Advanced Pinwheel™ Compact Controlled Reception Pattern Antenna (AP-CRPA) designed for Interference and Multipath Mitigation.

Waldemar Kunysz, *NovAtel Inc.*

BIOGRAPHY

Waldemar Kunysz obtained a BSEE from the Technical University of Nova Scotia in 1989. From 1991 to 1995 he worked on phased array antennas for Microwave Landing Systems with Micronav Inc. From 1995 to the present he has been with NovAtel Inc. He has published several technical papers and proceedings articles for various conferences. His current research interests include antenna theory and design, multipath mitigation techniques, genetic algorithms and electromagnetic compatibility.

ABSTRACT

This paper describes the design of a compact, dual GPS frequency L1/L2, multi element adaptive antenna array, where each array element is comprised of an aperture coupled spiral slot array. In short, it is an array of arrays. The design of a seven element array is described. The design is quite different from existing CRPA antennas which use a stacked patch approach. The aperture coupled spiral slot array methodology allows a reduction of mutual coupling between the adjacent elements of the array, and hence a reduction of the overall size of the antenna. In addition, its wide band performance will allow it to meet future GPS M-code requirements. The array has a low profile with a maximum height of 0.8”.

INTRODUCTION

GPS satellite navigation systems can benefit from equipping receivers with directional array antennas. Null steering technologies such as controlled reception pattern antenna (CRPA) and beam steering electronics (BSE) have been successfully used to cancel RF interfering signals and to mitigate multipath generated replicas of GPS signal. BSE can simultaneously maximize the desired signal and minimize the interfering signal by creating spatial nulls in the direction of the interferer through the means of adjusting the amplitude and phase from an adaptive antenna array.

In the past, the typical CRPA array was 14 inches in diameter and used 7 elements. There has been a great effort to reduce the size of CRPA array in the last few years by employing new antenna array technologies, materials, and by reducing the number of array elements from seven to five and even four. Reducing the number of array elements is not always desirable since the capability to create a multiple number of nulls is proportional to N-1 (where N is the number of array elements). There have been new CRPA array designs reported with an array having a maximum dimension of 6inches [8] and even 4.625 inches [9] in diameter. This paper focuses on 7-element array design that has diameter of 5.5 inches and a low height profile of 0.8 inches.

Slot antennas are widely used in many practical applications such as radar and satellite communications. The main advantage of slot antennas is wider bandwidth when compared with microstrip patch antennas. The demand of ever increasing performance, miniaturization and decreasing cost in many applications requires innovative design with a high integration level of active components, circuitry, and radiating elements. While compact circuit design is best achieved on high dielectric-constant substrates, optimum performance printed antennas are built on low-permitivity substrates [6].

In this paper the steps taken in the design of 7-element CRPA antenna are discussed, and the relative advantages and disadvantages to other designs are compared. Live GPS signal and anechoic chamber tests results using a 7-element CRPA antenna is presented. A commercially available electromagnetic simulation software (IE3D from Bay Technology) was used to optimize the array design from a mutual coupling point of view.

ANTENNA ELEMENT/ARRAY DESIGN

The antenna element is an array of multiple (eight) spiral slots that are electromagnetically coupled to a circular microstrip feeding network located underneath the slots[10]. Let's refer to it as an aperture coupled slot array antenna and denote it as a pinwheel type antenna, due to its internal layout nature. See Figures 1 and 2 for a board layout of 7-element, 8-arm spiral pinwheel antenna array. The pinwheel antenna is made out of a flat printed circuit board (PCB), with the upper layer being the ground plane layer. An antenna was constructed on 0.050-in. thick substrate (Rogers RT/duroid 6002 $\varepsilon_r = 6.15$). This antenna is designed for dual frequency operation, (longer slots corresponds to L2 signal reception, while shorter slots to L1 signal reception). The antenna can be classified as "outer-feed type" due to the location feeder with respect to the radiating slots. Typically these type of antennas employ the use of an absorber located at the center of the element in order to absorb the residual waves not radiated by the slots [7]. The impact of a RF absorber on the performance of the antenna element has not been evaluated in this case.

