Performance Analysis and Experimental Validation of a Doppler-Aided GPS/INS Receiver for JPALS Applications

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BIOGRAPHY

Tsung-Yu Chiou is a Ph.D. candidate in the Aeronautics and Astronautics Department of Stanford University. He received his B.S. in Aerospace Engineering in 1998 from Tamkang University, Taiwan and his M.S. from Stanford in 2002. His research currently focuses on the performance analysis and validation of Doppler aided GPS carrier-tracking loops.

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ENS Sarah E. Atwater, USNR, graduated from the U.S. Naval Academy in 2003 with a B.S. in Aerospace Engineering (Astronautics track). She is currently an M.S. student in Aerospace Engineering at Stanford and works as a Research Assistant in the GPS Laboratory.

Dr. Jennifer Gautier works as a Research Associate in the GPS Laboratory of the Aeronautics and Astronautics Department at Stanford University. She received her Bachelor's degree in Aerospace Engineering from Georgia Tech and her Master's and Doctoral degrees in Aeronautics and Astronautics from Stanford. She has worked for Lockheed, Honeywell Labs and Trimble Navigation, Ltd., and currently leads Stanford's JPALS research efforts.

Dr. Sam Pullen received his Ph.D. in Aeronautics and Astronautics from Stanford University in 1996. Since graduating, Dr. Pullen has served as Research Associate and as Technical Manager at Stanford, where he has supported GPS Local Area Augmentation System (LAAS) and Wide Area Augmentation System (WAAS) research and development and is now the LAAS project leader. His work in these fields and his support of the Johns Hopkins University Applied Physics Laboratory (JHU/APL) GPS Risk Assessment earned him the ION Early Achievement Award in 1999.

Dr. Per Enge is a Professor of Aeronautics and Astronautics at Stanford University. He received his B.S. in Electrical Engineering from the University of Massachusetts at Amherst in 1975, and his M.S. and Ph.D., both in Electrical Engineering, from the University of Illinois at Urbana-Champaign in 1979 and 1983. Professor Enge's research focuses on the design of navigation systems which satisfy stringent requirements with respect to accuracy, integrity (truthfulness), time availability, and continuity.

Dr. Dennis M. Akos completed the Ph.D. degree in Electrical Engineering at Ohio University within the Avionics Engineering Center. He has since served as a

faculty member with Luleå Technical University, Sweden, and then as Research Associate with the GPS Laboratory at Stanford University. Currently he is an Assistant Professor with the Aerospace Engineering Science Department at University of Colorado at Boulder.

Dr. Demoz Gebre-Egziabher is an assistant professor of Aerospace Engineering and Mechanics at the University of Minnesota, Twin Cities. His research interests are in the areas of navigation, guidance and control with an emphasis on sensor fusion and system integration issues. Prior to joining the faculty at the University of Minnesota, he was an officer in the US Navy and subsequently a member of the GPS Laboratory at Stanford University where he received a Ph.D. in Aeronautics and Astronautics.

Dr. Boris S. Pervan is an Assistant Professor of Mechanical and Aerospace Engineering at the Illinois Institute of Technology in Chicago. He received B.S. from the University of Notre Dame, M.S. from the California Institute of Technology, and Ph.D. in Aeronautics and Astronautics Engineering from Stanford University. His research interests are satellite-based and inertial navigation systems, Differential Global Positioning System (DGPS), Fault detection and isolation, High integrity navigation for automatic landing of aircraft, Carrier phase DGPS positioning and cycle ambiguity resolution, Navigation, guidance, and control of autonomous ground vehicles.

ABSTRACT

The Joint Precision Approach and Landing System (JPALS) is the next generation aircraft precision approach and landing system being sponsored by US Department of Defense. This GPS-based system will provide joint operational capability for military users to perform assigned conventional and special operations missions from fixed-base, tactical, shipboard, and austere environments under a wide range of meteorological and terrain conditions. JPALS is expected to operate in the presence of significant radio frequency interference (RFI) and hostile jamming, the presence of which will reduce the effective received signal power, and thus degrade navigation accuracy and integrity of the system. Previous research has proposed using Doppler-aided carrier-tracking loops as a component of the anti-jam solution. Since Doppler aiding removes platform dynamic stress, the required bandwidth of the carrier-tracking loop can be reduced to mitigate wide-band interference. Thus, Doppler aiding via an inertial measurement unit (IMU), can improve the robustness of the GPS receiver for operation in extreme RFI environments as well as in high dynamical situations.

To validate the benefits of Doppler aiding, three experimental data sets consisting of Intermediate Frequency (IF) samples from a GPS receiver and time-synchronized IMU measurements are collected. Three clock sources are used to drive a software GPS receiver for collecting the GPS data sets: a rubidium atomic standard, an oven-controlled crystal oscillator (OCXO) and a temperature-compensated crystal oscillator (TCXO). The inertial measurements are obtained from an automotive grade IMU (i.e., gyro in-run stability on the order of 180deg/hr) and a tactical grade IMU (i.e., gyro in-run stability between 1 and 10 deg/hr). Hence, six GPS/IMU data sets are collected to allow a comprehensive analysis on the impacts of the different combinations of critical components. The software receiver processing incorporates both the GPS and IMU measurements, and tracks the GPS carrier with a third order carrier-tracking loop. One of the metrics used for judging the carrier-tracking loop performance is the measured phase-error, which is evaluated with varying tracking-loop noise bandwidths. The results of this investigation show that for high-quality GPS oscillators (OCXO or atomic clocks) the bandwidth of the carrier-tracking loops can be reduced to about 1Hz with the use of Doppler-aiding from a GPS/INS navigation filter. Further reduction of the bandwidth is expected with more optimized navigation filters.

