

# IRNSS/NavIC On-Board Clock Characterization

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**ABSTRACT:** The stability and accuracy of the on-board clocks play an important role in the performance of any navigation system. The navigation user’s position is determined by measuring the time of travel of the signals broadcasted from satellites to the users. The error in the measurement of time interval effects the user position. Therefore the on-board clock behaviour has to be continuously monitored and any malfunctioning has to be noticed immediately to improve the capability of the timing system for accurate positioning of the user.

Each IRNSS satellite carries three Rubidium Atomic Frequency Standards (RAFS), one primary and two redundant clocks (Hot redundant & Cold redundant). The stability of these satellite clocks can change with time due to several factors, such as environmental effects and aging. Hence, it is important to characterize the time-varying clock behaviour. An algorithm was developed to measure the clock inaccuracies in terms of stability and detection of anomalies. This paper provides In-Orbit clock performance results of IRNSS RAFS using both conventional Overlapping Allan Deviation (OADEV) and Dynamic Allan Deviation (DADEV). All IRNSS satellites meet the desired stability specifications of  $5.0E-14$  at 10000 secs hence ensuring the user equivalent error due to clock noise is better than 0.4 ns

**KEYWORDS:** Satellite clock, Allan variance, Atomic Frequency Standard, Clock characterization.

## I. INTRODUCTION

Indian Space Research Organization (ISRO) has evolved an independent Indian Regional Navigation Satellite System (IRNSS) which is named as Navigation with Indian Constellation (NavIC) to provide position accuracy better than 20m over India and the region extending about 1500 kilometres around India. The space segment of IRNSS comprises of seven satellites: three satellites in GEO (Geo-stationary Earth Orbit) located at  $32.5^{\circ}E$ ,  $83^{\circ}E$ ,  $129.5^{\circ}E$  and four satellites in IGSO (Inclined Geosynchronous orbit) with longitude crossings at  $55^{\circ}E$  and  $111.75^{\circ}E$  [1]. All the IRNSS satellites carry 3 Rubidium Atomic Frequency Standards (RAFS): one primary and two redundant (hot redundant and cold redundant). RAFS produces a frequency of 10MHz and is converted in to fundamental frequency of 10.23MHz. This fundamental frequency is used to generate navigation signal in L5 and S bands.

To meet the navigation system requirements need a thorough understanding of the behaviour of the satellite clocks. Typically atomic clocks will have both deterministic and stochastic behaviour which cause the variation in frequency stability and accuracy. Deterministic behaviour of clock studied in terms of clock offset, frequency offset, and frequency drift where as clock stochastic behaviour is studied by frequency stability. Clock offset is the time difference between the satellite clock on board and the IRNSS Networking Time (IRNWT) which is ground reference time scale maintained within 20 ns ( $2\sigma$ ) with respect to UTC. Frequency offset and frequency drift are the time derivative of the clock offset and frequency offset respectively.

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Accuracy and repeatability of IRNSS will be ultimately determined by the inherent stability and accuracy of the on-board clocks. Frequency stability is widely used to measure the clock noise which indicates the degree to which an oscillating signal produces the same frequency for a specified interval of time. Depending on this information, one can judge the expected time error during navigation broadcast period. Overlapped Allan Deviation (OADEV) is a standard statistical tool to estimate clock stability which is a fundamental quantity used to assess the performance of a clock and its impact on the performance of the system that uses the clock [2].

The stability of IRNSS RAFS can change with time due to several factors, such as environmental effects and aging, hence an extension to OADEV known as Dynamic Allan Deviation (DADEV) was implemented to provide instantaneous frequency stability and detect anomalies viz. frequency jumps, increased noise. The DADEV has used in applications to space and satellite systems, in particular in monitoring the clocks of the Global Positioning System (GPS) [3], European Galileo project [4, 5], and in the NASA exploration of deep space [6].

In this paper on-board clock performance of all IRNSS satellites have been discussed. OADEV technique is used to study the long term behaviour and DADEV has been implemented to study instantaneous clock stability and thus detect the possible non-stationary behaviour and related clock anomalies.

## II. ON-BOARD CLOCK CHARACTERIZATION

IRNSS spacecraft carries phase meter payload which provides the phase error between primary and redundant RAFS. Also the carrier phase measurements obtained from navigation signals can be used to derive the absolute phase error of primary clock with respect to IRNWT. Below figure shows the on-board clock data flow for IRNSS.