Figure 1. 7-element CRPA array with 8-way combiner

The spatial difference between each two consecutive spiral arms is 45°; as well the electrical phase length of the feeding network is set to 45° between the points where two adjacent slots cross over the microstrip feed network (area of coupling region). This arrangement allows the antenna element to achieve proper circular polarization and stable phase center. The feeding network is a leaky wave microstrip circuit, in order to avoid complexity, keep it simple, and maintain relatively uniform amplitude excitation for all slots (achieved through the use of loose coupling).

Figure 2. 7-element CRPA array (bottom side)

To maintain a good front/back ratio a metal cavity is placed underneath the antenna board. This prevents the multipath generated replicas of GPS/Glonass signals to be amplified by the antenna by maintaining a good front to back ratio.

In the 7-element array design, the separation distance between the elements is 41.5 mm (1.633 inches) or 0.218 wavelength at the center frequency of the L_1 band.

To reduce the amount of mutual coupling and suppress higher modes each antenna element is rotated by the angle of $2\pi/N$ with respect to each other. The same phase gradient must be applied to all elements in order to form the main beam that is normal to the array. If zero phase gradient is applied across the array, a null normal to the array will be placed in the pattern (see Figure 3). The theoretical pattern shown in Figure 3 assumes no amplitude and no phase error across the array.

The depth of the null is degraded when antenna elements are combined with certain amplitude and phase errors. The 8-way combiner and RF cables shown in Figure 1 contribute to such errors. These errors were measured using network a analyzer and then included in the array simulations. The depth of the null degrades by 25 dB from –40 to –15 dB (both L1 and L2 channels). The actual measured depth of the null was only –7 dB for the L1 channel and –5 dB for the L2 channel (see Figures 7 and 8 in the Anechoic Chamber Measurement section). The mutual coupling between the elements further degrades the depth of the null.

