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IRNSS Satellite Parameter Estimation using Combination Strategy

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Abstract: Indian regional Navigation Satellite system (IRNSS) is going to be an independent, indigenous navigation satellite system fully controlled by India, planned by ISRO. A system was designed of regional navigation satellite constellation, as an alternate to GPS constellation, for providing space based navigation support to various land, sea and air navigation users over the Indian region. The proposed IRNSS constellation consists of 7 satellites (3 in GEO and 4 in inclined GSO with 29 deg inclination). The continuous visibility of GEO and GSO satellites for near-equator regions provides a promising alternative for regional navigation. The Signal In Space (SIS) broadcasts satellite ephemeris in quasi keplarian elements and satellite clock coefficients which forms the primary navigation parameters generated from navigation software located at INC (ISRO Navigation Centre), bylalu, India. The determination of these parameters is performed by two types of technique, batch least square (BLS) and Extended Kalman Filter (EKF). A combination of these strategies is being adopted in IRNSS to broadcast the primary navigation parameters. The BLS based navigation parameters are generated with longer validity period whereas the EKF based outputs are generated with short period validity. The main reason for this combination strategy is to limit the outage duration of satellite as minimal as possible under all circumstances. The events are triggered depending upon the anomalies that occur in SIS, mainly due to onboard frequency jumps and station keeping operations. The most facilitated important fact is that the IRNSS satellite are continuously visible to monitoring and control centre and thus able to uplink the updated navigation parameters as and when required based on the deviation from User Equivalent Range Error (UERE) as monitored through SIS from IRNSS Reference station’s Line of sight (LOS).

In this paper we have discussed the combination strategy and how user equivalent range error is mitigated during anomalous events and results.

Keywords: batch least square (BLS), extended kalman filter (EKF), signal in space (sis), line of sight (LOS), user equivalent range error (UERE).

I. INTRODUCTION

The IRNSS (Indian Regional Navigation Satellite System) is an initiative to build an independent Regional Navigation Satellite System based on a constellation of 3 Geo-stationary (GEO) and 4 Geo synchronous (GSO) satellites. The first satellite (IRNSS-1A) was launched in July 2013 and the second (IRNSS-1B) on April 4, 2014, the third satellite IRNSS-1C on 16 October 2014. Currently three satellites are in space, IRNSS-1A (longitude crossing 55 degree, inclination 29 degree, Right Ascending Node (RAAN) 130 degree), IRNSS-1B (longitude crossing 55 degree, inclination 29 degree and RAAN 310 degree) and IRNSS-1C (longitude crossing 83 degree with inclination 5 degree). The 8 (IRIMS (IRNSS Range and Integrity Monitoring Station) are currently operational. The below plot shows the orbit determination IRIMS stations and IRNSS satellites location.

Figure 1: IRIMS Station and IRNSS satellite location (Typical Snap Shot)

Keyword: batch least square (BLS), extended kalman filter (EKF), signal in space (sis), line of sight (LOS), user equivalent range error (UERE).
The IRNSS Network Timing Facility (IRNWT) maintains the precise and stable IRNSS time using an ensemble of atomic clocks that includes Hydrogen Master and Caesium clocks. It will be aiding the user position through 7 IRNSS satellites. The IRIMS (IRNSS Range and Monitoring Stations) continuously provides the one-way ranging of the IRNSS satellites to estimate and monitor the satellite position and satellite clock offset with respect to IRNSS system time. Precise Orbit determination for Geostationary and synchronous satellites from observations remains a key operation for the emerging regional navigation satellite system due to its minimal relative motion of the satellite with ground reference stations. The challenge is the ability to accurately determine the current position and velocity of the satellite along with onboard clock offset. These estimated state parameters (Ephemeris, clock bias and drift) needs to be predicted for the future which is then broadcast to the users to provide independent navigation solution in the service area of IRNSS, primarily within Indian Land mass. The following figure shows IRNSS satellites location and all the satellite beam points at 85degree longitude with 5 degree latitude.

Figure 2 : IRNSS constellation

All useful orbit determination methods produce orbit estimates, and all orbit estimates have estimation error because of input variation. Hence what methods can obtain best solution? There are several choices to make from available orbit determination methods. Should we prefer sequential methods to batch methods? One way to improve Orbit Determination (OD) of IRNSS satellites is to make use of a hybrid estimation techniques, this has been accomplished by applying the both estimation. This strategy provided substantial improvements in accuracy and convergence over the traditional techniques used in the existing orbit determination techniques. This technique is validated with real measurements and operational at INC.

II. ORBIT DETERMINATION METHOD

Two types of technique are used in IRNSS Navigation software for generation of primary parameter estimation. Though both these methods BLS and EKF are commonly used estimation process, here based on the occurrence of events a combination strategy is used were one compliments the other with inputs. In this section we discuss about both the estimation technique employed in IRNSS.

