Test Results from a Novel Passive Bistatic GPS Radar Using a Phased Sensor Array

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BIOGRAPHY

Alison Brown is the Chief Visionary 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. She was a member of the GPS-3 Independent Review Team and the Interagency GPS Executive Board Independent Advisory Team, and is an Editor of GPS World Magazine. She is an ION Fellow and an Honorary Fellow of Sidney Sussex College, Cambridge.

Ben Mathews is a Program Manager and Digital Signal Processing Section Manager at NAVSYS Corporation. His work includes the design and development of advanced GPS and integrated navigation systems and digital signal processing systems. He holds a BSEE from the University of Illinois at Urbana-Champaign and a MSEE from Virginia Tech.

ABSTRACT

GPS bistatic signals have applications for remote sensing in collecting data such as soil moisture content, surface altitude or wave speed. Prior research using these signals has been limited by the low signal power of the bistatic GPS signals. Leveraging off of a previous effort that used a 15-element array, NAVSYS Corporation has developed an advanced bistatic GPS receiver that uses a 109-element GPS antenna array and digital beam steering to provide gain to increase the ability to detect the weak bistatic GPS signals. The enhanced 109-element array offers 20 dB of gain over previous receivers, which use single element tracking and offers promise of retrieving usable return data from a much higher altitude.

In this paper, the design of the digital beam-steering receiver is described and data collected during flight tests with the array are presented. The data was collected with the antenna array installed on a Cessna aircraft. Flights were conducted over terrain and water and the data was recorded for post-test analysis. The results of the flight test show the increase in fidelity and observability of the bistatic GPS signals by using digital beam steering. The digital scanning capability of the receiver also increases the area of coverage over which data can be collected from a single aircraft pass. The enhanced data collected will be of benefit for all remote sensing applications using bistatic GPS signals.

INTRODUCTION

Early experimentation using NAVSYS' advanced Global Positioning System (GPS) receiver technology demonstrated the ability to track the reflected GPS signals from the surface of the earth in the early 90's [1]. Since then, further research has demonstrated the utility of these signals for applications such as surface altimetry [2], wave motion detection and wind sensing [3], and observing surface water content [4, 5] for mapping ice fields or wetlands.

Because of the extremely low power level of the returned bistatic GPS signals, this previous research has focused primarily on the strong specular bistatic signals. NAVSYS has developed a digital beam-steering GPS receiver, the High-gain Advanced GPS Receiver (HAGR), which can be used to increase the received signal/noise ratio from these weak bistatic signal returns allowing improved detection of both specular and diffuse GPS signals (Figure 1). The theoretical basis for the GPS bistatic sensing using these signal returns is included in Reference [6].

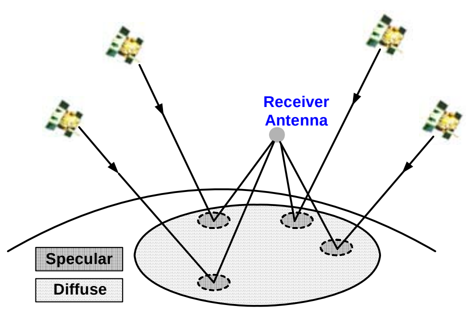

Figure 1 GPS Bistatic Geometry with Specular Reflection Points

DIGITAL BEAM-STEERING GPS RECEIVER

The NAVSYS High-gain Advanced GPS Receiver is a digital beam steering receiver designed for GPS satellite radionavigation and other spread spectrum applications.

This is installed in a rugged Compact PCI chassis (Figure 2) suitable for aircraft flight tests (Figure 2 through Figure 5).

The HAGR system architecture is shown in Figure 6. The signal from each antenna element is first digitized using a Digital Front-End (DFE). Each DFE card includes the capability to sample signals from 8 antenna inputs. These can be cascaded together to allow beam steering to be performed from a larger antenna array. The complete set of DFE digital signals is then used to create the composite digital beam-steered signal input by applying a complex weight to combine the antenna array outputs.

The HAGR can be configured with a variable number of antenna elements up to a total of 109-elements, as shown in Figure 6. For the first flight test a 15-element array was used; while the second flight test used 96 elements, with the elements shown in blue in Figure 7. Figure 8 shows the beam pattern created by the 96-element array. The advantage of digital beam steering can be seen in Figure 9, where we compare the CN0 values obtained from 5 individual elements with the CN0 value obtained using 96-element beam steering. Through the HAGR digital control, these beams can be directed at any point on the surface of the earth for data collection. The area they cover is a function of the beam width and the aircraft altitude, as illustrated in Figure 10. Up to 5 beams each, with +20 dB gain, can be independently directed by the HAGR signal processor.

