Phase Center Calibration and Multipath Test Results of a Digital Beam-Steered Antenna Array

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BIOGRAPHY

Kees Stolk is an engineer at NAVSYS Corporation working with simulation, design, and testing of NAVSYS advanced GPS systems including digital beam-steering, multipath estimation and reduction, and bistatic spatial signal processing. He has an MSc in Electrical Engineering from Twente University of Technology, Netherlands.

Alison Brown is the President and Chief Executive Officer of NAVSYS Corporation. 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 University. In 1986, she founded NAVSYS Corporation. Currently, she is a member of the USAF Scientific Advisory Board, a Member of the Interagency GPS Executive Board Independent Advisory Team (IGEB IAT), and an Editor of GPS World Magazine. She is an ION Fellow and was indoctrinated into the SBA "Wall-of-Fame" in 2003.

ABSTRACT

For precision GPS applications, such as GPS reference sites, antenna calibration is needed to characterize and compensate for carrier phase distortions caused by the antenna. This is generally attributed to two sources: phase center motion dependent on the satellite direction, and phase offsets caused by local multipath. The ability to reduce these error sources is critical for high accuracy kinematic GPS applications.

In this paper a digital beam-steered antenna array is described that has the capability to perform built-in calibration and characterization of carrier phase errors. The calibration process and test results showing the kinematic GPS performance possible with this receiver are described in this paper.

INTRODUCTION

The precise point whose position is being measured when a GPS baseline is determined is generally assumed to be the phase center of the GPS antenna. However, the phase center of a GPS antenna is neither a physical point nor a stable point. For any given GPS antenna, the phase center will change with the changing direction of the signal from a satellite. Ideally, most of this phase center variation depends on satellite elevation. National Geodetic Survey (NGS) has developed a procedure for calibrating GPS antennas to allow the phase center variation with satellite motion to be observed[1]. However, this requires the use of a special test site that is carefully calibrated for multipath error to allow for proper antenna phase center determination.

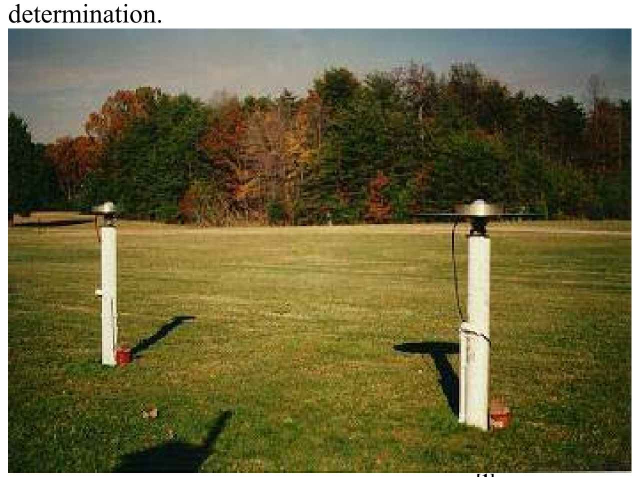

Figure 1 NGS Test Facility in Corbin VA[1]

The calibration procedure normally involves placing a reference antenna in two different locations and differencing the data to determine the phase center offsets, as shown in Figure 1. This procedure is carried out under somewhat perfect circumstances. For best results, every antenna should ideally be calibrated *at the site* of intended use. To do this, it is necessary to have a reference antenna with characteristics that are not affected by multipath.

NAVSYS has developed a digital beam-steering antenna array, the High-gain Advanced GPS Receiver (HAGR)[2]. This has the advantage of minimizing the effect of multipath errors, improving the accuracy of both the code and carrier phase[3]. The digital spatial signal processing also allows built-in calibration of the individual antenna elements. This calibration can be used to estimate and compensate for carrier phase offsets caused by receiver electronics and antenna effects.

In this paper this calibration process is described and test results are presented showing the HAGR performance for use in characterizing errors from other GPS reference sites and for kinematic positioning.

HAGR PRINCIPLE OF OPERATION

The NAVSYS High-gain Advanced GPS Receiver is a digital beam steering receiver designed for GPS satellite radio navigation and other spread spectrum applications. This is available for both military and commercial precision GPS applications and uses the modular assembly shown in Figure 2 to allow it to be easily configured to meet a user's specific requirements.

