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Precise Modeling of Solar Radiation Pressure for IRNSS Satellite

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Abstract

IRNSS-1A, IRNSS-1B and IRNSS-1C are the first three satellites of Indian Regional Navigation Satellite System (IRNSS) launched in 1st July 2013,4th April 2014 and 16th October 2014 respectively. IRNSS will provide regional navigation services independently over the IRNSS service area. For the precise positioning and navigation applications, precise orbit and clock information of the IRNSS satellites are essential. For High altitude satellites like IRNSS, Solar Radiation Pressure (SRP) force is the second largest perturbation force acting on the satellites after the gravitational attraction from Earth, Sun and Moon. It is the largest error source in the modelling of orbital dynamics of IRNSS, and hence its precise modelling is essential for accurate orbit determination. In this paper different approaches were studied to develop a highly precise solar radiation pressure model for IRNSS satellites using IRNSS-1A and IRNSS-1B observation data. Since IRNSS satellites shape, optical properties, physical properties as well as the attitude information are different from other Indian Communication satellites, a novel approach has been adopted here for precise modelling of SRP. The force due to SRP has been computed analytically for each of the spacecraft surfaces in the satellite body fixed frame which is further resolved in all required directions to compute the net force. To evaluate the performance of the SRP model, the orbit accuracy is derived from 1-day orbit overlaps at day boundaries of 2-day solutions. As a result, an orbit estimation accuracy of 25 meters has been observed by the model alone, while the estimation error is observed as 2.5m.Further beside the model, 3 constant co-efficient has been estimated in the three particular directions (namely DYB) which were following a right handed system. Again the model performance with estimated co-efficient has been analysed and the orbit accuracy is derived from the overlap test. As a result, an orbit estimation accuracy of 10 m has been observed, while the estimation error is about 1m.

Keywords: IRNSS, Navigation, Solar Radiation Pressure, orbit accuracy

1. Introduction

Indian Space Research Organization (ISRO) is in process of developing an independent satellite based navigation system of India. ISRO has taken its first step towards the realization of the same by successful launch of its first ever navigation satellite, IRNSS-1A on 1st July 2013. IRNSS-1A is placed in GSO orbit with longitude crossing of 55^0 with RAAN 139^0 and inclination of 27^0. The second satellite in the series, IRNSS-1B was launched on 4th April 2014, which is placed in GSO orbit with longitude crossing of 55^0 with RAAN 312^0 and inclination of 31^0. The third navigation satellite of IRNSS constellation, IRNSS-1C was launched on 16th October 2014 and is placed in GSO orbit with longitude crossing of 83.5^0 with RAAN 272^0 and inclination of 5^0. All three IRNSS Satellites are identical in their hardware and functional specifications and are operational now. IRNSS is designed to provide navigation services with position accuracy better than 20m for dual frequency users over India and the region extending about 1500 Km around India. IRNSS system consists of Space segment, Ground segment and User segment [1]. The IRNSS architecture is shown in Figure 1.

The Space segment of IRNSS constellation will consists of seven satellites. The constellation geometry provides visibility of all the satellites in the Indian region and ensures a Geometric Dilution of Precision (GDOP) of better than 3.0 in the primary service area[2].The Ground segment of IRNSS consists of IRNSS Navigation Control Centre (INC), IRNSS CDMA Ranging Stations (IRCDR), IRNSS Timing Facility (IRNWT), Satellite LASER Ranging Stations (SLR), IRNSS Spacecraft Control Facility (IRSCF) and IRNSS Range and Integrity Monitoring Stations (IRIMS) [2]. Currently, 12 IRIMS are operational and providing the one-way pseudo range measurements for all three IRNSS satellites.

The IRNSS user segment consists of Standard Position Service (SPS) and Restricted Service (RS) users. The navigation payload will have down links in L5 and S bands of the frequency spectrum. S-band signals are being used for the first time in the history of navigation. IRNSS will provide basically two types of services SPS and RS. These services will be provided on two signals with frequencies in L5 band and S-band. Thus, user receiver can be operated in either single and or dual frequency operation mode. The Telemetry and Tele-command subsystem provide links for uplink and downlink functions in C band. These infrastructures provide all the necessary facilities and tools for the required functionalities, covering the data acquisition , archiving, the operations of the major processing facilities, the management and wide dispatching of the results to internal and external users.

