

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

Toshiaki TSUJII*, Takeshi FUJIWARA*, Yoshimitsu SUGANUMA*, Hiroshi TOMITA*, and Ivan PETROVSKI**

Abstract: Robust tracking of a GNSS signal in a harsh environment such as a severe ionospheric scintillation is a challenge for the civil aviation. The use of an 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 is developed by using a software receiver, and a preliminary flight test is conducted. A navigation grade INS tightly-coupled with GPS as well as a low-cost MEMS INS loosely-coupled with GPS are installed to provide aiding information. In addition, two GPS front end units with different clock (TCXO and OCXO) are installed to collect digitized IF data. Off-line analyses during aircraft take-off show that the noise band width in tracking loop can be reduced to three hertz by the aiding. Also, the Doppler aiding by a low-cost MEMS INS shows a similar performance with the aiding by a navigation grade INS.

Key Words: Doppler aiding, GPS/INS, tracking loop, software receiver.

1. Introduction

A 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 an unmanned experimental vehicle in differential modes [1]. Although high accuracy at the level of Category III approach and landing was achieved, GAIA could not be used for the 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 is based on a filter bank method, was developed [2].

In addition to the ability to detect a satellite fault, a robust GPS signal tracking property is necessary under severe ionospheric scintillation conditions and in the presence of intentional/unintentional interference. To retain carrier tracking is important for a precision approach using GBAS, since the carrier phase is used for smoothing pseudorange measurements. If cycle slips occur 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 is compensated by the inertial measurements [3]–[5]. In the present paper we describe a prototype INS-aided GPS receiver for the aircraft navigation complex, that is under development by JAXA, 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 re-

ceiver gives us more flexibility in integration, especially when it comes to a tight integration, because it allows us to access the codes and carrier tracking loops inside the receiver.

A 2-hour flight test is conducted and INS data along with digitized IF GPS signal are 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 the aiding method, the flight test configuration, and analysis that are 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 3×10^{-9} stability, and Allan deviation from 1×10^{-12} per sec to 5×10^{-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. The software component of the receiver 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

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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 correlator 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 PLL part of this software receiver was modified for this work.

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 Fig. 1. Although third order loop filters are more robust than second order filters in high dynamics environments, they might be less stable and the transient response might be larger. Therefore, a second order loop filter was used as a prototype loop filter for all analyses hereafter.

The frequency of PLL is expressed as :

$$f_{PLL} = f_D + f_{clk} + f_{noise}, \quad (1)$$

where f_D and f_{clk} are Doppler and clock frequency [3].

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

$$f_{PLL} = f_{PLL0} + f_{AID} \quad (2)$$

Three types of aiding frequency such as delta Doppler (Δf_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:

$$f_D = \frac{\mathbf{e} \cdot (\mathbf{v}_S - \mathbf{v}_R)}{\lambda} \quad (3)$$

where \mathbf{v}_S , \mathbf{v}_R , \mathbf{e} , and λ 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:

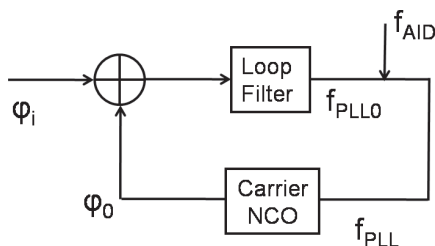


Fig. 1 Doppler aided PLL model.

$$\Delta f_D = \frac{-\mathbf{e} \cdot \mathbf{a}_R \cdot 0.001}{\lambda} \quad (4)$$

where \mathbf{a}_R is receiver acceleration.

In the second method, the Doppler frequency rather than Doppler increment is added. The receiver velocity (\mathbf{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_{PLL0} 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 [7],[8]. It is computed as follows:

$$f_{clk} = \frac{1}{N} \left(\sum_{i=1}^N (f_{PLL}^i - f_D^i) \right), \quad (5)$$

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 [9]. 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.

