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GNSS IN PROGRESS

IRNSS-1A: signal and clock characterization of the Indian regional navigation system

Steffen Thoelert · Oliver Montenbruck · Michael Meurer

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Abstract An initial characterization of the L5 and S-Band navigation signals transmitted by the first satellite of the Indian regional navigation satellite system (IRNSS) is presented. In the absence of a public signal specification, a 30 m high-gain antenna has been used to record the signal spectrum and the modulated chip sequences. For the IRNSS standard positioning service, use of a Gold ranging code is confirmed and relevant shift register parameters for the two frequencies are identified. Based on a prototype receiver, L5 single-frequency code and phase observations of IRNSS-1A have also been collected. The tracking performance is described, and the measurements are used to characterize the short-term clock stability of IRNSS-1A.

Keywords IRNSS · Signal monitoring · Rubidium clock · IGSO · BPSK-modulation · Gold codes

Introduction

Following Japan and China, India is the third nation aiming to build a regional satellite navigation service. Following Majithiya et al. (2011) and Ganeshan (2012), the Indian regional navigation satellite system (IRNSS) will comprise 3 satellites in geosynchronous orbit (GEO) and two pairs of satellites in inclined geosynchronous orbits (IGSOs). IRNSS will transmit navigation signals in both the L5-band and the lower S-band. A binary phase shift key [BPSK(1)] modulation will be employed for the open standard positioning service (SPS), while a binary offset carrier [BOC(5,2)] modulation will be used for the restricted/authorized service (RS). The latter offers both a pilot and a data channel (Sekar et al. 2012).

A first satellite of the new constellation, IRNSS-1A, was successfully launched on July 1, 2013 and reached its final orbit about 2 weeks later. At a 24 h orbital period and an inclination of 27°, the satellite ground track describes a distinct figure-of-eight over the Indian Ocean with a center longitude of 55° East (Fig. 1). Even though navigation signals were soon transmitted, no public signal specification has been released so far and IRNSS cannot yet be tracked by common GNSS receivers. An effort has therefore been made to analyze the IRNSS navigation signals using the signal monitoring facility of the German Aerospace Center (DLR) at Weilheim, Germany. It makes use of a 30 m deep space antenna and a spectrum vector analyzer to record high-rate inphase (I) and quadrature (Q) samples of the received signals. The facility has earlier been used for signal studies of GPS, GIOVE/Galileo and BeiDou satellites (Montenbruck et al. 2006, Hauschild et al. 2012, Thölert et al. 2012). It provides fully calibrated measurements (Thölert et al. 2009) over the full range of L-band frequencies, but can also be used for signals in the S-band frequency but without an exact power calibration.

The measurements discussed in this report have been collected in August 2013. They are representative of the signal transmission during the commissioning of IRNSS-1A but do not necessarily reflect the signals transmitted

S. Thoelert (✉) · M. Meurer
Institute of Communications and Navigation, Deutsches Zentrum für Luft- und Raumfahrt e.V., 82230 Wessling, Germany
e-mail: steffen.thoelert@dlr.de

