Simulation of IRNSS Navigation Payload Operations for End to End Payload Testing

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Abstract
Fault free operations of space vehicles have always been a challenging task. Every space mission requires stringent qualification process on ground for qualification of the space vehicle for mission operations. This paper deals with the simulation of IRNSS navigation payload operations on ground for end to end payload testing and qualification of the payload for broadcast of IRNSS navigation parameters. IRNSS is an emerging Indian regional navigation satellite system for providing the satellite based navigation service over India and neighboring region. The system is optimally designed for its space and ground segment to provide the best in class navigation service. The space segment comprises of 7 satellites with 4 satellites in geo-synchronous orbit and 3 in geo-stationary orbit. The navigation payload on-board every IRNSS spacecraft comprises of navigation signal generation unit, atomic clocks and ranging subsystems. For every IRNSS spacecraft, a series of tests are carried out during different phases of spacecraft integration and testing. The core elements of IRNSS navigation operations such as IRNSS navigation software, payload test receiver, atomic clocks and telecommand and telemetry subsystem all participate in simulation and end to end testing of navigation payload. This paper describes in detail the simulation of various mission scenarios with respect to navigation payload operations considering different phases of satellite operations, subsystems involved and environment. The simulation has been key to successful operations of IRNSS 1A and IRNSS 1B which are operational in IRNSS space segment.
Keywords: IRNSS, Navigation, payload, simulation

Introduction

IRNSS comprises of three segments: Space, Ground and User segment.

Space Segment

The space segment of IRNSS consists of constellation of satellites broadcasting navigation data and ranging code. IRNSS provides two types of services viz. Standard positioning service (SPS) and restricted service (RS) for civilian and authorized users respectively. The SPS and RS signals are transmitted on both L5 and S along with navigation data.

SPS signal is BPSK modulated on L5(1176.45MHz) and S(2492.028MHz) carriers. The navigation data at the rate of 25bps is modulo 2 added to PRN code chipped at 1.023Mcps.

IRNSS space segment is a constellation of 7 satellites comprising of 3 GEO and 4 GSO satellites. The 3 GEO satellites are located at 32.5ºE, 83 ºE and 131.5ºE. The 4 GSO satellites have longitude crossing of 55 ºE and 111.75 ºE. Major element of space segment of interest to end to end payload testing is the navigation payload of IRNSS satellite.

IRNSS Ground Segment

IRNSS ground segment is responsible for the operation and maintenance of the IRNSS constellation. The ground segment comprises of IRNSS spacecraft control centre, IRNSS navigation centre, IRNSS range and integrity monitoring stations, IRNSS timing centre, CDMA ranging station, Laser ranging stations and data communication links. Ground segment plays a major role in end to end testing as the navigation data is generated on ground and uplinked to spacecraft for further broadcast to the user. Before broadcasting the navigation data the navigation payload verifies the validity of the uplinked data, unpacks the data, modulates it on the desired frequency and transmits to the users.

Major elements of ground segment of interest to end to end payload testing are:

- IRNSS Navigation Centre: Responsible for generation and uplink of IRNSS Broadcast Navigation Parameters
- IRNSS Range And Integrity Monitoring Stations: Responsible for ranging of IRNSS spacecrafts and provide input for parameter generation and loop back validation
- Spacecraft Control Facility: Responsible for spacecraft health maintenance, data uplink and control
- Network Timing Facility: Responsible for precise time generation and dissemination

User Segment

The user segment mainly consists of single and dual frequency receiver capable of receiving SPS signal at either L5 or S band frequencies and both L5 and S band frequencies respectively. The user receiver forms an integral element of end to end payload testing as the tests are carried out in user domain.

Participating Elements in Test

IRNSS spacecrafts

IRNSS Spacecraft is depicted in the Figure 1.