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

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

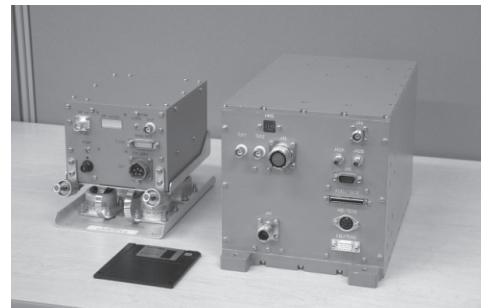


Fig. 2 GAIA (right, left is an uplink receiver for DGPS).



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

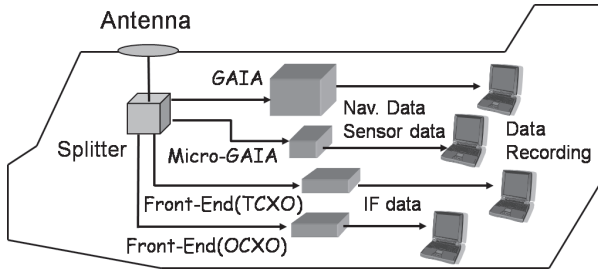


Fig. 4 Onboard equipments.



Fig. 5 GPS front-end (left: TCXO, right: OCXO).

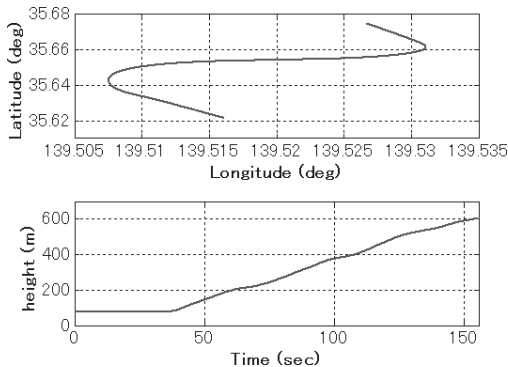


Fig. 6 Flight profile at take-off.

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

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 [10]. 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 PLL loop filter was reduced at three Hz from usual value of 25 Hz. Figure 9 depicts the carrier error (in cycles) for six satellites when aiding was not applied. The carrier error is the output of discriminator, atan (Q/I), where I and Q are in-phase

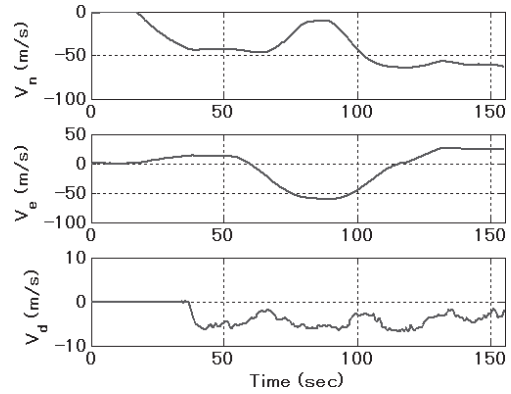


Fig. 7 Velocity (NED) at take-off.

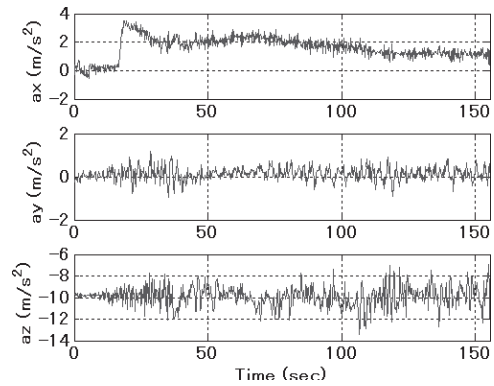


Fig. 8 Acceleration (in body frame) at take-off.

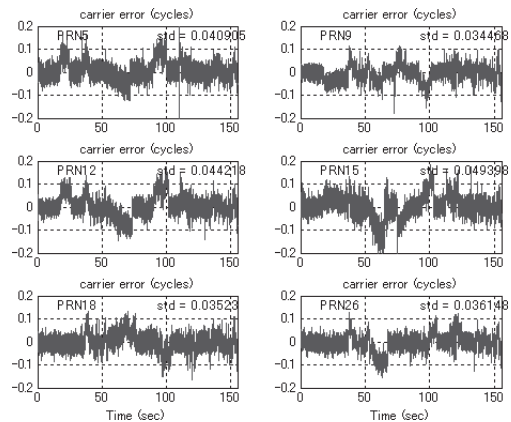


Fig. 9 Carrier error without INS aiding (TCXO, MEMS INS).

and quadrature phase signal integrated for one millisecond. The standard deviations (std) of the carrier error are also shown in the figure. 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 Fig. 10, with corresponding reduction of the standard deviations (4.2mm). The delta Doppler (in hertz) added into the loop are shown in Fig. 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.