Keywords: JPALS, anti-jamming, Doppler aiding, GPS/INS integration

I.   INTRODUCTION

The Global Positioning System (GPS) for the Joint Precision Approach and Landing System (JPALS) [1] application is considered to be a next generation carrier-phase differential GPS navigation system. Mitigation of radio-frequency interference (RFI) is a priority for the JPALS program, and is one of the primary difficulties hindering its development. RFI poses a severe threat to GPS continuity and integrity, which are the two most important issues currently facing the JPALS program. Inertial aiding of the carrier tracking-loops is one of the techniques being considered for reducing the effect of RFI on system continuity and integrity [2, 3, and 4]. A technique known as Doppler aiding is a potential alternative for achieving this goal, as it has most of the benefits of ultra-tight GPS/INS coupling and a relatively simple architecture.

The concept of Doppler aiding is not new. However, a full experimental validation has not been implemented to test performance under various types of interference, including wide-band, continuous wave, and pulsed wave signals. To advance this study, a unique and flexible test-bed has been developed to validate the Doppler-aiding technique. The objective of this paper is

to provide preliminary test results obtained with this test-bed, including a comparison of GPS reference oscillators and IMUs on allowable phase-lock loop (PLL) bandwidth reduction.

The outline of this paper is as follows: Section II covers an overview of both the Doppler-aiding concept and the third-order PLL model used in this study. In Section III, the data collection and the experimental setup are presented. The procedures for post processing the data are given in Section IV. Section V contains the experimental results and relevant discussions. Finally, the conclusions of this study and plans for future work are included in Section VI.

II. OVERVIEW OF DOPPLER AIDING GPS CARRIER-TRACKING LOOPS

This section presents a straightforward overview of GPS carrier-tracking loops. More thorough discussions of the GPS carrier-tracking loop are provided in [5 and 6]. Figure 1 shows the structure of a generic GPS phase-lock loop [6], with or without a Doppler aiding input. The input GPS signal has been down-converted to a proper intermediate frequency (IF)(1-20 MHz). A carrier wipeoff operation is performed by multiplying the down-converted signal with a local replica of its carrier, given by the numerically-controlled oscillator (NCO) in both in-phase and quadrature outputs. The in-phase output is represented by a cosine signal, while the quadrature output is represented by a sine signal. A code wipeoff is then achieved by multiplying in-phase (I) and quadrature (Q) channels by the prompt code replica. After these operations the signal has been down converted to base-band, and the predetection integration process is executed in an "integrate and dump" operation, which performs measurement averaging over at least one millisecond. The outputs of this process are the inputs to a phase discriminator, which gives a measurement of the phase offset between the true carrier and the replicated carrier. The loop filter is a compensator designed to track the phase (and frequency) of the input carrier with desired dynamic range and noise suppression performance. The output of the loop filter is a frequency command for the NCO, which steers the replicated carrier frequency to maintain phase lock.

The phase discriminator should tolerate the GPS navigation data modulation on the base-band signal. Generally, this type of carrier-tracking loop uses a Costas discriminator (phase offset ≈ QI). In this study, an arctangent discriminator is used (phase offset ≈ ATAN(Q/I)). A linearized model of this loop is illustrated in Fig. 2, which shows a familiar structure commonly used to study the characteristics of the PLL and design the loop filter. The model also includes an input branch that represents a Doppler-frequency estimate input.
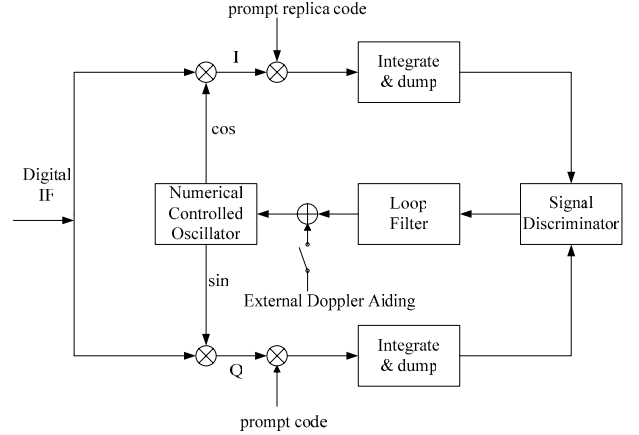

