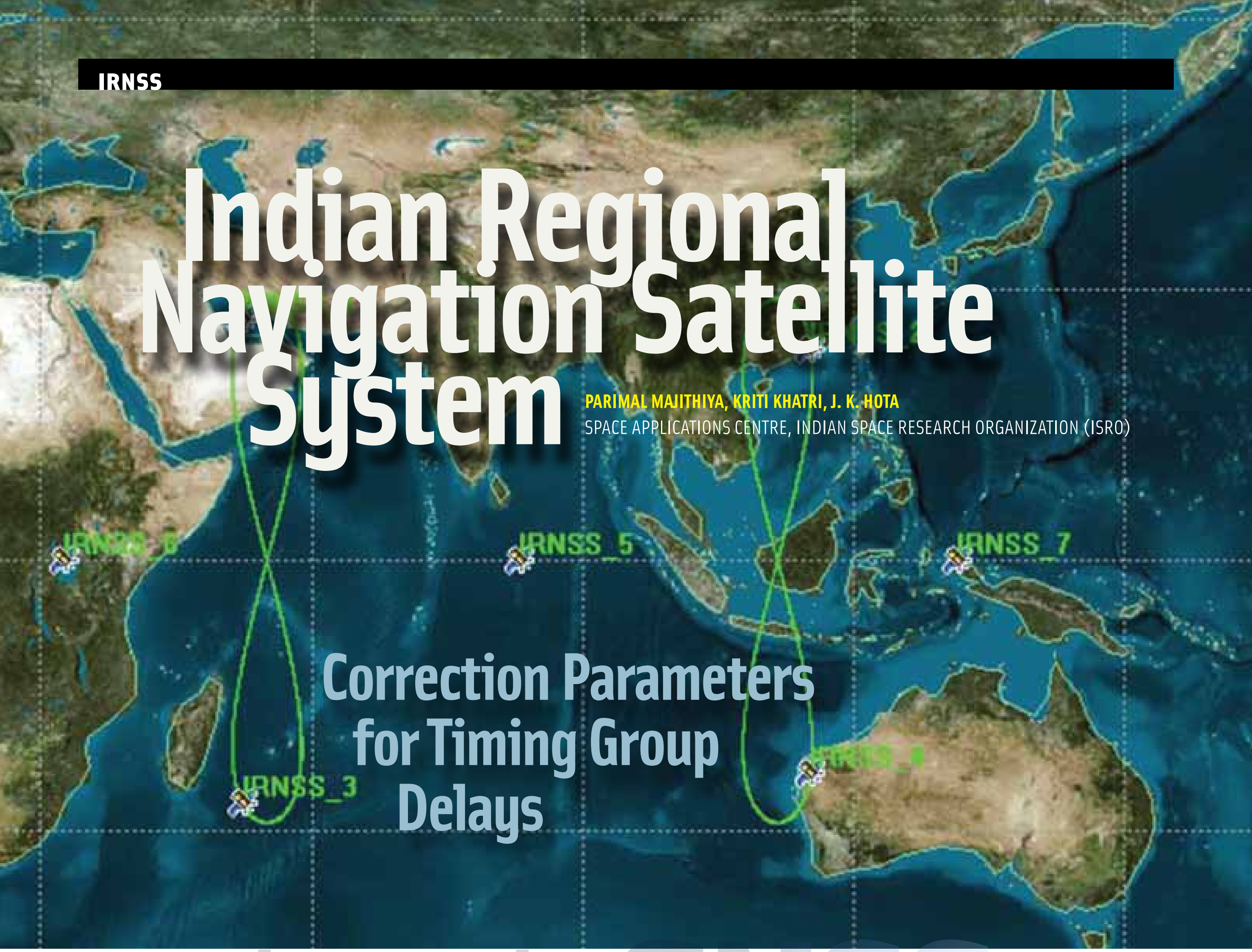

Indian Regional Navigation Satellite System

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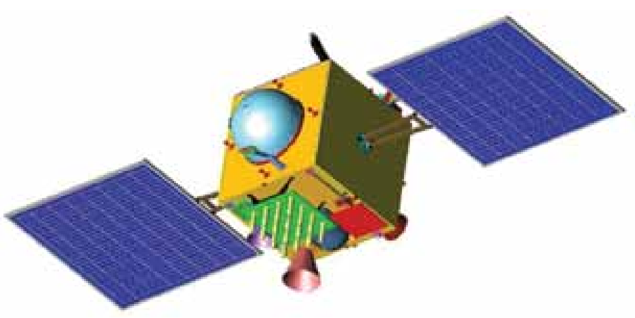
Correction Parameters for Timing Group Delays

India is developing a regional navigation satellite system that will broadcast GNSS signals — BPSK and BOC (5,2) — at L5 and S-band, with the first satellite scheduled for launch in the first half of 2012. As is common among GNSS services, the IRNSS signals will contain data to account for several sources of error, including a lesser-known source within a spacecraft itself: the hardware delay of the signal from its generation to radiation from the satellite antenna.