Figure 2 HAGR Receiver and Digital Recorder Installed on the Aircraft

Figure 3 96-Element Antenna Array before Installation

Figure 4 96-Element Antenna Array Installation

Figure 5 96-Element Antenna Array Mounted on the Aircraft

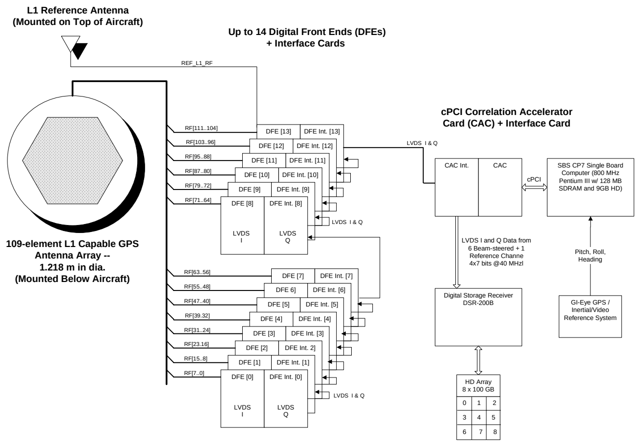

Figure 6 HAGR System Architecture

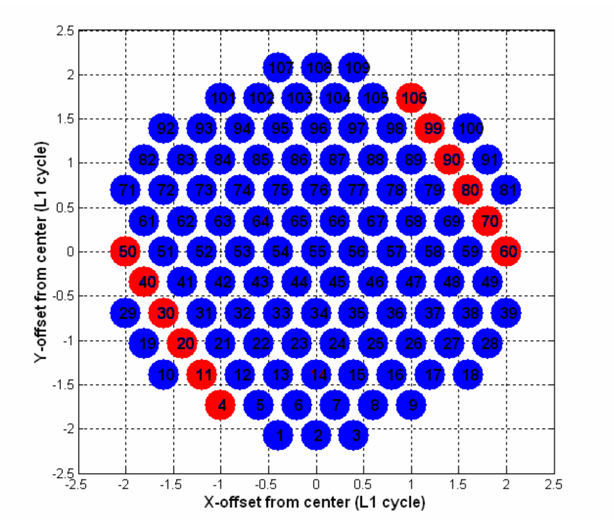

Figure 7 96-Element Phased Array

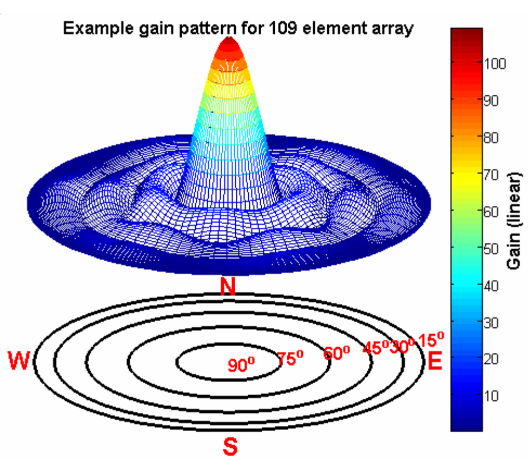

Figure 8 Beam Pattern of 109-Element Array

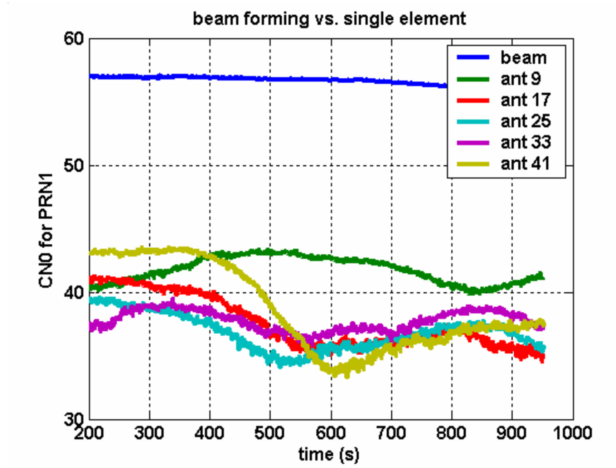

Figure 9 Beam forming Gain

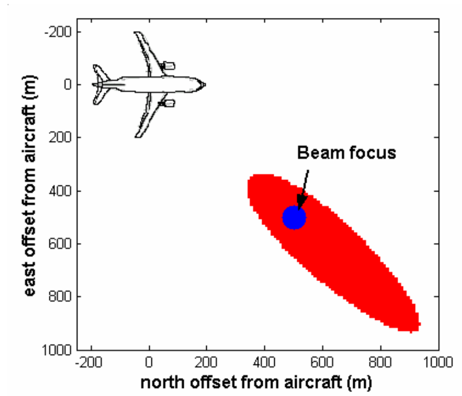

Figure 10 109-Element Beam Footprint (3dB contour from 500 m altitude)

