Proposed NAV Data Signal Design for Optimal TTFF in a Single frequency IRNSS Receiver

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BIOGRAPHIES

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ABSTRACT

India is planning to deploy an autonomous regional satellite based navigation system to cover its territorial footprint and surrounding areas. The purpose of this system as any other existing GNSS is to cater to the needs of both specific users (Precision Service (PS)) and civilian users (Standard Positioning Service (SPS)). The overall constellation consists of seven satellites, of which three will be in geostationary and four in geosynchronous orbits. This system will be used for surveying, telecommunication, transport, identifying disaster locations and public safety, along with a host of other applications (Vyasaraj et al 2011).

Time To First Fix (TTFF) is an important parameter used to assess a receiver’s performance. As a part of this research, attempt is made to understand this component in detail, namely its effect in various types of receivers and associated limitations. Subsequently, an optimal NAV data transmission method is deduced for single frequency application. A hardware simulator developed to generate this signal is described. To test this proposed signal, new receiver software is developed. Finally, the test methodology and the results are presented.

INTRODUCTION

The Indian Regional Navigation Satellite System (IRNSS) is in the early stages of signal design (Vyasaraj et al 2011). This provides ample opportunities for learning from the existing operational GNSS procedures to be incorporated into IRNSS. In addition, it serves as a platform to adopt new system level improvements proposed by academia and industry. The possible areas that may be explored during the signal design stages are sensitivity improvements, jamming margins, robustness towards spoofing, multipath related improvements, TTFF, etc, to name a few. TTFF is an important receiver specification that serves as a yardstick to inter-compare receivers from different manufacturers. Signal emanating from a satellite (say GPS L1) is as given in Equation (1). In order to process the signal, a GPS L1 receiver first establishes lock on code and carrier. Subsequently, in the lock condition, the NAV data from the satellite is demodulated. To compute user navigation solution, measurements (pseudorange, deltarange) and satellite state vectors (satellite position, velocity) from a minimum of four satellites is required.

For optimal TTFF performance, the time taken to compute measurements and subsequent data collection should be minimal. Work till now has focused on reducing the time required to acquire and lock the signal. Some investigators have also proposed to assist the receiver with NAV data on a separate link (Kaplan & Hegarty 2006). However, not much research has been carried out at the signal level to reduce Line of Sight (LOS) TTFF. This research proposes a new method of signal transmission (NAV data) to minimize TTFF relative to existing GPS or GLONASS L1 user.
In general, any GNSS signal can be characterized as follows (Kaplan & Hegarty 2006):

\[ y(t) = C(t) \cdot [r(t) \otimes d(t)] \]  

(1)

As explained earlier, the NAV data consists of the ephemeris and almanac. The ephemeris contains precise clock and Keplerian parameters, which are typically updated once every two hours. Satellite state vectors computed using the ephemeris is used for user position and velocity estimation. The almanac provides the course estimate of the satellite orbit, which is primarily used for satellite visibility computations. In addition, the parameters required for the ionosphere delay estimation (in a single frequency user) are also transmitted. Based on the current transmission method, it takes a longer time for almanac collection in a GPS receiver as compared to that of the ephemeris of a satellite. The delayed collection translates to the following delays (Kaplan & Hegarty 2006):

- Computing satellite visibility
- Ionosphere delay estimation
- Cross correlation detection based on the range estimated using almanac

The technique is an integrity check prescribed by FAA for beta-3 civil aviation receivers (EGNOS TRAN 2003)

The rest of the paper is organized as follows: A detailed analysis of a receiver’s parameters from power on to almanac collection (with a timing diagram) is provided in Section 2. Section 3 gives the relevant theory that serves as a basis for this research work. The derivation of the proposed NAV data is presented in Section 4 and the details of signal generation methodology in Section 5. A GPS-GLONASS receiver designed and developed at Accord Software and Systems Pvt Ltd is used as a platform for this research work. The existing top-level hardware and software design details are provided in Section 6, with emphasis on new algorithms developed. Following this is the test methodology described in Section 7. The results obtained are analyzed and compared with that of the existing operational GNSS. Finally, conclusions and future work are presented in Section 8.

**TTFF ANALYSIS**

At a top level, this section measures the time taken by various receiver subsystem components. The objective of this experiment was to establish the time associated with each functional component in the receiver and thus establish the need for an optimal NAV data signal design transmission or almanac streaming method.

GPSGLRX (Figure 10) is a GPS-GLONASS receiver, designed and developed by Accord Software & Systems. This receiver was used as a platform to profile functional parameters of a receiver. A graphical user interface (GGVISION) was used as a tool to profile the receiver status of various channels.