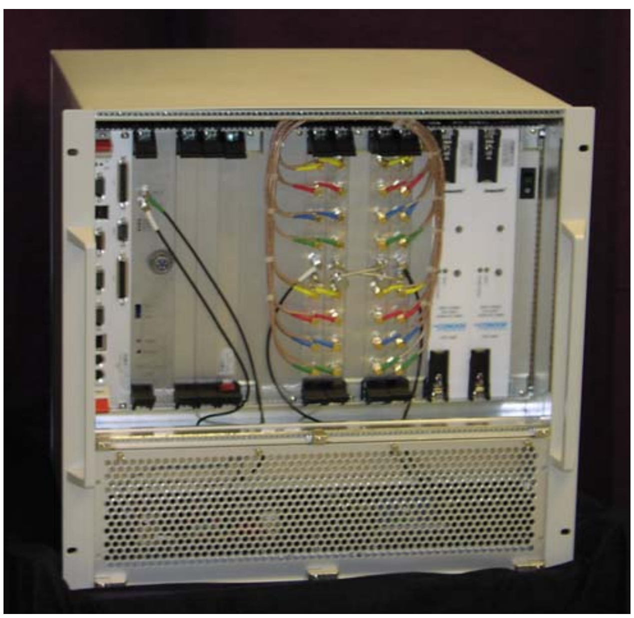

Figure 2 HAGR Assembly

The HAGR system architecture is shown in Figure 3. The signal from each antenna element is first digitized using a Digital Front-End (DFE). This bank of digital signals is then used to create the composite digital beam-steered signal input for each of the receiver channels by applying a complex weight to combine the antenna array outputs. As shown in Figure 3, the array weights are applied independently for each of the satellite channels. This allows the antenna array pattern to be optimized for each satellite signal tracked.

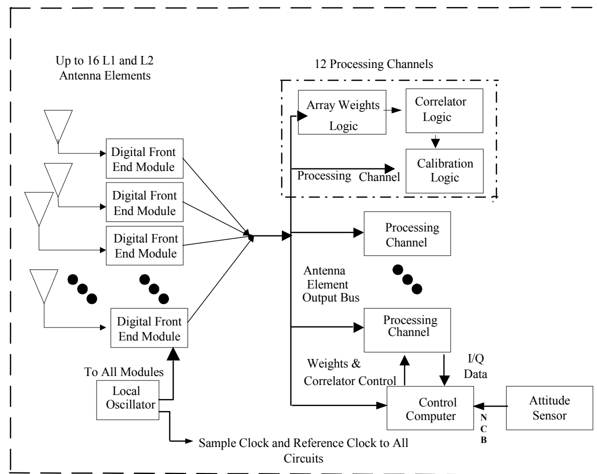

Figure 3 HAGR System Architecture

The weights for each channel are dynamically downloaded through software control. The HAGR software can automatically calculate the beam steering pattern for each satellite based on the known receiver location, the broadcast GPS satellite location, and the input attitude of the antenna array. For static applications, the array can either be configured pointing north (the default attitude) or the actual attitude is programmed into the configuration file. For mobile applications, the antenna array attitude is input through a serial port from either a magnetic compass and tilt sensor or and inertial navigation system. The HAGR also includes a mode where the antenna weights are read from a user definable file based on the satellite azimuth and elevation. Matlab tools exist for creating these antenna weights based on specific user requirements.

In Figure 4 and Figure 5, the antenna patterns created by the digital antenna array are shown for four of the satellites tracked. The HAGR can track up to 12 satellites simultaneously. The antenna pattern provides the peak in the direction of the satellite tracked (marked ‘x’ in each figure). The beams follow the satellites as they move across the sky. Since the L2 wavelength is larger than the L1 wavelength, the antenna beam width is wider for the L2 antenna pattern than for the L1.

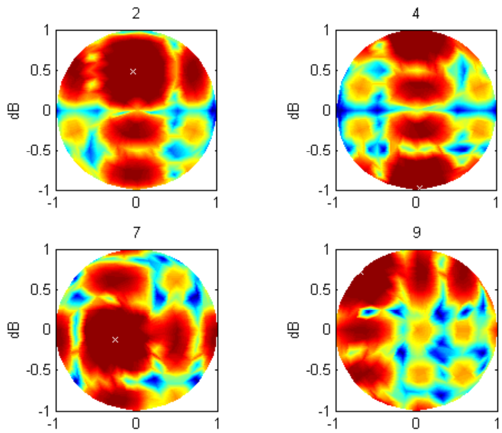

Figure 4 L1 Antenna Pattern

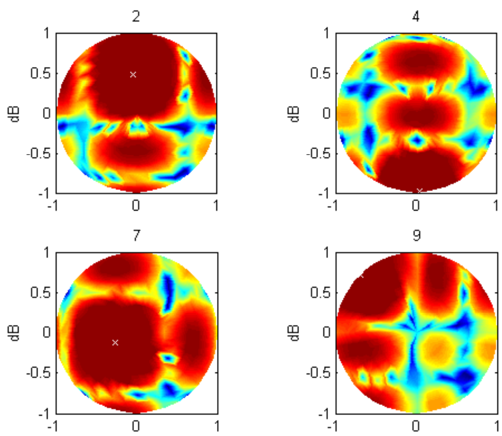

Figure 5 L2 Antenna Pattern

The HAGR can be configured with different antenna arrays, with a maximum of 16 elements. The tests described in this paper are done with a 16-element array and a 7-element array. Figure 6 and Figure 7 show some of the different antenna array configurations that the HAGR can use.

