A GPS RECEIVER DESIGNED FOR CARRIER-PHASE TIME TRANSFER

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BIOGRAPHY

Alison Brown is the President and CEO of NAVSYS Corp. She has a PhD in Mechanics, Aerospace, and Nuclear Engineering from UCLA, an MS in Aeronautics and Astronautics from MIT, and an MA in Engineering from Cambridge Univ. In 1986 she founded NAVSYS. Currently she is a member of the GPS-III Independent Review Team and Science Advisory Board for the USAF and serves on the GPS World editorial advisory board.

Randy Silva is the lead software architect at NAVSYS Corporation for our integrated GPS products. He has experience developing real-time and Windows-based applications and has over eight years experience with GPS navigation systems. Mr. Silva received his Bachelors Degree from the University of Colorado at Boulder.

Edward Powers is employed as an electronic engineer working in the Time Transfer section of the Untied States Naval Observatory (USNO) in Washington DC. Previously he worked with the Naval Research Laboratory (NRL) conducting research on various projects related to precise time keeping and GPS satellite clock development. He received both his BS and MS in Engineering from the University of Arkansas (84, 87).

ABSTRACT

The development of time transfer techniques using GPS carrier-phase observations promises the capability to deliver sub-nanosecond time transfer capabilities. Testing to date has shown that conventional GPS receivers introduce significant time offset in the carrier phase.

NAVSYS have developed a GPS receiver capable of making observations with high phase stability. Test data is presented in this paper showing the accuracy of the code and carrier phase observations from this receiver for time transfer applications.

INTRODUCTION

In this paper, the GPS carrier-phase time transfer technique is described and a discussion is included on the error components that currently limit the time-transfer accuracy using this method. Previous testing with conventional GPS receivers has shown that carrier phase instabilities can cause offsets on the order of 1-2 nanoseconds. This error source currently dominates the error budget when performing carrier-phase time transfer.

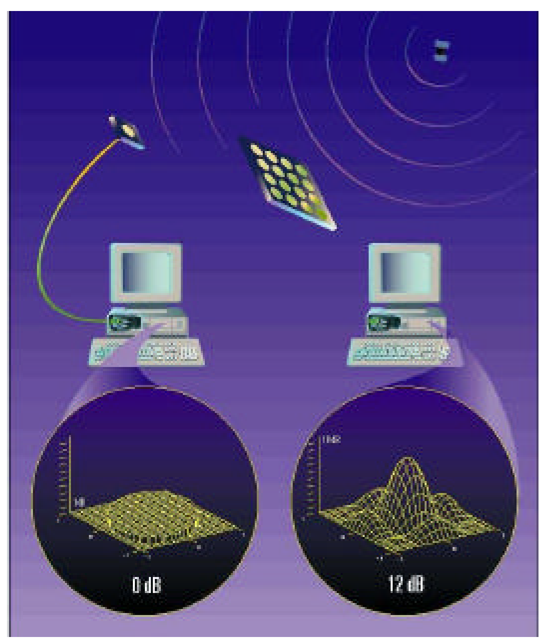

Figure 1 High-gain Advanced GPS Receiver (HAGR)

NAVSYS' High-gain Advanced GPS Receiver (HAGR) was originally developed to allow phase coherent measurements to be made from multiple antenna elements to enable digital beam forming to be performed (see Figure 1). This same design, however, also provides a highly phase stable observation of the GPS carrier, relative to a local reference oscillator, that enables precise time observations to be made for carrier-phase time transfer. The design of this receiver is described in this paper and test results included to show the carrier-phase time transfer accuracy.

GPS CARRIER PHASE TIME TRANSFER

GPS carrier-phase measurements provide the potential for much improved precision in time and frequency transfer ([1 2 3]). Time-Transfer errors approaching 100 picosecond (ps) are expected using this approach. The main reason for this expected improvement is due to the GPS carrier-phase measurement accuracy being 100 to 1000 times better than the code based pseudo-range measurements. Typical carrier phase measurement noise can be on the order of ten picoseconds (ps) whereas the code measurement noise can be as high as ten nanoseconds (ns). Multipath errors are also much smaller on the carrier-phase observations than on the code-based pseudo-range measurements.

Many carrier phase frequency transfer experiments have already shown the ability to compare remote clocks frequency offsets with stability approaching that of an Active Hydrogen Maser at averaging times as short as one day ([4 5]). But, so far, true time transfer experiments have been restrained because of limitations in resolving which carrier phase cycle a given receiver might be tracking and also in relating the carrier-phase measurement to the user's external clock in some calibrated fashion.