In satellite navigation, a GNSS receiver must account for several sources of error such as relativistic effects, atmospheric propagation delay, offset of satellite clocks from system time and satellite ephemeris. In order to accurately compute user position, velocity, and time (PVT), these errors need to be predicted/estimated precisely.

The navigation signals transmitted on each carrier frequency are imperfectly synchronized due to different hardware paths corresponding to each signal. Each satellite's navigation message contains parameters describing the timing bias. A user receiver uses these parameters to compute the clock correction for each observation.



Dual-frequency receivers directly employ such corrections. However, before a single frequency receiver can use the computed offset, it must be adjusted to account for the differential group delay between the principal signal and the signal on the other frequency. This timing group delay, annotated as T_{GD}, results from hardware differences in the onboard signal paths and will vary among satellites.

The dual-frequency signal timing difference is used to infer the line-of-sight delay caused by the ionosphere, subject to the bias difference between the satellite transmissions at the two frequencies. Recently, the satellite navigation community has improved the inter-frequency/signal correction values contained in navigation messages.

This article will describe the timing group delays anticipated in the Indian Regional Navigation Satellite System (IRNSS) and the inter-signal delay correction (ISC) parameters that will be included in the navigation messages in order to improve the system's PVT accuracy.

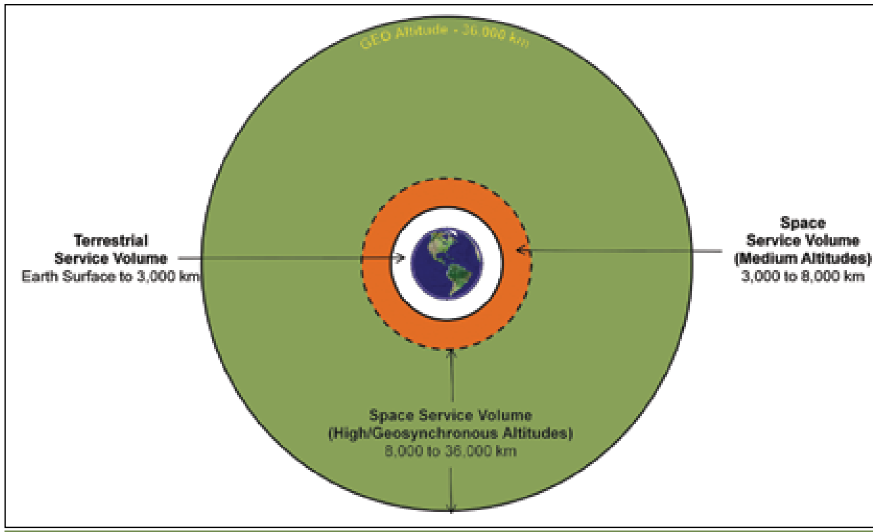
GNSS Service Regions

In the future, GNSS systems will have two types of service regions: a *terrestrial service volume* (TSV) and a *space service volume* (SSV). The IRNSS ISCs will take into consideration signal differences as they appear in these service regions.

We can characterize the TSV as a shell that begins at the surface of the earth and extends up to an altitude of 3,000 kilometers. The transmitted position-determination parameters are valid for the entire region, ensuring similar performance for all users within it. Users operating in the TSV have coverage from the main beams of the satellites.

The SSV is a shell extending from 3,000-kilometers to approximately the geostationary altitude, that is, around 36,000 kilometers. The SSV is further subdivided into two regions: from 3,000 to 8000 kilometers, and from 8,000 to 36,000 kilometers.

Space users (SU) will have varying levels of performance depending on the altitude. Within the SSV, nearly all navigation signals emanate from satellites across the limb of the Earth. Users within this region may experience periods during which no navigation satellite signals are available and, when they are, received power levels will be weaker than for the terrestrial users (TU). Timing correction for space users need to be provided. **Figure 1** shows the shells of the various service regions.