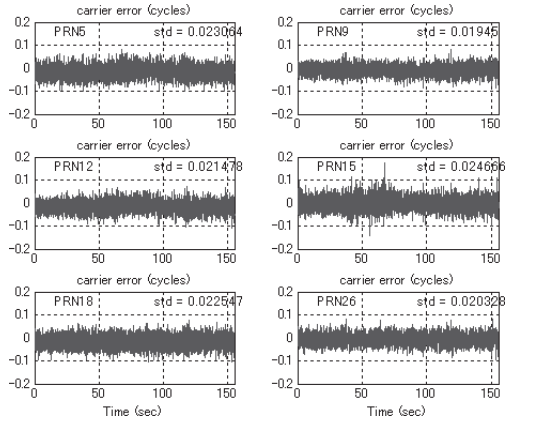


Fig. 10 Carrier error with INS delta-Doppler aiding (TCXO, MEMS INS).

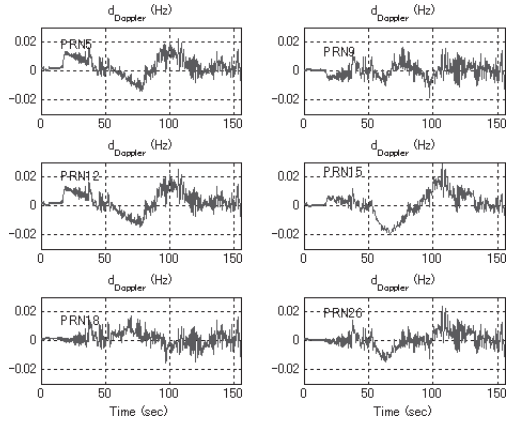


Fig. 11 Delta Doppler added in the loop (MEMS INS).

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

	TCXO		OCXO	
	Nav. INS (GAIA)	MEMS INS (Micro-GAIA)	Nav. INS (GAIA)	MEMS INS (Micro-GAIA)
σ_ϕ (mm)	4.1	4.2	3.9	4.0

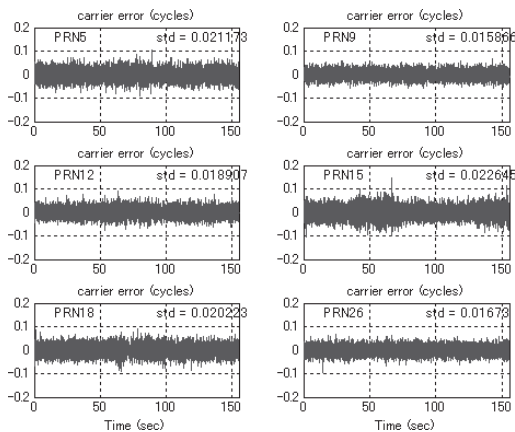


Fig. 12 Carrier error with INS Doppler aiding (OCXO, Nav. INS).

4.2 Doppler Aiding

In this section, the effect of Doppler aiding is verified. Figure 12 shows the carrier error (in hertz) when the Doppler frequency are aided into the tracking loop by using the output of tightly-coupled GPS/INS (GAIA) and the front-end with

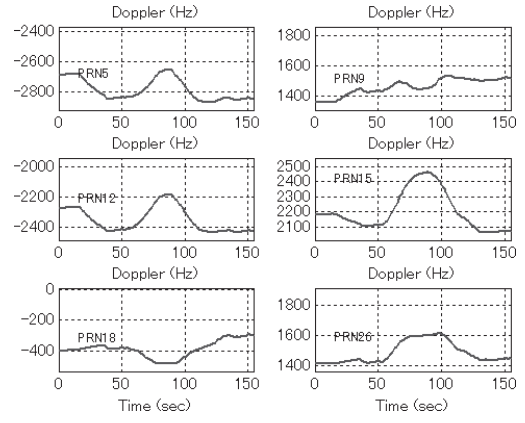


Fig. 13 Doppler frequency added in the loop.