GPS carrier-phase measurements cannot alone be used for time transfer because of the inherent ambiguity in resolving which carrier phase cycle a receiver is tracking. The much noisier GPS code measurements must be used to help solve for this carrier phase ambiguity. Averaging the code data over some interval and fitting the resulting data as to best match the carrier phase data is the method most commonly used to resolve for this carrier phase ambiguity.

The GPS system errors that affect the accuracy of the carrier-phase time transfer performance are listed in Table 1

Table 1 GPS System Errors

1. Dual Frequency Ionosphere errors (calibration bias, increase noise)
2. Troposphere errors (Weather data, Models)
3. Receiver Measurement Noise
4. Multi-path Noise
5. Satellite Position (Orbits)
6. Station Position (Location)

Test results have shown that the dominant errors currently affecting the accuracy of carrier-phase time transfer, are not the GPS system errors shown in Table 1, but are due to environmental effects within the GPS receiver.

The time delay of the GPS signal as it propagates through a complete GPS receiving system consists of the delay through the GPS receiver, GPS antenna cables and the GPS antenna with its associated antenna electronics. All of these GPS receiving system sub-components are affected by environmental influences. Studies of the temperature sensitivities of several of these GPS receiving systems have shown delay variations of as great as several nanoseconds per degree C.[6 7 8]

Table 2 GPS Receiver Temperature Sensitivity

	Temperature effect
Receiver Code Measurements	(150 – 1500) ps per C
Receiver Carrier Measurements	(10 – 200) ps per C
Antenna cable	0.5 ps per C per Meter
Antenna electronics	(5 – 50) ps per C

Since all of these temperature effects are common to all receiver channels, these errors are mapped into the users local clock error. This does not affect the use of this data for typical geo-location application, but for time transfer applications these temperature effects must be minimized. Specially constructed phase-stabilized antenna cables can be used that will reduce the delay fluctuations through the antenna cable by a factor of 20 or more. However, the GPS receiver front-end itself must also be designed to provide a highly stable carrier-phase reference over temperature variations. In the following sections, a GPS receiver design that was developed to maintain high phase stability in the receiver front-end is described.

HIGH GAIN ADVANCED GPS RECEIVER

The HAGR design is based on NAVSYS' Advanced GPS Receiver (AGR) PC-based digital receiver architecture integrated with a digital beam steering array[9]. Using a proprietary digital signal processing algorithm, the HAGR is able to combine the GPS signals from as many as 16 antennas and create a multi-beam antenna pattern to apply gain to up to eight GPS satellites simultaneously. The 16-element antenna array is shown in Figure 2.

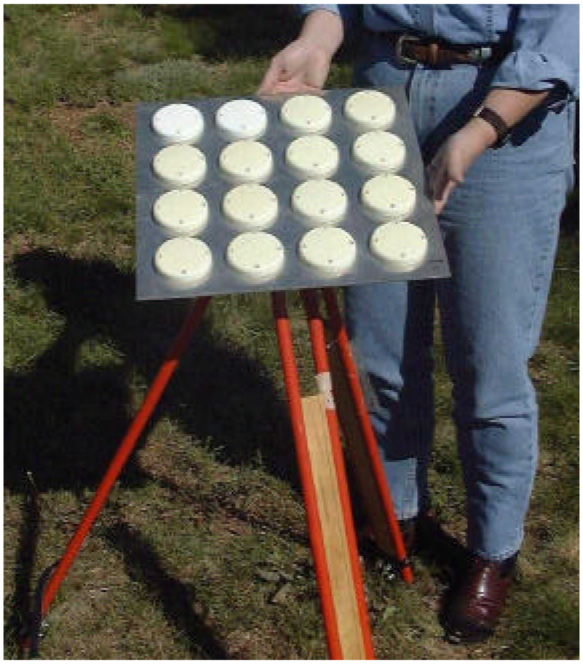

Figure 2 HAGR 16-element antenna array

The performance specifications for the HAGR for a 16-element, L1 C/A code version of this product are included in reference [10]. Currently an L1/L2 Precise Position System (PPS) version of the HAGR (the HAGR-200) is also in development.