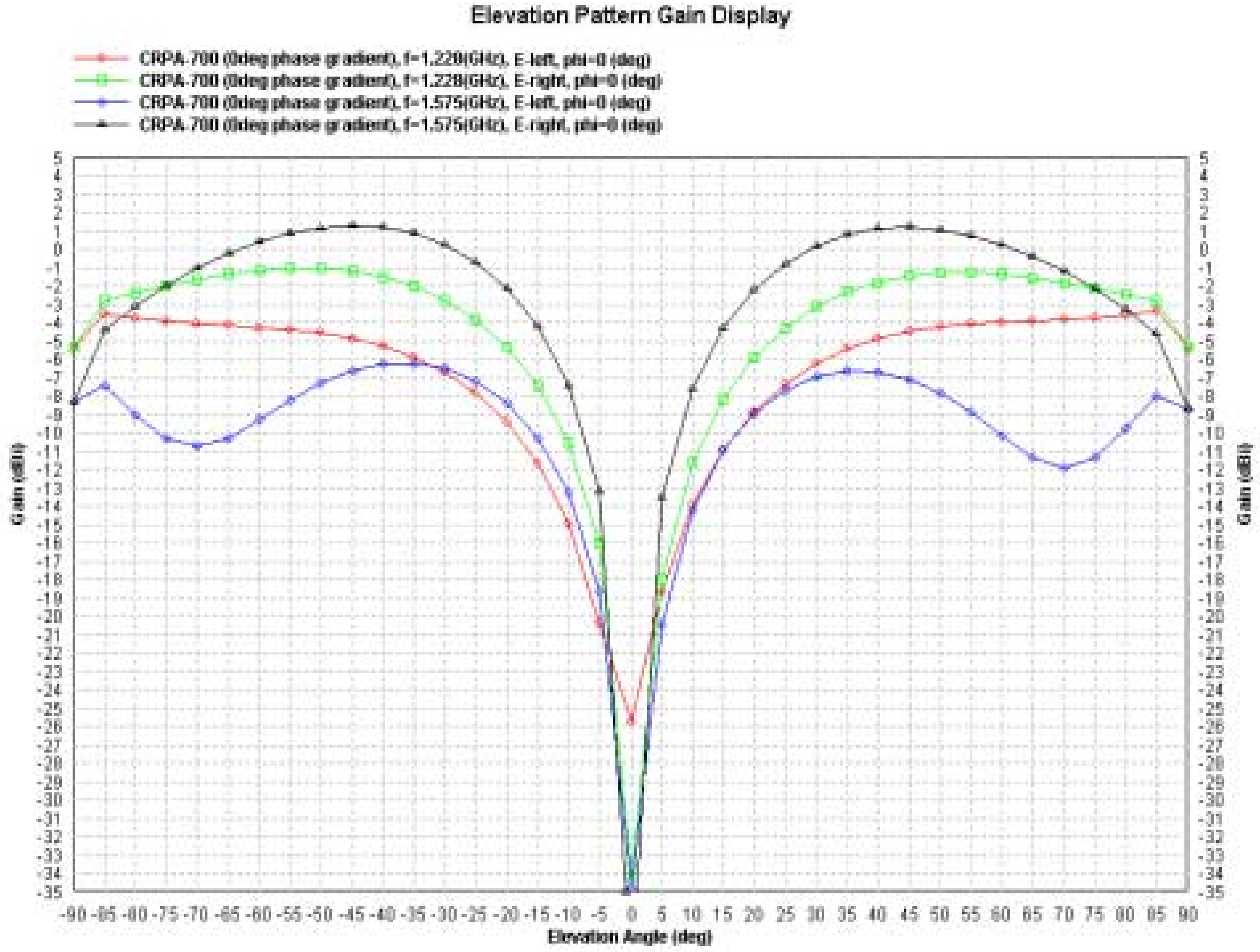

Figure 3. 7-element CRPA array – theoretical null depth and location (zero phase gradient across the array)

MUTUAL COUPLING

An appreciable level of mutual coupling between printed antenna elements is of great importance in array design, because it can result in a mismatch of the individual elements to their feed and the distortion of the radiation pattern of each element and subsequently the radiation pattern of the array. The mutual coupling as a function of the spacing between adjacent elements has been extensively studied and measured by many authors. G. Feng had shown that for spacing of less than λ/4 the mutual coupling could exceed –10dB [1][3][4][5] between circularly polarized antenna elements. Four-element CRPA array reported in [9] has a significant amount of mutual coupling (between –11 to –8 dB) due to close proximity of adjacent elements. Mutual coupling is also dependent on the dielectric constant of the substrate and the thickness of the substrate[9].

U. Kraft proposed a method of a 2x2 sequential-rotation array as a solution to suppress higher modes and reduce mutual coupling [2]. Use of circularly polarized elements is not the best choice when designing small antenna arrays, since they are more sensitive to mutual coupling than dual- or linearly polarized alternatives [2].

Measurements of the S-parameters for the 7-element prototype are made using an HP8753D network analyzer. The measured mutual coupling between any pair of adjacent elements is shown in Figure 4. The isolation between any two adjacent elements is -14 dB at the L1, and -16 dB at the L2 GPS frequency**.** The achieved mutual coupling is better by an average of 6 dB as compared to the CRPA described in [9], for similar element spacing.