The test apparatus to measure various timing components is shown in Figure 3. The receiver was connected to a GPS GLONASS antenna exposed to open sky. A Digital Storage Oscilloscope (DSO) was connected to the boot-pin of a Digital Signal Processor (DSP) to profile the application boot time. The receiver, which outputs the data in the RS232 format, was plugged to a laptop, which had GGVISION, whose snap-shot is shown in Figure 2.

With power-on, the receiver took a finite time to load the program and display the first set of data on the test console. This time can be split into two parts: boot and communication latency. The boot time is a feature associated with a particular application and is dependent on the receiver software. This component is applicable only at power-on or a reset. The communication latency is the time required to transmit the parameters to the console. This is based on the baud-rate at which the receiver outputs the data. Once configured, it remains the same for each data transacted with the console. The boot-time with this receiver was around 250 ms as shown in Figure 4. Generalizing this component, let

\[ T_b \] be the time taken to boot the receiver application  

(2)

Subsequent to booting, the receiver was programmed with 32 GPS and 14 GLONASS satellites to respective channels for further processing. The visible satellites took anywhere between 2 to 8 s for signal acquisition. Generalizing this component, let

\[ T_a \] be the time required to acquire the visible satellites  

(3)

Subsequent to acquisition, each channel took a finite time for bit-synchronization. This typically was around 1.2 s. Generalizing this component, let

\[ T_{bs} \] be the time required for bit-synchronization  

(4)

The next activity on each of the bit-synchronized channel was collection of NAV data, specifically the ephemeris. This took anywhere between 18 to 30 s for GPS and 8 to 30 s for GLONASS channels, respectively. Let this component be represented as

\[ T_{eph}, \text{ which is the ephemeris collection time} \]  

(5)

Finally, from the NAV data extracted and the measurements made, the receiver computed the user position. This computation took around 1 s.

Let this component be represented as \( T_{pos} \)  

(5)

Using Equation (2) through Equation (6), the following can be deduced for representing the TTFF for any LOS receiver:

\[ \text{TTFF} = T_b + T_a + T_{bs} + T_{eph} + T_{pos} \]  

(6)
Based on several power on-offs (50 times), the time taken by each of the above parameters was grouped and analyzed. Figure 1 illustrates the timing components within the receiver. For each tracked channel, the almanac was then collected. However, the almanac collection status took 12.5 minutes from the instant of the first tracked channel for GPS and 2.5 minutes in case of GLONASS as given in Figure 2. Let this component be represented as $T_{\text{alm}}$, the time required to collect the almanac.

Typically, a single frequency GNSS receiver depends on the ionosphere correction term, which is transmitted as a part of the almanac data. The receiver applies the ionosphere correction to the measurements (pseudoranges) to provide a relatively accurate solution. Accounting for this component, the overall timing equation of the receiver is

$$T_{\text{pos}} = T_b + T_a + T_{bs} + T_{\text{eph}} + T_{\text{pos}} + T_{\text{alm}}$$  \hspace{1cm} (7)

From Figure 1, it is very evident that the major component contributing to the TTFF for open sky users is $T_{\text{eph}}$. This component is totally dependent on the navigation data structure design of a particular constellation and is independent of the receiver.

The objective of this research is to design an optimal navigation data structure for IRNSS to improve TTFF performance of single frequency receivers by reducing $T_{\text{eph}}$.
THEORY

GPS transmits the NAV data in a framed manner, referred to as sub-frames (GPS ICD 200C). Likewise, in GLONASS it is termed “strings”. In GPS, as a part of NAV data the Keplerian parameters are transmitted while in GLONASS, the absolute state vectors of a satellite are transmitted. The current GPS L1 sub-frame structure is shown in Figure 5a. The first three sub-frames constitute the ephemeris and the last two are dedicated to the almanac. Each sub-frame contains 10 words and each word has 24 NAV data and 6 parity bits, respectively. The data bits are transmitted at 50 bps. In all, it takes 30 s to transmit one complete frame.

Some points that are noteworthy from a new design perspective are:

- The major drawback in this existing scheme is that for every 24 bits, six redundant bits are transmitted. This constrains the actual data collection and delays the TTFF.

- In each sub-frame, existing words and bits necessarily need to be transmitted [e.g.: Telemetry (TLM), Hand Over Word (HOW), sub-frame id].

- The almanac is transmitted in two sub-frames. In addition, it contains ionosphere correction terms and UTC parameters. However, from a user perspective, the latter data needs not be transmitted very frequently.