Satellite lift-off mass is around 1425 kg of which the dry mass is around 600 Kilograms. Navigation Payload functions in L5 and S Bands with three rubidium clocks onboard. Two clocks functions in hot redundant mode while one is spare. The navigation signals are transmitted through shared aperture circular array antenna mounted on the EV(Earth view) top. Two sided solar panel generates power using standard multi-junction solar cells. TTC(Telemetry and Telecommand) system in C-Band provides links with the ground. CDMA Ranging Transponder and Laser Ranging Retro Reflector provide the two way ranging service. Spacecraft commands are processed by a separate system and control function is done by attitude and orbit control electronics. Spacecraft is designed to have around 10 years life and is capable of meeting the operational requirements in standard laboratory environments, vacuum (pressure less that 10-6 torr) and operational environments during the entire mission. The TTC system operates in C-band (6/4 GHz) both during transfer orbit and synchronous orbit. The normal on-orbit telemetry operation shall be through the Earth coverage global horn antennas while the command function shall be exercised through the omni-directional receive antenna.

The telemetry systems collects and transfers data on all spacecraft subsystems in quantities, accuracies and at time intervals sufficient to determine spacecraft performance, attitude, need for commanding and to support analysis of failures. The telemetry unit is operational during all phases of spacecraft systems tests, pre-launch operations from the time the spacecraft is transferred to internal power prior to launch and throughout the spacecraft operational life. The Tele-command equipment provides the capability to control the spacecraft from the ground control stations. Reception of false commands, originating either from any communications signals in any of the frequency band used in the spacecraft or from other sources, shall be precluded to the maximum extent possible. The decoder used shall be identified by the telemetry data. Ground command override of any automatic command function shall be provided. The TTC subsystem provides redundant ranging capability through the combined use of the command and telemetry equipment.

IRNSS satellites have stringent requirements such as:

- The satellite beam centre need to point continuously at 83°E and 5°N on the Earth throughout their orbital period.
- Thermal management is complex as the satellites are in the inclined orbits and the atomic clocks have to be operated between -5 to +15 deg centigrade

The satellite carries three types of sensors- Sun sensor, Star sensor and Inertial Reference Unit (IRU) consisting of Dynamically Tuned Gyros. Sun sensor and Star sensor provide reference in the form of absolute attitude and attitude errors whereas IRU provides the attitude rates as well as incremental angles about all the three axes

Navigation Payload and its interfaces with user receiver, control segments are the elements tested under end to end payload testing.

Navigation Payload

The major functional elements of navigation payload tested during end to end payload testing are:

- Rubidium Atomic Frequency Standard(RAFS)
- Atomic Clock Monitoring Unit(ACMU)
- Navigation Signal Generation Unit(NSGU)

The rubidium atomic frequency standard acts as a clock source for the payload. The navigation data is uplinked periodically through telecommand and telemetry unit which is formatted and processed in NSGU for modulation on navigation signals. The modulated signal is up converted and amplified. The high power amplifier output after power combining is fed to the navigation antenna which transmits the navigation signal to users in L5 and S band. NSGU consists of MIL-STD-1553B bus interface for telecommand interface, microcontroller for navigation data processing and FPGA for navigation frame generation

ACMU is part of the Timing Subsystem for the Navigation Payload of the IRNSS satellites that derives the 10.23 MHz on-board Master Timing Reference (MTR) based on a set of atomic frequency standards. One of the clocks is selected to provide the reference for the frequency conversion from 10.00 MHz to 10.23 MHz. The synthesizers are programmable in hyperfine frequency increments (< 1e-13) in order to adjust for long term frequency drifts or offsets of the atomic references. Phase jumps are programmable for test and alignment reasons. As for operational reasons two clocks are operated in hot redundancy, the redundant clock can be characterized against the active clock by a phase comparison system to determine the phase and frequency drifts between both.

IRNSS satellites have an independent C-band bent pipe transponder for CDMA based two way ranging from ground ranging stations.

The navigation signal generation unit(NSGU) functionalities specific to acquisition and storing onboard the generated navigation data uplinked by ground elements, formatting, coding, and repacking of the same to broadcast on L5 and S carriers are tested. NSGU broadcast navigation data through a data structure that consists of 4 sub-frames at an interval of 48 seconds with the data rate of 25bps. The navigation data broadcast by NSGU is fundamentally classified into primary and secondary navigation data. The primary navigation parameters are broadcast through sub-frame 1 and 2 whereas the secondary navigation data are broadcast through sub-frame 3 and 4. The length of each subframe is 600 symbols that build up a master frame of size 2400 symbols as shown in figure 2. The navigation data is available through 4 downlink signals i.e. restricted service and standard positioning service on both L5 and S. For more information on signal structure refer 1. The different types of navigation data and its broadcast interval are shown in table 1.

