Analysis of Carrier Phase and Group Delay Biases Introduced by CRPA Hardware

Ung Suok Kim, *Stanford University*

BIOGRAPHY

Ung Suok Kim is a Ph.D. candidate in the Department of Aeronautics and Astronautics at Stanford University. He received B.S.E.s in Aerospace Engineering and Mechanical Engineering from the University of Michigan at Ann Arbor in 1998. He received his M.S. in Aeronautics and Astronautics from Stanford in 2000. His current research interest is in CRPA arrays, and their application in the JPALS program.

ABSTRACT

The benefits afforded by Controlled Reception Pattern Antennas (CRPAs) in multipath and interference mitigation are well documented, and they find use in many applications today. As such, CRPAs are being considered for use in the Joint Precision Approach and Landing System (JPALS) program. The Navy variant of JPALS, Sea-based JPALS, will be a dual-frequency, carrier phase, differential GPS system whose operational environment is expected to be very harsh in terms of multipath and RFI. For any carrier phase differential GPS system, phase integrity is critical for correct integer ambiguity resolution. In addition, JPALS has extremely stringent navigation performance specifications, and with any technology being considered for JPALS, any potential unwanted effect on the CRPA output signal which may degrade navigation performance must be analyzed.

This paper will present an analysis of the signal biases introduced by the CRPA hardware. The effects can be broken down into two major sources: phase delay and group delay. Both of these sources vary according to incident signal direction and the configuration of the adjacent antenna elements. The analysis presented will be for a single frequency patch antenna CRPA designed and constructed at Stanford University. The phase effects of CRPAs have been published in previous work. This paper will present the effects of antenna group delay on the code phase of the received signal. More importantly, this paper will present an analysis of these effects for the CRPA output signal. This analysis will show that CRPAs will introduce biases in both the code and carrier phase of the signal, and depending on what kind of processing algorithm is used for the CRPA, will require some form of mitigation of these effects.

INTRODUCTION

The Navy variant of the Joint Precision Approach and Landing System, called Sea-based JPALS, is being developed to provide navigation for landings on aircraft carriers. The performance specifications for this system are expected to be extremely stringent. In order to meet the very tight accuracy requirements, a dual frequency carrier phase differential GPS architecture is being pursued along with some newer technologies such as GPS/INS integration. To make matters more difficult, these specs must be met in a very challenging operational environment. Figure 1 shows a typical island superstructure of an aircraft carrier. The reference antenna is expected to be located on the mast arm of the island superstructure. As can be seen from the figure, the reference antenna location is potentially a very harsh multipath and RFI environment. In addition, service must be provided in the presence of jamming. To help facilitate these concerns, Controlled Reception Pattern Antennas (CRPAs) are being considered for use in JPALS. However, with any new technology being considered for JPALS, any unwanted effect or biases that may be added to the received GPS signal must be analyzed and compensated for.

Figure 1. Island superstructure of USS John C. Stennis (CVN 74)

Signal biases introduced by the CRPA hardware can be sorted out into two main categories: phase delay and group delay. Both of these effects are dependent on the incident signal direction and the mutual coupling environment imparted by the adjacent antenna elements. The phase delay of individual antenna elements in a CRPA has been studied in previous research [1]. The group delay leads to biases in the code phase measurement of the GPS signal and will be the main subject of discussion in this paper. This bias on the code phase introduced by differential antenna group delay has potentially detrimental consequences on the integer ambiguity resolution. Also, if the GPS position solution is used at all in the transference of the navigation solution from the reference antenna to the touchdown point, this code phase error will eat into the overall system error budget. The research described in this paper implements in simulation the overall effect of the phase and group delay seen in each channel of a CRPA; combines the signals using a deterministic beam-forming algorithm; and investigates the biases seen in the output signal of the CRPA.

ANALYSIS TOOLS AND METHODOLOGY

The antennas used in this study are single probe fed L1 rectangular patch antennas designed and constructed here at Stanford University as shown in Figure 2. The rectangular patch with the diagonal feed determines the RHCP characteristics of the antenna. Also shown are the hexagonal, seven-element, half wavelength array and the corresponding simulation model used for the analysis in this paper [2]. The seven-element array configuration was chosen due to its similarity to the configuration of the GAS-1 (GPS Antenna System -1) CRPA, which is an antenna array system in use by the U.S. military.