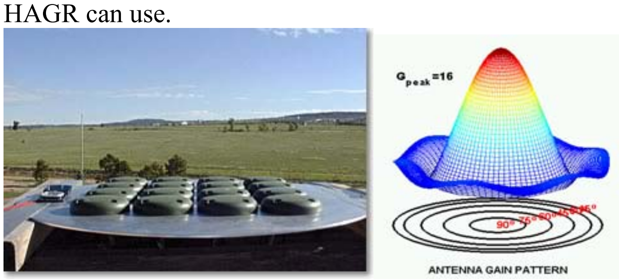

Figure 6 16 Element Array and gain pattern

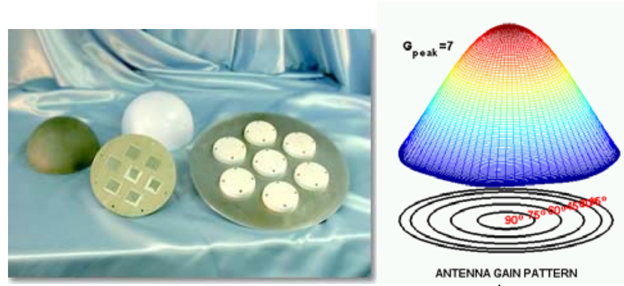

Figure 7 7-element Array and Mini-Array[4]

HAGR BUILT-IN CALIBRATION PROCEDURE

The phase shift measured between individual antenna elements consists of two components. The first component is caused by the spatial separation of the antenna elements. The second component is constant for all directions of arrival and is caused by differences in cable length and phase shifts in the antenna electronics. The relative phase shift between an element and the array center is expressed as:

Equation 1

$$\Delta\phi = \frac{\vec{x} \bullet \vec{l}}{\lambda} + \phi_{cal}$$

Where:

$\vec{x}$	vector from array center to element (m)
$\vec{l}$	line of sight vector from antenna to satellite
ϕ_{cal}	calibration angle, independent of DOA (λ)
λ	GPS signal L1 or L2 wavelength (m)

The HAGR is equipped with a calibration feature to estimate the calibration angle, ϕ_{cal} , from measurements collected over a period of several hours. Based on the user provided antenna layout and satellite location the relative space induced phase shifts are computed and subtracted from the total measured phase shift. The result is assumed to an estimate of the calibration angle ϕ_{cal} . Individual estimates are affected by multipath, but by taking data over time, these effects can be averaged out. The calibration process will not observe the absolute phase motion of the antenna elements with satellite azimuth and elevation as this is common to all of these elements. However, this can be characterized using NGS antenna calibration facility and used as part of the built-in phase calibration compensation within the array. This is planned as a future test activity.

HAGR CALIBRATION TEST RESULTS

To test the performance of the phase center calibration process, two antenna arrays, a 12-element and a 7-element, were calibrated using the HAGR built-in calibration feature for a period of 24 hours. Figure 8 shows the estimate of the calibration angle for one of the antenna elements over time. Typical standard deviation of the estimate for successful calibration is approximately 1/20 of a cycle. This indicates that the multipath on a single element is around +/- 1 cm. By averaging this error over time, the antenna phase offset can be calibrated to a finer degree of precision.

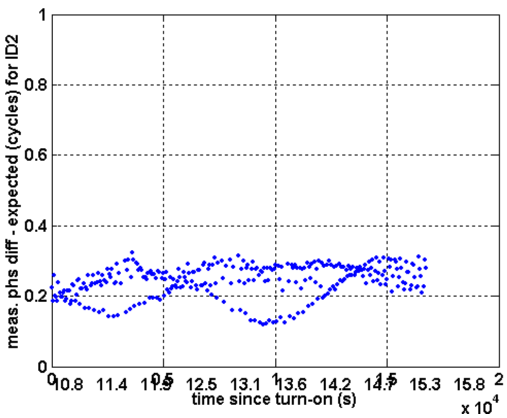

Figure 8 Typical Estimate Of Phase Calibration Over Time

CORS GPS REFERENCE SITES

In order to test the carrier phase performance, data was used from the nationwide grid of Continuously Operating Reference Stations referred to as CORS[5]. Figure 9 shows an overview of the CORS reference site locations. Data from each of the locations is available for download on the Internet and provides GPS observations that can be used for differential and kinematic positioning.