GNSS Service regions

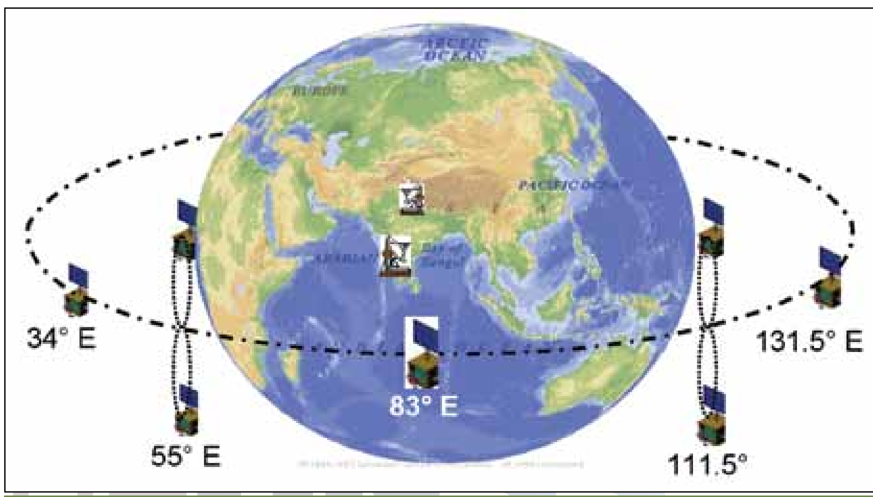


FIGURE 2 IRNSS constellations

IRNSS

The Indian Regional Navigation Satellite System envisages establishment of a constellation made up of a combination of geostationary Earth orbit (GEO) and geosynchronous orbit (GSO) spacecraft over the Indian region.

The IRNSS constellation will consist of seven satellites —three in GEO orbit (at 34° E, 83° E and 131.5° E) and four in GSO orbit inclined at 29 degrees to the equatorial plane with their longitude crossings at 55° E and 111.5° E (two in each plane) as shown in **Figure 2**. All the satellites will be continuously visible in the Indian region for 24 hours a day.

Figure 3 shows a detailed diagram of the IRNSS system configuration.

The IRNSS is expected to provide position accuracy (two sigma) of better than 20 meters over India and a region extending outside the land mass to about 1,500 kilometers. The system will provide two types of services, a *Standard Positioning Service* hereafter referred to as SPS, and a *Restricted/Authorized Service* or RS. Both of these services will be provided at two frequencies, one in the L5 band and the other in S-band.

SPS will use bi-phase shift keying BPSK(1) modulation, whereas the RS service will employ binary offset carrier (BOC (5, 2)) modulation. An additional BOC pilot signal is being provided for the RS Service in order to help provide better acquisition and performance. As each L5 and S band contains three signals, the IRNSS design adds an interplex signal in order to maintain the constant envelope characteristic of the composite signal.

The transmission is done using L-band and S-band helix array antenna to provide global coverage in right-hand circularly polarized (RHCP) signals. Thus, user receivers can operate in single- and/or dual-frequency mode.

The IRNSS ground segment includes the major systems for controlling the satellite constellation and will consist of the Spacecraft Control Facility (SCF), IRNSS Navigation Center (INC), IRNSS range and integrity monitoring stations (IRIMS), ranging stations, a timing center, telemetry, tracking, and control (TTC) and uplink stations, and data communication links.

Sixteen IRIMS sites will be distributed across the country for orbit determination and ionospheric modeling. Four ranging stations, separated by wide and long baselines, will provide two-way code division multiple access (CDMA) ranging. The IRNSS timing center will consist of highly stable clocks. The navigation center will receive all this data through communication links, then process and transmit the information to the satellites.

Timing Group Delay

The time of radiation of the navigation signals on each carrier frequency and among frequencies is not synchronized due to the different digital and analog signal paths that each signal must travel from the IRNSS satellite signal generator to the transmit antenna. This *hardware group delay* is defined as a time difference between the transmitted RF signal (measured at the phase center of a transmitting antenna) and the signal at the output of the onboard frequency source.

Three different parameters comprise this group delay: a fixed/bias group delay, a differential group delay and a group delay uncertainty in bias and differential value.

The *fixed delay* or hardware group delay is a bias term included in the clock correction parameters transmitted in the navigation data and is, therefore, accounted for by the user computations of system time in the appropriate GPS interface specifications cited in the Additional Resources section at the end of this article. More specifically, this delay represents the amount of time it takes the signal to start from the common clock, travel through each code generator, modulator, up-converter, transmitter, and finally emerge from the satellite antenna.

The hardware group delay uncertainty reflects the variability in the path delay due to changeable conditions in the operational environment and other factors. The effective uncertainty of the group delay will be in the range of few nanoseconds (on the order of one to three nanoseconds).

Each IRNSS navigation signal has two hardware paths — main and redundant. The hardware will be different for each path in terms of data generator, modulator, up converter, travelling-wave tube amplifier (TWTA), cable, and integration components.