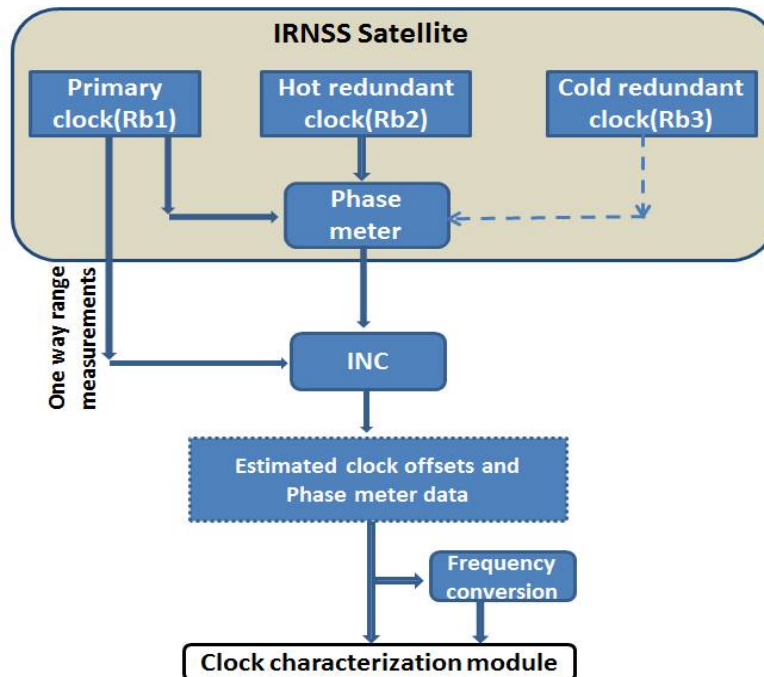


Figure 1: On-board clock data flow in IRNSS

One way range measurements driven by primary clock are available at ISRO Navigation Centre (INC) from various reference ranging stations. Absolute satellite clock offsets can be obtained from reference IRIMS by removing all other

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errors except satellite clock [7]. Estimated clock offsets are embedded with measurement noise and orbit inaccuracies, whereas relative clock offsets obtained from phase meter are free from external noise sources and hence provides better resolution of RAFS behaviour. Hence, the characterization is done using relative clock offsets from phase meter. Relative clock offsets are further converted to frequency domain for characterization.

Since primary and redundant RAFS are identical, statistically it can be assumed that half of the measured variance comes from each RAFS, thus the measured Allan deviation can be corrected for one RAFS by dividing it by  $\sqrt{2}$  [8]. Phase meter data is available with sampling of every 2 sec through spacecraft telemetry; hence the stability is available from minimum averaging time of 2 sec. Following table provides the specifications of IRNSS on-board RAFS.

Parameter	Specifications
Frequency accuracy	+/-1.0E-9
Frequency drift	5.0E-13/day
Frequency stability	
1s	5.0E-12
10s	1.5E-12
100s	5.0E-13
1000s	1.5E-13
10000s	5.0E-14
Mass	3.2kg
Power	< 35W

Table 1: IRNSS RAFS specifications

Currently, IRNSS clock behaviour is being characterized in terms of long term stability using OADEV in offline and short term clock stability using DADEV in near real time. OADEV can be estimated from a set of M frequency measurements for averaging time  $\tau = m\tau_0$ , where m is the averaging factor and  $\tau_0$  is the basic measurement interval, by the expression [9]

$$\sigma_y(\tau) = \sqrt{\left( \frac{1}{2m^2(M-2m+1)} \sum_{j=1}^{M-2m+1} \left\{ \sum_{i=j}^{j+m-1} [y_{i+m} - y_i] \right\}^2 \right)}$$

But OADEV has its own limitations and it cannot capture anomalies and the non-stationary behaviour in the random signal. It indicates the average stationary behaviour of the clock for the given dataset. Also events such as data gaps, phase jump and frequency jump cannot be easily handled using OADEV. To overcome the above limitations, a new algorithm has been recently developed known as DADEV [10-12]. DADEV is a sliding version of the Allan deviation where the time series is truncated at a window of length T centered at the epoch  $t_1$ , and the Allan variance of the windowed data is then estimated. The window is slide to a second epoch  $t_2$ , and the Allan deviation is estimated around that epoch. The repetition of this procedure results in the evolution of the Allan variance with time. This algorithm also captures the periodic variations present in the satellite clocks [13]. The Allan deviation obtained through DADEV is represented using 3D graph.

### III. RESULTS AND DISCUSSIONS

IRNSS on-board clock performance was studied using both conventional OADEV and DADEV along with the frequency offset. Datasets were chosen specifically to highlight non-nominal performance to show the effectiveness of DADEV.

#### A. OADEV performance:

To study the long term stability, minimum dataset of 4 days has been used for each satellite and the results are compared with the specifications. Below figure shows the frequency stability for IRNSS.