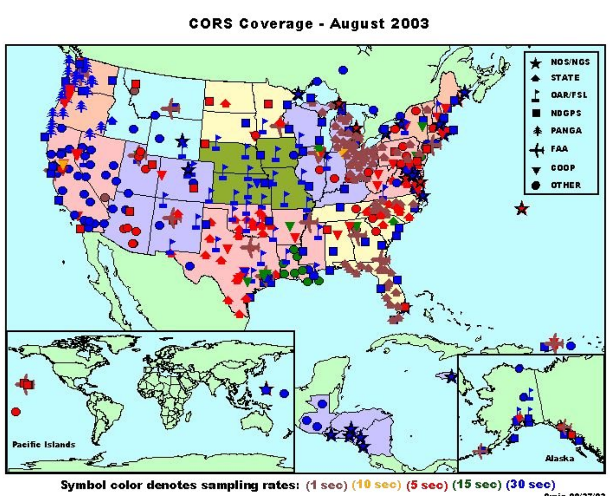

Figure 9 Nationwide CORS Grid of Reference Sites

KINEMATIC GPS PROCESSING

To test the carrier phase performance of the digital beam steering receivers and observe their relative accuracy to an existing CORS reference site, we used NAVSYS' Kinematic GPS (KGPS) processing software[6]. This software package is part of our InterNav product[7] and generates pseudo-range and carrier-phase corrections in accordance with the RTCM SC-104 data standard[8]. Table 1 and Table 2 show the quantities contained in the correction messages.

Table 1 Pseudo-Range Correction Message

PRC Message (for each satellite on L1 and L2)		
t	GPS time of correction	s
prn	SVID correction applies to	
prc	pseudo range correction	m
rrc	rate of change of correction	m/s
iod	issue of data for ephemeris	
σ_{prc}	estimated accuracy of correction	m

Table 2 Carrier Phase Correction Message

CPC Message (for each satellite on L1 and L2)		
t	GPS time of correction	s
prn	SVID correction applies to	
cpc	carrier phase correction	m
cloc	loss of lock counter	
σ_{cpc}	estimated accuracy of correction	m

GPS CARRIER PHASE CORRECTIONS

Per RTCM-SC104 [8] standard the carrier phase corrections contain among others the information shown in Table 2. The carrier phase correction is a measure for the difference between the actual and measured increase in range to the satellite.

In theory, the carrier phase corrections for a single satellite form a smooth curve over time, changing slowly due to physical effects in the atmosphere and ionosphere. In practice, this curve is distorted by several other phenomena, multipath being just one of them.

Errors in satellite ephemeris will cause deviations from the smooth curve. These fluctuations are common to *receivers* located within a limited geographic area.

Carrier phase noise represents the error in the measurement of fractional cycles by the receiver. This is assumed to be white noise and manifests itself as a high frequency fluctuation added to the smooth curve. This type of error has no common component.

Clock errors can cause a deviation from the expected smooth curve. Clock noise affects the carrier phase correction much like the carrier phase noise, whereas clock drift causes a "ramp" to be added to the smooth curve. Clock related errors are common between all *satellites* tracked by the same receiver.

Antenna phase center motions create a slow, periodic drift component which can be related to elevation changes. The period is assumed equal to the time the satellite is in view of the receiver, typically several hours.

Reference location errors affect the corrections in a way similar to antenna phase center motions, except they are not necessarily periodic, especially when horizontal errors are involved.

Multipath manifests itself as a fluctuation component in the carrier phase corrections. The period can vary depending on the source of multipath, but is typically between 1 and 10 minutes. Multipath is assumed uncorrelated between antennas.

CARRIER PHASE TEST SET UP

Two HAGRs, one with 16 elements and one with 7 elements are placed on a flat, metal roof at the NAVSYS facility, a location known to cause severe multipath (Figure 11). Data was downloaded from the Alternate Master Clock (AMC2) reference site, located at Schriever Air Force Base (Figure 12) for use in comparison with the HAGR performance. The AMC site includes an AOAD/M_T choke ring antenna[9] with an ASHTECH Z-XII3T receiver.