Figure 1: GPS carrier-phase tracking loop

The transfer function of the loop filter implemented in this work is as follows:

$$F(s) = \frac{2\omega_n s^2 + 2\omega_n^2 s + \omega_n^3}{s^2} \qquad (1)$$

where ω_n is the natural loop frequency in rad /sec. The resulting closed-loop transfer function with this loop filter is:

$$H(s) = \frac{G(s)F(s)}{1+G(s)F(s)} = \frac{2\omega_n s^2 + 2\omega_n^2 s + \omega_n^3}{s^3 + 2\omega_n s^2 + 2\omega_n^2 s + \omega_n^3} \qquad (2)$$

where $G(s)$ represents the transfer function of the NCO in Fig. 2. An important characteristic of the PLL is its single-sided, closed-loop noise bandwidth (B_L) which is defined as follows [7]:

$$B_L = \int_0^\infty |H(j\omega)|^2 \, df \qquad (3)$$

Evaluating this equation for the third-order PLL, gives a relationship between B_L and ω_n:

$$\omega_n = 1.2 B_L \qquad (4)$$

where the units of B_L and ω_n are rad/sec and Hz, respectively.

In Fig. 2, f_{PLL} represents the carrier-frequency deviation from the IF. This frequency deviation is primarily made up of three components: the Doppler frequency (f_{dopp}) due to the relative motion between the receiver and the satellite, frequency errors due to the receiver oscillator (f_{clk}), and errors due to thermal noise and interference (f_{noise}). Equation 5 represents f_{PLL} in terms of these components:

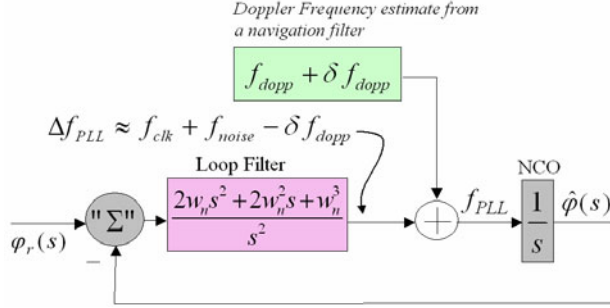$$f_{PLL} = f_{dopp} + f_{clk} + f_{noise} \qquad (5)$$

Figure 2: A Linear Model of a Phase-Lock Loop with Doppler Aiding (3rd order PLL with Doppler Aiding from a GPS/INS Navigation Filter)

Doppler aiding is implemented by adding the external Doppler-frequency estimate to the output of the loop filter. This external input may come from a GPS/INS navigation filter, whose navigation outputs are mostly based on inertial measurements in the short term. Inclusion of the external Doppler-frequency estimate removes the task of tracking vehicle dynamics from the PLL, but may introduce a different form of dynamic stress in the form of errors from the external Doppler estimates. Therefore, the PLL with Doppler aiding must be designed to track phase-dynamics due to the receiver oscillator instability and Doppler-estimate errors. Conclusively, the value of the loop-filter frequency output for a Doppler-aided PLL is:

$$\Delta f_{PLL} \approx f_{clk} + f_{noise} - \delta f_{dopp} \qquad (6)$$

Assuming that the dynamics of the Doppler-estimate errors are slower than vehicle dynamics, the use of Doppler aiding allows for noise bandwidth reduction when compared to a traditional PLL, hence improving its noise-suppression performance.

The quantity of interest in this paper is frequency/phase-tracking stability, which can be quantified by the tracking error of the PLL and measured directly by the output of the phase discriminator. The phase-jitter of the loop, which is the root-mean-square (rms) of the phase-error measurement, will be used to quantify phase-tracking stability.

A full performance analysis of the Doppler-aided GPS carrier-tracking loops is given in [2]. The focus of this paper is to provide preliminary test results of the Doppler aiding technique using the test-bed developed by the GPS lab at Stanford University. In the section highlighting test results, the performance of phase-jitter as a function of PLL closed-loop noise bandwidth is evaluated.

III. DATA COLLECTION AND EXPERIMENTAL SETUP

Data Collection Experiment

The data collection experiment was conducted on the top level of the five-story parking structure shown in Figs. 3 and 4. To include both static and dynamic data, the following drive-test scenario was used: the vehicle was static for 4 minutes and then drove one loop around the top level of the parking structure (about one minute of movement). Figure 5 illustrates the shape of the trajectory, as measured by stand-alone GPS and by the GPS/INS navigation filter. The same data collection scheme was repeated with three different GPS reference oscillators: a rubidium atomic clock, an oven-controlled crystal oscillator (OCXO), and a temperature compensated crystal oscillator (TCXO). In addition to the three different GPS oscillators, data was collected from two collocated IMUs, such that the phase-jitter performance could be studied for different combinations of GPS clock and IMU. A set of three antennas in an equilateral triangle configuration were used as part of an automobile GPS attitude system, to measure the vehicle attitude as part of the measurement vector for the navigation filter. The IMUs and GPS antennas are shown in Fig. 6, mounted on a rigid frame fixed on the test-vehicle's roof rack.

Figure 3: The parking structure where the experiment was conducted

The antenna array shown has 1 meter baselines, and the IMUs are mounted near the geometric center of the antenna array to simplify the kinematic equations of the navigation filter. Three Novatel Allstar GPS receivers are connected to the three antennas, and connected to a common clock to allow attitude determination with single-difference carrier-phase measurements.

