Development of INS-Aided GPS Tracking Loop and Flight Test Evaluation

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Abstract: Robust tracking of GNSS signal in a harsh environment such as a severe ionospheric scintillation is a challenge for civil aviation. The use of inertial sensor would improve the tracking performance since the Doppler frequency caused by aircraft dynamics could be compensated by the inertial measurements. In order to evaluate such an aiding, an INS aided GPS tracking loop was developed by using a software receiver, and a preliminary flight test was conducted. A navigation grade INS tightly-coupled with GPS as well as a low-cost MEMS INS loosely-coupled with GPS were installed to provide aiding information. Also, two GPS front end units with different clock (TCXO and OCXO) were installed to collect digitized IF data. Off-line analyses during aircraft take-off showed that the noise bandwidth in tracking loop could be reduced to three hertz by aiding. Also, Doppler aiding by a low-cost MEMS INS showed a similar performance with aiding by a navigation grade INS.

Keywords: Doppler aiding, GPS/INS, Tracking loop, Software receiver

1. Introduction

GPS/INS integrated navigation system has been a candidate for a new satellite based integrated navigation system for aircrafts because of its superior precision and reliability. Japan Aerospace Exploration Agency (JAXA) developed a GPS/INS systems called GAIA (GPS Aided Inertial navigation Avionics) and succeeded in automatic landing of unmanned experimental vehicle in differential mode [1]. Although high accuracy at the level of Category III approach and landing was achieved, GAIA could not be used for civil aviation since its integrity was not ensured. Therefore, JAXA commenced research on integrity monitoring for GPS/INS navigation system, and a prototype software for fault detection (FD), which based on a filter bank method, was developed [2]. In addition to the ability to detect a satellite fault, robust GPS signal tracking is necessary under severe ionospheric scintillation conditions and in a presence of intentional/unintentional interference. To retain a carrier tracking is important for precision approach using GBAS, since the carrier phase is used for smoothing pseudorange measurements. If cycle slips have occurred in several channels, the corresponding smoothing procedures have to be restarted, and would cause a missed approach. An implementation of an inertial sensor will improve the tracking performance if the Doppler frequency caused by aircraft dynamics could be compensated by the inertial measurements [3-5]. In the presented paper we are describing a prototype INS aided GPS receiver for aircraft navigation complex, that is under development by JAXA, and intended in particular to be engaged in approach and landing.

One of the innovations of the proposed solution is that a software GPS receiver is used. The usage of the software GPS receiver gives us more flexibility in integration, especially when it comes to tight integration, because it allows us to access code and carrier tracking loops inside the receiver. We used iPRx real-time software GPS receiver, which we have especially customized for our application.

A 2-hour flight test has been conducted and INS data along with digitized IF GPS signal have been recorded for further analysis. We use a navigation grade INS as well as a low-cost MEMS INS to provide aiding information and two different types of GPS front end with different clock (TCXO and OCXO) to collect intermediate frequency data. The outline of aiding method, the flight test configuration, and analysis that has been conducted using the data, are presented in the paper.

2. Doppler Aided Tracking Loop

2.1 Software Receiver

The GPS receiver in navigation complex is iPRx software receiver. The receiver can be seen as consisted of two major components. One is a USB front end, which has functions to receive L1 GPS signal, down-convert it and digitize. The digitized signal is repacked and decimated if required and sent to PC through a USB. The sampling rate is 16 mega samples per second. The core of the front end is Rakon front end module. Two types of front end have been used in this work. The Eagle front end has TCXO. The EHS front end contains Rakon GRM-8650 module with TCXO removed. The reference signal frequency is provided by embedded Golledge 16.36760 OCXO. The OCXO has 3x10^{-9} stability, and Alan deviation from 1 x10^{-12} per sec to 5 x 10^{-12}. The digitized intermediate frequency data are sent to a computer through a USB either for immediate processing or for logging for future post-processing.