As shown in table 1, the primary navigation parameters are broadcast at a fixed time interval in subframe 1 and 2 whereas the secondary navigation parameters are broadcast within their maximum broadcast interval. IRNSS broadcast data structure incorporates a hybrid frame structure wherein first two subframes: subframe 1 and 2 are fixed w.r.t the parameters they broadcast and subframe 3 and 4 flexible as they broadcast secondary navigation parameters in the form of embedded messages. There are 64 message types in IRNSS among which 8 message types are defined and 56 message types are reserved for future. The NSGU is built with enough flexibility to be able to add/remove or modify the IRNSS messages with onboard message scheduler.

End to End payload test

Objective of end to end payload test is verification of the proper functioning of navigation payload. End to end test involves qualifying the functionality of navigation elements by the analysis/verification of their ultimate product/functionality. The pre-requisite functionalities to ensure navigation services are PRN code generation, modulation of navigation data, precise & stable time keeping, synthesis of fundamental frequency, scheduling of primary and secondary navigation data formatting and transmission of data to user. This paper focuses on the end to end payload tests specific to navigation data and onboard clock performance monitoring.

Test Environment

As the spacecraft needs to carry out the required functionality in space environment, the space environment is simulated on ground. The testing is initiated while the spacecraft is being assembled. Therefore the testing is carried out in various phases such as: Disassembled, Assembled and thermovac(thermo-vacuum).

Dis-assembled test

The test is carried out under the condition where the spacecraft elements are integrated at harness level but not at physical level. The clock stability is not analysed during the test as the atomic clock is kept off. The testing is carried out at ambient temperature and pressure in a clean room.

Assembled test

The test is carried out under the condition where the spacecraft elements are integrated at harness level as well as physical level. Like dis-assembled mode test, clock stability is not analysed during the test as the atomic clock must be switched on under controlled environment.

Thermovac phase test

Thermovac mode of testing is the crucial phase of the satellite test that subjects the satellite to on-orbit environment. The satellite is subjected to extreme hot and cold cycle under vacuum condition during which the stability of atomic clock is analysed. The atomic clocks are switched on during this phase. The facility for end to end payload test has all the segments that form the navigation system viz. Satellite, control segment elements and user receiver. The architecture of the facility is shown in figure 3.

The test setup consists of IRNSS satellites, telecommand and telemetry system that issues and receives telecommand and telemetry respectively, Navigation software, Payload test receiver(PTR), IRIMS and validation software. IRIMS stands for IRNSS range and integrity monitoring station that provides code range measurements for navigation data generation. Navigation data is generated by navigation software using the range measurements and uplinked to satellites for further broadcast to the user. The uplinked data is received by PTR and IRIMS for validation against the uplinked data. The navigation software also interfaces with spacecraft telemetry to receive navigation payload telemetry.

Payload test receiver (PTR)

The payload test receiver is used to validate the SPS and RS user services for data integrity. The payload test receiver is a dual frequency receiver with graphical user interface for data integrity validation.

Simulation of End to End test

The tests are classified into

- Broadcast Navigation Data tests
- Onboard clock synchronization tests
- Onboard Clock Stability Tests

- Telemetry And Telecommand Data Test
- Frequency Synthesizer Tests

Broadcast Navigation data tests

The navigation data is generated using the simulated measurements. The simulated measurements are fed to navigation software with coarse orbit and clock information to generate both primary and secondary navigation parameters in line with the operational scenario. The navigation data tests qualify navigation signal generation unit particularly the main and redundant units. IRNSS broadcast navigation parameters are broadly classified as: Primary navigation parameters and Secondary navigation parameters. Primary navigation parameters are the satellite ephemeris, clock corrections, ranging accuracy and group delay parameters whereas secondary navigation parameters are the additional need based parameters such as ionosphere delay corrections, satellite almanac, IRNSS system time offset w.r.t UTC and other GNSS, text messages, differential corrections, earth orientation parameters. In operational scenario, each type of parameter is estimated at a predefined interval and uplinked to spacecrafts for further broadcast to the user. In order to test the end to end functionality, all the scenarios are simulated and parameters are generated and uplinked to spacecraft. The broadcast of the parameters are validated by receiving through IRIMS and PTR. The primary navigation parameters are uplinked and verified under normal mode, contingency mode and AutoNav mode of operations as shown in table 2. The ability of NSGU to switch between normal and AutoNav mode and vice versa are tested by uplink of current day and AutoNav parameters with appropriate time of applicability. Every navigation frame consists of an integrity flag viz., alert flag that indicates whether the satellite is usable for navigation service or not. All the aspects of navigation data generation, uplink and validation on ground are tested by simulating various modes of spacecraft such as normal, contingency, manoeuvre, safe and AutoNav and results are validated. The alert set and reset is also verified by uplink of valid and invalid primary navigation parameters