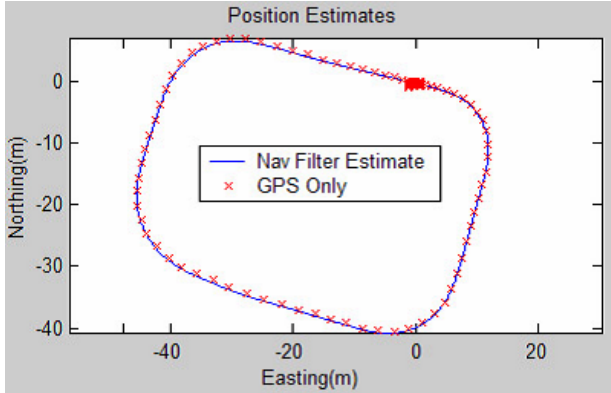**Figure 4: The top level of the parking structure**

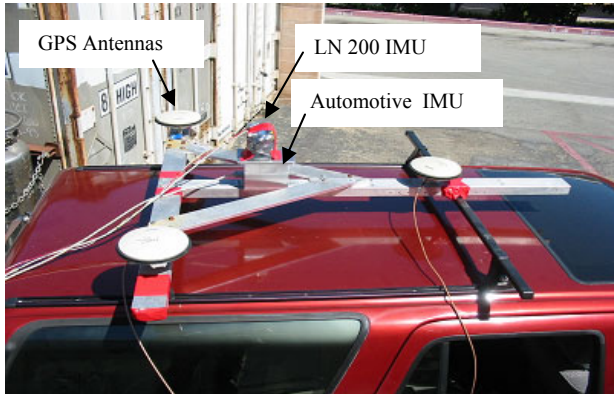**Figure 5: The trajectory of the data collection**

Figure 6: The Triangular Antenna Array and the IMUs

Data Collection Hardware Setup

Figure 7 depicts the data collection hardware setup. The front end of a NordNav software receiver down-converts the L1 GPS signal to a 4.092 MHz IF, and the streamer samples the data at 16.368 MHz.

As shown, one of three GPS reference oscillators could be used, and three sets of GPS front-end data were collected, one for each type of reference oscillator. Figure 7 also illustrates a dedicated computer to collect data from a tactical-grade IMU (LN200), providing linear

acceleration and angular rate measurements at 400 Hz. The third branch of data-collection setup includes three Novatel receivers and an automotive grade IMU. A GPS/INS attitude system was used to provide attitude measurements at 10 Hz, in addition to the 10Hz velocity and 2Hz position measurements provided by the GPS receivers. The attitude system also includes circuitry to generate a 100Hz sampling signal synchronized to the pulse-per-second signal from one of the Novatel receivers, which allows for GPS time-tagging of IMU measurements. The synchronized automotive IMU data samples were then used to synchronize the LN200 samples by correlating the two IMU data sets.
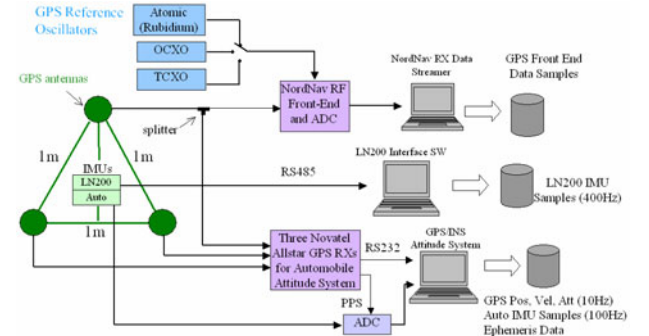

Figure 7: The Data Collection Hardware Setup

IV.   POST PROCESSING PROCEDURE

The post-processing procedure consisted of two steps. First, the recorded GPS measurements from the Allstar receivers (position, velocity, attitude) and synchronized IMU data were passed through a GPS/INS navigation filter and the filter's velocity estimates were used along with satellite ephemeris data to compute Doppler estimates. Second, the Doppler estimates were used to implement Doppler-aided phase-tracking on the recorded GPS IF samples. This step was realized with the use of a modified NordNav software receiver, customized to use external Doppler information in replay mode. Figure 8 illustrates the post processing procedure. As shown, the two key components are the GPS/INS navigation filter and the modified NordNav software receiver. The details of the navigation filter are beyond the scope of this paper, but it is important to note that the dynamic equations are written for the overall car position and velocity, and do not include its suspension dynamics. This limitation may cause some of the suspension dynamics to be omitted from Doppler estimates, particularly at transverse acceleration (not rotational) body mode of the car around 1Hz. In addition, the navigation filter velocity estimates always represent a blended GPS/INS solution, and no GPS outages have been included in the data at this time. Thereby, it will be shown that IMU sensor instability is negligible in the accuracy of Doppler estimates while GPS calibration is available at a high rate (10Hz in this case), but sensor

instability is expected to have a large impact on dead-reckoning mode when GPS navigation solution is not present.