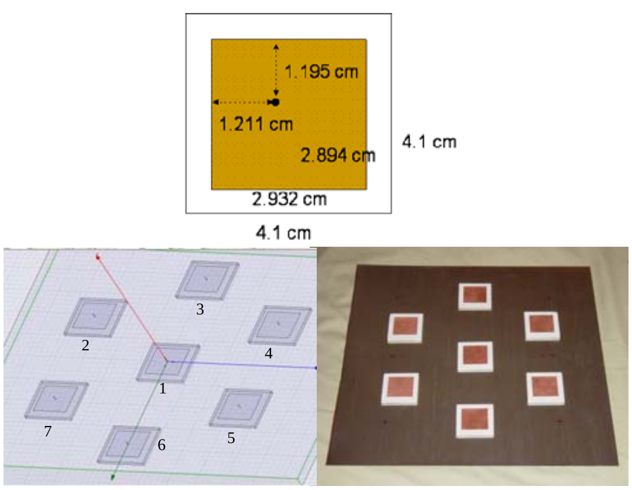

Figure 2. Single probe fed rectangular patch antenna and 7 element array

Carrier phase biases introduced by CRPA hardware has been analyzed and published in reference [1]. Phase responses of individual patch antennas were studied in simulation and validated using anechoic chamber measurements. This showed the received phase variation versus the incident signal direction. Also, similar studies were done with arrays of patch antennas in various configurations to demonstrate the effects of mutual coupling in the phase response of individual antenna elements in arrays.

This paper describes the group delay characteristics of antenna elements in CRPA arrays. More specifically, both the magnitude frequency response and the phase frequency response (group delay) are considered and their effect on the received code phase of the GPS signal investigated. Figure 3 illustrates how this effect is studied. First, the GPS code sequence is converted into the frequency domain via MATLAB's FFT algorithm. Then, the antennas' magnitude and phase frequency responses are mixed into the frequency content of the GPS code. Finally, the mixed frequency content is brought back to the time domain via IFFT. The altered code sequence is then studied in the correlation function to determine the overall effect on the code phase of the GPS signal.

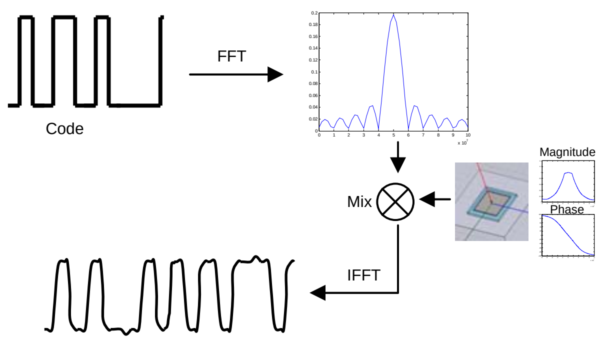

Figure 3. Antenna group delay effect on code

ANTENNA PHASE DELAY OF CRPA ELEMENTS

Reference [1] shows detailed analysis of the phase pattern characteristics of antenna elements in CRPA arrays. This paper presents some results from this previous work. Figure 4 below shows the phase pattern taken in a chamber for a single antenna element, as well for a couple of different antenna elements in a seven-element array. First, the single-element pattern shows the amount of phase variation possible versus incident signal direction for a microstrip patch antenna of this type. The array plots show how much this pattern is altered by the mutual coupling of the adjacent antenna elements in an array.

This kind of phase response characteristic versus incident signal direction are used below when both phase and group delay effects are implemented on each channel of a

CPRA simulation. Then, the channels are combined using a given CRPA algorithm, and the overall effect on the CRPA output signal is presented.