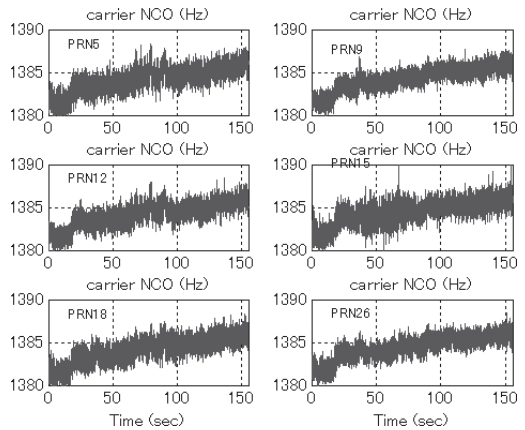


Fig. 14 Loop frequency other than Doppler (TCXO, Nav. INS).

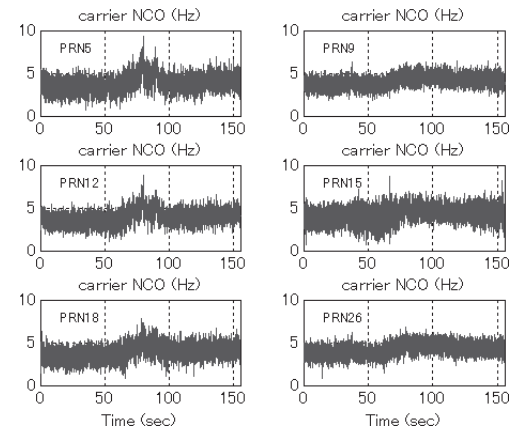


Fig. 15 Loop frequency other than Doppler (OCXO, Nav. INS).

OCXO. Compared with Fig. 10, the standard deviation of carrier error was reduced from 4.2mm to 3.7mm.

The vertical axes of Fig. 13 indicate the Doppler frequency (in hertz) 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 Fig. 11.

Figure 14 shows the loop frequency other than aiding frequency (f_{PLL0} in Eq. (2), units: hertz) when the IF data from the front-end with TCXO were processed. The clock drift of the TCXO is clearly seen since f_{PLL0} contains clock frequency and noise.

The f_{PLL0} (in hertz) computed by using the IF data from the front-end with OCXO are shown in Fig. 15. The clock drift is

Table 2 Standard deviations of carrier phase error for various combinations of equipments when Doppler is aided.

	TCXO		OCXO	
	Nav. INS (GAIA)	MEMS INS (Micro-GAIA)	Nav. INS (GAIA)	MEMS INS (Micro-GAIA)
σ_ϕ (mm)	3.8	3.8	3.7	3.7

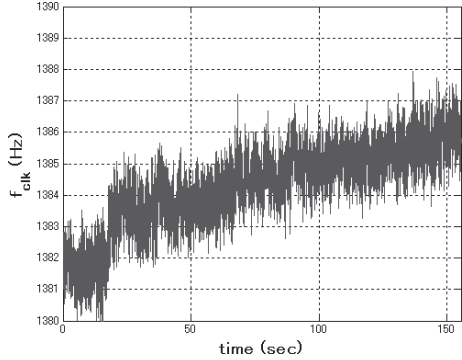


Fig. 16 Estimated clock frequency (TCXO, Nav. INS).

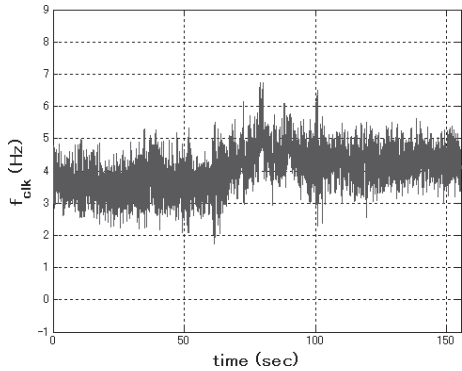


Fig. 17 Estimated clock frequency (OCXO, Nav. INS).

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.

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 16 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 Fig. 14. The clock frequency when OCXO was used is shown in Fig. 17 and again it is similar to the tendency seen in Fig. 15.