Finally, data passes through the other key component, the modified software receiver. The carrier-tracking loops are modified such that the estimated Doppler frequency from the GPS/INS navigation is fused into the phase-lock loop of the software receiver. The estimated Doppler is added directly to the original command output from the loop filter. After a transition time, the Doppler term in the original command output from the loop filter drops down to zero, as the dynamics have been removed by the external estimated Doppler. One should note that this aiding scheme is equivalent to applying a frequency step into the PLL, unless the integrator outputs in the loop filter are reset when Doppler aiding is applied. A too-large initial frequency step would cause the loss of lock since the frequency step may exceed the pull-in range of the PLL. Therefore, one possible scheme for transition into a Doppler-aided mode is to increase the frequency aiding gradually, such that the PLL can track the smaller rate of change in input frequency. To improve the speed of post-processing, a scheme that resets the integrator outputs of the loop filter will be used in future implementations of this test bed, though it is not expected that this change will have an effect on the steady-state phase-jitter results.
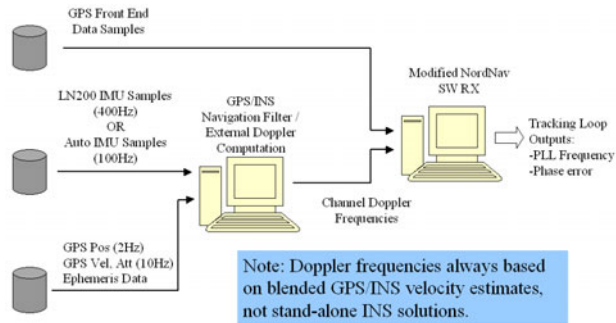

Figure 8: Post Processing Procedure

V. RESULTS AND DISCUSSIONS

As discussed previously, the PLL phase-jitter performance depends on its bandwidth, signal-to-noise ratio, the quality of GPS reference oscillator, and in the case of a Doppler-aided PLL, the accuracy of external Doppler estimates. Before showing the phase-jitter performance with different combination of GPS clocks and IMUs, it is instructive to illustrate the quality of receiver clocks and the quality of estimated Doppler from the blended GPS/INS navigation filter. Figures 9, 10, and 11 show the channel frequencies with the three different clocks and the corresponding estimated Doppler frequencies computed with velocity outputs from the GPS/INS navigation filter (using both IMUs). The

channel frequencies on each plot reflect the scenario of the test drive: for the first 3-4 minutes, the vehicle was static and started to move only at the beginning of the last minute. As will be seen, the excessive frequency instability of the TCXO (Figure 9) has a large adverse effect on the tracking performance of both the unaided and Doppler-aided case. With this frequency instability, the required noise bandwidth to maintain phase-jitter below 15° is very high (~ 60 Hz) when the receiver is in motion. Based on prior observations of TCXO behavior [3], it is believed that the TCXO in this test behaved abnormally, possibly due to vibration and/or external circuitry required to interface the TCXO with the signal generator acting as a reference oscillator. Clearly, the Doppler aiding in this case would not be effective, when compared to that with the other two clocks. Hence the comparison of different clocks when the receiver is in motion is only meaningful for the OCXO and the atomic clock. The blue line on Figs. 9, 10, and 11 serves as a reference for the estimated Doppler from GPS/INS navigation filter. This line is the estimated Doppler frequency calculated by using the surveyed starting point of the tests and the satellite positions. Obviously, this estimation is valid only when the receiver is static. The other feature shown in Figs. 10 and 11 is the estimated Doppler frequency. The estimated Doppler captures the motion of the vehicle well, as can be seen on the detail window of Figs. 10 and 11.
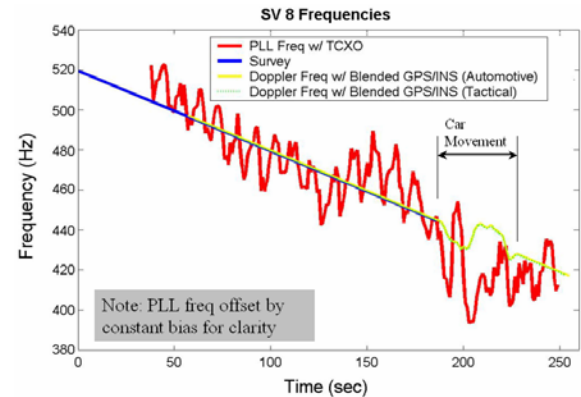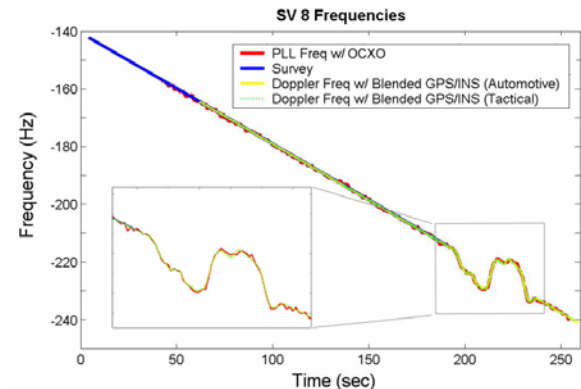