In the present paper, the performance of the developed Solar Radiation Pressure (SRP) model for IRNSS Satellites using one way measurement is presented. This paper is organized in different sections. The section 2 presents the IRNSS spacecraft body fixed co-ordinate system. Section 3 presents the theoretical approach for the computation of SRP force on the different surfaces of the IRNSS spacecrafts. Section 4 presents the results of the performance of the developed Solar Radiation Pressure (SRP) model. Section 5 presents the conclusion of the paper.

1.2 IRNSS-Mesasurement System

The prime source of measurement data for IRNSS mission is the one-way pseudorange observables provided by IRIMS reference stations located within and outside the territory of Indian region. The location of active IRIMS contributing the measurements for Orbit and Clock estimation for available IRNSS satellites are shown in the **Error! Reference source not found.** . The measurements are with respect to the onboard primary RAFS. The multi-channel IRIMS G-III reference receivers from Novatel are configured to generate the pseudorange and phase observables. The coverage area of the active IRIMS stations is shown in Figure 4. The onboard satellite clocks of all the available and configured satellite are characterized using the Orbit and Clock Estimation algorithm which processes the smoothened one-way pseudorange measurements.

All Computations are done with respect to the IRNSS Network time (IRNWT). The reference clock IRNWT is the paper clock obtained through the ensembling of Active Hydrogen Masers and Cesium atomic clocks. The IRNSS system reference time, IRNWT is maintained by ISRO Tracking, Telemetry and Commanding Center, Bangalore India. All IRNSS Satellite onboard clocks and IRIMS reference station clocks are synchronized with IRNWT. The IRNSS reference clock, IRNWT is continuously monitored and compared with respect to external reference time scales as the Universal Coordinated Time (UTC) realized by the BIPM.

The Orbit and Clock Estimation process solves for satellite state vectors, onboard clock parameters, and the reference station parameters. This algorithm uses dedicated algorithms to deal with different effects (ionosphere, troposphere, relativity, phase center offsets corrections, tides, site displacements, ocean loading etc) [6].

Any mismodeling of the involved deterministic effects will propagate together with other dominant perturbances and noise, which can result in abnormal effects on user position. The apparent clock behavior estimated as phase offset with respect to IRNWT will not coincide with the real physical onboard clock behavior since it includes stochastic and deterministic residuals errors introduced by the measurement System. And hence it is very important to separate the errors and provide the correct orbit and satellite clock information to users.

2. Solar Radiation Pressure Model

Many navigation based application requires highly accurate orbit information for the system spacecrafts. The accurate orbit relies on accurate modeling of the forces acting on the spacecraft. For the GEO-Synchronous satellites, force due to SRP will play a crucial role besides the third body perturbation and Earth gravity. Although the third body perturbation and Earth gravity is well understood and modeled, SRP modeling is still a challenge for such a system where demanding orbit accuracy is of few centimeters, and to achieve this accuracy SRP should be modeled as precise as the third body perturbation.

In recent years, empirical models for SRP have been derived for GPS satellites. These empirical models have been derived from the analysis of highly redundant system comprising large networks of continually operating widely spread reference stations.

In contrast to empirical modeling, analytical modeling of SRP is a problem because it requires a great visualization of the scenario. The current paper describes the approach for the calculation of Solar Radiation Pressure analytically for IRNSS spacecrafts.

A solar radiation pressure model is, in the contexts of astro-dynamics and satellite geodesy, a spacecraft specific mathematical function which enables the user to calculate the forces acting on the spacecraft due to the interaction of the solar photon flux and the surface materials of the spacecraft. The model can be developed theoretically, empirically or by using a combination of theoretical and empirical methods. In this paper, we treat a satellite as a set of flat and cylindrical surfaces and the model is expressed in the SV body coordinate system. The +X direction is towards the Earth and therefore along the spacecraft antennas. The +Z direction is points along the pitch direction, and +Y completes a right-handed system (Figure 2).