BISTATIC GPS FLIGHT TEST

The flight test was conducted with the digital beam-steering receiver and the 96-element HAGR antenna array. The antenna array was installed on the underside of a Cessna test aircraft, Figure 11, and a reference antenna was installed on the upper-side of the aircraft. A similar flight test was previously flown using a 15 element array. During these flight tests, the HAGR was used to track the GPS satellites, and our digital storage receiver [7, 8] was used to record the raw broadband data from each beam and from the roof-mounted reference antenna. Approximately one hour of bistatic maritime data and one hour of bistatic land data was collected during each flight. This data was then played back into the HAGR from the digital storage receiver for signal processing post-test.

Figure 11 Cessna Test Aircraft before Flight

Figure 12 Test Aircraft with 96-Element Array in Flight

SPECULAR DATA ANALYSIS

Analysis of the specular returns over water are expected to be stronger than over land and can be used to provide information on vehicle detection, wave motion detection, wind sensing, and observing surface water content. For example, Figure 13 shows that using the 96-element array without post-processing, the HAGR receiver was able to track much more frequently off of the specular points on water than it was off of specular points off of land.

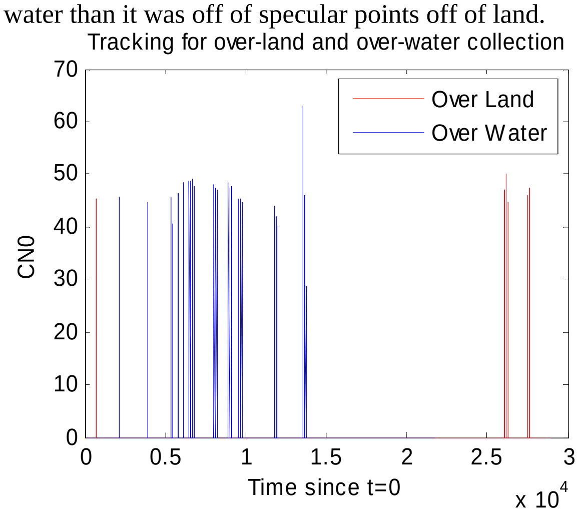

Figure 13 Bistatic Tracking over Land and Water

In Figure 14 an example of the kind of returns is shown. In this case, the HAGR receiver is able to track off of the two specular points that occur over the water (SV11 and SV27), while the specular points that occur over land (SV8 and SV31) do not return sufficient power to be tracked without additional post processing.

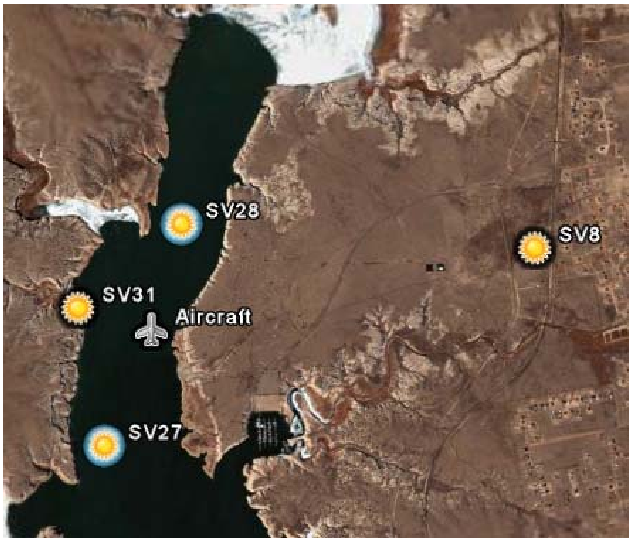

Figure 14 Aircraft and Specular Points over Land and Water

Figure 15 shows a dramatic increase in return power during the first flight test with a 15-element array when the specular point crosses the Pearl River in a forest on the Mississippi-Louisiana border. The rough surface formed by the treetops provides a low specular return whereas the smooth river surface provides a very strong return.

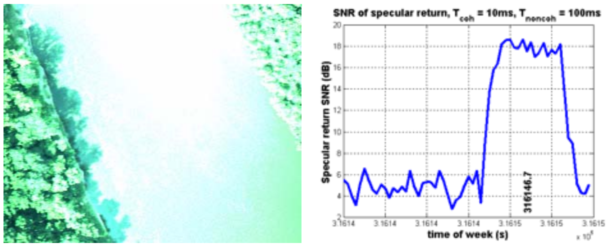

Figure 15 Pearl River Crossing, Specular Power Increase

An analysis on the data shown in Figure 13 was conducted. We examined the difference between the CN0 values obtained when we tracked off of the specular points and the expected CN0 values calculated, considering factors such as the beam forming gain, the satellite power and elevation, and the loss associated with the type of terrain that the specular point is reflecting off. These results are shown in Table 1. Using digital beam forming, the HAGR receiver was able to track off of the specular points with typical CN0 values comparable to those of single element tracking directly off of the satellite.