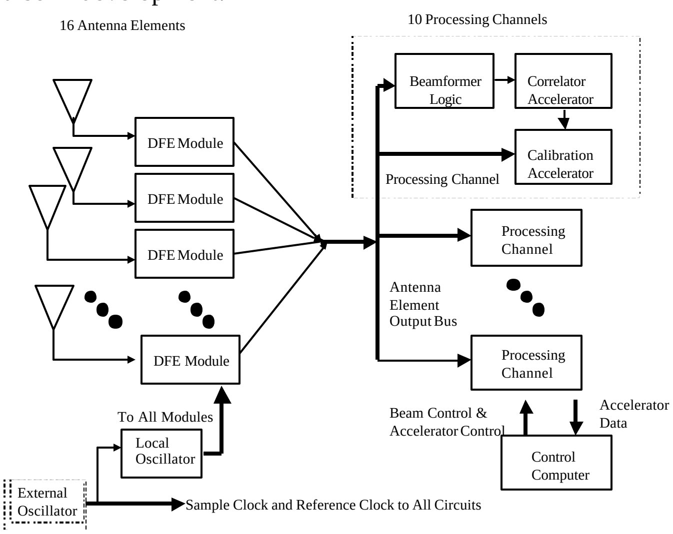

Figure 3 HAGR System Block Diagram

The HAGR system architecture is shown in Figure 3. The signal from each antenna element is digitized using a Digital Front-End (DFE). The bank of digital signals is then processed by the HAGR digital-beam-steering card to create a composite digital beam-steered signal input for each of the receiver channels.

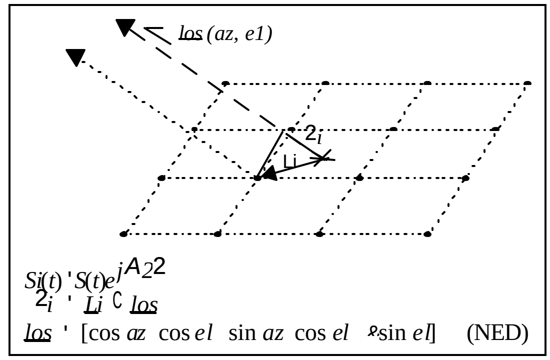

Figure 4 Beam forming satellite geometry

If attitude data (pitch, roll, yaw) is provided from an inertial navigation system or attitude sensor, the HAGR will operate while the antenna is in motion[11]. The default mode, for static operation, is to align the array pointing north.

The digital beam forming provides significant benefits in improving the measurement accuracy due to the narrow beam antenna pattern directed at each satellite tracked. As shown in Figure 5, a 16-element array will provide up to 12 dB of additional gain on each satellite tracked.

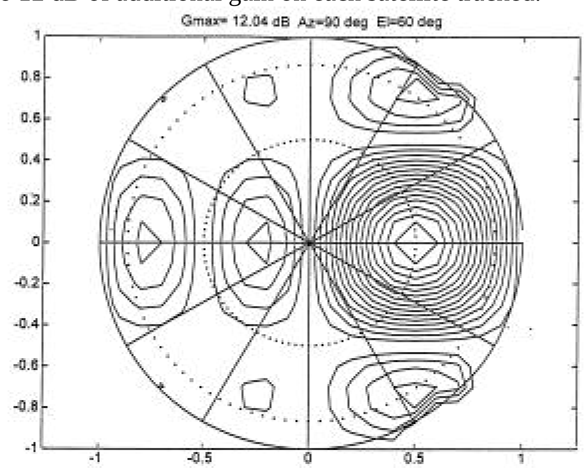

Figure 5 16-element array composite beam pattern

The HAGR digital beam forming has the effect of also increasing the signal-to-noise ratio from the GPS satellites. In Figure 6 to Figure 8, performance data is shown from a HAGR unit compared against two conventional GPS reference receivers [9]. From these plots, it can be seen that the HAGR C/N_0 is significantly higher than the reference receiver, demonstrating the effect of the gain from the digital beam forming.