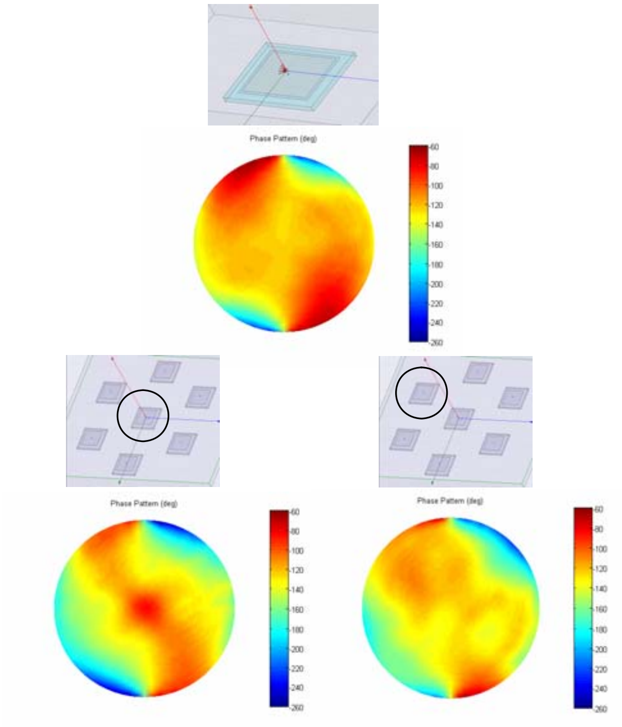

Figure 4. Phase pattern of CRPA elements

ANTENNA MAGNITUDE RESPONSE AND GROUP DELAY OF CRPA ELEMENTS

To determine the antenna effect on the code phase of the received signal, both the magnitude frequency response and the group delay response must be considered. Basically, group delay is just the change in received phase versus the change in frequency, i.e. the derivative over frequency of the phase frequency response.

$$GD(\omega) = \frac{\partial \phi(\omega)}{\partial \omega}$$

Whether presented as group delay or as phase versus frequency, this characteristic conveys the same information. Since the implementation of the analysis method shown in Figure 3 requires a magnitude and phase response, the antenna phase response is presented as phase versus frequency, not as group delay.

Figure 5 shown below presents the magnitude and phase response of a stand alone single patch antenna for a variety of incident signal directions. The top two figures show the frequency responses with a sweep in the elevation angle of the incident signal, while the bottom two figures show those for an azimuth sweep in incident signal. The figure shows that the magnitude frequency response is more sensitive to the elevation of the incident signal, while the azimuth angle of the signal seems to have a more pronounced effect on the phase response.

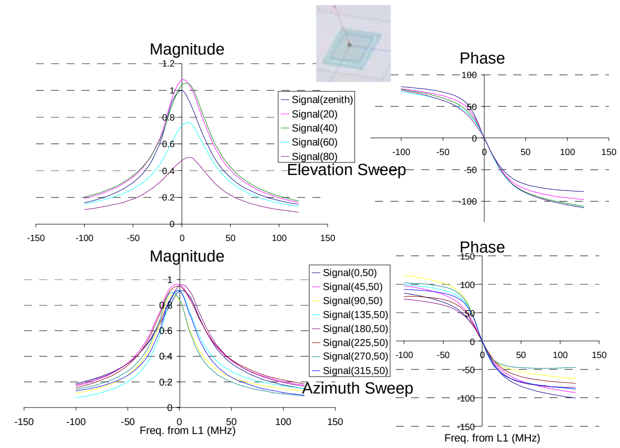

Figure 5. Frequency response of single antenna with sweep in incident signal direction: magnitude and phase responses

Figure 6 illustrates the effect that mutual coupling can have on the frequency response of the antennas. The magnitude and phase frequency responses are shown for a signal coming in at zenith for three different cases: single stand-alone antenna; the center element of a hexagonal, half-wavelength baseline, seven-element array; and a different element in that same seven-element array. This shows that the exact same antenna element can have rather different frequency response characteristics,, depending on the configuration of the adjacent elements which dictate the mutual coupling environment of the antenna element.

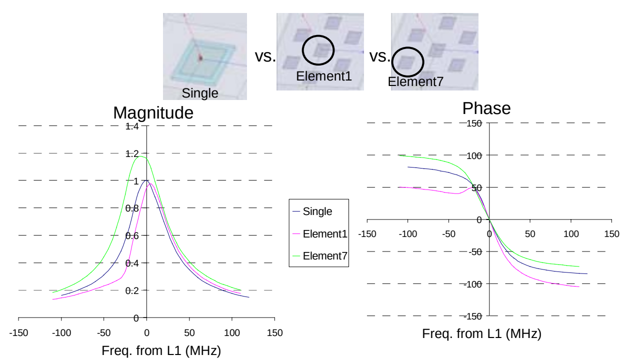

Figure 6. Frequency response comparison of single antenna vs. different antenna elements in a 7 element CRPA: magnitude and phase responses

These different frequency responses lead to differing effects on the code phase of the received GPS signal. This occurs due to the distortion of the frequency content of the GPS code. To help visualize this, Figure 7 below will show how a single GPS code chip is affected by the antenna frequency responses presented above. Shown in the figure below is a P(Y) code chip with a bandwidth of 20 MHz, which lies mostly in the linear region of the phase response. The first figure shows the filtered P(Y) code chip for different incident signal directions for a single stand-alone antenna, and the bottom figure shows the filtered chip for two different elements in an array receiving the same signal. Generally speaking, the magnitude response determines the step size of the chip while the phase response determines the amount of delay in the chip. The reason for the step size being larger than one for the filtered chip of the signal in element 7 of a 7-element array shown in the bottom figure is that the magnitude responses have been normalized using the stand-alone single antenna measurement from zenith. The figure shows that certain incident signal directions and certain elements in an array add more delay in the chip step response.