Figure 9: Channel Frequencies with TCXO
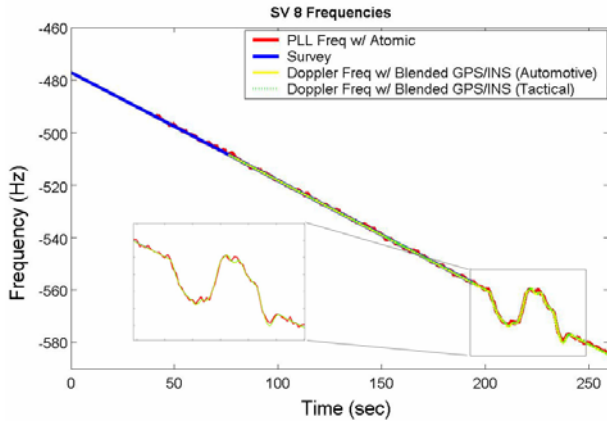

Figure 10: Channel Frequencies with OCXO

Figure 11: Channel Frequencies with Atomic Clock

The estimated Doppler frequencies from the two grades of blended GPS/INS are almost identical. As stated previously, this result was anticipated because of the constant availability of GPS navigation solutions, which allow continuous calibration of the IMU, and make the effect of IMU sensor instability negligible to Doppler-estimate accuracy.

The metric used for evaluating the effectiveness of Doppler-aiding is the allowable reduction of PLL noise bandwidth that maintains acceptable phase-jitter performance in dynamic conditions. The amount of phase-jitter that constitutes an "acceptable" level may depend on system requirements. For example, this level could be defined as the maximum phase-jitter tolerable by the PLL to maintain phase-lock within a certain probability, or it could be based on the 15° accepted limit for linear behavior of a Costas phase discriminator [2], or 5° for high reliability in spread-spectrum data demodulation [7].

Figures 12 and 13 show the phase-jitter performance for both the static and dynamic conditions, respectively. The data on these plots was collected up to the lowest PLL bandwidths that the software receiver would tolerate, and still generate a navigation solution. As expected, the phase-jitter performance stays the same for each case (unaided and Doppler aided) when the noise bandwidth is high (>10 Hz). With this high bandwidth, the phase-jitter due to untracked clock instability and Doppler-estimation errors is much lower than that due to thermal-noise. If the noise bandwidth is reduced low enough, the phase-jitter increases dramatically as phase-tracking error is dominated by the untracked dynamics of receiver clock frequency and phase noise. From Fig. 12, the phase-jitter with the TCXO is much larger than that with the OCXO and atomic clock. This behavior is consistent with Fig. 9. The excessive frequency instability introduces large phase-jitter in the PLL. The allowable noise-bandwidth reduction with the OCXO and the atomic clock is comparable, whether the receiver is static or in motion. Tables 1 and 2 summarize allowable

minimum bandwidth for all test cases. Note, the minimum bandwidths stated in these tables are selected based on two criteria: the minimum bandwidth where the software receiver lost navigation tracking, and the minimum bandwidth to maintain phase-jitter below 15°. The boxes labeled "N/A" (not applicable) are for cases where the software receiver is unable to track to yield a phase-jitter measurement.
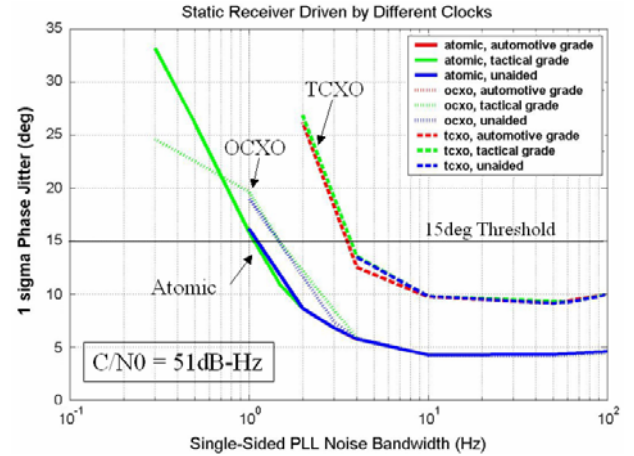

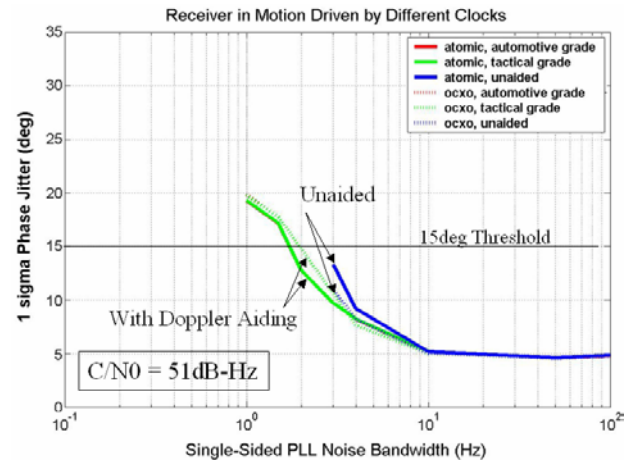**Figure 12: Phase-jitter Performance (Static Antenna)**