In case of failure, the signal will be diverted from the main subsystem to the redundant subsystem. The delay of main and redundant subsystem will be different and thus cause a difference in the

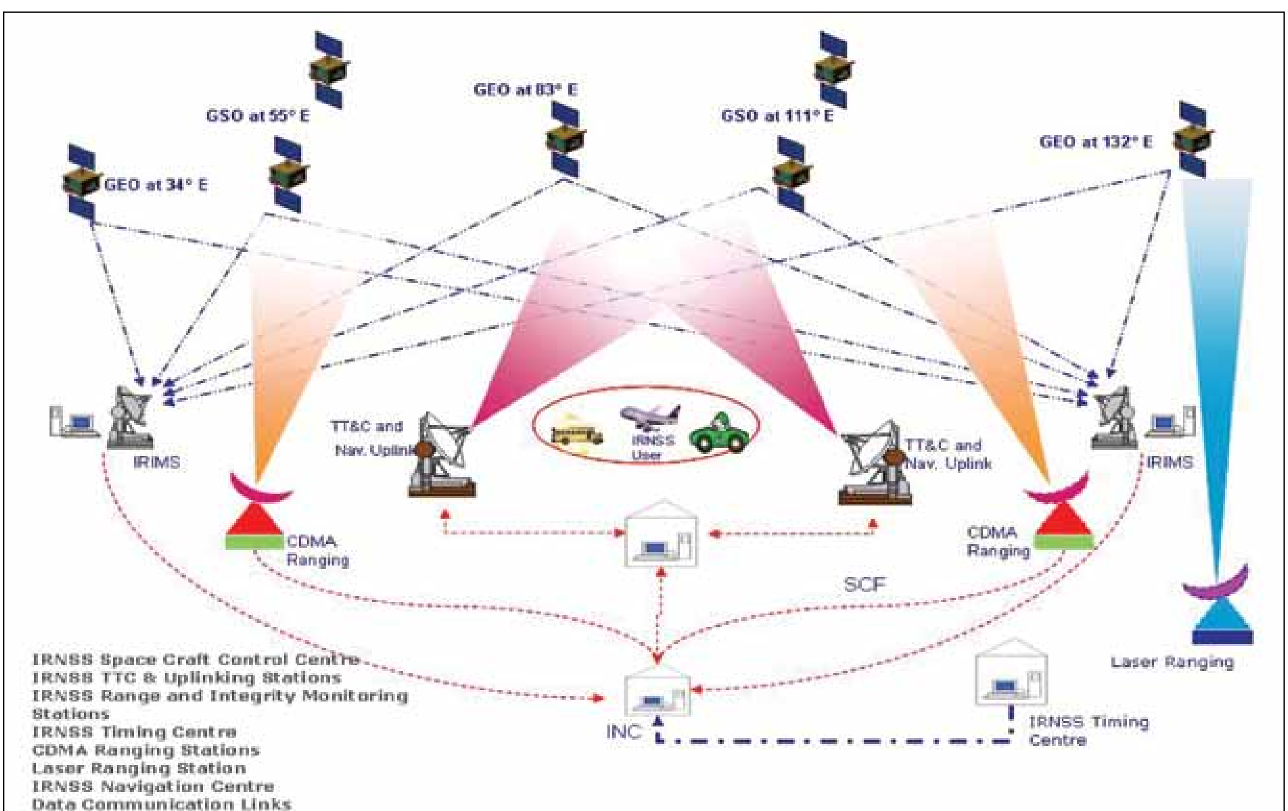


FIGURE 3 IRNSS system configuration

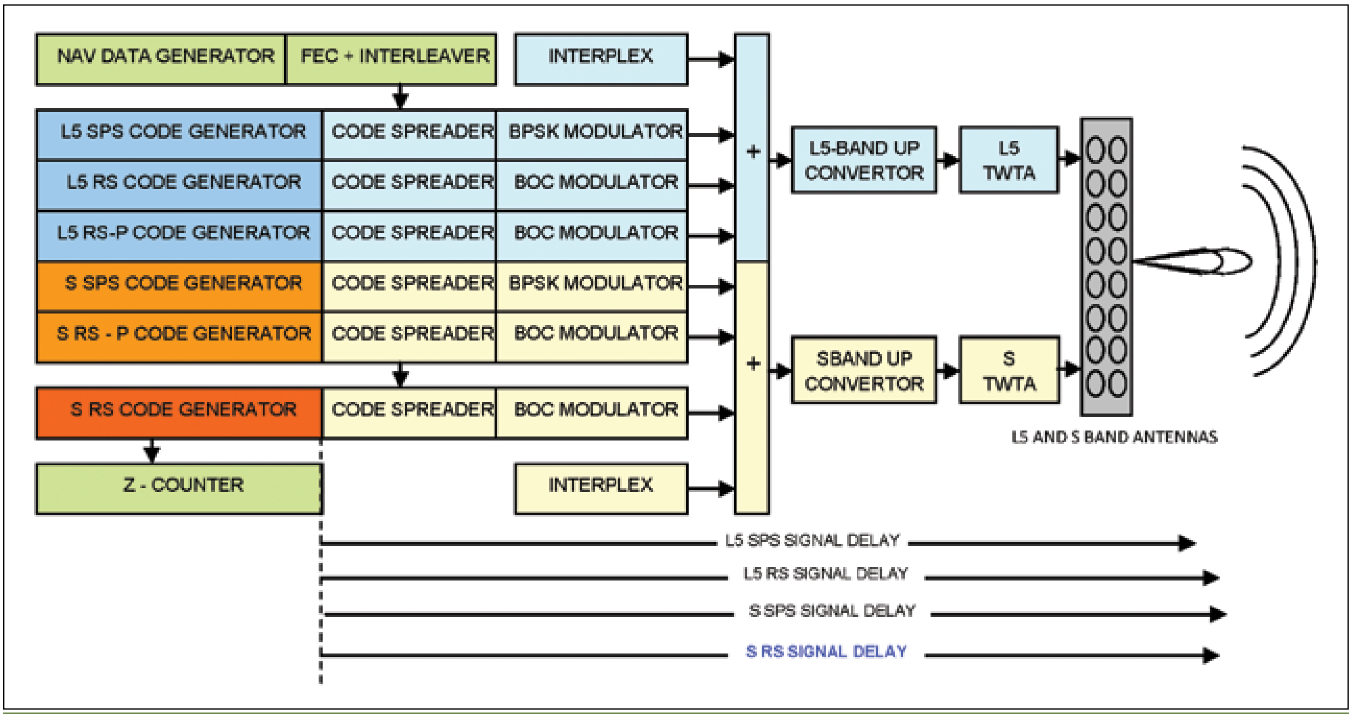


FIGURE 4 Navigation signal group delay in IRNSS Payload

mean path delay based on the selected path for the navigation signal.

Differential group delay is the difference in delays between two navigation signals. It consists of random plus bias components. The *mean differential* is defined as the bias component and will be either positive or negative. For a given navigation payload redundancy configuration, the absolute value of the mean differential delay shall not exceed a few nanoseconds, i.e., on the order of 15 to 30nsec.

The random variations about the mean will be in the range of one to three nanoseconds (two sigma). To correct the bias component of the group delay, T_{GD} and inter-signal correction (ISC) parameters are provided to the user in the navigation message, as described in the paper by C. Hegarty cited in Additional Resources.

The navigation signals in IRNSS are transmitted using helix array antennas, which will have amplitude and phase contours for an off-nadir angle. The delay variation depends on the off-nadir angle and frequency; so, there is a phase contour that gives a delay difference for space navigation users with respect to terrestrial users.

This latter delay bias, hereafter called space user delay (SUD), should be measured at the time of payload testing. The SUD will give additional accuracy to the space users who are using the signal over the limb of the earth at the off-nadir angle of greater than 8.4 degrees with respect to the IRNSS satellite. This bias term is frequency-specific and satellite-specific.