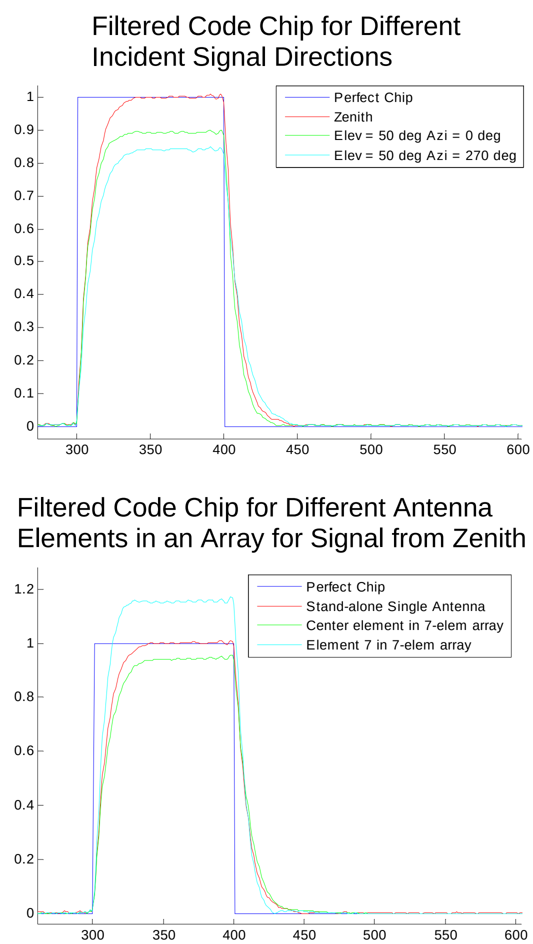

Figure 7. Antenna frequency response effect on code chip

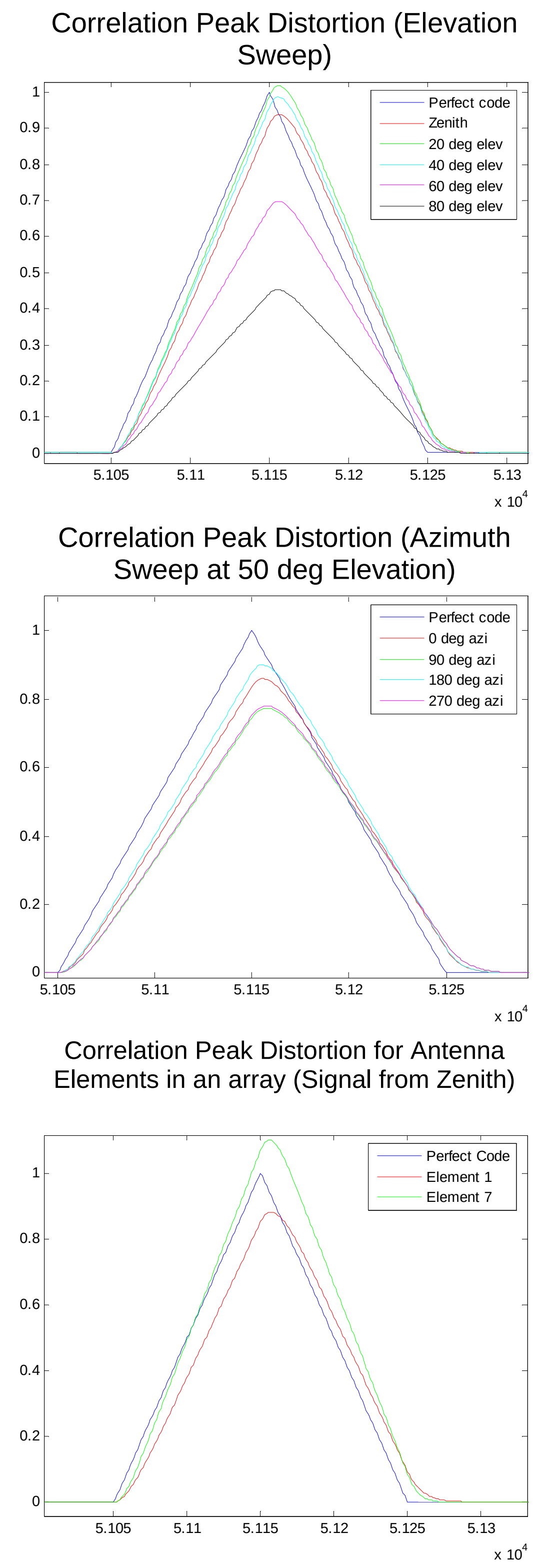

Figure 8. Correlation Peak Distortion

Figure 8 illustrates how a sequence of the filtered code chips shown in Figure 7 result in a distortion of the correlation peak for each of the cases outlined above. Generally speaking, there is an overall delay effect in each of the cases, in addition to a change in the peak magnitude. Also, there is a slight lean in the correlation peak, i.e. the peak is no longer symmetrical. This is a little hard to visualize in the correlation peak plots, but will become more apparent in the next figure.

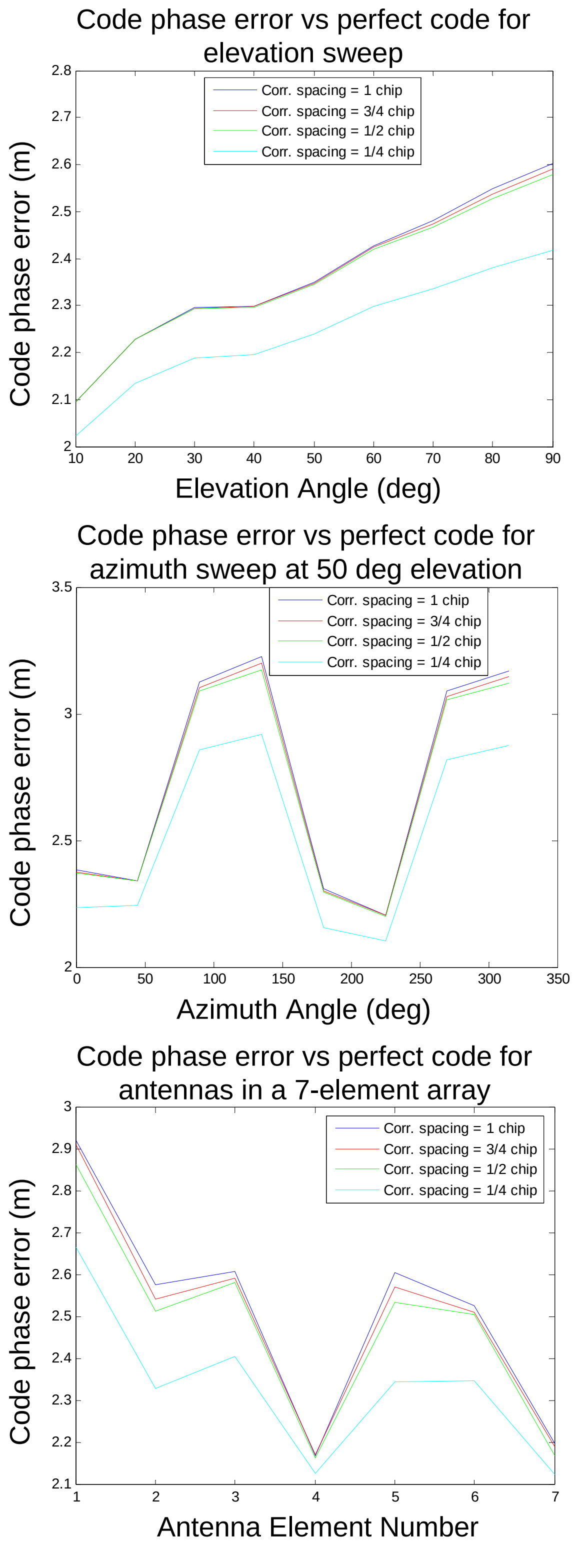

Figure 9. Code phase errors for different correlator tracking pair spacings

Figure 9 shows how the distorted correlation peaks, shown in Figure 8, lead to a code phase error. This error is shown for different correlator tracking pair spacings. Each of the plots shows the error between the code phase determined from an unfiltered, perfect correlation peak and a correlation peak that has been distorted according to the magnitude and phase frequency responses of the antenna. The code phase error over elevation sweep of the incident signal shows that the magnitude of error, compared to a perfect code, is actually largest near the zenith of the antenna and slowly decreases as the elevation angle becomes smaller. Also notice that the 1-chip, ¾-chip, and ½-chip correlator spacings have nearly identical results, while the ¼-chip correlator spacing leads to a sudden drop in the magnitude of the error. This is due to the lean in the correlation peak that was mentioned above. As the correlator spacing becomes smaller, the pair is tracking closer to the top of the peak which starts to lean towards the perfect correlation peak, more so than the base of the peak. This effect can be seen in all of the plots in Figure 9, and this lean in the correlation peak seems to be a general effect of the frequency response type seen in the antenna studied.