The receiver can operate in two modes, real-time and post-processing. The real-time mode requires some optimization technique and there is a trade-off between accuracy and speed of operation. Computer incorporates the second software component of the receiver. It includes baseband processing and navigation processing parts. The base band processor includes acquisition and tracking modules. Code tracking loop in the
receiver is implemented as a non-coherent second order delay lock loop (DLL). The tracking loop currently uses two types of DLL discriminators. One is early minus late envelope normalized by the early plus late envelope [6]. It is used for post-processing mode and has a highest computational load, it provides good tracking error and a good stability for dynamic applications with 1.5 chip input error stability range. The other discriminator has been developed especially for optimization purpose and constructed as early minus late divided by prompt correlators and has a lowest baseband computational load in comparison with the first one and other discriminators described in [6]. The carrier tracking loop is implemented as a second order Costas phase lock loop (PLL). The receiver allows to use different discriminators. One, which has been used for this work is a two-quadrant arctangent. It was chosen because it has optimal characteristics in terms maximum likelihood estimation and its high computational load is tolerable in post-processing mode.

The receiver allows to use predicted ephemeris in IGS SP3 format and can read broadcast navigation message and decode broadcast ephemeris. The receiver can also use a combination of the predicted and broadcast data to decrease a time to first fix TTFF. The positioning itself is done through least-squares estimator (LSE) and can be done with only three satellites in view. The typical RMS in post-processing mode currently is about five meters.

2.2 Doppler Aiding for PLL

A simple Doppler aiding in phase lock loop has been developed for a preliminary test, and the effect of INS aiding is evaluated in this paper. The Doppler aided PLL model is shown in Figure 1. A second order loop filter was used for all analyses hereafter.

\[
\text{noise\_clk\_DPLL} = f_{PLL}\quad(1),
\]

where \(Df\) and \(clk\_f\) are Doppler and clock frequency [3].

If the loop is aided, the frequency of PLL can be rewritten as:

\[
f_{PLL} = f_{PLL\_0} + f_{AID}\quad(2)
\]

Three types of aiding frequency such as delta Doppler (\(\Delta f_D\)), Doppler (\(f_D\)), and Doppler and clock frequency (\(f_D + f_{clk}\)) are tested in this paper.

The Doppler frequency is computed as follows:

\[
f_D = \frac{e \cdot (v_S - v_R)}{\lambda}\quad(3)
\]

where \(v_S\), \(v_R\), \(e\), and \(\lambda\) are satellite velocity, receiver velocity line-of-sight unit vector, and L1 wave length, respectively. Before aiding Doppler information, we assume that the carrier is tracked by usual loop. Therefore, the delta Doppler between coherent integration time is added to the loop. Since current coherent integration time is 1 msec, the delta Doppler neglecting the effect of satellite motion is expressed as:

\[
\Delta f_D = \frac{-e \cdot a_R \cdot 0.001}{\lambda}\quad(4)
\]

where \(a_R\) is receiver acceleration.

In the second method, the Doppler frequency rather than Doppler increment is added. The receiver velocity (\(v_R\)) is obtained from GPS/INS integrated navigation filter. A better performance of tracking would be expected because velocity is normally not noisier than acceleration. However, initialization procedure of aiding should be considered carefully since \(f_{PLL\_0}\) in Eq. 2 is abruptly changed while \(f_{PLL}\) remains unchanged.

The aiding of clock frequency is not aiding by INS in a precise sense since the clock frequency is not obtained from INS and needs to be estimated. However, the information of clock frequency would be useful if it was used for acquisition and tracking of weak signal since it was common for all channels [9, 10]. It is computed as follows:

\[
f_{clk} = \frac{1}{N} \sum_{i=1}^{N} (f_{PLL}^i - f_{D})\quad(5),
\]

where the superscript ‘i’ indicates i-th channel and N is number of tracked channels.

3. Flight Test Configuration

Two types of GPS/INS navigation system were used for the flight experiments. The first one is a tightly coupled GPS/INS which we call GAIA (GPS Aided Inertial navigation Avionics) [1]. GAIA consists of a Kearfott T-24 Inertial Measurement Unit (IMU) with ring laser gyro and servo accelerometer, an Ashtech G12 single-frequency GPS receiver, and a DX4 (66MHz) CPU for navigation processing. Figure 2 shows a photograph of the GAIA.

Another one is a miniaturized GPS/INS navigation system named Micro-GAIA which consists of MEMS gyros and accelerometers, U-blox LEA-4T GPS receiver, and triaxial magnetometers [7]. A 15-state loosely coupled GPS/INS Kalman filter is adopted to suppress the growth of the position error.
caused by the MEMS inertial sensor errors. Figure 3 shows a photograph of the GAIA.