GPS L5 has adopted a new scheme of NAV data transmission as shown in Figure 5b, which is a Text message transmitted at a defined rate (NAVSTAR GPS L5 ICD 2002). Each message is identified based on a message-id. Here, rate ½ FEC is adopted with 100 sps. The signal transmitted from an L5 satellite is at -157 dBW. The new method introduced here is that the frequency of message transmission can be varied.

The messaging scheme is considered as a reference for the signal design proposed herein. A high level NAV data format of GALILEO is shown in Figure 5c (Galileo SIS ICD 2008). GALILEO adopts sub-frame architecture as in GPS. The NAV data contains a synch pattern, followed by NAV data bits and finally, the tail bits. The entire packet has one Cyclic Redundancy Check (CRC) polynomial. As with any other modern GNSS system, GALILEO adopts a rate ½ FEC. A major change from GPS is that integrity bits are added to a packet of NAV data. This method is taken as an input for this research work.

DESIGN DETAIL OF THE PROPOSED NAV DATA

This section explains the proposed NAV data in detail to reduce $T_{eph}$ with an objective to improve TTFF

The first major design constraint while developing the NAV data structure is not to compromise any of the major existing data fields that are present in GPS, which was taken as a reference. As explained earlier, $T_{eph}$ is the main constraint for achieving a good TTFF in an open sky scenario. The design objective is to evolve an optimal structuring of the NAV data and thus ensure that $T_{eph}$ is relatively reduced.

As a first step, an architecture with three sub-frames of NAV data is proposed, which accommodates all major ephemeris and almanac parameters (w r t GPS NAV data). A second design criterion is the selection of an integrity algorithm for the NAV data bits. As explained earlier GPS has six integrity bits per 24 NAV data bits. This effectively constrains the data bandwidth and delays TTFF. To overcome this, an algorithm similar to that used in GALILEO (for one complete sub-frame navigation data content) is adopted. Coupled with this, a rate of ½ FEC is adopted with 100 sps. The base signal power level from the satellite is assumed as -157 dBW for SPS operation.
The final objective was to pack the data bits into the three sub-frames. The first two sub-frames accommodated the ephemeris parameters. The third sub-frame constituted various text messages including coarse Keplerian parameters and ionosphere coefficients (almanac), health information, time corrections w.r.t UTC and other GNSS etc.

Based on the above three design parameters, the NAV data structure shown in Figure 6 is deduced. This gives an optimal NAV data structure to relatively enhance the TTFF (in particular $T_{p0}$). Each subframe has 239 NAV data bits. The constituents of each subframe and detailed explanations of each parameter are given in Appendix A.

![Figure 5: High-level Navigation data structure](image)

![Figure 6: Proposed Navigation data structure for IRNSS](image)
To generate the proposed signal, a test system (used as an internal tool) at Accord Software & Systems Pvt Ltd was taken as a reference hardware platform for proposed IRNSS signal generation. This section highlights the top-level hardware schematic and software routines written specifically to generate the proposed IRNSS signal. The various simulation parameters are given in Table 1. The block diagram of a 7-channel IRNSS signal generator is shown in Figure 7. The basic parameters required to initiate the RF signal generation are almanac, user position and time.

The console generates all the proposed data-bits (NAV) and measurements (pseudoranges and delta-ranges) for the visible satellites in respective channels. To generate the necessary interface data, the console communicates these parameters to the hardware platform at a high data rate (12 Mbps).

The main components of the hardware platform are the Field Programmable Gate Array (FPGA) and the Digital Signal Processor (DSP). A dedicated channel is present for each of IRNSS channel both in FPGA and DSP. The code and carrier are generated based on the pseudorange and delta-range values corresponding to each interface data.

The NAV data is modulated on the code, which is translated to obtain the Intermediate Frequency (IF) signal. The IF signal is translated to IRNSS L5 and S1 band using an RF up-converter module. Figure 8 shows the top-level flow of the simulation modules. For this research work, only L5 signals were generated. This was with the assumption that the results can be subsequently extended to S1.

The data (d(t)) component of the IRNSS signal (Equation (1)) is generated based on the NAV data as deduced in the previous section and detailed in Appendix A.