O. Montenbruck
German Space Operations Center, Deutsches Zentrum für Luft- und Raumfahrt e.V., 82230 Wessling, Germany

M. Meurer
Institute of Navigation, RWTH Aachen University, 52062 Aachen, Germany

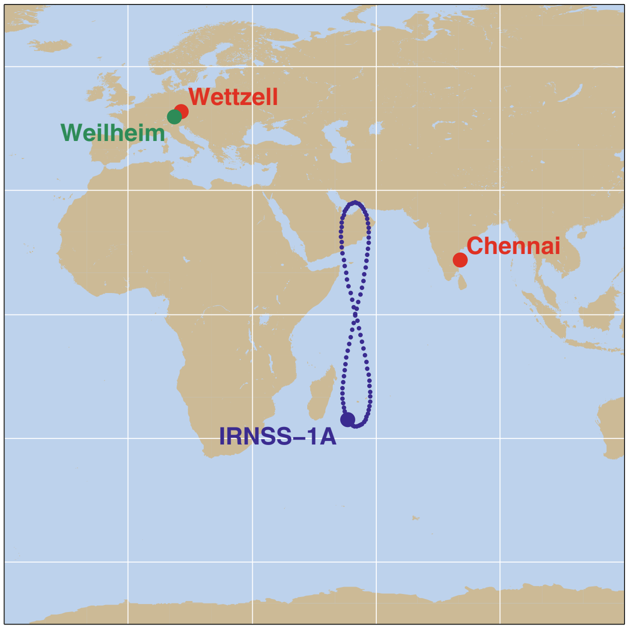

Fig. 1 IRNSS-1A ground track and location of the Weilheim high-gain antenna as well as GNSS monitoring stations (Chennai, Wettzell) used in this study

during a future operational phase of the IRNSS constellation.

We start with a description of the signal structure and ranging codes inferred from the high-gain antenna data. In a second section, tracking data collected with a modified receiver are presented and an initial analysis of the IRNSS-1A clock performance is provided.

Signal analysis

On July 23, a first signal of the IRNSS-1A satellite was received in the L5-band by the DLR signal monitoring facility (Langley et al. 2013). A second observation of the satellite on August 8 shows signal transmissions both in the L5-band and in the S-band. Based on the data acquisition of this day, an analysis of the signal structure, signal power and the ranging codes was performed.

Fig. 2 shows the spectra and IQ constellations of the measured signals of the IRNSS-1A satellite, where the assignment to inphase and quadrature channel is arbitrary and can also be swapped. For the L5-band, absolute flux densities are given based on a fully calibrated gain of the antenna and measurement system. The S-band spectrum, in contrast, is normalized due to the unavailability of adequate calibration data and may also suffer from unknown gain variations over the given frequency range.

A brief analysis of the recorded spectra reveals that at least BPSK(1) and BOC(5,2) components are contained in both frequency bands. Therefore, ideal chip wave forms for BPSK(1), BOC_{cos}(5,2) and BOC_{sin}(5,2) were generated, and cross correlations between these wave forms and the isolated I and Q component of the calibrated and Doppler corrected measurement data were determined. The correlation results lead to the conclusion that each signal (L5 and S-band) contains a BPSK(1) and BOC_{sin}(5,2) at the I-channel as well as a BOC_{sin}(5,2) and an additional interplex signal BPSK (2)—also termed intermodulation product (IM)—in the Q-channel. This interplex component is a result of the "Coherent Adaptive Subcarrier Modulation" (CASM) technique (Dafesh et al. 1999, Falcone et al. 2006) used to ensure a constant envelope of the signal constellation and consequently to operate the amplifier in efficient states. These results confirm that the transmitted signals are in line with Majithiya et al. (2011) and Ganeshan (2012) stating that three independent signals using BPSK(1) and BOC(5,2) modulation should be used in each frequency band. However, information about the specific type of BOC modulation has not been publicly released before to the authors' knowledge.

The combination of the calibrated received power measurements and the satellite-to-antenna range predicted from publicly available two-line orbital elements (TLEs) yields the effective isotropically radiated power (EIRP) of the satellite within the L5-band. Results are shown in Table 1. Based on IQ samples in the time domain, also the power and power relation of the different signal components can be derived using either the correlation with the ideal chips or the determination of the mean square of the amplitudes of each signal component. In case of the IRNSS-1A L5 signal, the relative power of each component is presented in Table 1.

For tracking of IRNSS signals by navigation receivers, information about spreading code, code rate and chip rate is needed. Using the 30 m dish at Weilheim, the acquired signal was raised above the noise floor. This allows the detection of the code chips based on the separated I and Q time domain representation as shown in Fig. 3. Based on the auto-correlation properties of the received signal, the code sequence of the BPSK component is found to repeat after 1,023 chips. This matches the use of a 1,023 chips Gold code sequence announced in the IRNSS receiver specification of Ganeshan (2012). Based on the common structure of a Gold Code generator (Misra and Enge 2001) with 10-bit G1 and G2 shift registers, the code for the BPSK signal was derived for L5 using a G2 shift of 448 and for S-band with a G2 shift of 541. Further derived information about the codes is summarized in Table 1.