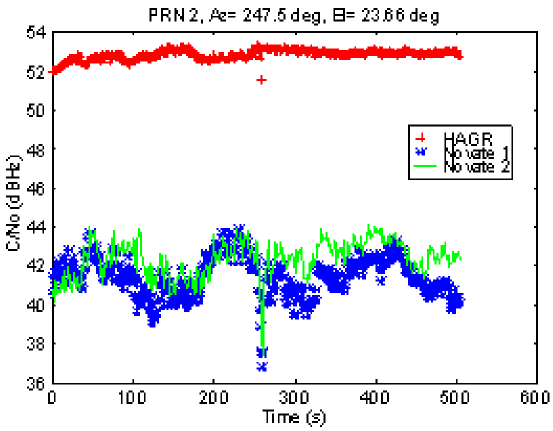

Figure 6 SNR Comparison Between 16-Antenna HAGR and Novatel's for PRN 2

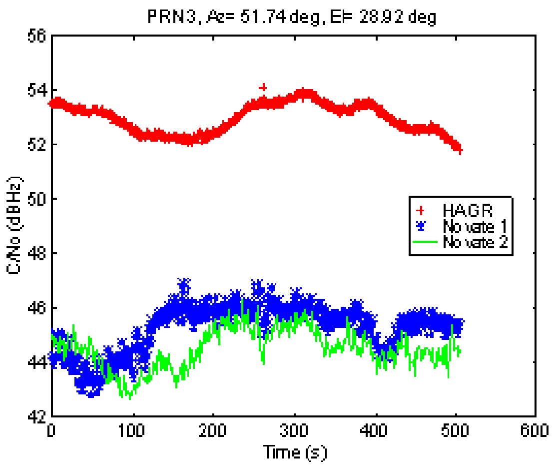

Figure 7 SNR Comparison Between 16-Antenna HAGR and Novatel's for PRN 3

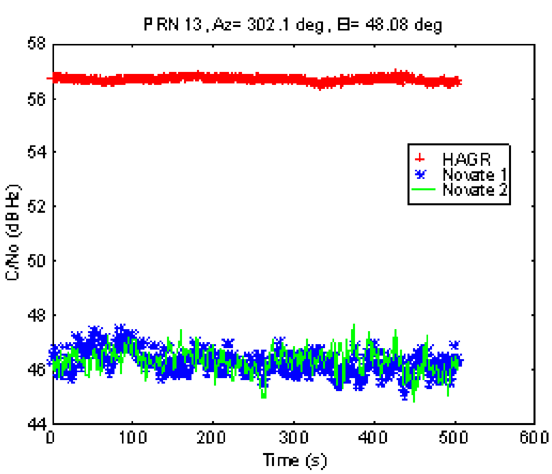

Figure 8 SNR Comparison Between 16-Antenna HAGR and Novatel's for PRN 13

The increased gain also results in improved pseudo-range and carrier-phase tracking performance, and the directionality of the beam-steering antenna array reduces the effect of multipath on the solution. In Table 3, the short term noise is listed for each of the two HAGR units tested. The gain provided by the beam steering has maintained the signal-to-noise generally above 50 dB-Hz, providing sub-meter level short term noise on the pseudo-range performance. This increased accuracy reduces the time needed to resolve the carrier-cycle ambiguities needed for computing the carrier-phase time transfer solution.

Table 3 HAGR PR Noise Performance Data

SVID	AZ	EL	C/N0 1	s_{PR}	C/N0 2	s_{PR}
3	285	36	49	0.89	51	0.46
6	173	18	44	0.60	44	0.48
8	134	21	48	0.46	45	1.05
9	90	28	50	0.50	48	0.77
17	113	57	55	0.21	55	0.19
21	291	50	54	0.26	53	0.31
23	21	66	55	0.35	54	0.47
26	43	13	49	0.33	52	0.27
29	212	40	52	0.38	53	0.36

HAGR FRONT-END CARRIER PHASE STABILITY

The design of the HAGR digital front-end is shown in Figure 9. The key element of the DFE design is the ability to make phase coherent measurements between the antenna elements. The DFE design is optimized to accomplish this coherency (patent pending). The L1 or L2) signals are first filtered and amplified from each antenna. A broad-band filter is used, sufficient to eliminate out of band interference, but not sufficiently narrow to cause different phase distortions between elements. A common local oscillator is distributed to the DFEs generated from the input reference signal. This mixes the RF signals to a 70 MHz IF.