IRNSS Group Delay Parameters

The uploaded data and the onboard-generated data will be formatted in a specific IRNSS format. As code, data, sub-frames, and main frame are synchronized to the space vehicle (SV) time (t_{SV}), the principal code (RS) epoch is used to generate SV time.

The SV time is measured relative to the leading edge of the first chip of the first code sequence of the first frame symbol and represents the time of transmission of the signal from the satellite. The reference of transmission of signals is the antenna phase center. But, as mentioned earlier, a time delay occurs in the navigation payload between the time of signal generation and its actual time of transmission from the antenna array, as shown in Figure 4.

The six separate IRNSS signals each have different ranging codes. Each signal carries the same navigation data (except the dataless pilot signal– P). We identify the three signals in each frequency (L5 and S-band) as $L5_{SPS}/S_{SPS}$, $L5_{RS}/S_{RS}$ and $L5_{RS-P}/S_{RS-P}$, respectively.

Estimated Differential Group Delay. T_{GD} is a measured mean group delay differential of two frequency (S_{RS} and $L5_{RS}$) multiplied by the scaling factor

$$\frac{1}{(1 - \gamma_{SL5})}$$

The IRNSS control station generates T_{GD} to account for the effect of SV group delay differentials based on measurements made during payload ground testing at the time of manufacturing. This correction term is only for the benefit of "single-frequency" (S_{RS} or $L5_{RS}$) users.