In BLS, we use multi days of data to estimate the parameter. The estimation parameters includes receiver clock coefficients of all reference stations, satellite state vectors, solar radiation pressure coefficients and satellite clock coefficients with respect to IRNSS system time. During the signal travel from transmitter to receiver, the measurement undergoes different error sources. After modeling and removal of medium errors, the main error contribution remains in each LOS is the error due to onboard and receiver clock. The separation of these errors from each LOS, mainly clock and orbit separation becomes cumbersome in simultaneous estimation. Thus differencing techniques were adopted to overcome.

The differencing techniques used to estimate receiver clock, satellite clock and satellite state vectors along with SRP coefficients, by holding and estimating the other in each of the process. By this method simultaneous estimation is avoided and hence estimation of all parameters is accurate in separation of errors.

But the limitation of the BLS comes in the event of clock jump, since the measurement data used for estimation contains the onboard clock frequency variation as shown in Figure[8-10]. Then the resultant satellite clock coefficients if obtained in this method will be inaccurate, also if parameters uplinked the user solution will also be erroneous.

In such events the new set of uplink parameters is estimated using EKF, since the sequential process depends only on the current measurements. Thus the clock coefficients obtained from this estimation process
is more realistic than the other method. In order to compute the updated clock biases state vector is held fixed and used from previous estimate of BLS. Under nominal conditions both these methods yields results, and at every instant EKF results were compared with BLS estimates and if found to be exceeding certain threshold EKF is reinitialized. Thus EKF is controlled and aligned with BLS, also the uplink parameters are generated and broadcasted with frequent update intervals and validity. The process noise and measurement noises [10] were obtained from adaption process. The limitations of the EKF based estimated solution is assumed to be poorer for long duration propagation because of the slow varying relative motion between the satellite and receiver geometry. Thus the broadcast parameter from EKF solutions is valid for shorter duration of about 900seconds and thus gets updated frequently during such onboard satellite clock anomaly event occurrence.

### III. Propagation Model

The two estimation techniques uses two types of numerical integration techniques namely Runge Kutta 4th order (RK4) and Adams-Bashforth-Moulton Method 12th order (ABM) method. In EKF for satellite state vector prediction RK4 is employed for simplicity and complexity reduction for real time usage. Whereas BLS uses ABM technique for long duration propagation under normal behaviour of range measurements.

The satellite is usually assumed to be influenced by a variety of external forces, including gravity, solar radiation pressure, third-body perturbations, Earth tidal effects, and general relativity in addition to satellite propulsive manoeuvres. The complex description of these forces results in a highly nonlinear set of dynamical equations of motion. The IRNSS orbits are propagated by numerically integrating, gravitational accelerations due to the Earth, Moon, Sun and other solar planets, together with the accelerations due to solar pressure. The gravity model used is of the order of 20x20 EGM-2008 model. The predicted positions of the Earth, Moon, Sun and other planets such as Venus and Jupiter are from JPL DE405 ephemeris. The solar pressure model used is (SPIRS) Solar pressure model for Indian regional satellite. The figure [3] shows the typical acceleration acting on the IRNSS satellites. The IRNSS satellites orientation is maintained in such a way that the sun is always contained in positive yaw and negative roll plane. The other important mission aspect is that the satellite under goes flipping twice a day and positive roll direction of the satellite never allowed to facing the sun as atomic clocks are mounted in the positive roll panel. The following figure [4] represents the IRNSS spacecraft body axis definition.

### IV. Residue Computation

Estimation technique is based on minimization of residue by iterative update of state parameters. In orbit determination method the residue is difference between observed range measurement and computed range measurements. To compute range residue to the computed range sum of all measurement error models are added. The error includes station displacement, sagnac effect, relativity effect, ionospheric delay, tropospheric delay, receiver and satellite clock error, satellite and receiver hardware delay, phase centre offsets. Firstly the smoothened ionospheric free measurements are obtained from observed range using code carrier smoothening technique with dual frequency (L5 and S) measurement combination and ambiguity resolution. The accuracy of the estimation technique depends upon the accuracy of measurement error model and quality of the measurements. Typical range residues from all IRNSS reference stations are shown in figure [5-7].
Figure 3: Range Residue for IRNSS-1A satellite using all IRIMS stations

Figure 4: Range Residue for IRNSS-1B satellite using all IRIMS stations

Figure 5: Range Residue for IRNSS-1C satellite using all IRIMS stations
V. Station Keeping Operation and Onboard Anomalies

The broadcast navigation parameters becomes obsolete during sudden variation in the measurements occurs. In the event of pre-defined station keeping operations and when sudden anomalous behaviour of the clock jumps occurs such as phase or frequency jump happens, the user gets affected due to large measurement variations. On such occasions the user has to receive updated navigation parameters. Like all other satellites, the IRNSS satellite has to be maintained in the window of 0.1 deg Equatorial from its desired longitude location. Since IRNSS works on minimum satellite constellation design (7 satellites), outage of single satellite will increase the desired Dilution of Precision (DOP). These make the ground operations challenging in minimisation of the outage duration. In the first part of the section describes the station keeping (SK) operations and estimation strategy. For IRNSS satellites the station keeping operations were carried out regularly within 30-45 days interval. These are East west station keeping (EWSK) operations with very small delta-v corrections. Thus during EWSK the user may experience loss of SIS due to attitude reorientations for SK operations.