The secondary navigation parameters are tested in the similar fashion as for primary navigation parameters. The test involves uplink of all secondary navigation parameters defined in table 1 and validation of the same using the validation module that interfaces with navigation software and broadcast data.

Message scheduler of NSGU provides functionality such as disabling and enabling of secondary navigation parameter of interests, allocation of required number of segments, priority setting, validation and invalidation of secondary navigation parameters. Except validation and invalidation, other functionalities of message scheduler do not apply to primary navigation parameters. All these functionalities are qualified through uplink of various secondary navigation parameters and message attributes.

Onboard clock stability tests

The functionality of clock monitoring unit(ACMU) is the generation of fundamental frequency (10.23 MHz) using onboard rubidium atomic frequency standards. There are three RAFS onboard IRNSS satellite among which one clock is the primary clock and the other are redundant. Clock monitoring unit synthesizes the fundamental frequency as well as provides the phase offsets between the primary and secondary clock for onboard clock stability monitoring in real time. The phase meter data enables analysis of frequency drift between primary and hot redundant clocks. The other functionalities of clock monitoring unit are phase offset and drift corrections on need basis through commanding. The synthesized master clock from clock monitoring unit is fed to NSGU for the generation of sub-frames. All the functionalities provided by onboard clock monitoring unit are tested during onboard clock stability tests including the stability of the clocks itself during thermovac test phase.

The elements and its test case evaluation methodology using simulation are shown in table 3.

Onboard clock synchronization tests

All IRNSS satellites in the constellation are synchronized to IRNSS reference time before declared usable for navigation service. The capability is tested by interfacing navigation software with downlink signal and deriving time offset using the measurements provided by master reference station. Here the reference receiver acts as master reference station whose measurements are fed to navigation software to compute onboard time at three levels for synchronizing on-board to reference time. The three levels are coarse correction, mid-level corrections and fine corrections as shown in table 4.

The pre-residue of the master reference station with NSGU is measured to derive the achieved onboard clock synchronization

Navigation payload related telemetry tests

Navigation payload telemetry is received by ground control segment. Onboard clock stability, payload health, atomic clock health and status of various equipments onboard are monitored on a continuous basis by ground segment. All these tests are carried out during end to end payload testing.

Summary

The simulated and real test cases described here are used to qualify the navigation payload for data integrity, atomic clock stability, clock monitoring unit functionality and navigation payload specific telemetry. The tests are conducted in an on-orbit condition using thermovac chamber subjected to cyclic temperature variation under vacuum. These tests are proved to be an efficient and effective means by which three satellites viz., IRNSS-1A, IRNSS-1B and IRNSS-1C are qualified and functioning as expected. The performance of these spacecraft's is meeting the mission requirements.

References

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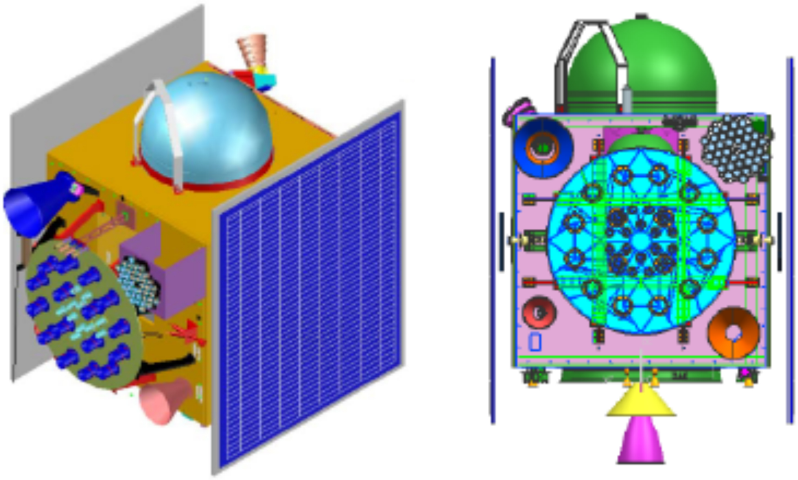