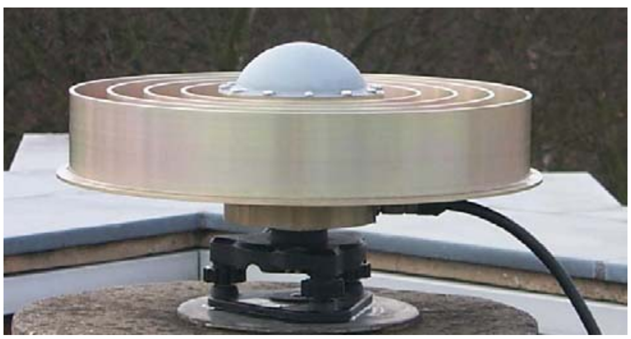

Figure 10 AOAD/M_T Antenna

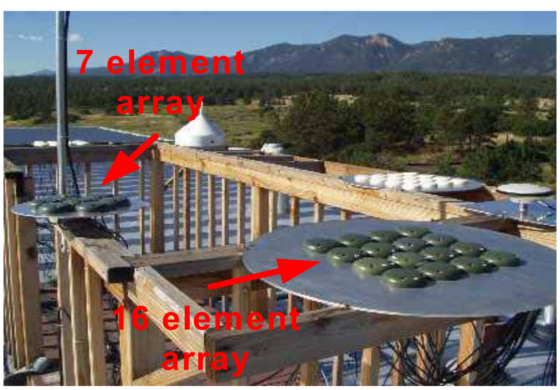

Figure 11 Two HAGR Arrays, Located on Roof

Figure 12 Geographic Locations of NAVSYS and AMC2 Sites

To perform the carrier phase analysis, a total of one hour of data was collected for both HAGRs and the same hour of data was downloaded from the Internet for the AMC2 site. A set of 6 satellites, tracked non-stop on all receivers, was used for comparison.

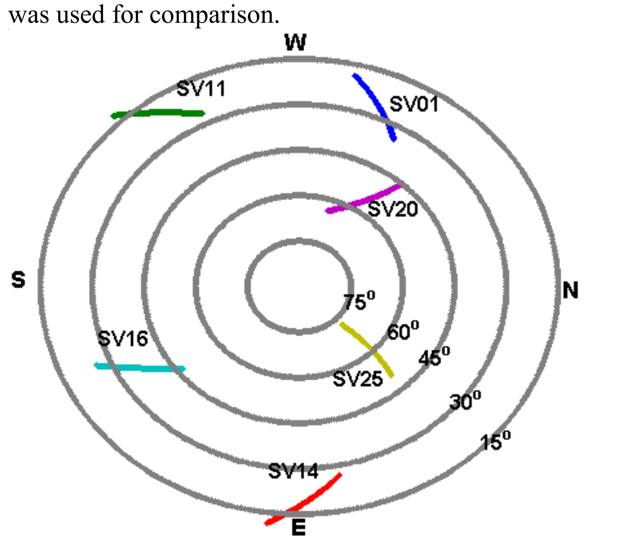

Figure 13 Set of Six Satellites Selected for Comparison

MULTIPATH CHARACTERIZATION

To estimate the multipath performance for the three receivers, the error components attributed to the satellite and clock errors were first removed.

Figure 14 shows the carrier phase corrections for individual satellites for each receiver over the one hour period. The relative drift between HAGRs and AMC2 station indicates slow uncommon error components such as clock drift, phase center variations and errors in assumed location.