In the event of SK operation as soon as the satellite reoriented towards the earth view, in order to limit outage duration as minimal as possible, new set of uplink parameters are uploaded just before the SK operations with appropriate delta-v corrections applied on earlier BLS estimates and on the propagated state vectors. And when the signal emerges back after re-orientation, the EKF estimates the satellite state vectors holding clock parameters using the received measurements from all reference receivers. Thus the outage is minimised and frequent uplink of navigation parameters are being done with short validity period of about ∼900seconds, with Issue of data (IODE) varying between 160 and 255. The uplink process continues in this mode until BLS accumulates sufficient hours of data post SK operations. Then after reception and accumulation of sufficient data BLS estimates updated satellite state vectors holding clock parameters. From there onwards the uplink of navigation parameters will be based on BLS with two hours validity and the process continues and becomes normal until multi days data available for all parameter estimation. The following graphs show the normal user equivalent range error during normal and post SK operations for IRNSS satellites.

The second part of the section deals with anomalous behaviour of onboard clock. The SIS encounters sudden change in range measurement variation in all LOS that emerges from a satellite, called satellite clock jump (in frequency or phase). In the event of this scenario the user using the predicted broadcast clock coefficients may not be valid yielding error in user solution and increased user equivalent range error [11]. Several such phenomenons had occurred in operational IRNSS satellites. In IRNSS through telemetry, the relative performance of the onboard clock (primary and secondary) is monitored through phase meter data. The following figures [8-10] shows such frequency variations from relative phase meter data of onboard atomic clock.
Through Ground reference receiver measurements the jumps of the onboard were identified whether the jump is on primary or secondary. The figure [8-10] shows occurrence of jump on primary clock and its effect on UERE from one of the IRNSS reference station (IRIMS at Bangalore 13deg N 77 deg E location)

In the below figure [8] shown the relative clock jump variation between onboard RAFS for IRNSS-1C (SAT 03)

![Figure 6 : Frequency jump for IRNSS-1C](image)

The below figure [9] shown the relative clock jump variation between onboard RAFS for IRNSS-1B (SAT 02), In this satellite we can observe a phenomenon such as the drift variation in the clock was increasing with time.

![Figure 7 : Frequency Variation for IRNSS-1B](image)

In the below figure [10] shown the relative clock jump variation between onboard RAFS for IRNSS-1A (SAT 01)
VI. IRIMS Bangalore UERE

This section deals with accuracy of the IRNSS SIS. To access the accuracy of the IRNSS broadcast parameters measurements from one of the reference receivers (IRIMS Bangalore) were used for demonstration. These are dual frequency receivers at precise surveyed locations. The LOS measurement was treated for various measurement errors as discussed earlier. The residual error due to broadcast signals is plotted in figures [11-13] over a typical day in nominal conditions and when there is no occurrence of any events. The estimated solution (satellite state vectors and onboard clock coefficients) is based on BLS with previous multi day’s data.

Currently, three satellites (IRNSS-1A, IRNSS-1B and IRNSS-1C) are operational and broadcasts SIS.

The below figure shows the UERE variation along IRIMS Bangalore before and after EWSK operations on IRNSS-1A satellite. The satellite undergone SK operations after 11 Hrs. The uplink parameters were EKF based estimates with short period validity.
The below plots shows typical onboard primary clock jump occurrence on IRNSS-1A. The Jump was occurred at about 3.6 Hrs. The UERE of IRIMS Bangalore shows the effect of frequency jump, resulting in deviation and sharp increase in UERE. The detection and uplink of new parameters were done from 6 Hrs onwards. The updated clock coefficients were based on EKF estimates with short period validity.

**Figure 10**: LOS Error of IRNSS-1A Before and After manoeuvre

**Figure 11**: LOS error after clock jump detection of IRNSS 1A

**VII. SUMMARY**

In the present paper two different Orbit determination methods were employed in determining the state parameters such as satellite state vectors and onboard clock parameters for IRNSS satellites. The Batch least square techniques is unfavourable during the occurrence and sudden inclusion of clock jump events. On the other hand EKF techniques under considered circumstances yields good solution but cannot be used for longer duration as the propagation error increases. Thus combinations of both the estimation strategies is employed in IRNSS navigation software, thus overcomes and mitigates the anomalous event limiting the user equivalent range error within certain acceptable limit. We have discussed both the technique and its utilization with the results from operational satellites. Continuous efforts were being made to reduce the SIS error both in modelling, measurement handling and in improved strategy adaptation.

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