Figure 6. IRNSS spacecraft in stowed condition

Subframe 1	Subframe 2	Subframe 3	Subframe 4
600 Symbols	600 Symbols	600 Symbols	600 Symbols

Figure 7. Master Frame Structure

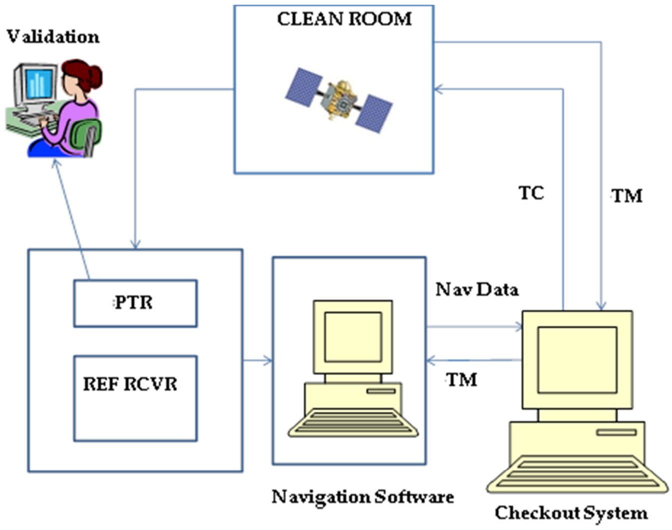

Figure 8: Architecture for assembled and disassembled mode test

Table 1. Broadcast parameters by NSGU

S.NO	Subframe/Message data	Subframe Id/Message id	Maximum Broadcast Intervals (@ 25bps)	Parameter type
1	Ephemeris	SF 1 & SF 2	48 sec	Primary
2	Clock	SF 1	48 sec	Primary
3	Ionosphere grid parameters	MT 5	5 min	Secondary
4	Almanac	MT 7	60 min	Secondary
5	IRNSS time offset with respect to UTC & GPS	MT 9	20 min	Secondary
6	Ionosphere coefficients & EOP	MT 11	10 min	Secondary
7	Differential corrections	MT 14	as needed	Secondary
8	Text	MT 18	as needed	Secondary
9	IRNSS time offset with respect to UTC(NPLI) & other GNSS	MT 26	20 min	Secondary
10	AutoNav parameters(Uplinked in advance for 7 days)	SF1 & SF2	48 sec(when no uplink from ground station for more than a day)	Primary
11	Null Message	MT 0	as needed	Secondary
12	Alert Flag	SF1, SF2, SF3, SF4	12 secs	Primary

Table 2. Broadcast navigation parameter mode

S.NO	Primary Navigation Data Broadcast Mode	Navigation data update
1	Normal	Once / day
2	Contingency	Every 15 minutes
3	AutoNav	Broadcast of degraded primary navigation parameters uplinked in advance for 7days when no uplink for more than a day

Table 3.Sub-system and its test case evaluation methodology

S.NO	System	Evaluation methodology
1	NSGU M/R	1. Integrity of primary and secondary broadcast data. 2. Time synchronization accuracy 3. Normal and Autonav mode operations 4. Message scheduler functionality
2	Clock Monitoring Unit	1. Integrity of phase meter data 2. Frequency and phase adjust functionality
3	Rubidium atomic frequency standard	1. Frequency stability 2. Light and signal variations
4	Interface between navigation S/W and Spacecraft telemetry	1. Parameter magnitudes and consistency 2. Validity of payload configuration 3. Integrity of primary navigation parameters
5	Navigation software	1. onboard clock synchronization correction computation 2. Primary and secondary Command generation and its integrity

Table 4.On-board time setting resolution for IRNSS

S.NO	Onboard Time corrections	Resolution(Target)
1	Coarse level	1 seconds
2	Milli-second correction	1e-3 seconds
3	Fine corrections	<100 Nano seconds