3. Theoretical Approach

The following are the parameters available for the modeling of Solar Radiation Pressure:

- A structural description of the spacecraft
- State vectors of Satellite and Sun
- Area and dimension of spacecraft components

- Spacecraft mass
- Optical properties of surface of SV components
- Solar irradiance value

The resultant force components, normal and shear to the flat surface are

$$F_s = -\left(\frac{AE}{c}\right)(1-\mu\nu)\sin\theta\cos\theta$$

$$F_n = -\left(\frac{AE}{c}\right)\cos\theta\left\{(1+\mu\nu)\cos\theta + \frac{2}{3}(1-\mu\nu)\right\}$$

where,

F_n = the force acting normal to the surface

F_s = the force acting shear to the surface

and the resultant force components, normal and shear to the cylindrical surface are

$$F_n = -\left(\frac{AE}{c}\right)\cos\theta\left\{\left(1+\frac{\mu\nu}{3}\right)\cos\theta + \frac{\pi}{6}(1-\mu\nu)\right\}$$

$$F_s = -\left(\frac{AE}{c}\right)(1-\mu\nu)\sin\theta\cos\theta$$

where,
E = Solar irradiance constant,
C = speed of light,
A= Cross-section area of spacecraft component which is illuminated by light at an angle of incidence θ,
The reflectivity and specularity coefficients of the SV component material are ν and μ respectively.

To resolve the forces in their respective direction, the latitude and longitude of Sun in the body fixed frame has been used.

Summing all the normal and shear components of force for each satellite component along their respective axes, will give $F_x = \left[F_{n,x} + F_{s,x}\right]$

where F_x is the force due to SRP acting on the satellite in the X-direction in body fixed frame,

$$F_y = \left[F_{n,y} + F_{s,y}\right]$$

where F_y is the force due to SRP acting on the satellite in the Y-direction in body fixed frame,

$$F_z = \left[F_{n,z} + F_{s,z}\right]$$

where, F_z is the force due to SRP acting on the satellite in the Z-direction in body fixed frame. The forces obtained in the body fixed frame are converted into inertial frame for further computation.

It has been observed that with the model alone, the orbit overlap accuracy is good but further improvement is required to improve the orbit overlap accuracy. Therefore to improve the model performance, in addition to the SRP model, 3 constant co-efficient has been estimated in the three directions i.e Satellite-to-Sun direction, along the solar panel direction and the third making the right handed system to absorb un-modeled acceleration.

4. Results

To test the model performance, various test cases have been studied. The results of some of cases are being discussed in the paper for IRNSS-1A and IRNSS-1B only. The model performance has been discussed in term of orbit estimation accuracy. Orbit estimation accuracy is a measure of the error in the estimated orbit from the truth orbit; however, direct computation of the estimation error is only possible for simulation studies in which the truth orbit is known. In the absence of a truth orbit for orbit estimation, the orbit accuracy must be accessed via other metrics, such as the post fit measurement residuals, RTN (Radial, Tangential and Normal) error in overlap period etc. The estimated orbit is propagated for one day and radial, normal and tangential components are computed.

a. TEST CASE 1: Model performance with 3-days one-way measurement data for orbit estimation with the model alone

To evaluate the SRP model performance, 3 days of measurement data has been taken on sliding basis with 2 days data common duration. The following table shows achieved overlap consistency results of IRNSS-1A and IRNSS-1B, GSO satellite in terms of RTN components. From the Figure-1 & Figure-2 it can be seen, the position is observed to be approximately 25 meters. The radial error component is mainly contributing to the user position accuracy and is observed to be less than 4 meters.

b. **TEST CASE 2**: **Model performance with 2-days one-way measurement data for orbit estimation with the model alone**
To evaluate the SRP model performance, 2 days of measurement data has been taken on sliding basis with 1 day data common duration. The following table shows achieved overlap consistency results of IRNSS-1A and IRNSS-1B, GSO satellite in terms of RTN components. From the Figure-3 & Figure-4 it can be seen, the position is observed to be approximately 35 meters. The radial error component is mainly contributing to the user position accuracy and is observed to be less than 5 meters.

c. **TEST CASE 3: Model performance with 3-days one-way measurement data for orbit estimation with the model alone+3 estimated co-efficient**
To evaluate the SRP model performance, 3 days of measurement data has been taken on sliding basis with 2 days data common duration. The following table shows achieved overlap consistency results of IRNSS-1A and IRNSS-1B, GSO satellite in terms of RTN components. From the Figure-5 & Figure-6 it can be seen, the position is observed to be approximately 10 meters. The radial error component is mainly contributing to the user position accuracy and is observed to be less than 2.5 meters.