For the BOC components of both the I- and Q-channels, autocorrelation peaks at 4 ms intervals are obtained in accord with the code length of 8,184 chips

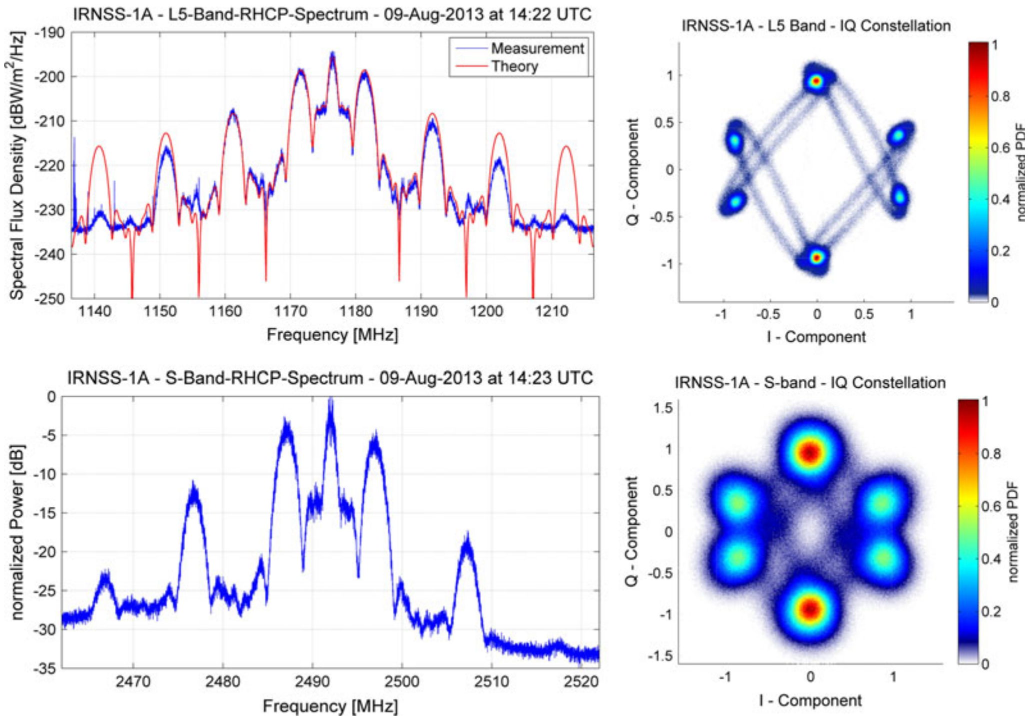

Fig. 2 Measured signals in L5-band (*top*) and S-band (*bottom*) for IRNSS 1-A, *Left* Measured Spectrum (*blue*) and expected theoretical spectrum (*red*) based on analysis results, *Right* Inphase/Quadrature (IQ)—diagram of signal constellation

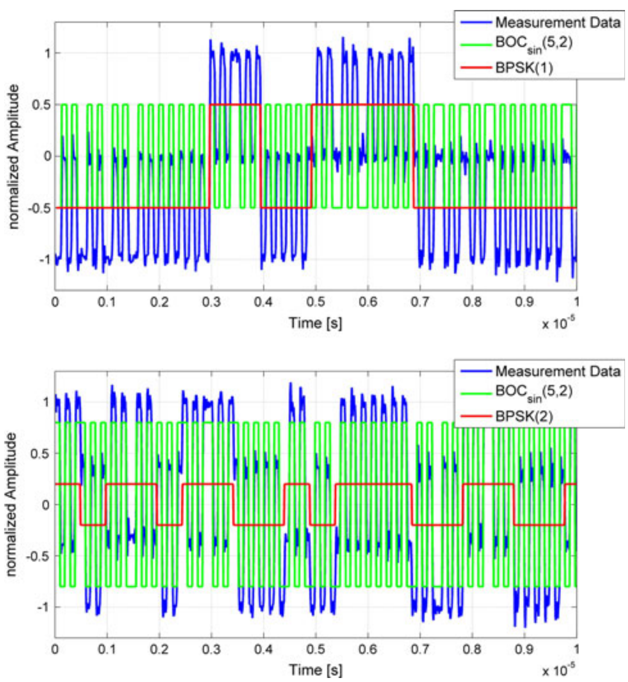

Fig. 3 Inphase (*top*) and quadrature (*bottom*) channel of IRNSS-1A L5 signal modulation versus time

specified in Ganeshan (2012). Even though the overall data set recorded in the campaign is limited to roughly 250 ms, a secondary autocorrelation peak has been recognized at 160 ms for the BOC component of the I-channel. This matches the announced duration of the secondary code (40 chips) and allows us to identify that channel as the pilot channel.