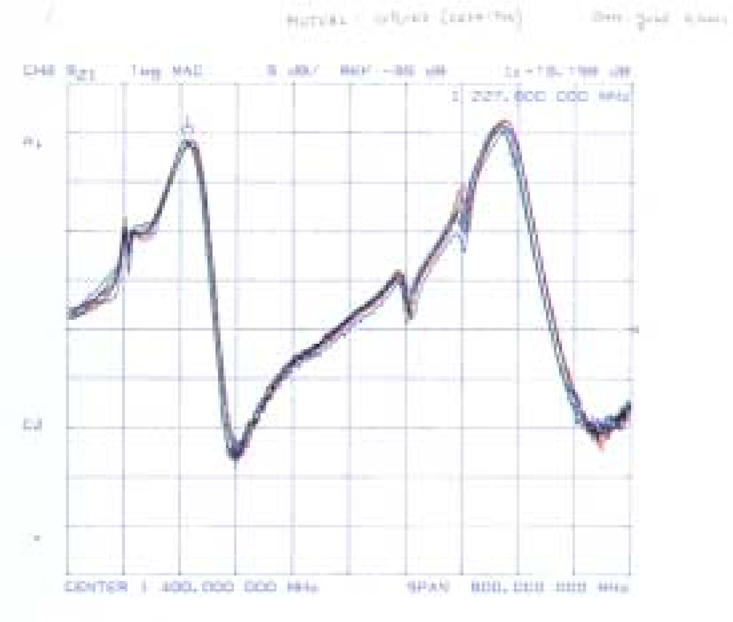

Figure 4. Measured mutual coupling between any pair of adjacent elements of 7-element CRPA

The mutual coupling across the array was measured to be a maximum –25 dB and –35 db (depending on the geometry and the distance between antenna elements of interest).

The field F(θ,φ) generated by N uniformly excited radiating elements arranged in a flat ring of radius ρ, the i-th element having element factor g_i and angular position β_i is given by

$$F(\theta,\phi) = I\sum_{i=1}^{N} g_i e^{jk[\rho\sin\theta\cos(\phi-\beta_i)]} \qquad (1)$$

Where k is the wavenumber and I is the common excitation. For a pencil beam, the ϕ dependence is minimized by placing the elements at uniform intervals on the ring: $\beta i = 2\pi/N$.

To place a null in the direction normal to the array a phase gradient β_i is applied across the array and hence the field is now calculated as

$$F = \sum_{i=1}^{N} a_i e^{jk\alpha_i} + \sum_{i=1}^{N} \gamma_i e^{jk\gamma_i} \qquad (2)$$

The first term in equation (2) is the field component computed in (1) at the center of the coordinate system (x=y=0) and some far-field distance z combined with progressive uniform phase gradient βi across the array. The second term in (2) describes the total amplitude and phase error contribution due to the mutual coupling and/or receiver channel errors. In the ideal case (second term is zero) the null exists if the following condition is met:

$$\sum_{i=1}^{N}\alpha_i = n\cdot\pi \qquad (3)$$

This condition can be met in two ways: one way is to apply $2\pi/N$ phase gradient across the array and have antenna elements oriented the same way. Another way is to have all elements oriented in such way that they are progressively rotated by phase $2\pi/N$ with respect to each other, and with zero phase gradient applied to all elements. The second method reduces the mutual coupling effects, suppresses higher modes [2] and also randomizes the amplitude/phase radiation pattern contributed by each individual antenna element (Refer to Figures 5 and 6). The second method was used to design the 7-element CRPA array described in this paper.

There is another interesting twist to it. By applying zero phase gradient we should expect a perfect null. Any degradation of it comes from the second term in equation (2). The second term can be nulled the same way as the first term using the principle of equation (3) with the modification that a small amplitude adjustment may be also necessary. What I just described above could be used as a calibration method to eliminate and/or greatly reduce errors induced by each receiver channel path, and by the mutual coupling existing between antenna elements.

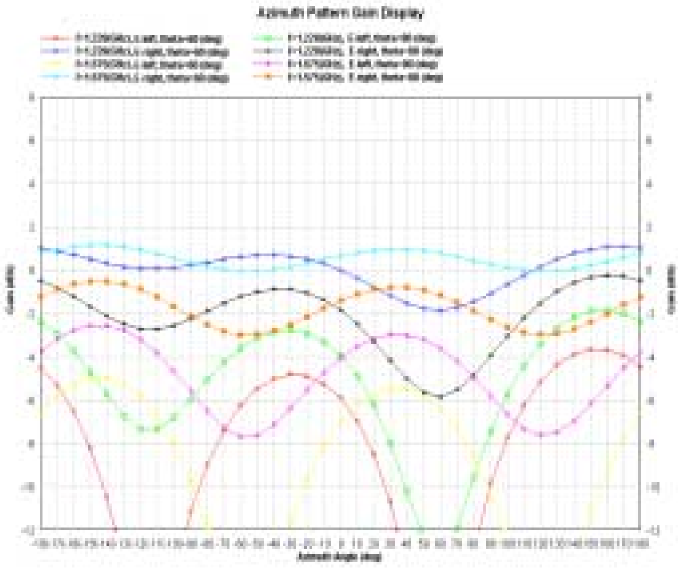

Figure 5 Single element azimuth gain pattern at elevation angle of 30° (θ=60°) and 10° (θ=80°)