d. **TEST CASE 4: Model performance with 2-days one-way measurement data for orbit estimation with the model alone+3 estimated co-efficient**
To evaluate the SRP model performance, 2 days of measurement data has been taken on sliding basis with 1 day data common duration. The following table shows achieved overlap consistency results of IRNSS-1A and IRNSS-1B, GSO satellite in terms of RTN components. From the Figure-7 & Figure-8 it can be seen, the position is observed to be approximately 15 meters. The radial error component is mainly contributing to the user position accuracy and is observed to be less than 3 meters.

5. Conclusion

The present work is focused on the testing of the performance of SRP model developed for IRNSS satellites. Therefore the preliminary results of the 1-way orbit overlap accuracy have been presented. Results of estimated orbit are discussed for both IRNSS-1A and IRNSS-1B for typical days of different months. It is observed that even though the performance of the model is good, further improvement in the model is required to improve the overlap accuracy. The un-modelled acceleration has been compensated by estimating three co-efficient in the particular directions, where the overlap accuracy has been observed as approximately 10m as discussed in the case-3. The orbit estimated by one-way range measurements is validated by orbit estimated by two-way range measurement data where the orbit overlap between these two has been observed as 10-15m.

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ISRO

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ISRO

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ISRO

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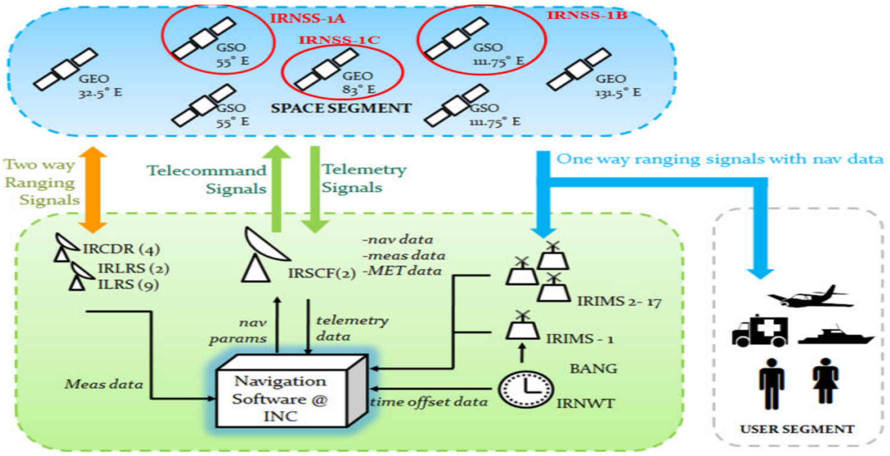