Combining all the derived aforementioned information about the signal and following the notation in Majithiya et al. (2011), the signal structure can be summarized as:

$$s(t) = \frac{\sqrt{2}}{3}\left[s_{\mathrm{RS-P}}(t) + s_{\mathrm{SPS}}(t)\right] \cdot \cos(2\pi f t) + \frac{1}{3}\left[2 s_{\mathrm{RS}}(t) - s_{\mathrm{SPS}}(t) s_{\mathrm{RS}}(t) s_{\mathrm{RS-P}}(t)\right] \cdot \sin(2\pi f t)$$

where $f = 1176.45$ MHz or 2492.028 MHz and

$$s_{\mathrm{RS}}(t) = d_{\mathrm{RS}}(t) c_{\mathrm{RS}}(t) \cdot \mathrm{sign}(\sin(10\pi f_s t)); \quad (\mathrm{RS}),$$
$$s_{\text{RS-P}}(t) = c_{\text{RS-P}}(t) \cdot \mathrm{sign}(\sin(10\pi f_s t)); \quad (\text{RS-P}),$$
$$s_{\mathrm{SPS}}(t) = d_{\mathrm{SPS}}(t) c_{\mathrm{SPS}}(t) \cdot \mathrm{sign}(\sin(2\pi f_s t)); \quad (\mathrm{SPS}),$$

denote the modulated signals of the regulated service data channel (RS), the regulated service pilot channel (RS-P) and the standard positioning service (SPS). In this expression, f_s represents the subcarrier frequency of the SPS signal, which has been selected to match the SPS chip rate $f_c = 1.023$ MHz. The symbols $d_{\mathrm{RS}}(t)$ and $d_{\mathrm{SPS}}(t)$ denote the data bits for regulated service (RS) and SPS, whereas $c_{\mathrm{RS}}(t)$, $c_{\text{RS-P}}(t)$ and $c_{\mathrm{SPS}}(t)$ describe the chips of the used spreading codes for RS, RS-P and SPS. The

Table 1 Results of IRNSS-1A signal analysis based on high-gain antenna measurements

Band	Frequency [MHz]	Signal component	Service	Modulation	Code rate [Mcps]	Code length [Chips]	Code duration [ms]	EIRP [dBW]	Relative power [%]
L5	1176.450 ± 12.0	A (Inphase)	SPS	BPSK(1)	1.023	1023	1		22.4
		B (Inphase)	RS Pilot	$BOC_{sin}(5,2)$	2.046	8184 Primary	4		22.4
						40 Secondary	160	31.5	
		C (Quadrature)	RS Data	$BOC_{sin}(5,2)$	2.046	8184	4		44.2
		D (Quadrature)	IM	BPSK(2)	2.046				11.0
S	2492.028 ± 8.25	A (Inphase)	SPS	BPSK(1)	1.023	1023	1		
		B (Inphase)	RS Pilot	$BOC_{sin}(5,2)$	2.046	8184 Primary	4		
						40 Secondary	160	Not available	
		C (Quadrature)	RS Data	$BOC_{sin}(5,2)$	2.046	8184	4		
		D (Quadrature)	IM	BPSK(2)	2.046				

EIRP and relative power measurements are limited to the L5-band due to a low gain and lacking calibration of the S-band measurements system

chip duration and data bit duration for SPS are $T_{c,SPS} = 1/f_c \approx 1\ \mu s$ and $T_{b,SPS} = 1023 * T_{c,SPS} = 1$ ms, respectively. The RS signal components employ a 5 times higher subcarrier frequency and a 2 times higher chip rate.