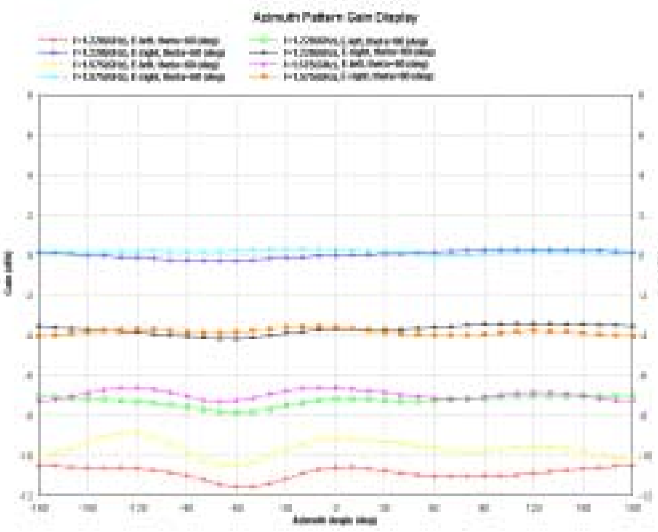

Figure 6 ***Combined array (7-element with phase gradient of 2π/7) azimuth gain pattern at elevation angle of 30° (θ=60°) and 10° (θ=80°)***

Note the improvement in amplitude ripple from the case of single antenna elements as compared to a combined array with rotated antenna elements. This translates to improved axial ratio that doesn't change with azimuth angle.

ANECHOIC CHAMBER MEASUREMENTS

The antenna performance was validated by performing detailed anechoic chamber measurements and various GPS live signal tests. The main purpose of the anechoic chamber measurements was to determine the radiation pattern characteristics of a single array element and the performance of the entire 7-element CRPA array (using configuration shown in Figure 1).

Note that Figures 7 and 8 have reverse angle notation. The antenna boresight angle of 0° corresponds to a GPS elevation angle of 90°, and vice-versa where an antenna angle of 90° corresponds to a GPS elevation angle of 0° (Horizon plane).

As previously mentioned in the ANTENNA ELEMENT/ARRAY DESIGN section of this paper, the measured null depth on antenna boresight is degraded by by the combining circuit errors and the existing mutual coupling. It was determined that combining ciruit errors degraded the null by 25 dB from –40 to –15 dB (for both L1 and L2 channel)s. The remaining null degradation is most likely due to surface wave modes excited within a substrate and due to mutual coupling. The null depth at the L2 band is –5 dB while at the L1 band it is –7 dB (See Figures 7 and 8).

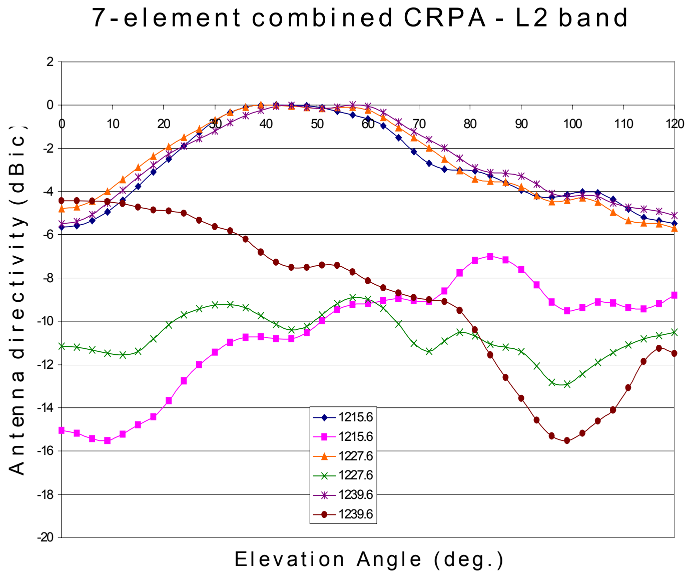

Figure 7. ***Normalized single element directivity (L2 band) - anechoic chamber measurement***