Table 1: Signal Specifications Summary

<table>
<thead>
<tr>
<th>Navigation Data Specifications</th>
<th>Encoding Scheme : Convolutional Encoding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Code Rate : 1/2</td>
<td>Constraint Length : 7</td>
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<tr>
<td>Generator Polynomial : G1-171, G2-133</td>
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</tr>
<tr>
<td>NAV data field Description : Refer Appendix A</td>
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</table>

<table>
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<tr>
<th>Ranging Code Specifications</th>
<th>Type : Gold Code [1 to 7 of GPS C/A code]</th>
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<tbody>
<tr>
<td>Chip Rate : 1.023 Mcps</td>
<td>Number of chips : 1023</td>
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<tr>
<td>Code Length : 1 ms</td>
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</table>

<table>
<thead>
<tr>
<th>Carrier Specifications</th>
<th>Carrier Frequency : 1575.42 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth : 2 MHz</td>
<td>Modulation Type : Binary Phase Shift Keying (BPSK)</td>
</tr>
<tr>
<td>RF Power Level : -157 dBW</td>
<td></td>
</tr>
</tbody>
</table>

A 24-channel GPSGLRX receiver developed at Accord Software & Systems Pvt. Ltd shown in Figure 10 was taken as a reference to implement the software based on the above-proposed signal. To test and demonstrate the improvements, two versions of the software were implemented. The first was a 7-channel IRNSS receiver with proposed NAV data and the second was with NAV data as in GPS (5 sub frames).

The receiver has a RF front-end for down converting the GPS signal. The down converted signal is then digitized and given to the correlator, which is implemented in FPGA. The correlation values from FPGA are taken by the DSP and further processing such as acquisition, tracking, and data bit demodulation are performed in DSP. Apart from the correlation values, the measurement data is also given by FPGA. The navigation algorithm is implemented in DSP. The output on serial link in RS232 format is given to the laptop where GGVISION is plugged. The data logged is used to measure the relative performance of the new scheme with that of GPS.

Figure 7: Test system used for proposed IRNSS signal generation
The basic ranging codes used were as in GPS (since IRNSS ICD is yet to be released). As such the acquisition and tracking modules were retained as in the existing GPSGLRX receiver. The Data Collection and Extraction module was newly written as per the proposed NAV data. Figure 9 shows a top-level bubble diagram depicting the various software modules of the GPSGLRX receiver. The modules in blue do not require any modification. The module (in dark) was newly written in accordance with the proposed structure as given in Figure 9.

The GPSGLRX is capable of operating at the GPS L1 frequency. Since the signal generated was at 1176.45 MHz of IRNSS, an up-converter was used to translate the L5 IRNSS signal to GPS L1 band. Subsequently, the signal was fed to the GPSGLRX card for further processing. Figure 11 shows the flow diagram of data extraction for IRNSS from the incoming signal. The incoming data bit stream is first searched for the sync pattern.

Under normal conditions, sync pattern is expected once every 588 bits of data. Having achieved the subframe synch, 588 FEC encoded symbols are decoded using the Viterbi algorithm to get 294 bits of data. Following this, a 24-bit CRC is computed and is validated with the received CRC. The receiver can start receiving the data from any symbol within a subframe.
Figure 10: GPSGLRX and its High-level Block Diagram

Figure 11: Flow diagram for proposed NAV data collection within a receiver.
Normally, the data bits received before the subframe sync word is detected are discarded as depicted in Figure 12. After subframe sync is achieved, the receiver will collect two more sub frames in the worst case to collect the ephemeris data. The receiver would have collected more than 1800 data symbols in this process; in such cases the time is wasted in collection of the data bits before the sync word. In order to optimize the data collection time, a new method is proposed for data collection as shown in Figure 13.

**Figure 12: Conventional Data collection method**

In this case, the data symbols collected before the subframe sync are stored in the receiver. Subframes 1 and 2 repeat every 18 s. The data content of subframe 1 and 2 will not change except for the TOW, provided the ephemeris data of the satellite is not updated.

Considering this as a valid assumption, the data symbols before sub-frame synchronization can be combined with the data symbols collected from the subsequent broadcast of the same subframe by updating the TOW field. In this process, the receiver needs to collect only 1800 data symbols. This method of subframe synchronization needs to be performed only if the receiver latches (bit synchronization, first time) on to a data symbol of subframes one or two. If the receiver latches on the third subframe, the reconstruction is not possible as it is a text message and not required as subframe 1 and 2 will be collected in next 12 s. After reconstruction of the subframe, CRC is validated. Subsequent to validation subframe-id is extracted from the HOW. The data (ephemeris, almanac and various other text messages) is grouped based on subframe-id. The subsequent modules of the receiver compute satellite state vectors corresponding to the measurement time. The user solution is computed based on measurements and satellite state vectors.

**TEST METHODOLOGY AND RESULTS**

The signal generator and receiver described in the previous sections were used to test the proposed navigation data. Figure 14 shows the test set-up. The signal generator and receiver described in the previous sections were used to test the proposed navigation data. Two versions were simulated for an effective comparison of T\text{eph} performance improvement.

