A Compact 1 to 18 GHz Planar Spiral Antenna for Interferometer and other Direction Finding Applications

D. E. Baker[1] J. B. du Toit[1]

Abstract – **This paper discusses the development of a compact light-weight planar spiral antenna for use in amplitude comparison and interferometer direction finding (DF) applications covering 1 to 18 GHz. The antenna uses a slow-wave (zigzag) spiral radiator which results in a cavity diameter which is only 68% of the wavelength at 1 GHz. The two-arm spiral is fed by a Marchand balun and achieves a VSWR of less than 1.5:1 over almost the entire 1 to 18 GHz frequency range. The spiral antennas are supplied in phase and amplitude tracking sets for wideband DF applications. Amplitude and phase tracking performance for a fully integrated linear interferometer DF panel which includes the radome and feed cable effects are presented. Phase DF performance for the panel with pulse receivers as measured in an anechoic chamber is discussed.**

1 INTRODUCTION

The planar, cavity-backed spiral antenna has been the workhorse for the interception of incident radar signals for radar warning receivers and electronic support measures equipment for more than 50 years. The antennas can be extremely broadband (e.g. 0.7 to 40 GHz in a single compact antenna [1]), they have wide beamwidths which are suitable for many types of direction finding (DF) and are circularly polarized. The antennas can be nearly flush mounted and this with their other properties makes them very attractive for airborne systems. Since their original development in the 1950s [2], [3] much effort has been spent on improving the performance of individual spiral antenna elements (improved far-out axial ratio beyond 70° off boresight, lower squint, reduced beamwidth variation as a function of frequency, conical cut concentricity, amplitude and phase tracking between antennas in large production batches, etc.). An excellent review of the spiral antenna art appears in [4].

An aspect which has also been addressed is size reduction. Size reduction by introducing zigzags into the normally smooth tracks has been known for a long time [5], [6]. Dielectric loading of the cavity can play a role but this technique often restricts the bandwidth. Significant size reduction can also be achieved by means of the "spiral-helix" antenna [7]. Here the free ends of a conventional planar spiral antenna (either Archimedean or equiangular) are extended into a two-arm backfire helix [9]. The backfire helix is wound on a dielectric cavity and the free ends of the helix are resistively terminated. A 50% reduction in diameter is possible. About the lowest octave of the frequency band radiates from the helix portion of the antenna. This part of the antenna cannot be recessed below a metal surface without significant degradation of the patterns and gain.

This paper looks at a particular size-reduced spiral antenna developed for interferometer and amplitude comparison DF systems covering 1 to 18 GHz using a planar zigzag spiral element. For a low profile interferometer panel the cavity is recessed below the radome and the antennas are closely spaced in the array. At the lower end of the frequency range these two factors can disturb the patterns and significantly degrade the phase tracking. The planar spiral antenna is less sensitive to these effects than the spiral helix antenna. For this reason a compact, low-profile planar spiral antenna was selected for the interferometer.

2 RATIONALE FOR NEW SPIRAL ANTENNA

Many systems use compact 2 inch (50.8 mm) diameter spiral antennas to cover 2 to 18 GHz. Such a 2 inch spiral antenna has a circumference only about 6% larger than the wavelength at 2 GHz. The nominal cavity height is around 26 mm. If this antenna is simply scaled to operate down to 1 GHz its diameter will double to 101.6 mm and the cavity height will also double. Such an antenna is too large for a compact interferometer DF panel operating from 1 to 18 GHz. Inputs from the systems engineers developing the DF and ambiguity resolution algorithms for the interferometer restricted the outside diameter of the new 1 to 18 GHz planar spiral antenna to be no more than 65 mm. This gives a circumference of 204.2 mm which is only 68 % of the wavelength at 1 GHz. In addition, the interferometer panel was to be nearly flush mounted resulting in a total cavity height restriction to less than 30 mm.

No spiral antenna covering 1 to 18 GHz and meeting the above size constraints was commercially available. It was therefore decided to develop a new antenna for the particular application by exploiting the techniques developed earlier for the compact 0.7 to 40 GHz spiral antenna [1].