The middle plot shows the errors for an azimuth sweep in incident signal at 50 degrees of elevation. The plot shows that the magnitude of the code phase error has some periodicity as the incident signal sweeps around in an azimuthal circle. The bottom plot shows the code phase errors for each of the antenna elements in a hexagonal seven-element array receiving a signal from zenith. Even when all of the antenna elements in an array are receiving the same signal, they all have different received code phases due to the different mutual coupling environment leading to different frequency responses of the antenna.

DIFFERENTIAL SYSTEM ERRORS

The effects presented above must be viewed in context of a differential GPS system. As mentioned, Sea-based JPALS will be a dual-frequency, carrier phase DGPS system. For a differential system, the important issue is not the absolute code phase error or the absolute carrier phase error, but rather the differential code phase and differential carrier phase errors. Therefore, if both the reference and the user antenna are identical and looking at the same geometry of incident signals, all antenna code and carrier phase errors will be canceled out in the double differencing algorithm, and there would be no need to account for any of the signal biases mentioned above. However, such is not the case in most cases. For starters, the reference antenna and the user antenna are most likely not the same antennas, and thus have different magnitude and phase responses. Therefore, some differential code and carrier phase errors will be introduced into the double differenced signal. Even if the reference and user antennas are the same, the geometry of the incident signals will rarely be the same. In the case of Sea-based JPALS, the reference antenna on the aircraft carrier superstructure will have a certain geometry of satellites in view. The airborne user will be at an angle-of-attack on approach and will have rather different relative line-of-sights to the same set of satellites as the reference antenna. This is where the incident signal direction dependent errors come in. From Figure 9 above, rather than looking at the absolute values on the y-axis scale, the relative changes over incident signal directions is of more interest.

Intuitively, to be able to get a correct integer resolution solution, the differential code phase error should preferably be less than one full wavelength, and the differential carrier phase error should be less than one half wavelength. Again, Figure 9 shows that differential code phase errors can exceed one full wavelength (~19cm at L1), especially when there is azimuth variation in incident signal direction between the reference antenna and the user antenna. Ideally, better antennas with wider bandwidth, and thus less susceptibility to signal direction dependent code phase error variations, are desirable. In addition, a compensation algorithm may be implemented if the antenna frequency response induced code phase errors can be modeled.

CRPA ALGORITHM

Phased array beam-forming is achieved by shifting the phases of each channel signal to combine in-phase, and thus creating a more powerful signal [3]. Figure 10 below illustrates this concept in a simple 2D drawing.

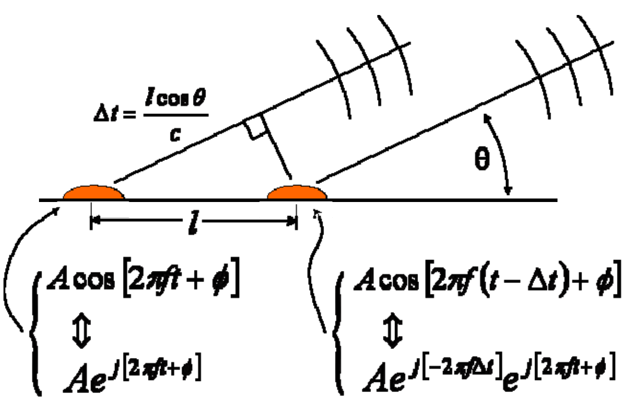

Figure 10. Phased array beam forming

The phase is usually shifted using a complex weighting scheme in each channel. There are many different methods by which the amount of required phase shift in each channel is determined. This weighting can be done deterministically by leveraging the knowledge of the geometry of the problem (incident signal direction, and the orientation and the baseline of the array), or it can be done adaptively (maximizing signal-to-noise ratio of the GPS signal, minimizing the power of total received signal, driving the weights with reference signal, etc.) [4]. Whichever method is used, it can be seen from Figure 10 that when the phase shifting is done precisely, and the “beam” is formed directly at the incident signal, the output signal of the CRPA will be an exact in-phase combination of each channel and will not have any phase biases. However, signals that are not coming in at the boresight of the beam will have added phase biases due to the complex weighting of each channel [5]. This is the reason why it is the opinion of the author that any kind of adaptive algorithm is unsuitable for use in a carrier phase differential GPS system like Sea-based JPALS, where carrier phase integrity is essential to meeting overall system accuracy, integrity, availability, and continuity requirements. Figure 11 below will help illustrate this point.