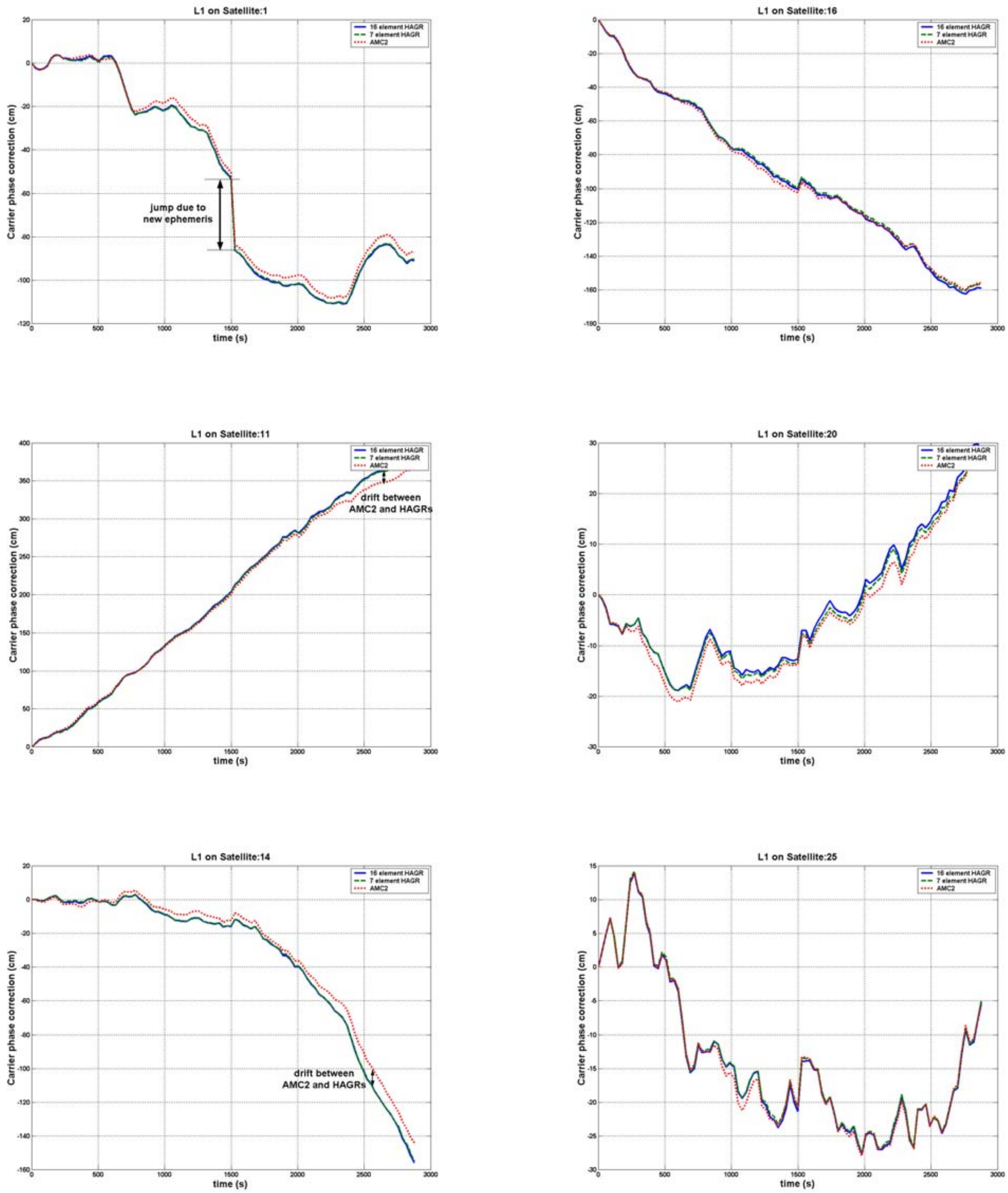

Figure 14 Individual L1 carrier phase corrections

A smooth polynomial curve fit is subtracted from the carrier phase corrections to show higher frequency fluctuations (T<10 minutes). The result, displayed in Figure 15, indicates the majority of the fluctuations are common and, therefore, related to satellite ephemeris. This test data shows that the carrier phase correction data is correcting for about +/-10 cm of fluctuating error attributed to the satellite ephemeris data.