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 [7],[8].

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 Fig. 18. It is clear that the OCXO is much more stable than TCXO, therefore a better carrier frequency/phase is expected.

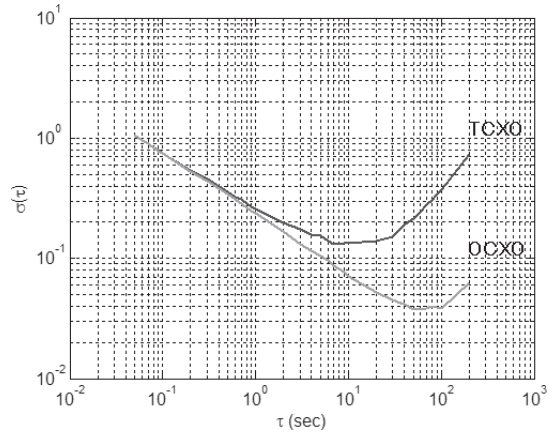


Fig. 18 Allan variances obtained by processing static data.

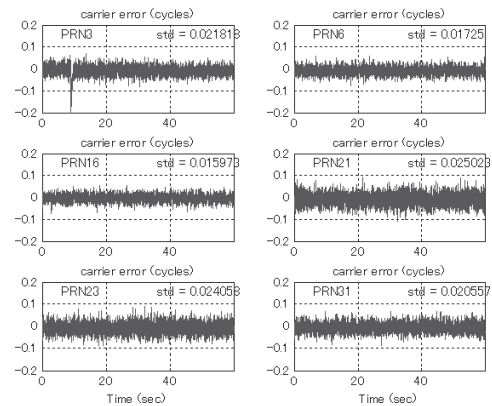


Fig. 19 Carrier error with 2 Hz bandwidth (TCXO, static).

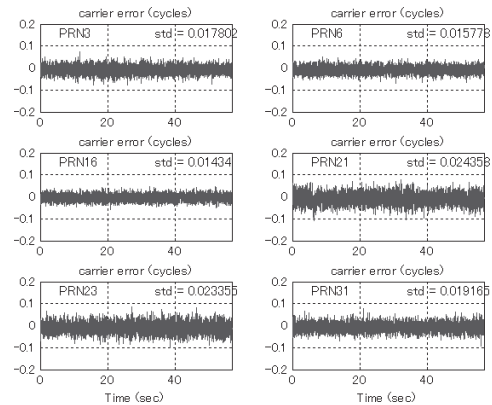


Fig. 20 Carrier error with 2 Hz bandwidth (OCXO, static).

Figure 19 shows carrier phase error (in hertz) for the case of static data with reduced noise bandwidth (2 Hz) when TCXO was used. On the other hand, Fig. 20 shows the carrier phase error (in hertz) when OCXO was used. It can be seen as expected that the standard deviations were reduced for all satellites when OCXO was used. The carrier errors for PRN 21 and PRN 23 were larger than those for other satellites in both figures. The elevation angles of these two satellites were lower than others and therefore signal propagation effect would result in worse carrier phase errors.

Going back to flight data, Figs. 21 and 22 show the loop frequency other than aiding frequency (f_{PLL0} in hertz) 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

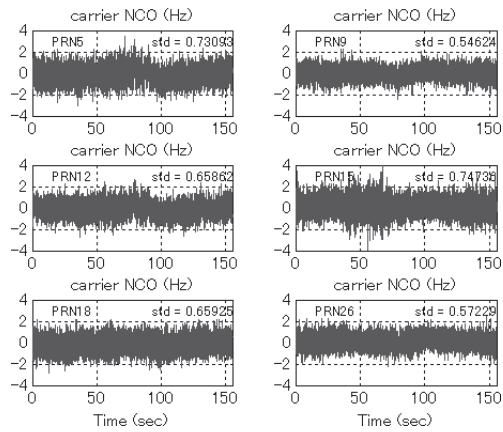


Fig. 21 Loop frequency other than Doppler and clock frequency (TCXO, Nav. INS).