Tracking and clock characterization

Based on the Gold codes of the IRNSS SPS signal derived above, a prototype firmware was developed by Trimble for a precision multi-GNSS receiver and operated at a test site (CHEN) in Chennai, India. Single-frequency L5 observations from this station have been made available for initial testing. Throughout a day, the elevation at the near-equatorial station varies between a minimum of about 35° and a maximum of about 60° while the resulting carrier-to-noise density ratio (C/N_0) ranges from about 50 to 55 dB-Hz. Compared to other signals and constellations, the measured C/N_0 values suggest a similar ground-received signal power for IRNSS and GPS L5 signals, but a 2–6 dB higher power than that of QZSS L5, Galileo E5a and BeiDou B2 signals. Based on the short-term scatter of the code-carrier difference, a code tracking noise of about 0.2 m (1σ) can be inferred. In the absence of dual-frequency measurements, a characterization of the multipath properties cannot be presently performed, but the above results already indicate a proper tracking performance in good overall accord with other constellations.

The lack of an adequate ground receiver network currently inhibits a precise orbit determination and clock offset determination of IRNSS-1A. However, information on the short-term stability of the onboard frequency standard can still be derived from a 3-way carrier-phase (3WCP) analysis making use of the early tracking data collected with the Chennai receiver. The 3WCP concept (Hauschild et al. 2013) builds on the 1-way carrier-phase (1WCP) clock analysis proposed by Gonzalez and Waller (2007) but does not require a high-precision ground clock attached to the station tracking the satellite under investigation. Instead, carrier-phase observations of IRNSS-1A collected with a receiver in India are differenced against observations of a common-view GPS satellite. This acts as a relay to link the observations to a GNSS reference station (WTZ3) in Wettzell, Germany, which is equipped with a highly stable hydrogen maser (Fig. 4). After considering the known range variation on the three legs and after compensating the residual atmospheric and modeling errors through a polynomial adjustment, the resulting time series represents essentially the difference of the IRNSS-1A onboard clock and the reference clock at the Wettzell ground station.

The resulting Allan deviation of IRNSS-1A for correlation times of 1 s to 420 s is shown in Fig. 5 along with reference values obtained for four GPS satellites and a Galileo IOV satellite using different types of Cesium clocks and Rubidium Atomic Frequency Standards (RAFS). All graphs show an Allan deviation of about 10^{-11} near $\tau = 1$ s, which is dominated by white phase noise at the 1 mm level for each of the involved links in the 3WCP analysis. At a correlation time between 10 and 100 s, physical clock noise stands out well beyond the measurement noise for the GPS Block IIA and IIF Cesium clocks of PRN G08 (SVN 38) and G24 (SVN 65) as well as the GPS Block IIR Rubidium clock of PRN 12 (SVN 58). On the other hand, an Allan deviation of $2–3 \cdot 10^{-13}$ at $\tau = 100$ s is observed for IRNSS-1A as well as the advanced RAFS on GPS Block IIF PRN G25 (SVN 62) and the Galileo IOV satellite PRN E20 (GSAT 104), which

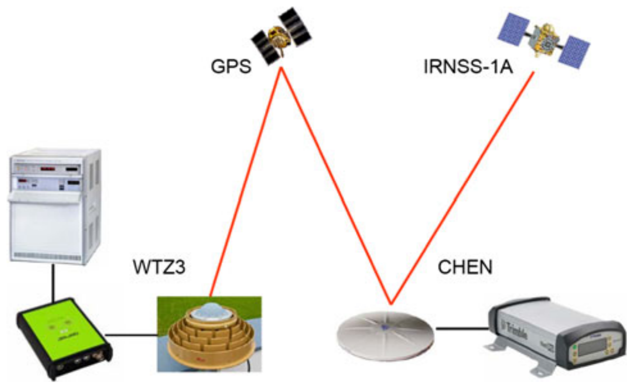

Fig. 4 Concept of 3-way carrier-phase analysis of IRNSS-1A clock stability

operated on a Rubidium clock at the time of this analysis. This value must again be considered as an upper threshold for the physical clock performance since the impact of measurement noise and uncompensated atmospheric delays at this time scale may still be of similar order.