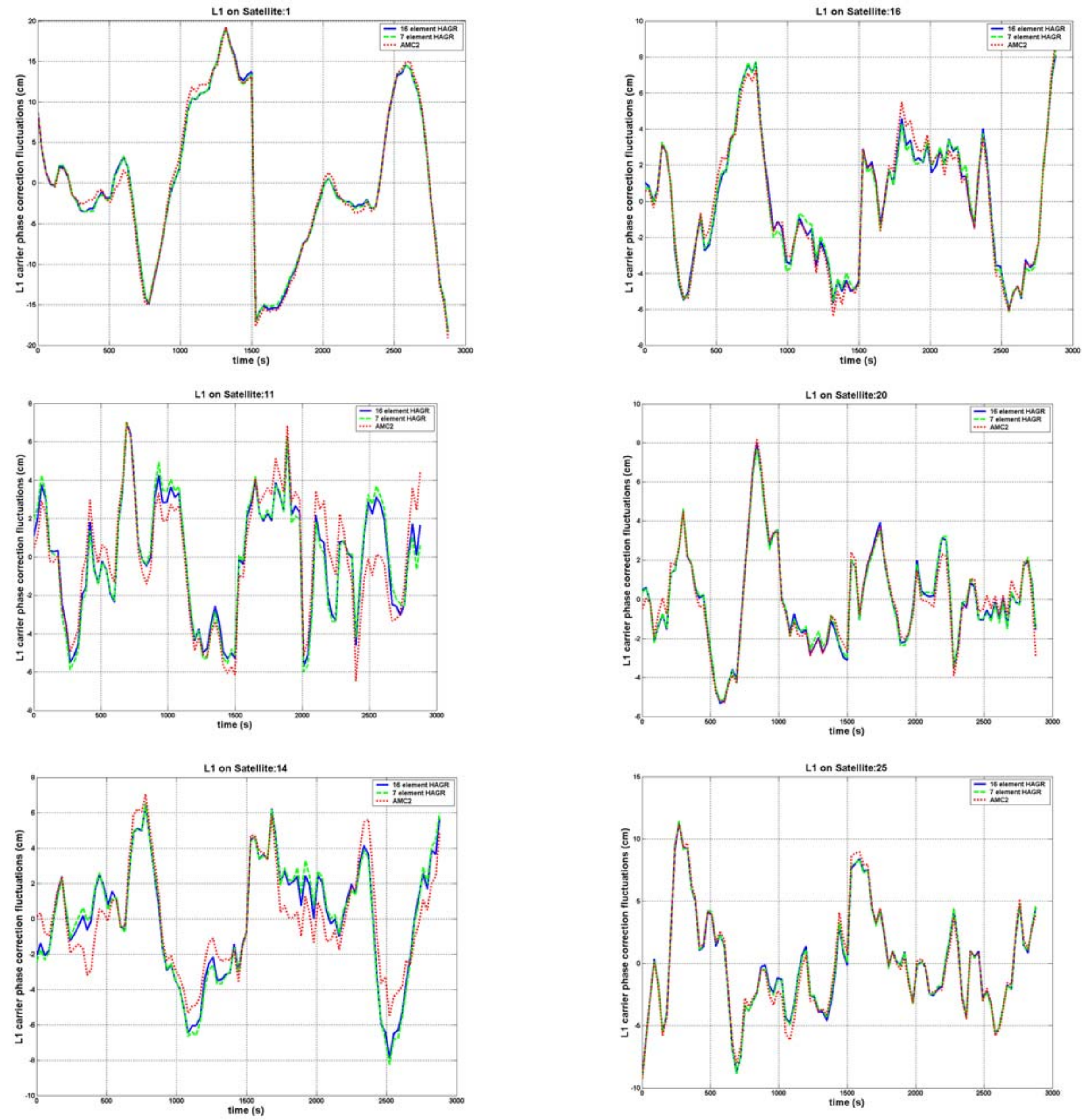

Figure 15 Carrier phase fluctuations

To remove clock related errors common between satellites, the carrier phase corrections for each receiver are first single differenced across the satellites. Satellite 25 is used for single differencing since its high elevation makes it the least susceptible to multipath. (If the setup allows it, use of the same clock for all tested receivers eliminates the need for single differencing, and avoids replacing a common clock error with the multipath related to the satellite used in differencing.) Next, these single differenced carrier phase corrections are differenced across receivers to remove satellite related fluctuations common across the receivers. The results (Figure 16) allow the *combined* multipath to be estimated.

The multipath related phase differences between the 16 and 7-element HAGRs are small, within 1 cm typically. Assuming equal contribution to this error from both HAGRs, the estimated carrier phase fluctuation due to multipath for a HAGR is approximately ¾ cm. The multipath differences between the 16 element HAGR and the AMC2 reference data is much larger, typically around 2 cm. Based on this it is estimated that the AMC carrier phase fluctuation due to multipath is approximately 1 ¾ cm, or 1 cm worse that the HAGR.