Figure 1. IRNSS Architecture

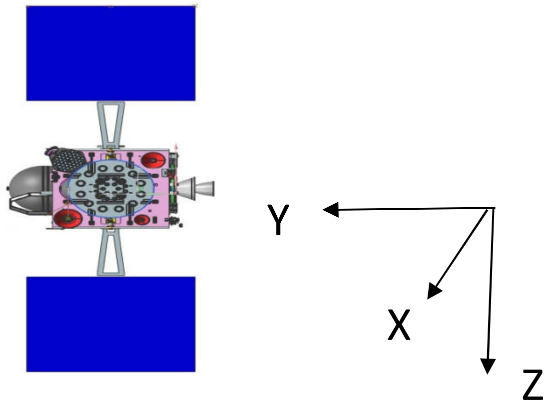

Figure 2. IRNSS spacecraft body fixed co-ordinate system

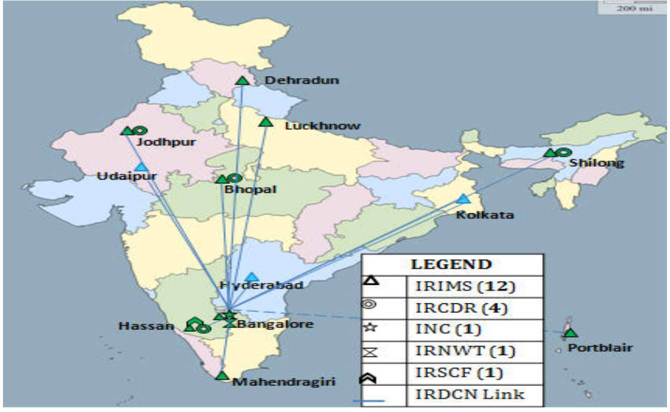

Figure 3. Location of IRNSS Infrastructures

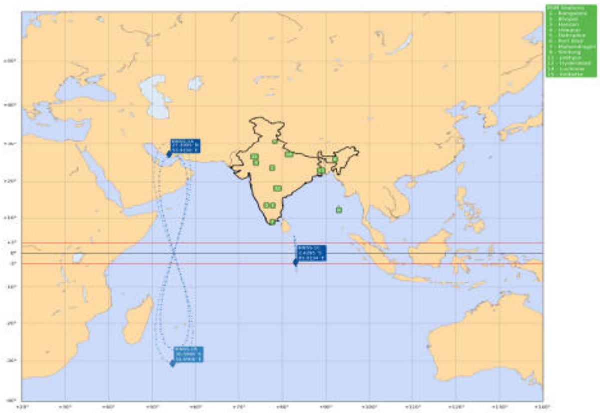

Figure 4. Coverage of the operational 12-IRIMS network

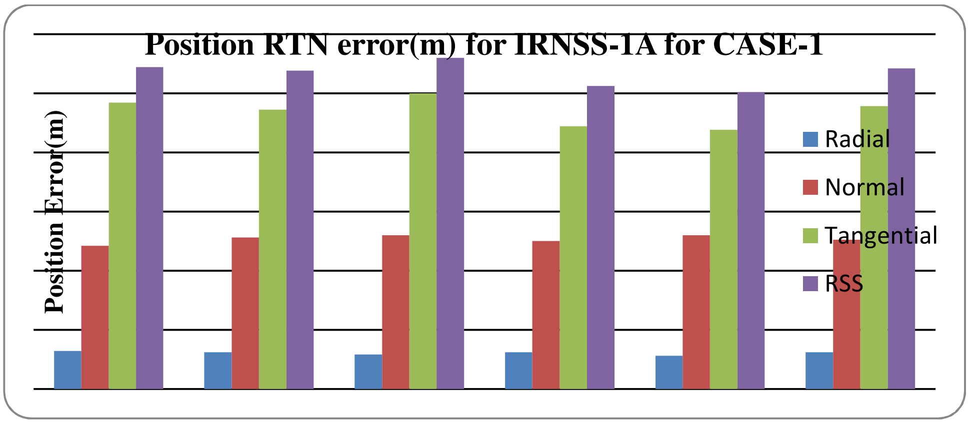

Figure 5. Position RTN error (m) for IRNSS-1A for CASE-1