Figure 3. Micro-GAIA (MEMS-based GPS/INS)

GAIA and Micro-GAIA were installed in JAXA’s experimental aircraft Beechcraft Model 65 QueenAir. Onboard equipment system is depicted in Figure 4. The sensor data (acceleration) of INS as well as velocity, attitude/heading output of the GPS/INS filter were used for offline analyses.

Figure 4. Onboard equipments

Two GPS front-end units with different clock (TCXO and OCXO) were installed (Figure 5) and GPS IF data were recorded. The IF frequency and sampling rate are 4,130,400 Hz and 16,367,600 Hz, respectively.

Figure 5 GPS Front-End (Left: TCXO, Right: OCXO)

The flight test was conducted on 20 May, 2009, and data at takeoff were used for the analysis hereafter. Figure 6 shows the flight profile at takeoff, while Figure 7 and 8 show the velocity in navigation frame (NED) and acceleration in body frame coordinate.

Figure 6. Flight profile at take-off

4. Test Results

4.1 Delta-Doppler Aiding

The effect of delta-Doppler aiding, in which the calibrated acceleration from the tightly coupled GPS/INS (GAIA) was used, was shown in previous paper [8]. In this section, the effect of using the low-cost MEMS INS (Micro-GAIA) is depicted. In order to see the aiding effect, the noise bandwidth of the loop filter was reduced at 5 Hz from usual value of 25 Hz. Figure 9 depicts the carrier error for six satellites when Doppler aiding was not applied. The digitized IF data from the front-end with TCXO were processed. The standard deviation calculated from six channels was 7.2 mm.

On the other hand, when delta Doppler was added in the loop, these errors were largely removed as shown in Figure 10, with corresponding reduction of the standard deviations (4.2mm). The delta Doppler added into the loop are shown in Figure 11. Although the magnitude seems very small, these values are added at every coherent integration time (1 msec). When the navigation grade INS was used for aiding, the standard deviation of carrier phase error was very similar (4.1 mm). When OCXO was applied, the standard deviations were slightly reduced as shown in Table 1.

Figure 7. Velocity (NED) at take-off

Figure 8. Acceleration (in body frame) at take-off
4.2 Doppler Aiding

In this section, the effect of Doppler aiding is verified. Figure 12 shows the Doppler frequency added into the tracking loop by using the output of tightly-coupled GPS/INS (GAIA). Since it is based on the velocity output rather than acceleration, it is very smooth compared with Figure 11.

Figure 13 shows the loop frequency other than aiding frequency \( f_{PLL_0} \) in Eq. (2) when the IF data from the front-end with TCXO were processed. The clock drift of the TCXO is clearly seen since \( f_{PLL_0} \) contains clock frequency and noise.

Table 1. Standard deviations of carrier phase error for various combinations of equipments when delta-Doppler was aided

<table>
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<tr>
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<th>TCXO</th>
<th>OCXO</th>
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<tbody>
<tr>
<td>Nav. INS (GAIA)</td>
<td>MEMS INS (Micro-GAIA)</td>
<td>Nav. INS (GAIA)</td>
</tr>
<tr>
<td>( \sigma_\phi ) (mm)</td>
<td>4.1</td>
<td>4.2</td>
</tr>
</tbody>
</table>

Figure 14. Loop frequency other than Doppler (OCXO, Nav. INS)
The $f_{PLL}$ computed by using the IF data from the front-end with OCXO are shown in Figure 14. The clock drift is much less than the case of TCXO as expected.

The standard deviations of the resultant carrier phase error are summarized in Table 2. Compared with delta-Doppler aiding as shown in Table 1, the phase noise was fairly reduced. However, there was no significant difference between equipment combinations.

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<tr>
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<th>OCXO</th>
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<tbody>
<tr>
<td>Nav. INS (GAIA)</td>
<td>$\sigma_\phi$ (mm)</td>
<td>3.8</td>
</tr>
<tr>
<td>MEMS INS (Micro-GAIA)</td>
<td>3.8</td>
<td>3.7</td>
</tr>
<tr>
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<td>3.7</td>
<td></td>
</tr>
<tr>
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<td>3.7</td>
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</table>

4.3 Doppler and clock frequency Aiding

The results of adding the estimated clock frequency (Eq. 5) in addition to Doppler are shown in this section. Figure 15 shows the estimated clock frequency added into the tracking loop when GAIA and the front-end with TCXO were used. The clock frequency is common for all channels and similar to the loop frequency shown in Figure 13. The clock frequency when OCXO was used is shown in Figure 16 and again it is similar to the tendency seen in Figure 14.