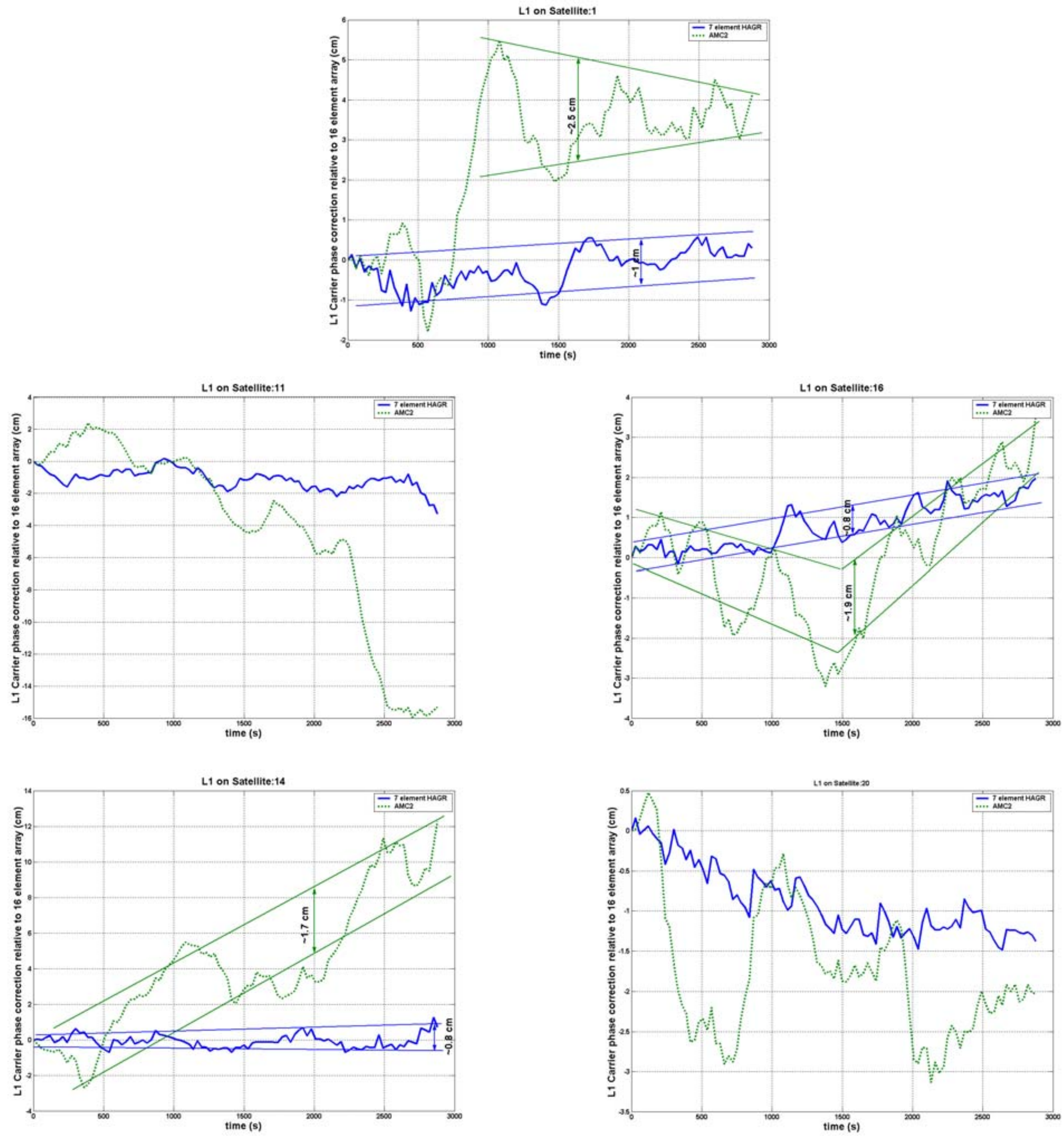

Figure 16 L1 Multipath Related Fluctuations Relative to 16 Element HAGR

KINEMATIC POSITIONING RESULTS

The improved accuracy of the HAGR carrier phase observations also allows increased precision for differential and kinematic positioning. Figure 17 shows widelane kinematic positioning results between the 16 element and 7 element array and between the AMC2 and the 7 element array. The standard deviation of the error is approximately twice as large when using the AMC2 carrier phase corrections. The error characteristics of the AMC2 KGPS solution is highly cyclic indicating that the position solution errors in this case are dominated by carrier phase multipath. The increased widelane precision between the two HAGRs demonstrates the multipath improvement that digital beam steering provides.

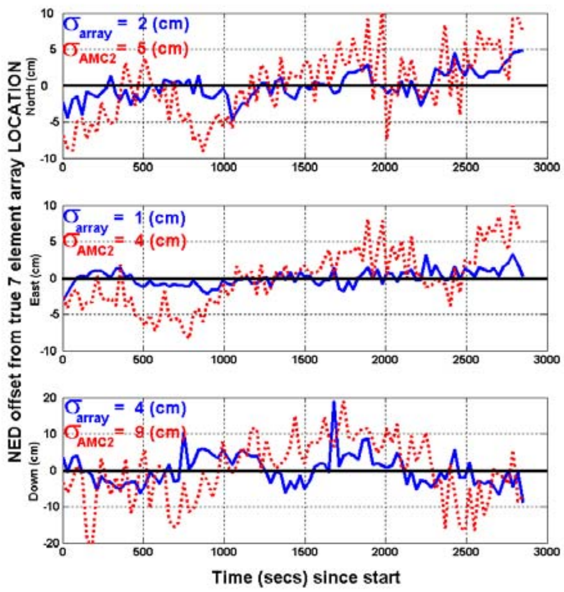

Figure 17 Widelane Kinematic Solutions (HAGR-HAGR (blue) and HAGR-AMC2 (red))

CONCLUSION

The testing performed to date has demonstrated the following performance advantages for a Digital-Beam-Steered antenna array for precision carrier phase observations.

1) Built-in phase calibration capability in the HAGR can be used to observe the relative phase offsets between multiple antenna elements to mm level performance
2) Digital beam-steering minimizes the effect of multipath on the carrier phase observations, even in a strong multipath environment
3) High accuracy relative kinematic positioning is possible using a digital beam-steering GPS receiver

The capabilities of the HAGR digital beam-steering antenna array can be leveraged for the following applications.

The network of precision GPS reference sites operated by commercial and government facilities could benefit from the increased precision of the HAGR and also its robustness to multipath. This includes reference sites such as CORS[5], IGS[10], or the sites being installed for use with the LAAS precision approach and landing system, where multipath can cause a significant safety hazard.

The HAGR also provides a mobile capability for performing antenna phase center determination and calibration of GPS antennas. Currently antennas must be taken to test ranges, set up under "ideal" conditions to collect this test data. The ability of the HAGR to provide near ideal observations even in a strong multipath environment (such as the metal roof test site used to collect the data in this paper) allows it to be used to provide a "mobile" test range capability that can be used to perform on-site calibration of antenna installations.

ACKNOWLEDGEMENTS

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