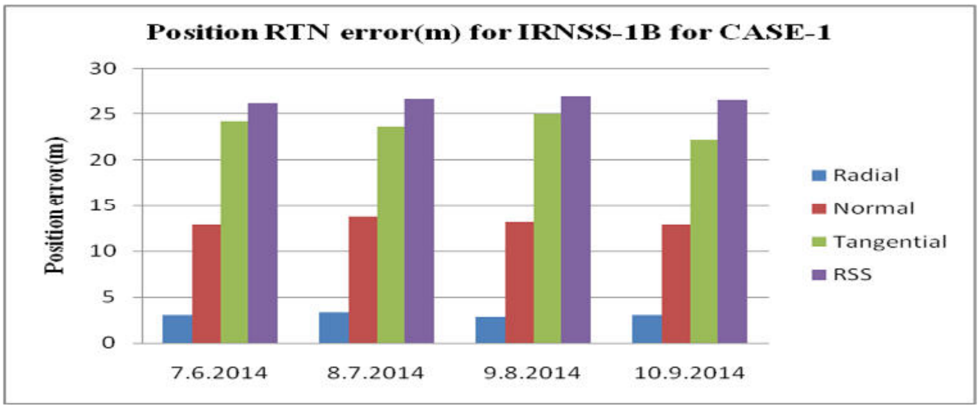

Figure 6. Position RTN error (m) for IRNSS-1B for CASE-1

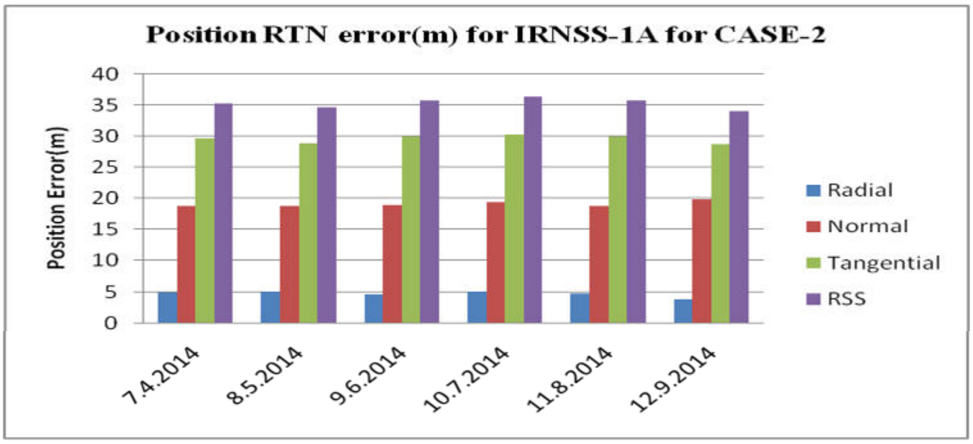

Figure 7. Position RTN error (m) for IRNSS-1A for CASE-2

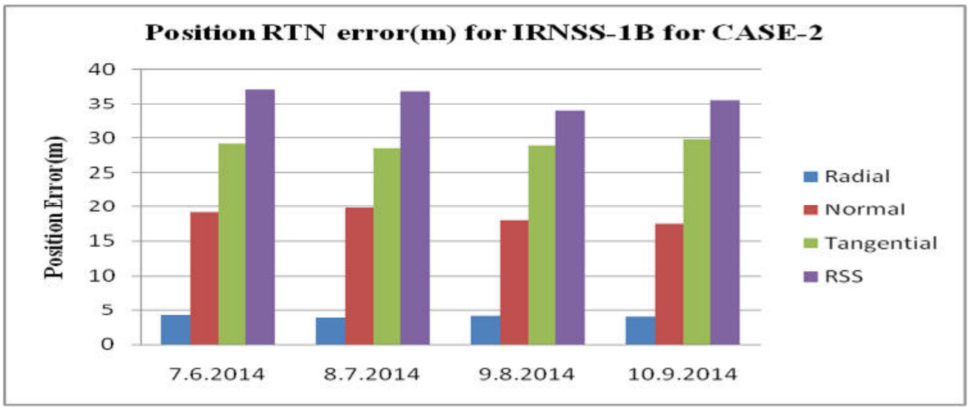

Figure 8. Position RTN error (m) for IRNSS-1B for CASE-2

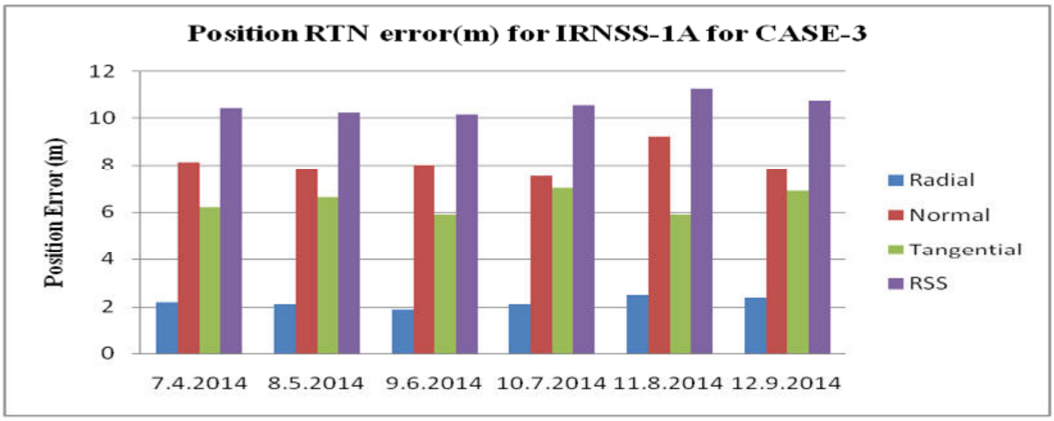