Thus, T_{GD} is

$$T_{GD} = \frac{(t_{S-RS} - t_{L5-RS})}{(1 - \gamma_{SL5})} \qquad (1)$$

where,

$$\gamma_{SL5} = \left(\frac{f_S}{f_{L5}}\right)^2 = \left(\frac{2492.028}{1176.45}\right)^2$$

with f_{L5} and f_S denoting the nominal center frequencies of L5 and S, respectively, and $t_{S-RS/L5-RS}$ is the time of transmission from the satellite antenna phase center of an S/L5 frequency RS code signal (at a specific epoch of the signal).

For IRNSS, eight bits are allocated in the navigation message for T_{GD}, having 2^{-31} as the LSB (least significant byte) scale factor. The value of T_{GD} for each satellite may be subsequently updated based on estimation to reflect the actual on-orbit group delay differential because with time the value may change.

Group Delay Differential Correction. The satellite clock time used to solve for user position is

$$t = t_{SV} - \Delta t_{SV} \quad (2)$$

Where t_{SV} is the SV pseudorandom noise (PRN) code phase time at the time of transmission. Each user will use the satellite clock correction term (Δt_{SV}), which is approximated by a polynomial

$$\Delta t_{SV} = a_{f0} + a_{f1}(t - t_{oc}) + a_{f2}(t - t_{oc})^2 + \Delta t_R \quad (3)$$

Where a_{f0}, a_{f1}, a_{f2} are the polynomial correction coefficients corresponding to phase error, frequency error, and rate of change of frequency error, respectively. The relativistic correction term is Δt_R, and t_{oc} is a reference time for clock correction.

Satellite orbits typically have slight eccentricity and this causes the satellite to change the altitude periodically during the orbit. The relativistic periodic effect can be compensated by the correction term Δt_R as

$$\Delta t_R = F e\sqrt{a}.\ \sin E_k = 2\ R.\left(\frac{V}{c^2}\right)$$

where $F = -2\sqrt{\mu}/c^2$
μ= Earth universal gravitational parameter
c= speed of light
R= instantaneous position vector of the space vehicle
V= instantaneous velocity vector of the space vehicle
e= space vehicle orbit eccentricity
E_k= eccentricity anomaly of the satellite orbit
a = semi major axis of the satellite orbit

IRNSS Group Delay Correction Algorithm

GNSS receivers designed to process IRNSS signals should account for the group delays, depending on the specific signals used and the service region in which they will operate.

Single Frequency S-RS and L5-RS Users. Authorized terrestrial users who utilize the S_{RS} signal only shall modify the code phase offset in accordance with the equation

$$(\Delta t_{SV})_{S-RS} = \Delta t_{SV} - T_{GD} \quad (4)$$

where T_{GD} is provided to the user in the first subframe of navigation data.

The S_{RS} space user should incorporate the following equation instead of (4)to get additional accuracy:

$$(\Delta t_{SV})_{S-RS} = \Delta t_{SV} - T_{GD} - SUD_S \quad (5)$$

For the terrestrial user who utilizes $L5_{RS}$ only, the code phase modification is given by

$$(\Delta t_{SV})_{L5-RS} = \Delta t_{SV} - \gamma_{SL5} T_{GD} \quad (6)$$

The $L5_{RS}$ space user should use the following equation instead of equation – (6) to get additional accuracy:

$$(\Delta t_{SV})_{L5-RS} = \Delta t_{SV} - \gamma_{SL5} T_{GD} - SUD_{L5} \quad (7)$$

Single Frequency S-SPS and L5-SPS Users. By taking into account the code phase offset correction terms, single-frequency receivers can improve their positioning accuracy. The correction terms, ISC_{L5-SPS} and ISC_{S-SPS}, are initially provided by the control station to account for the effect of SV group delay differential between S_{RS} and $L5_{SPS}$ and between S_{RS} and S_{SPS}, respectively, based on measurements made during ground testing of payload at the time of manufacturing. The values of ISCs for each SV may be subsequently updated to reflect the actual on-orbit group delay differential.

The values of ISC are measured values that represent the mean SV group delay differential between the S_{RS} code and the respective signal as follows:

$$ISC_{ix} = t_{S-RS} - t_{ix} \quad (8)$$

where, t_{ix} is the IRNSS time of *i*th frequency *x* signal, i.e. $L5_{SPS}$, S_{SPS}, (at a specific epoch of the signal) is transmitted from the SV antenna phase center. ISC_{ix} is the inter-signal delay correction of *i*th frequency *x* signal.