The estimated frequency is noisy since it is calculated by using loop frequency not by using an external sensor. A more sophisticated algorithm to estimate clock frequency may be necessary to make use of this aiding method [9, 10]. In order to evaluate the stability of the TCXO/OCXO, the Allan variances were computed by processing static data logged on a different day and shown in Figure 17. It is clear that the OCXO is much more stable than TCXO, therefore a better carrier frequency/phase is expected.

Figure 15. Estimated clock frequency (TCXO, Nav. INS)

![Figure 15. Estimated clock frequency (TCXO, Nav. INS)](image)

Figure 16. Estimated clock frequency (OCXO, Nav. INS)

![Figure 16. Estimated clock frequency (OCXO, Nav. INS)](image)

Figure 17. Allan variances obtained by processing static data

![Figure 17. Allan variances obtained by processing static data](image)

Figure 18 and 19 show the loop frequency other than aiding frequency ($f_{PLL}$) calculated by using IF data from the front-end with TCXO and OCXO, respectively. It consists of estimation error of Doppler/clock frequency and noise, therefore the mean values were close to zeros. The standard deviations of carrier phase/frequency error for various combinations of equipments are summarized in Table 3. There was no significant difference between the case of TCXO and OCXO. Since there were residual Doppler errors, their effect would be larger than the effect of clock error. Figure 20 shows the frequency error when the low-cost MEMS INS was used for Doppler aiding. Comparing them with Figure 18, they were more fluctuated especially at the start of acceleration for take-off (time was about 20 sec, see Figure 8). Since velocity accuracy of Micro-GAIA is generally worse than GAIA, the residual Doppler errors in Figure 20 seem larger than those in Figure 18. However, the resultant phase errors shown in Table 3 were very similar between the case of GAIA and Micro-GAIA.

Figure 18. Loop frequency other than Doppler and clock frequency (TCXO, Nav. INS)

![Figure 18. Loop frequency other than Doppler and clock frequency (TCXO, Nav. INS)](image)

Figure 19. Loop frequency other than Doppler and clock frequency (OCXO, Nav. INS)

![Figure 19. Loop frequency other than Doppler and clock frequency (OCXO, Nav. INS)](image)
Table 3. Standard deviations of carrier phase/frequency error for various combinations of equipments when Doppler and clock frequency are aided

<table>
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</tr>
<tr>
<td>$\sigma_\phi$ (mm)</td>
<td>3.7</td>
<td>3.7</td>
</tr>
<tr>
<td>$\sigma_f$ (Hz)</td>
<td>0.66</td>
<td>0.69</td>
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3. Conclusion

An INS-aided carrier tracking loop was developed by using a software receiver. A flight experiment was conducted in order to evaluate the aided loop where a navigation grade INS tightly-coupled with GPS as well as a low-cost MEMS INS loosely-coupled with GPS were installed to provide aiding information. Also, two GPS front end units with different clock (TCXO and OCXO) were installed to collect digitized IF data. Off-line analyses during aircraft take-off showed that the noise band width in tracking loop could be reduced to three hertz by aiding. Three types of aiding frequency such as delta Doppler, Doppler, and Doppler and clock frequency are tested. Doppler aiding showed smaller carrier phase errors than delta-Doppler aiding. The aiding of clock frequency in addition to Doppler did not give significant improvement. A more sophisticated algorithm to estimate clock frequency may be necessary to make use of this aiding method. The performance difference between TCXO and OCXO was not clearly seen. This could be because the residual Doppler error was more significant than the clock instability. Also, Doppler aiding by a low-cost MEMS INS showed a similar performance with aiding by a navigation grade INS.

Future work will include development and implementation of more sophisticated tracking algorithms in which clock frequency and Doppler are estimated more precisely. Also, in order to evaluate the performance of aided tracking, we will develop a specially designed IF data simulator. It gives a possibility to extend test and analysis applicability to more extreme aircraft movement. In addition, the simulator creates the IF data which simulates an ionospheric scintillation, an intentional/unintentional interference, and a faulted satellite signal. This test extension will make it possible to demonstrate an improved continuity/availability of precision approach under such severe environment.

Reference