Figure 9. Position RTN error (m) for IRNSS-1A for CASE-3

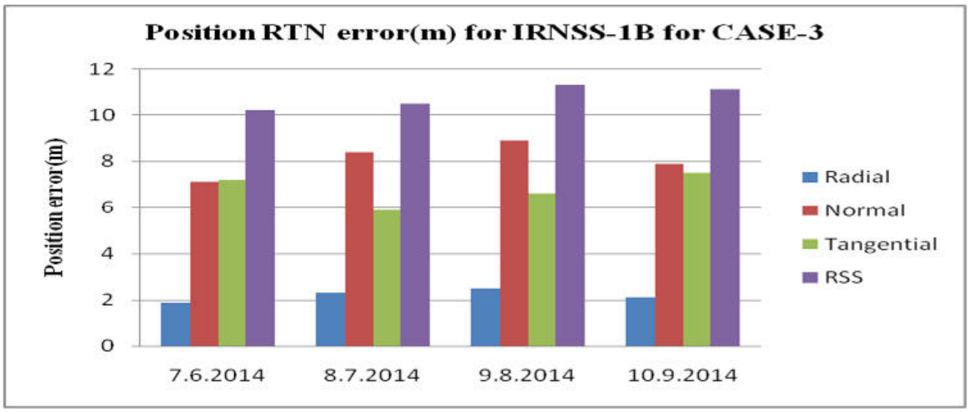

Figure 10. Position RTN error (m) for IRNSS-1B for CASE-3

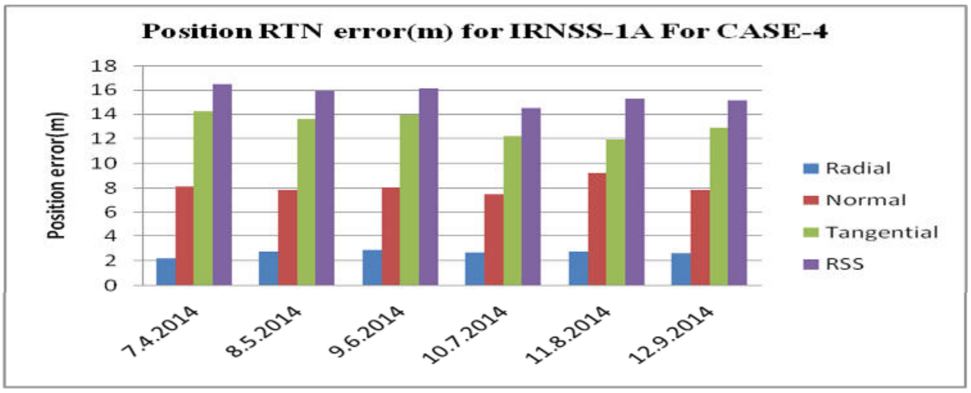

Figure 11. Position RTN error (m) for IRNSS-1A for CASE-4

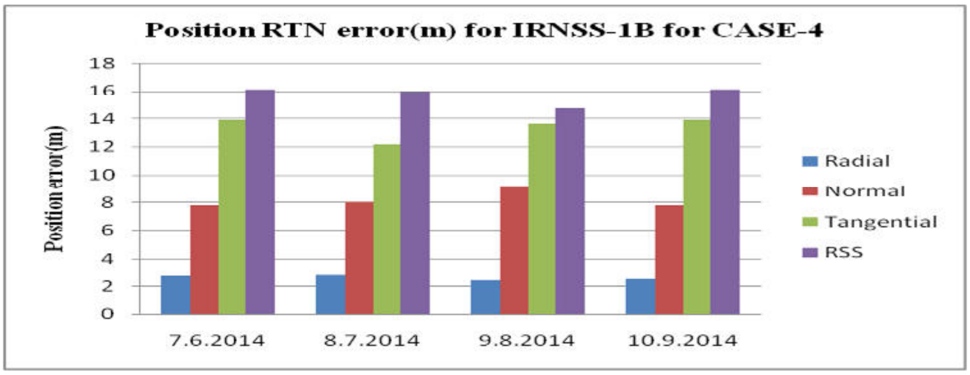

Figure 12. Position RTN error (m) for IRNSS-1B for CASE-4

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