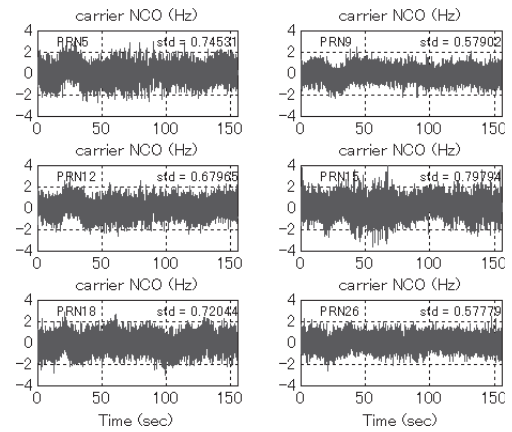


Fig. 23 Loop frequency other than Doppler and clock frequency (TCXO, MEMS INS).

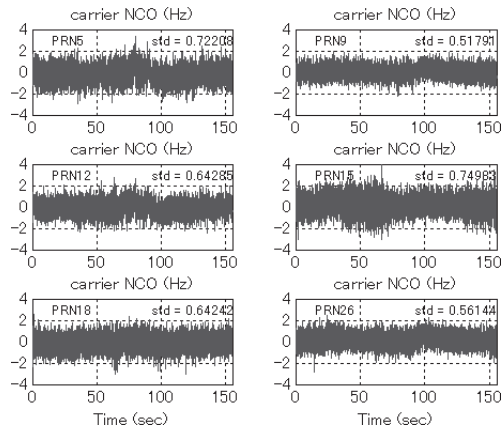


Fig. 22 Loop frequency other than Doppler and clock frequency (OCXO, Nav. INS).

Table 3 Standard deviations of carrier phase/frequency error for various combinations of equipments when Doppler and clock frequency are aided.

	TCXO		OCXO	
	Nav. INS (GAIA)	MEMS INS (Micro-GAIA)	Nav. INS (GAIA)	MEMS INS (Micro-GAIA)
σ_ϕ (mm)	3.7	3.7	3.6	3.7
σ_f (Hz)	0.66	0.69	0.64	0.69

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. Also, the aircraft vibration would affect the clock performance. Figure 23 shows the frequency error (in hertz) when the low-cost MEMS INS was used for Doppler aiding. Comparing them with Fig. 21, they were more fluctuated especially at the start of acceleration for take-off (time was about 20 sec, see Fig. 8). Since velocity accuracy of Micro-GAIA is generally worse than GAIA, the residual Doppler errors in Fig. 23 seem larger than those in Fig. 21. However, the resultant phase errors shown in Table 3 were very similar between the case of GAIA and Micro-GAIA.

5. 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 a GPS as well as a low-cost MEMS INS loosely-coupled with a 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. Although many articles have reported the techniques of INS aiding, most of the results are based on theory and simulation. This paper emphasised the analyses of real data from different types of equipments. 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 frequencies such as delta Doppler, Doppler, and Doppler and clock frequency have been tested. Though the Doppler aiding showed smaller carrier phase errors than delta-Doppler aiding, the difference is not much. Several articles developed complicated aiding algorithms and demonstrated superior performances [5],[8]. On the other hand, this paper has shown that even a very simple method (e.g. the delta Doppler aiding) can improve the tracking performance to some extent. This method has an advantage in the implementation aspect because of its simplicity. The aiding of the clock frequency in addition to Doppler did not give a significant improvement. A more sophisticated algorithm to estimate the 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, the Doppler aiding by a low-cost MEMS INS showed a similar performance with aiding by a navigation grade INS. Therefore, the use of the low-cost INS seems sufficient for unmanned aerial vehicles and the general aviation. However, integration with a navigation grade INS guarantees superior continuity during the GPS outage, and suited for a precision approach.

Future work will include development and implementation of more sophisticated tracking algorithms in which the clock frequency and Doppler are estimated more precisely. Also, in order to evaluate the performance of the aided tracking, a specially designed IF data simulator is planned to be developed. The simulator will create the IF data which simulates an ionospheric scintillation, an intentional/unintentional interference,

and a faulted satellite signal. This test extension will makes it possible to demonstrate an improved continuity/availability of the precision approach under such a severe environment.

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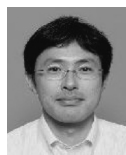
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