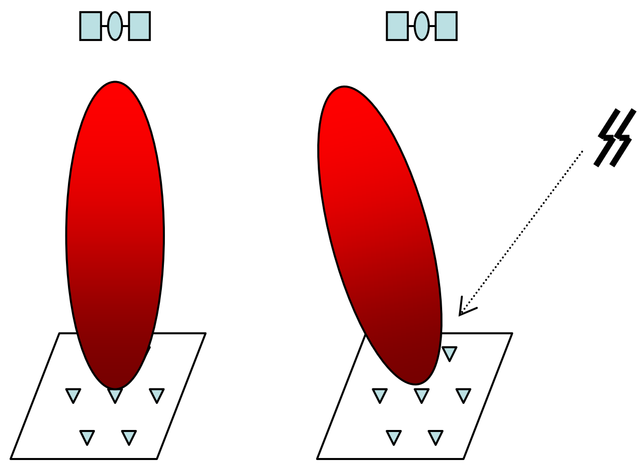

Figure 11. Deterministic beam forming vs. adaptive processing

The image on the left in Figure 11 represents a nominal state case where there are no interference or multipath sources. Both the deterministic and adaptive methods will ideally have the same result: the boresight of the beam pointed directly at the satellite. Now let there be an interference source present, as shown on the right. Any type of adaptive algorithm (whether it is trying to maximize the GPS signal power or minimize the overall received power) will shift the weights such that the boresight of the beam is no longer pointed straight at the satellite, and a null is placed in the direction of the interference source. Even though the interference may be rejected, the output of the CRPA will now have a phase bias associated with the weights that were shifted to create the null. This is because no adaptive processing algorithm has a “truth” carrier phase reference by which to guarantee that the CRPA output signal will not have any phase biases. A deterministic system will keep the boresight of the beam pointed towards the satellite and not introduce any phase biases, even if the received GPS signal may be a little weaker than an adaptive array due to the interference. It will be better to perhaps give up a little bit of availability for a guarantee of phase integrity. The obvious problem occurs when the interference source is too close to the incident signal direction, but such a case is a difficult scenario to handle even for an adaptive algorithm. Thus, it is the author's opinion that for Sea-based JPALS, a parallel "channel" deterministic beam-forming scheme be used to point the boresight of the beam towards a given satellite in each "channel".

In order to minimize phase biases for such a scheme, there are a few requirements. The geometry of the problem must be well known (line-of-sight vectors to satellites, orientation of the array). Also, the carrier phase center movement (versus incident signal direction) of each antenna element must be modeled accurately and compensated for in the deterministic weight forming. This modeling was demonstrated in reference [1]. The compensation is trivial as it can be implemented in the deterministic weight forming in each channel. Even though this method has some additional requirements as compared to adaptive processing, the greater confidence in the accuracy of the carrier phase of the CRPA output signal makes it worthwhile.

EFFECT ON COMBINED CRPA OUTPUT SIGNAL

Taking all of the individual antenna element code and carrier phase effects outlined so far in this paper, and implementing a deterministic beam-forming algorithm mentioned above, the effect on the code and carrier phase of the CRPA output signal can now be studied. Figure 12 illustrates how this is investigated in simulation.

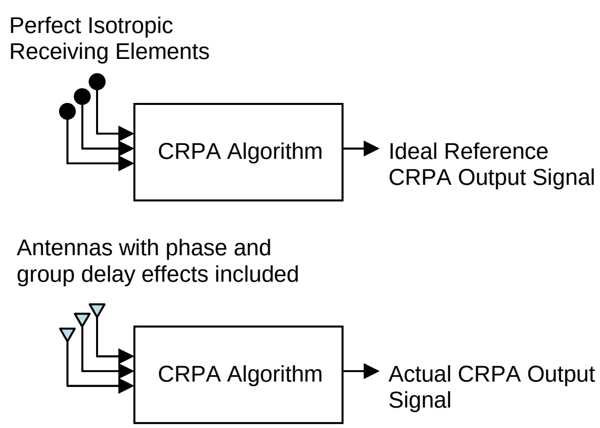

Figure 12. Flowchart for CRPA signal simulation

For a given satellite, the signal is received by a hexagonal, seven-element, half-wavelength baseline antenna array composed of perfectly isotropic receiving elements. These signals are weighted to form an exact beam towards the satellite, and the output of that algorithm is taken as a "truth" reference. Then the process is repeated with antenna elements which include all of the carrier phase and code phase biases outlined above. Again, after the beam-forming algorithm, this CRPA output signal is compared to the isotropic array "truth" signal to determine the overall bias in code and carrier phase of the CRPA.