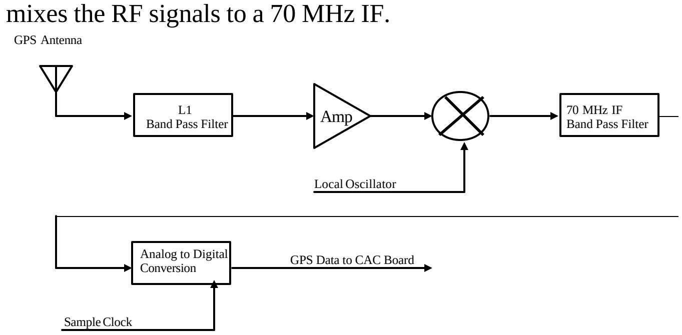

Figure 9 Basic Digitizing Front End Architecture

A 70 MHz SAW filter is used to band-pass filter the IF signals. This filter is the most critically controlled element of the DFE design. Any change in the frequency response pattern of this filter between elements or over time, will result in phase offsets between the individual antenna elements.

A built-in-calibration function is included in the HAGR to observe and calibrate for these phase offsets. Our test data indicates that we can maintain phase stability between different DFEs, operating from a common LO reference, to around 0.01 cycles (see Figure 10 to Figure 12). This indicates that the DFE should be able to provide a carrier phase observation tied to an external reference oscillator to a precision of 6 pico-seconds.

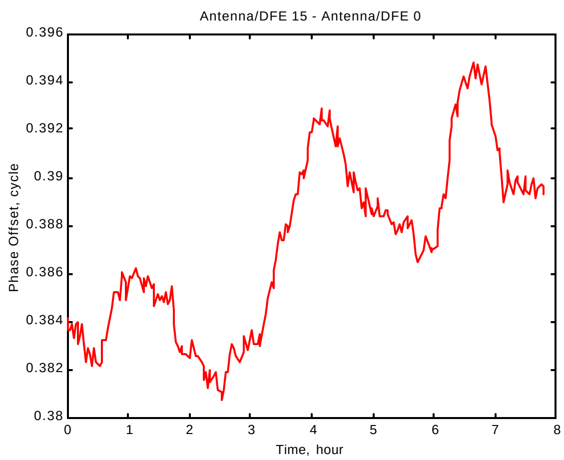

Figure 10 Phase Stability (DFE 15)

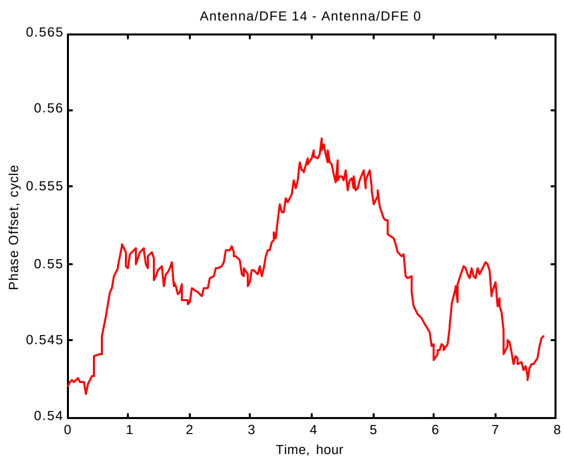

Figure 11 Phase Stability (DFE 14)

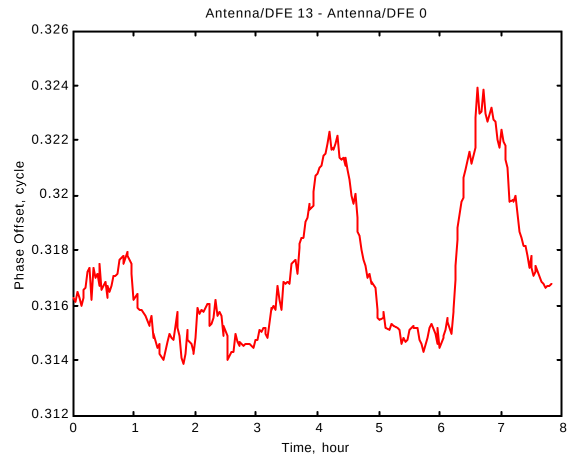

Figure 12 Phase Stability (DFE 13)

TIME TRANSFER LAB TEST RESULTS

To test the time transfer performance of the HAGR receiver, two receivers were set up to operate using a common 10 MHz time reference and also a common antenna. This test will cancel the GPS system errors shown in Table 1, leaving the effect of the carrier phase observation and uncalibrated receiver errors on the solution.