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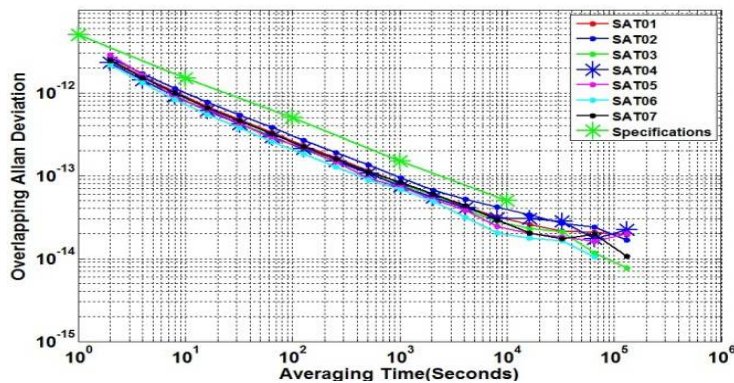


Figure 2: Frequency stability for all IRNSS satellites

From the above figure, it is clear that all IRNSS RAFS have similar performance and meets the navigation requirements. The stability at 10000 sec is better than  $4.0E-14$ , which corresponds to uncertainty of better than 0.3 ns.

### B. DADEV performance:

Various kinds of anomalies observed in the on-board clocks have been chosen from the dataset of 3 years from Jan2014-Dec2016. The raw frequency obtained from phase meter is smoothed using exponential weighted moving average filter for aiding frequency jump detection. DADEV performance is shown for nominal dataset, frequency jumps, increased noise and missing data. The window length of 3000 sec was chosen for the computation.

Figure 3 and 4 shows the frequency and its DADEV during nominal behaviour. The short term stability can be clearly assessed and it meets the desired specifications.

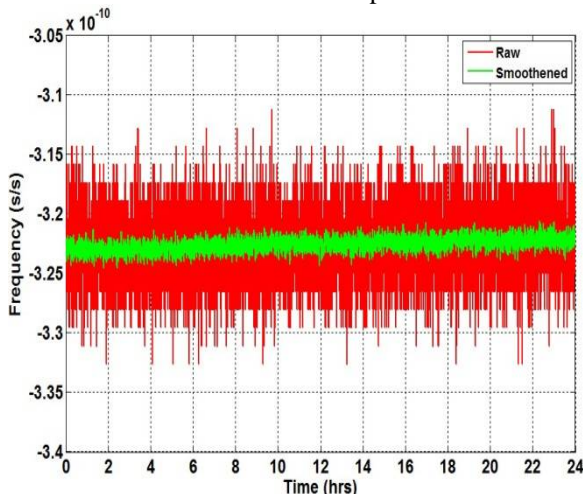


Figure 3: Nominal frequency behaviour

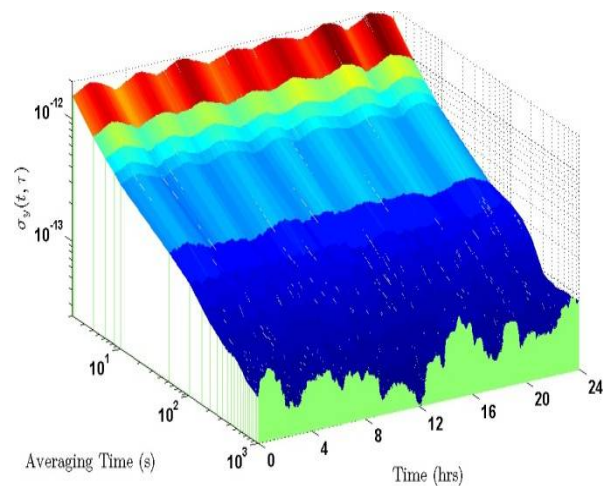


Figure 4: DADEV during nominal frequency behaviour

Figure 5 and 6 shows the frequency and its DADEV in the presence of frequency jumps. It can be observed that DADEV graph shows disturbance during the jumps and hence can be used as the statistic for jump detection. From our analysis, it was seen that jump magnitude upto  $5.0E-13$  was easily detected by the DADEV.