Figure 13: Phase-jitter Performance (Antenna in Motion)

Table 1: Allowable Minimum Bandwidths (Hz) for Static Antenna

Clock Type	Based on NordNav RX Ability to Give GPS PVT		Based on 15° Phase-Jitter Threshold	
	Unaided	Doppler Aided (Both IMUs)	Unaided	Doppler-Aided (Both IMUs)
Atomic	1.0	0.3	1.1	1.1
OCXO	1.0	0.3	1.4	1.4
TCXO	4.0	2.0	N/A	3.8

Table 2: Allowable Minimum Bandwidths (Hz) for Dynamic Antenna

Clock Type	Based on NordNav RX Ability to Give GPS PVT		Based on 15º Phase-Jitter Threshold	
	Unaided	Doppler Aided (Both IMUs)	Unaided	Doppler-Aided (Both IMUs)
Atomic	3.0	1.0	N/A	1.7
OCXO	3.0	1.0	N/A	2.0
TCXO	N/A	N/A	N/A	N/A

In static conditions, Doppler aiding has limited benefits as it only removes the need to track satellite dynamics, which change slowly. In these cases, the achievable bandwidth reduction for the receiver to remain tracking is 0.7 Hz for both the atomic clock and OCXO while the bandwidth reduction is 2 Hz for TCXO. When the antenna is in motion, the bandwidth reduction is 2 Hz for both atomic clock and OCXO, and for both IMUs.

Ideally, the lowest allowable bandwidth with Doppler aiding should be the same for both static and dynamic antenna. However, the lowest allowable bandwidth with Doppler aiding shown on Table 2 (dynamic) is 1 Hz for the receiver to remain tracking, while it is 0.3 Hz on Table 1 (static). The 1 Hz lower limit on PLL bandwidth is most likely due to imperfect Doppler estimates, which may contain error due to suspension dynamics, not well captured by the current GPS/INS navigation filter implementation.

Since the dynamics created by the car movement were not large in these tests, the lowest allowable bandwidth without Doppler aiding was 3 Hz, suggesting relatively slow acceleration and vibration. With faster vehicle dynamics, the unaided minimum PLL bandwidth would be considerably higher, and the bandwidth reduction gained with Doppler aiding would be more pronounced. However, Doppler estimate errors may also be greater with higher dynamics, so the advantages gained by Doppler aiding with faster dynamics will have to be tested empirically. Another issue to consider under more aggressive dynamics is the behavior of the clock under vibration. The clock instability in such conditions may worsen, further limiting the benefit of Doppler aiding [2 and 3].

The effect of carrier-to-noise ratio (C/N0) on the influence of Doppler aiding is also important. For the data shown, C/N0 is 51 dB-Hz. The results may vary with different C/N0, as the optimum PLL bandwidth to minimize phase-jitter changes with C/N0.
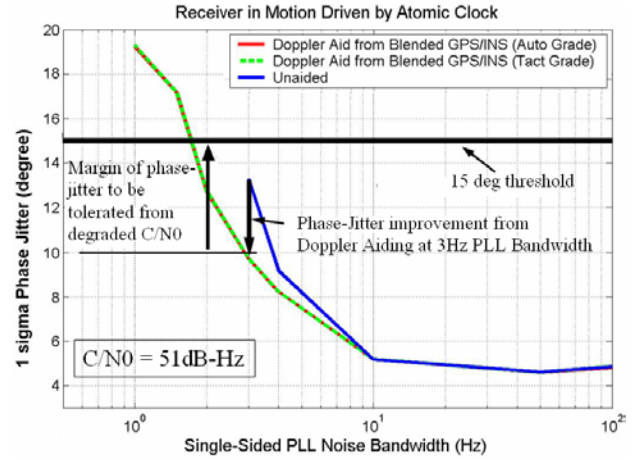

Figure 14: Phase-jitter Improvement by Doppler Aiding

Figure 14 depicts the phase-jitter improvement by Doppler aiding when the GPS software receiver is driven by the atomic clock. Note, the lowest allowable bandwidth such that the receiver can track is not likely to be the best operating choice. Seeking the absolute lowest bandwidth with this criterion only considers phase-jitter caused by wideband noise or interference. At low PLL bandwidths, however, the phase-jitter is dominated by receiver clock dynamics, vibration effects, and Doppler-estimate errors. Therefore, the phase-jitter is minimized at a certain bandwidth (normally between 1 and 10 Hz) for a given C/N0, and the bandwidth that minimizes phase-jitter is lower for decreasing C/N0. Selection of a fixed PLL bandwidth should accommodate the lowest C/N0 expected, in which case it will not be optimal for higher C/N0. For this reason, an adaptive noise bandwidth mechanism may be implemented to attempt to optimize phase-jitter for changing values of signal-to-noise ratio.