Table 1 Comparison of Expected and Actual CN0 values

Case	Expected CN0 (db-Hz)	Actual CN0 (db-Hz)
1	49	45
2	48	46
3	48	45
4	42	46
5	51	47
6	54	48
7	56	49
8	53	49
9	50	49
10	46	48
11	53	48
12	55	45
13	49	40
14	52	49
15	51	50
16	55	47

In Figure 16 and Figure 17 the expected and actual bistatic returns are shown from a point located in an urban area of Monument, Colorado. The characteristic horseshoe shape of the return can be seen in both images. With the gain provided by the use of beamsteering, sufficiently strong returns are obtained to provide useful measurements for a variety of remote sensing applications.

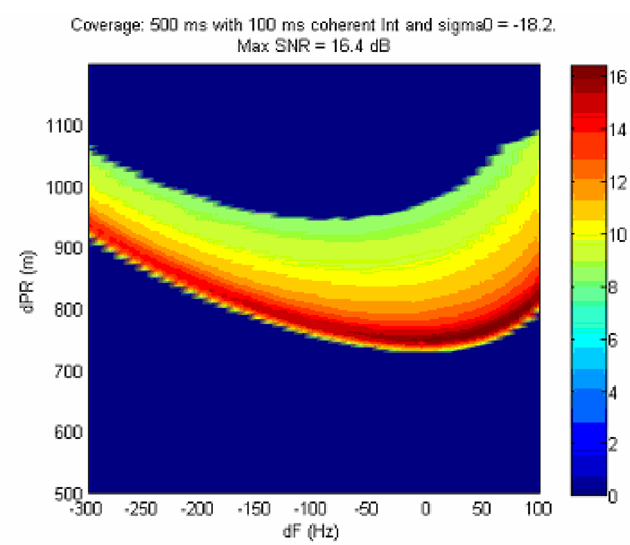

Figure 16 Expected Bistatic Returns

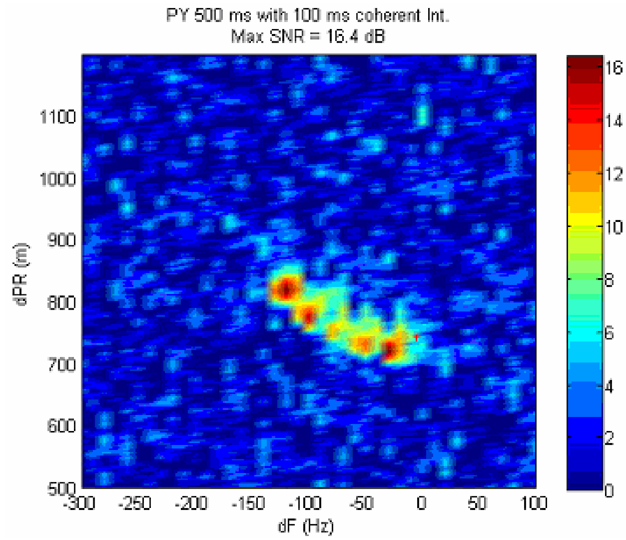

Figure 17 Actual Bistatic Returns

CONCLUSIONS

Test results and analysis described in this paper have demonstrated the ability of the HAGR receiver to improve the GPS bistatic remote sensing capability by using digital beam steering, to allow the weak bistatic GPS signal returns to be detected over a larger area. The test data taken has successfully shown that with the +20 dB gain provided by the ISR array and receiver, we are able to robustly track the specular and some diffuse signal bistatic GPS returns that were not trackable under previous efforts that used only a single antenna [9]. Using the ISR array, we were able to reliably detect signals returned from surfaces with clutter coefficients as low as -21 dB, which would have been undetectable using single antenna approaches.

We have demonstrated the following advantages of the ISR array for GPS bistatic signal tracking:

- Provides a wide-area, passive, intelligence, surveillance, and reconnaissance capability
- Provides fine resolution range/Doppler data using encrypted P(Y) code signal processing
- Allows robust detection of weak GPS specular and diffuse signal returns over a variety of terrain
- Passive operation enables use for covert detection operations.

Higher power GPS signals planned for the GPS IIF and GPS-3 satellite constellation will extend the range of operation of this system.

ACKNOWLEDGMENTS

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