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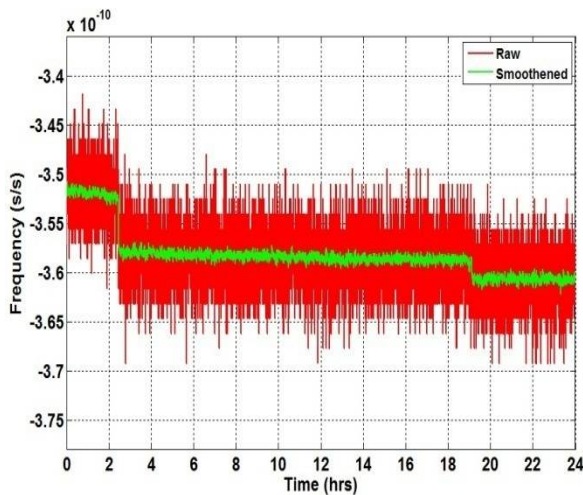


Figure 5: Frequency data with jumps

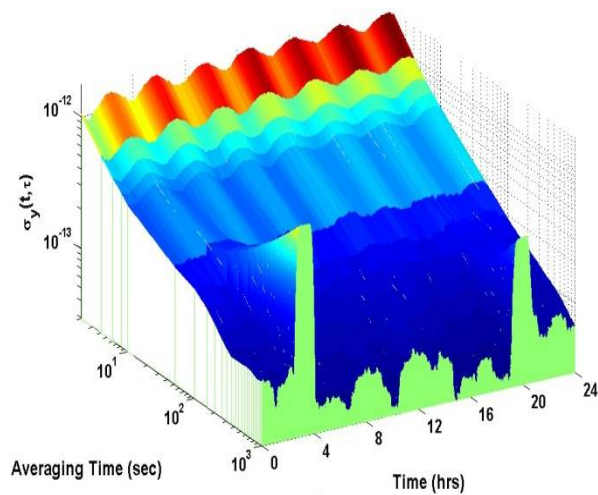


Figure 6: DADEV for frequency data with jumps

Figure 7 and 8 shows the frequency and its DADEV with multiple events i.e. missing data, large noise and frequency jumps. Simultaneous effect of two events viz. reduction in noise and frequency jumps can be seen to be immediately adapted by the DADEV statistics.

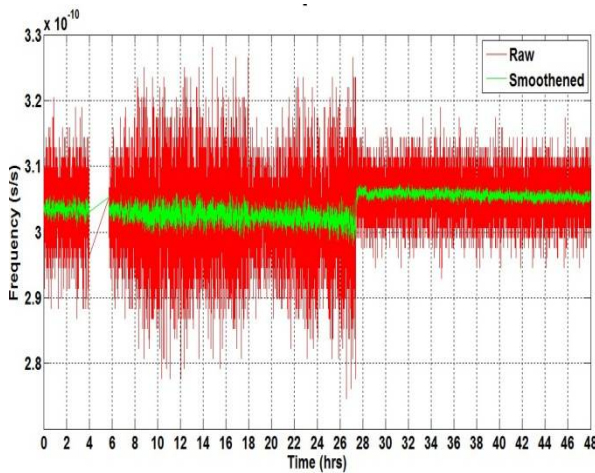


Figure 7: Frequency data with data gap, increased noise and jump

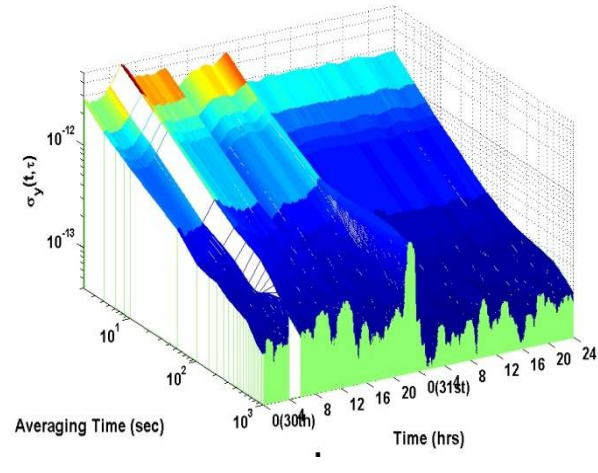


Figure 8: DADEV for frequency data with data gap, increased noise and jump

## IV. SUMMARY AND CONCLUSION

IRNSS on-board clock characterization has been carried out for all IRNSS satellites. OADEV has been used for studying long term stability performance. All satellites are seen to meet the desired specification of  $5.0E-14$  at averaging time of 10000 sec which ensures that the user equivalent error due to clock noise is better than 0.4 ns. DADEV has been used to capture the time varying behaviour of the clock in near real time. Various events were

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identified from large dataset of around 3 years. The results have been shown for events such as missing data, large noise and frequency jumps. The statistics derived from DADEV graphs can be used to clearly identify all these events and aid the Navigation Center to take appropriate action. The frequency jump magnitude upto  $5.0E-13$  can be easily detected using the DADEV graphs.

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