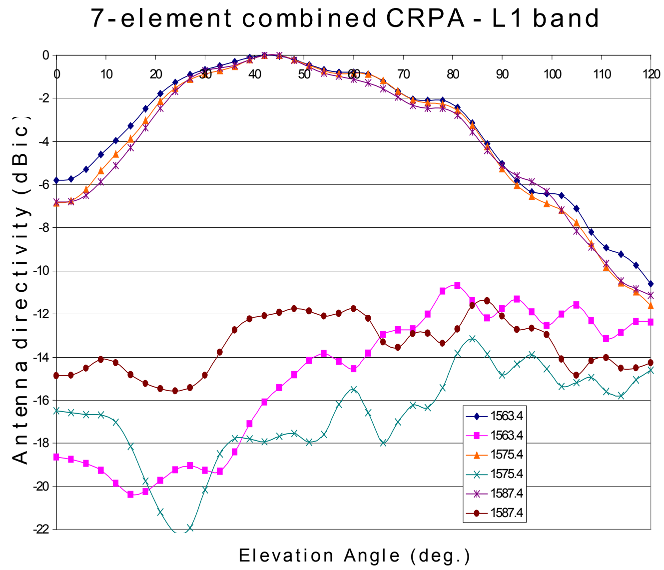

Figure 8. ***Normalized single element directivity (L1 band) - anechoic chamber measurement***

LIVE GPS SIGNAL MEASUREMENTS

The array antenna performance was validated by performing live GPS signal type measurements. The following figures of merit were used to determine the antenna performance: carrier to noise (C/No) variation with azimuth angle and elevation angle of a tracked satellite. The antenna was mounted on the roof of the NovAtel building.

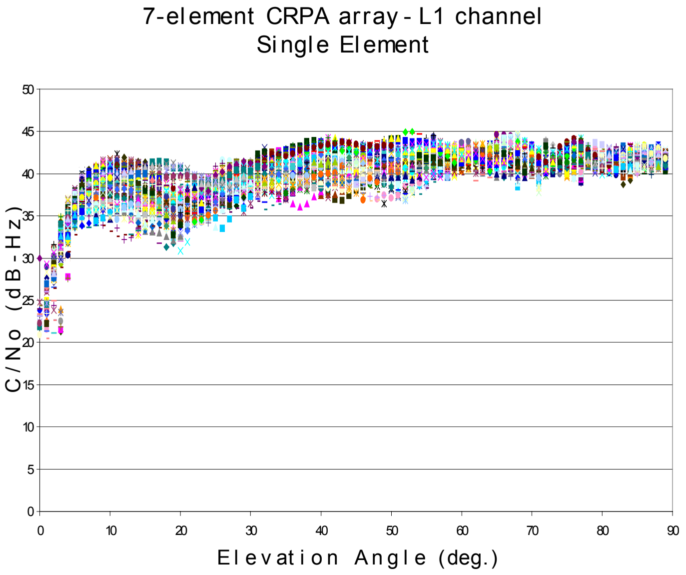

Figure 9. Received C/No of single element (L1 band)