In the first case, the IRNSS signal as per the proposed NAV data was simulated and in the second, it was similar to GPS NAV subframe definition. Figure 15 shows the altitude plot of the receiver. This plot was selected to illustrate clearly the effect of the proposed navigation data structure on the TTFF of the receiver. The T\text{eph} measure as a function of subframe synchronization achieved with various subframe (id) for both versions is shown in Table 2. The assumption made here is that the bit synchronization happens on the first bit of the subframe. The results are shown in Figure 15, which is attributed to the T\text{eph} improvement.
This effectively translates into a 40% improvement in TTFF for a single frequency user, which is the optimal figure to date from any existing or proposed GNSS.

ACKNOWLEDGMENT

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APPENDIX A

<table>
<thead>
<tr>
<th>SFID</th>
<th>Description</th>
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<tbody>
<tr>
<td>00</td>
<td>Subframe One</td>
</tr>
<tr>
<td>01</td>
<td>Subframe Two</td>
</tr>
<tr>
<td>10</td>
<td>Subframe Three</td>
</tr>
<tr>
<td>11</td>
<td>Not Used</td>
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SUBFRAME-N

<table>
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<tr>
<th>TOW</th>
<th>Subframe ID</th>
<th>SVID</th>
<th>Data</th>
<th>CRC</th>
<th>Tail</th>
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</thead>
<tbody>
<tr>
<td>17 Bits</td>
<td>2 Bits</td>
<td>6 Bits</td>
<td>239 Bits</td>
<td>24 Bits</td>
<td>6 Bits</td>
</tr>
</tbody>
</table>

SUBFRAME 1

- AutoNAV: 1 Bit
- WN: 10 Bits
- \( T_{pd} \): 8 Bits
- \( T_{dc} \): 16 Bits
- \( A_{d2} \): 8 Bits
- \( A_{d1} \): 16 Bits
- \( A_{w1} \): 22 Bits
- \( C_{2r} \): 16 Bits
- \( C_{2c} \): 16 Bits
- \( C_{2a} \): 16 Bits
- \( M_0 \): 32 Bits
- \( e \): 32 Bits
- \( \sqrt{A} \): 32 Bits
- URA: 4 Bits
- Health: 2 Bits
- SV Health Information: 8 Bits
- IODE: 8 Bits

SUBFRAME 2

- AutoNAV: 1 Bit
- \( \Delta t \): 16 Bits
- \( \Omega \): 32 Bits
- \( \Omega_0 \): 32 Bits
- \( \omega \): 32 Bits
- \( \Omega_0 \): 24 Bits
- \( \Delta \Omega \): 14 Bits
- \( \Delta m \): 16 Bits
- \( C_{2c} \): 16 Bits
- \( C_{2a} \): 16 Bits
- \( C_{2c} \): 16 Bits
- \( C_{2a} \): 16 Bits
- \( IS-L5 \): 8 Bits
- \( IS-C \): 8 Bits
- \( IS-C \): 8 Bits
- \( IODC \): 8 Bits
- Spare: 1 Bit
<table>
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<th>SUBFRAME-3</th>
<th>TOW</th>
<th>Subframe ID</th>
<th>SVID</th>
<th>MSG ID</th>
<th>Data</th>
<th>CRC</th>
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<tbody>
<tr>
<td></td>
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<td>2 Bits</td>
<td>6 Bits</td>
<td>8 Bits</td>
<td>231 Bits</td>
<td>24 Bits</td>
<td>6 Bits</td>
</tr>
</tbody>
</table>

### Almanac Message
- **SVID**: 6 Bits
- **Wn**: 10 Bits
- **An**: 16 Bits
- **Bn**: 8 Bits
- **In**: 32 Bits
- **Om**: 16 Bits
- **Omic**: 16 Bits
- **Omega**: 16 Bits
- **M0**: 16 Bits
- **Delta N**: 11 Bits
- **A1**: 11 Bits

### Ionosphere / UTC Corrections Message
- **SVID**: 6 Bits
- **A0**: 32 Bits
- **A1**: 4 Bits
- **Delta T**: 8 Bits
- **Lc**: 8 Bits
- **UT time reference Time of Week**: 8 Bits
- **WN**: 8 Bits
- **WN LF**: 8 Bits
- **Delta T**: 8 Bits
- **Delta W**: 32 Bits
- **P10-P15**: 32 Bits

### 231 NAV DATA BITS
- **Spare**: 55 Bits

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