For better accuracy, the single frequency terrestrial users must use the correction terms to make further modifications to the code phase offset with the equation

$$(\Delta t_{SV})_{ix} = \Delta t_{SV} - T_{GD} + ISC_{ix} \quad (9)$$

For space users, the code phase offset equation should be replaced with the following equation to obtain additional accuracy

$$(\Delta t_{SV})_{ix-SU} = \Delta t_{SV} - T_{GD} + ISC_{ix} - \frac{(SUD_S - SUD_{L5})}{(1-\gamma_{SL5})} \quad (10)$$

ISC_{L5-SPS}, ISC_{S-SPS}, SUD_S, and SUD_{L5} are provided to the user in the navigation data.

Corrected Pseudo Range For Dual Frequency Users. The estimated SV clock offset reflected in the a_{f0} clock correction coefficient is based on the effective PRN code phase as it appears with two-frequency (S_{RS} and $L5_{RS}$) ionospheric corrections. Thus, the user employing both L5 and S in the ionospheric correction need make no further correction.

The dual-frequency ($S_{RS}/L5_{RS}$) terrestrial user shall correct their measured pseudorange for the group delay and ionospheric effects by

$$PR_{RS-TU} = \frac{(PR_{L5-RS} - \gamma_{SL5} PR_{S-RS})}{(1-\gamma_{SL5})} \quad (11)$$

Space users should replace equation (11) with the following equation to get additional accuracy

$$PR_{RS-SU} = \frac{(PR_{L5-RS} - \gamma_{SL5} PR_{S-RS}) + c(SUD_{L5} - \gamma_{SL5} SUD_S)}{(1-\gamma_{SL5})} \quad (12)$$

Dual-frequency (S_{SPS} and $L5_{SPS}$) receivers for terrestrial users should correct their pseudorange for the group delay and ionospheric effects by applying the relationship

$$PR_{SPS-TU} = \frac{(PR_{L5-SPS} - \gamma_{SL5} PR_{S-SPS}) + c\,(ISC_{L5-SPS} - \gamma_{SL5} ISC_{S-SPS})}{(1-\gamma_{SL5})} - c.T_{GD} \qquad (13)$$

The space user should replace equation (13) with the following equation to get additional accuracy

$$PR_{SPS-SU} = \frac{(PR_{L5-SPS} - \gamma_{SL5} PR_{S-SPS}) + c\,(SUD_{L5} - \gamma_{SL5} SUD_S) + c\,(ISC_{L5-SPS} - \gamma_{SL5}\, ISC_{S-SPS})}{(1-\gamma_{SL5})} - c.T_{GD} \qquad (14)$$

where

$PR_{RS/SPS\text{-}TU/SU}$ = pseudorange corrected for ionospheric effects for RS/SPS-terrestrial/space users,

$PR_{RS/SPS}$= pseudorange measured for RS/SPS service,

$ISC_{RS/SPS}$ = inter-signal correction for RS/SPS service,

c = speed of light

Figure 5 shows the proposed group delay correction model for IRNSS single- and dual-frequency users. The ground control station will generate upload data based on predictions and estimates for the clock and atmospheric delay correction (Δt_{iono}, Δt_{tropo}). The relativistic effect will have clock offset Δt_R, which will be estimated by the user receiver from the satellite orbit data. The onboard clock will have a bias and will drift with time.

This correction will be done as per the coefficients transmitted in the navigation message. Equation 3 will be used to compute the clock correction. The total clock offset (Δt_{SV}) will be corrected by different users as Δt_{SVix} for ith frequency x users, where x is RS, SPS, and space users (SU).

Single-frequency receivers should correct ionospheric and tropospheric delay effect based on their cofficients to determine their pseudorange. Δt_{SVe} is the estimated clock error and will be predicted on ground.