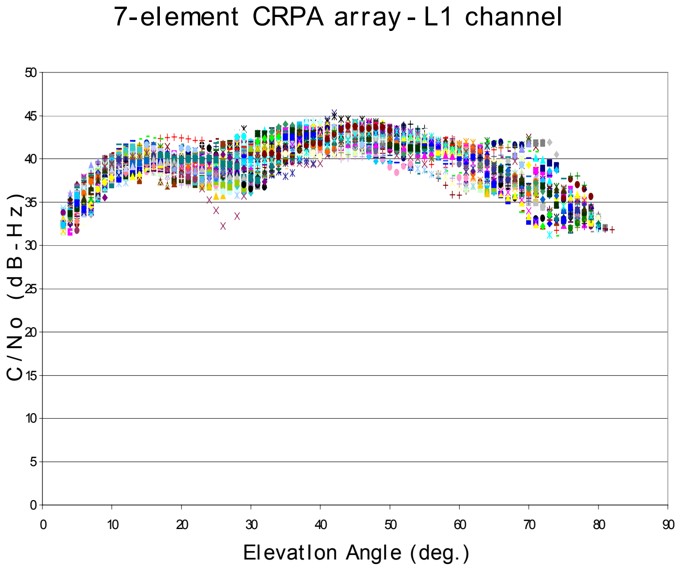

Figure 10. Received C/No of a combined array shown on Figure1 (L1 band)

As predicted a null is placed on the boresight of the antenna (Elevation angle of 90°) where no satellites are tracked beyond 80°, see Figure 9. The null depth is at least –10 dB when estimating the live GPS signal test results from Figures 9 and 10. The discrepancy between the anechoic chamber and live GPS measurements is unknown.

CONCLUSIONS

A promising, new concept in CRPA array technology has been applied to develop smaller version of adaptive antenna array. This antenna offers a dual frequency performance and it could support suppression of wide-band jammers as in the case of M-code military applications. It could also be applied to successfully mitigate multipath in standard surveying applications.

The low profile of the antenna makes it suitable for such applications such as vehicle, aircraft, missile/rocket and manpack applications.

This type of antenna would be simple to manufacture and could easily meet harsh environmental requirements, making it also suitable for marine and arctic applications.

ACKNOWLEDGMENTS

The author gratefully acknowledges the assistance and help provided during this antenna research and development by Pat Fenton, Andrew Polivka and Pheonix Chen. The financial support provided by NovAtel Inc. to fund this project is also greatly appreciated.

REFERENCES

[1] Gao Feng, “A simple approach to mutual coupling between circular microstrip antennas,” in *IEEE Int. Antennas Propagat. Symp. Dig., vol. 26, pp.1156-1159, June 1988.*

[2] Ulrich R. Kraft, “An experimental study on 2x2 sequential-rotation arrays with circularly polarized microstrip radiators,” in *IEEE Trans. Antennas Propagat. vol. AP-45, pp. 1459-1466, Oct. 1997.*

[3] E.H. Van Lil and A.R. Van de Capelle, “Transmision Line Model for mutual coupling between microstrip antennas,” ,” in *IEEE Trans. Antennas Propagat. vol. AP-32, pp. 816-821, Aug. 1984.*

[4] A. Mohammadian, N.M. Martin, “A theoretical and experimental study of mutual coupling in microstrip antenna arrays,” ,” in *IEEE Trans. Antennas Propagat. vol. AP-37, pp. 1217-1223, Oct. 1989.*

[5] M.A. Khayat, J.T. Williams, D.R.Jackson and S.A. Long, “Mutual coupling between reduced surface-wave microstrip antennas,” in *IEEE Trans.*

Antennas Propagat. vol. AP-48, pp.1581-1593, Oct. 2000.

[6] D. M. Pozar, “Considerations for millimetre wave printed antennas,” *IEEE Trans. Antennas Propagat. vol. AP-33, pp. 740-747, Sept. 1983.*

[7] N. Goto ,”Single-Layered Radial Slot Antenna, ”*United States Patent No.: 5,175,561 Dec. 1992.*

[8] C.W. Manry, K. Rouzbehani, D. Nathans, A. Brown, H.-W. Tseng, and S. Atterberg, ”Advanced mini array antenna design using high fidelity computer modelling and simulations”, *ION-2000 Proc., Salt lake City, pp. 2485-2490, Sep. 2000.*

[9] B. R. Rao, J. H. Williams, C.D. Boschen, J.T. Ross, E.N. Rosario and R.J. Davis,”Characterizing the effects of mutual coupling on the performance of a miniturized GPS adaptive antenna array” *ION-2000 Proc., Salt lake City, pp. 2491-2498, Sep. 2000..*

[10] W. Kunysz, “A Novel GPS Survey Antenna” *Technical Session of ION, Anaheim, CA, January 2000.*