The raw carrier phase difference was computed between the two receivers for each satellite tracked. This was corrected for the integer ambiguity offset only. The residual error between two data sets for each satellite is plotted in Figure 13 and Figure 14. The HAGR was power-cycled between these two data sets. As can be seen, both data sets observed a common bias between the units of around 0.02 cycles and has a standard deviation of the carrier-phase difference residual of 16 psecs. Each satellite observes a common offset between the units of 14 psecs +/- 3 psecs, indicating that the HAGR units should be able to be calibrated to this level by averaging the satellite observations.

Table 4 Carrier-phase time difference accuracy

SVID	1	14	16	18	22	25
Mean offset (cycles)	0.022	0.020	0.022	0.026	0.022	0.020
Mean offset (psec)	14.3	12.4	14.1	16.8	13.7	12.4
Std Dev (psec)	15.1	17.6	16.3	16.4	15.4	9.2

This testing indicates that the HAGR units can provide carrier phase observations consistent with a time transfer performance of 16 psecs 1-sigma, post-calibration. The testing performed using the HAGR highlighted the benefit of a highly stable front-end and also identified key requirements for the LO generation which are being designed into our core product. Testing on these units is continuing to show their phase stability from turn-on to turn-on and also repeating these tests over temperature. Testing is also planned using a dual-frequency (L1/L2) P(Y) code version of the HAGR.

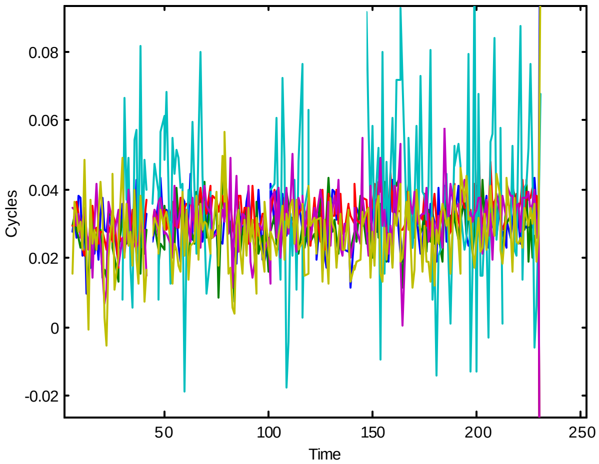

Figure 13 Unit1-Unit2 Time Offset (cycles) Time Set 1

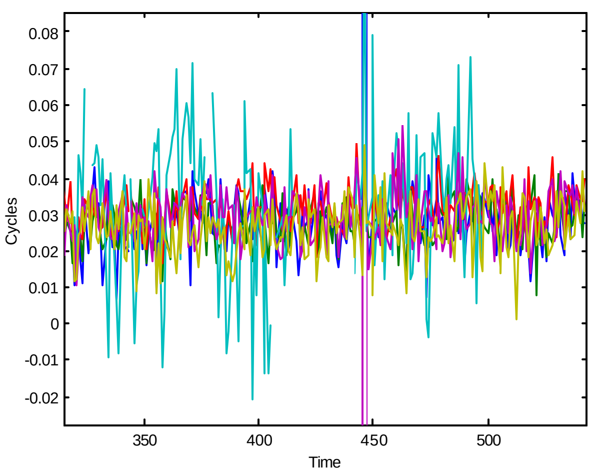

Figure 14 Unit1-Unit2 Time Offset (cycles) Data Set 4

CONCLUSION

In conclusion, the test data taken to date on two single-element HAGR units, indicates that the HAGR is capable of maintaining the mean relative carrier phase offset between units to an accuracy of a few picoseconds. This testing did not take into account the effect of system errors on the carrier phase time transfer performance. The carrier phase random errors (1-Hz) were maintained at around 16 picoseconds (1-sigma). When these errors are smoothed against a precision clock, the time transfer error could be expected to approach the tolerance of the HAGR phase calibration, which was shown to be around +/- 3 psecs in these tests. Further improvements are also anticipated in the carrier phase performance when using the multiple-element beam-forming version of the HAGR.

Based on these results, and previous testing of the HAGR for kinematic GPS applications [10], this GPS receiver has the following advantages for precise carrier-phase time transfer applications.

- Highly stable, phase-coherent front-end, phase-locked to an external 10 MHz oscillator
- Increased C/N0 to the satellite observations using beam-steering
- High accuracy pseudo-range and carrier-phase observations for rapid carrier-cycle ambiguity
- Multipath minimization on both pseudo-range and carrier-phase from the digital beam-steering
- L1/L2 P(Y) code HAGR in development

ACKNOWLEDGEMENT

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