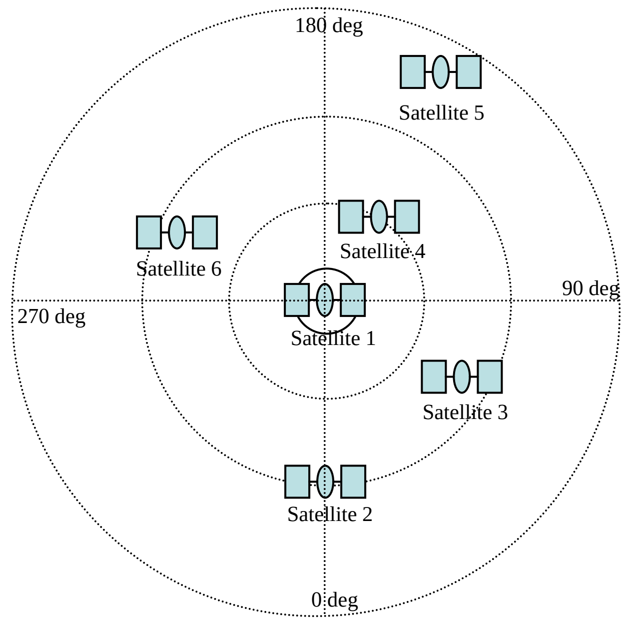

Figure 13. Sample constellation

Figure 13 shows a sample constellation studied. The line-of-sight direction and the code and carrier phase error for each satellite is presented in Table 1 below.

Satellite #	Elevation (deg)	Azimuth (deg)	Code Phase Error (m)	Carrier Phase Error (deg)
1	90	-	2.465	-14.2
2	30	0	2.496	-8.9
3	47.5	60	2.106	20.5
4	75	155	2.476	30.8
5	20	155	2.548	46.2
6	47.5	250	2.139	-48.3

Table 1. CRPA Hardware Biases for Sample Constellation (Code phase error at ½ chip correlator spacing)

While these numbers look rather disconcerting, keep in mind that these are the absolute bias values. As mentioned before, we are concerned with differential bias residuals in the double differenced signals. To determine how bad those are, the user antenna must be simulated also.

CONCLUSIONS

This paper presented a study of the possible CRPA hardware effects on the code and carrier phase of the received signal in each of the CRPA channels. For a probe-fed microstrip patch antenna array designed and built at Stanford University, a simulation study detailing the code phase effects of magnitude frequency response and group delay response of the antenna was presented. Also, a recommendation for a CRPA algorithm for Sea-based JPALS was given, and using this recommendation, the code and carrier phase errors of the entire CRPA system for a sample constellation of satellites was provided. With the variation in the code phase errors seen in this sample constellation, it is certainly feasible that differential code phase errors in the differenced signal between the user and the reference can exceed a half wavelength. Thus, these hardware effects must be modeled and compensated for in order to expedite correct integer ambiguity resolution.

FUTURE WORK

Future work will include the expansion of CRPA hardware simulation to cover entire visible sky. In addition, other CRPA algorithms may be pursued. Also, accurate phase and group delay modeling and compensation will be investigated. Ultimately, the simulation will include the above mentioned models and compensation methods, and carry on to determine the overall gain in the integer ambiguity resolution as shown in the figure below.

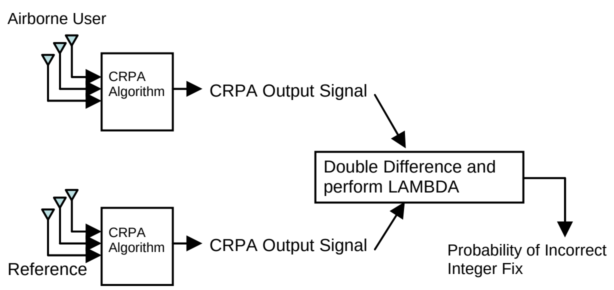

Figure 14. Code and carrier phase error effects on integer ambiguity resolution

ACKNOWLEDGMENTS

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