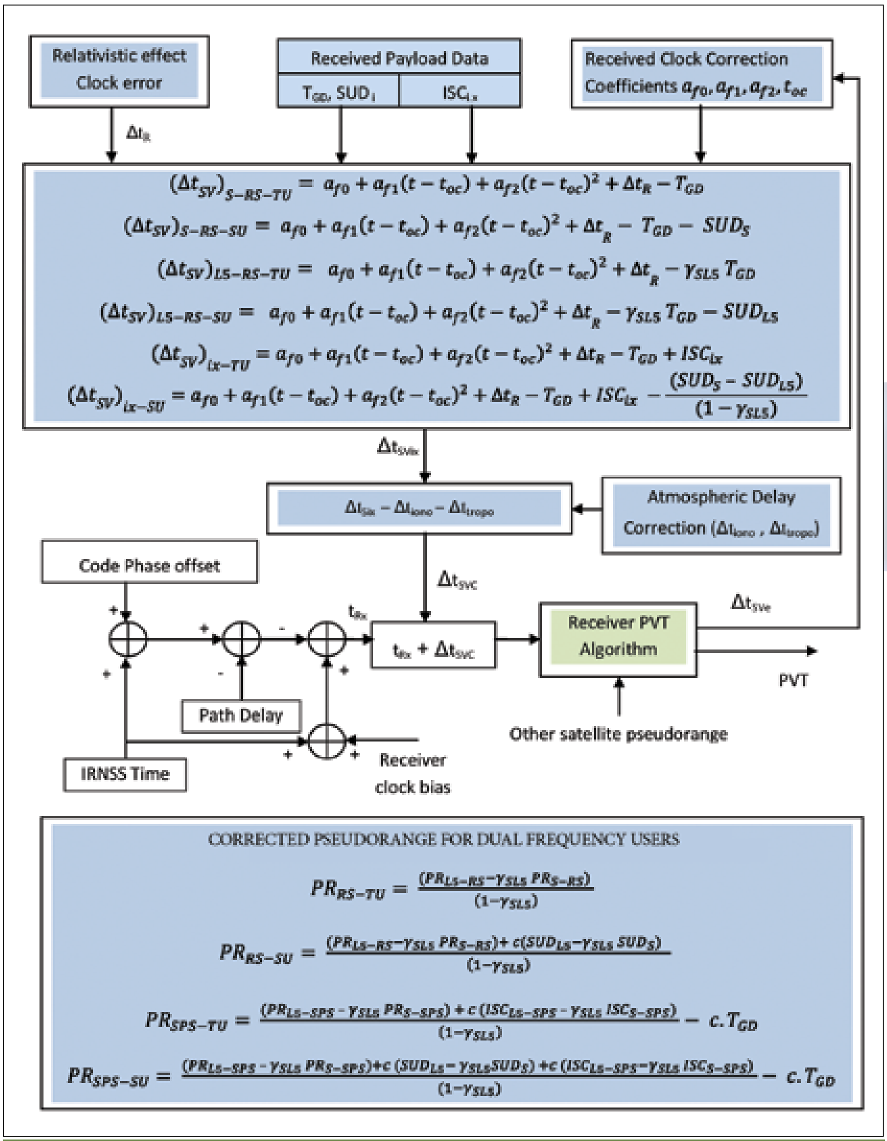


FIGURE 5 Proposed Group Delay Correction Model for IRNSS System

Conclusion

The IRNSS signal structure has one group delay differential correction parameter (T_{GD}). T_{GD} is to correct for S- and L5- band RS signal group delays. To obtain better position accuracy, other single-frequency users require inter-signal group delay correction parameters ($ISC_{L5\text{-}SPS}$, $ISC_{S\text{-}SPS}$). For space navigation users with off-nadir angles greater than 8.4 degrees with respect to an IRNSS satellite, an SUD correction is required. The SUD bias will provide additional improvement on the order of three nanoseconds to space users. These will be transmitted in navigation data in the future.

Acknowledgments

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Authors

Parimal Majithiya received his B.E. (electronics and communication) from Gujarat University and an M.Tech degree in satellite communications from Andhra University. He joined the Indian Space Research Organization (ISRO) in 1987 and worked in the field of satellite communication system engineering as a project manager. He has been extensively involved in the INSAT-2, INSAT-3, GSAT series, and in METSAT. He contributed in the areas related to regional satellite mobile communication system, on-board processor for satellite-aided search and rescue system, and optical inter-satellite link for data relay system. He has also given a novel onboard down link rain fade mitigation technique for multibeam Ka-band system. Presently he is working as a project manager for the IRNSS payload system engineering and contributed in defining IRNSS payload configuration and signal structure. He has developed many types of navigation-specific hardware for satellites, such as modulation scheme, composite signal generator, signal switching, and onboard clock synchronization. He may be contacted at <p_majithiya@sac.isro.gov.in>.

Kriti Khatri received her B.E (electronics and communication) from Maharishi Dayanand University. With SAC-ISRO since 2005, she is actively contributing towards the system engineering of IRNSS and GAGAN payloads. She has developed many navigation-specific hardware innovations for satellite, including modulation schemes, signal switching, and onboard clock synchronization.

J. K.Hota graduated in engineering from associated members of the Institution of Engineers India. He joined Indian Space Research Organization in 1976. His work has focused mainly on system engineering, integration and testing of satellite communication Earth stations and satellite payloads. He is currently working on the IRNSS project. IG