As shown in Fig. 14, the lowest bandwidth tolerated by the receiver, 1 Hz, also results in phase-jitter much larger than the 15º threshold of a linear Costas discriminator, and would not be considered a good operating bandwidth. However, for a noise bandwidth between 3 and 10Hz, the Doppler-aided PLL has a larger margin of phase-jitter to be tolerated from degraded C/N0. The amount of phase-jitter margin labeled in Fig. 14 is for a bandwidth of 3Hz. If a bandwidth between 1.7 and 3Hz is used, the margin for remaining below the 15º threshold is smaller. However, the phase-jitter contribution from wideband noise also decreases with a smaller bandwidth. A quantified study of this tradeoff would yield the best bandwidth for a given C/N0, and is part of the agenda for future work.

From Fig. 13, this phase-jitter margin is not obvious for the OCXO. This observation suggests that the OCXO was more sensitive to car motion, and the improvement in phase-jitter gained by Doppler aiding was canceled by the vibration effect on clock stability.

VI. CONCLUSIONS AND FUTURE WORK

Conclusions

This investigation demonstrates that the use of Doppler aiding permits reduction of PLL noise bandwidth, thereby improving phase-jitter performance at the low bandwidths of interest for a JPALS application. For the moderate dynamics generated by slow car motion and the navigation filter used in this work, the achievable reduction in noise bandwidth was 2 Hz (from 3 to 1 Hz) for the software receiver to remain tracking. It is expected that faster vehicle dynamics will make the reduction of noise bandwidth more pronounced, as the PLL noise bandwidth without Doppler aiding would most likely have to be higher than 10Hz. It was also concluded that with continuous, high quality stand-alone GPS navigation measurements to blend with the inertial measurements, the quality of IMU does not affect the accuracy of Doppler estimates or phase-jitter performance.

The results shown in this paper are applicable for relatively high C/N0 (51 dB-Hz). At the low PLL bandwidths of interest for JPALS (<2Hz), phase-jitter tends to be dominated by the reference oscillator noise for C/N0 as low as 37 dB-Hz [3], so similar effects should be expected for typical signal-to-noise ratios without jamming. However, the presence of RFI may degrade C/N0 to below 30dB-Hz, in which case phase-jitter from wideband noise/interference can be significant, and the benefit of Doppler-aiding in such conditions remains to be investigated.

For low C/N0 under RFI and low PLL bandwidths, the performance of the local oscillator is of critical importance, as it will be the limiting factor on reduction of PLL bandwidth. Part of the goal of these experiments was to observe the effect of having different GPS reference oscillators on the benefits of Doppler aiding. Although results with the TCXO are inconclusive, prior research has suggested that the lowest bandwidth possible with such inexpensive oscillators is on the order of several Hz (~3Hz) [3]. For better oscillators, results shown in this paper show that the OCXO and the atomic clock have the necessary stability (static tests, without significant vibration) to reduce the PLL bandwidth below 1Hz, as long as the Doppler-aiding is accurate enough. When comparing results obtained with the atomic clock and OCXO, it was found that using the atomic clock had only a slight advantage in phase-jitter performance.

Future Work

Since the test-bed described in this paper has been developed to accommodate significant flexibility, various interference scenarios and dynamic environments can be implemented and verified in the future. To make the effect of using Doppler-aiding more meaningful, faster dynamics will be used in future tests, and the navigation filter will be modified to account for suspension dynamics. Further validation of the ability to track signals with low C/N0 will be done by applying Gaussian white noise into collected GPS data. Some of the current observations suggest that the GPS reference oscillators are behaving differently in dynamic environments, so the effects of acceleration and vibration on these clocks must be quantified. Furthermore, the reasons for poor TCXO performance will be investigated. It is also of interest to investigate the effectiveness of Doppler-aiding performance for a stand-alone INS, with degraded or absent GPS aiding. In such cases, it is expected that the tactical-grade IMU will perform much better when compared to the automotive IMU.

REFERENCES

[1] Johnson, G., Lage, M. and et al, "The JPALS performance Model," Proceeding of the ION-GPS 2003, Portland, OR, September 2003.

[2] Gebre-Egziabher, D. Razavi, A., and et al, "Doppler Aided Tracking Loops for SRPS Integrity Monitoring," Proceeding of the ION-GPS 2003, Portland, OR, September 2003.

[3] Alban, S., "Design and Performance of a Robust GPS/INS Attitude System For Automobile Applications", Ph.D. Thesis, Stanford University, 2004

[4] Alban, S., Akos, D. and et al, "Performance Analysis and Architectures for INS-Aided GPS Tracking Loops," Proceedings of ION National Technical Meeting, ION-NTM 2003. Anahiem, CA. pp. 611-622.

[5] Misra, P. and Enge, P., *Global Positioning System: Signals, Measurements and Performance*, Ganga-Jamuna Press, Lincoln, Massachusetts, USA, 2001. pp. 356.

[6] Ward, P., Satellite Signal Acquisition and Tracking, in *Understanding GPS Principles and Applications*, Artech House, Washington, D.C., 1996. pp. 119-208.

[7] Spilker, J., *Digital Communication by Satellite*, Prentice-Hall, Cambridge, Massachusetts, 1977. pp. 336-397