Overall, the observed short-term clock stability is well compatible with press statements indicating that IRNSS-1A is equipped with a total of three Rubidium clocks manufactured by Spectra Time. The same company has previously supplied similar units for the GIOVE-A/B satellites as well as the Chinese BeiDou system and also provides the RAFS clocks for the Galileo IOV and FOC satellites. Compared to the Allan deviation of $2{\cdot}10^{-11}/\sqrt{\tau}$ ($\tau = 1$–100 s) reported in Ghosal et al. (2011) for a prototype of a space qualified Indian Rubidium standard, the clock in use on IRNSS-1A clearly exhibits a notably better performance and meets the expectations of a modern navigation system.

Summary and conclusions

An analysis of the signals transmitted by the IRNSS-1A satellite was performed. The results reveal that the signals transmitted by this first IRNSS satellite are well in agreement with the information publicly available about future IRNSS signals. It could be shown that three signal components are available in L5- and S-band using $BOC_{sin}(5,2)$ and BPSK(1) modulation. The spreading codes, code rates and code lengths used by IRNSS-1A were determined, which were not publicly available yet. This paves the way to their implementation into commercial navigations receivers and opens the door for tracking the signal to perform further analysis or use it for positioning solutions.

Despite obvious limitations of the 3WCP analysis, the collected data indicate a very promising performance of the IRNSS-1A onboard clock and encourage further

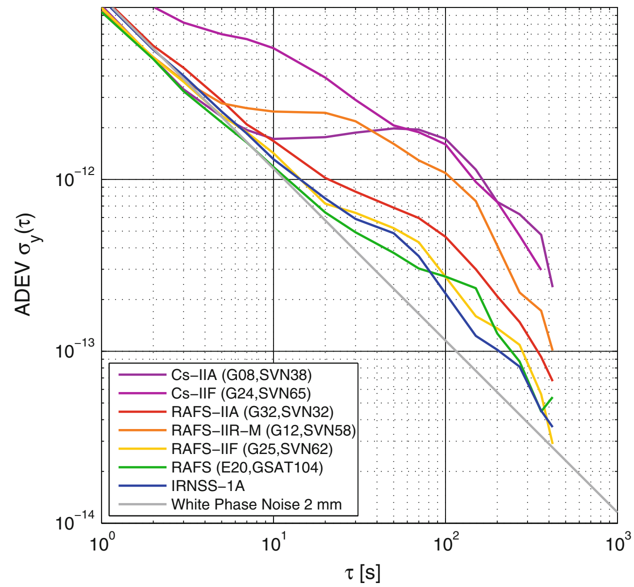

Fig. 5 Allan deviation of IRNSS (I01) in comparison with Cesium clocks of GPS Block IIA (G08) and Block IIF satellites (G24), Rubidium Frequency Standards of GPS Block IIA (G32), Block IIR-M (G12) and Block IIF (G25) satellites as well as Galileo satellites operating on a Rubidium Frequency Standard (E20) and a Passive Hydrogen Maser (E19)

monitoring as enhanced tracking networks and orbit determination solutions become available.

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Author Biographies

Steffen Thoelert received his diploma degree in electrical engineering at the University of Magdeburg in 2002. Since 2002, he is a research associate at the German Aerospace Center (DLR). In 2006, he joined the Department of Navigation at the German Aerospace Center (DLR), Institute of Communications and Navigation. Currently, he is working within the topics of signal in space analysis, satellite payload characterization and calibration.

Oliver Montenbruck is head of the GNSS Technology and Navigation Group at DLR's German Space Operations Center. His research activities comprise spaceborne GNSS, precise orbit determination as well as new GNSS signals and constellations. Oliver Montenbruck chairs the Multi-GNSS Working Group of the International GPS Service and serves as a lecturer at Technische Universität München.

Dr. Michael Meurer is the head of the Department of Navigation of the German Aerospace Center (DLR), Institute of Communications and Navigation, and the coordinating director of the DLR Center of Excellence for Satellite Navigation. In addition, he is a professor of electrical engineering and director of the Institute of Navigation at the RWTH Aachen University. His current research interests include GNSS signals, GNSS receivers, interference and spoofing mitigation and navigation for safety–critical applications.