The planar spiral antenna consists of three main parts - the backing cavity, the two-arm spiral radiator and the balun. This paper briefly discusses some of the

[1] Saab Electronic Defence Systems, P.O. Box 11212, Swartkops, 0051, South Africa
e-mail: dirk.baker@za.saabgroup.com and johan.dutoit@za.saabgroup.com, tel.: +27 12 674 3500

978-1-4673-0405-4/12/$31.00 ©2012 IEEE

key design challenges presented for these parts by the compact 1 to 18 GHz planar spiral antenna. Successful resolution of these challenges is illustrated by means of measured data for the basic spiral antenna. Four such spiral antennas were integrated behind a radome to form a linear interferometer DF panel. The installed amplitude and phase tracking performance of this DF panel is discussed and some measured interferometer DF performance for the array is presented.

3 COMPACT SPIRAL ANTENNA

Figure 1 shows a drawing of the final antenna with the main dimensions. The cylindrical backing cavity is loaded with a combination of honeycomb and ferrite absorbers whose function is to reduce and eliminate the backward radiation from the spiral face. Internal reflections off the cavity base degrade the axial ratio of the antenna. The external 'ears' at the base of the antenna cavity are for mounting the antenna in the interferometer housing and for phase rotation of the installed antenna. A mechanical rotation of a specific angle of the spiral antenna about its axis results in a uniform phase shift of the same angle over the entire frequency band of the antenna. This important property of spiral antennas is exploited during phase alignment of spiral antennas in an interferometer DF array. The mass of the antenna is only 140 g.

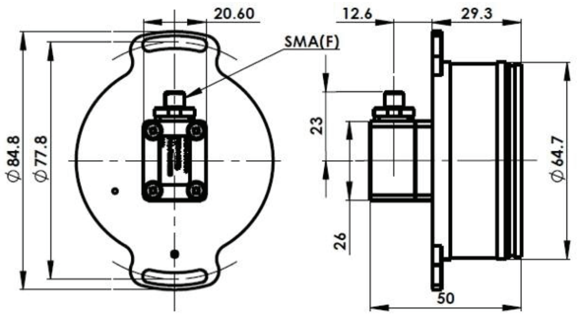


Figure 1 Outline drawing of compact 1 to 18 GHz spiral antenna.

To achieve the compact size one cannot use a conventional self-complementary Archimedean spiral where the tracks grow in the form of $r = r_0 + b\phi$ where r is the radius of the spiral, r_0 is the radius at the start, b is the growth rate and ϕ is the angle being 2π per turn. The present design exploits a self-complementary, slow-wave (zigzag) spiral architecture. The two-arm spiral starts as a conventional Archimedean spiral which slowly introduces zigzags as the spiral grows to the outer diameter as opposed to the square zigzag spiral in [5]. The spiral is more tightly wound than the more open spiral recently proposed in [9]. The spiral is etched on a 0.254 mm thick low dielectric constant substrate ($\epsilon_r = 2.2$). A higher ϵ_r will reduce the lowest frequency by a few percent but will also draw the 18 GHz active zone closer to the centre where interactions with the balun can degrade the high-frequency performance [10]. Proper termination of the free ends of the spiral is critical to achieve good axial ratio in the 1 to 2 GHz band. Reflections from the free ends cause radiation in the opposite circular polarization thereby degrading the desired circular polarization. The free ends of the spiral are terminated using a combination of resistive and absorptive paint loading [4, p. 13-25].

A compensated Marchand balun is used to feed the two-arm planar Archimedean spiral antenna [11], [12]. The spiral radiator is self complementary; for a free-space antenna this gives a real impedance of 60π ohms. The filling factor of the substrate and the presence of the absorber filled cavity reduce the impedance to about 160 Ω. For a 50 Ω input connector, the balun must perform significant impedance transformation to achieve good VSWR. The design target for the balun was to achieve a reflection coefficient of less than -14 dB (VSWR ≤ 1.5:1) for the spiral antenna. Some measured data for the fully assembled antenna is presented in the next section.

4 MEASURED PERFORMANCE OF SPIRAL

Figure 2 shows the measured VSWR of the new spiral antenna. Note that the plot extends from 0.5 to 18.5 GHz. The VSWR is below 1.5:1 over most of the 1 to 18 GHz frequency range and the 2.5:1 VSWR bandwidth of the antenna is 21.5:1, a remarkable result. It is generally not possible to achieve such a low VSWR in production because of material variations and time pressures. The low basic VSWR leaves enough headroom to achieve a VSWR of ≤ 2.5:1 in a production environment.

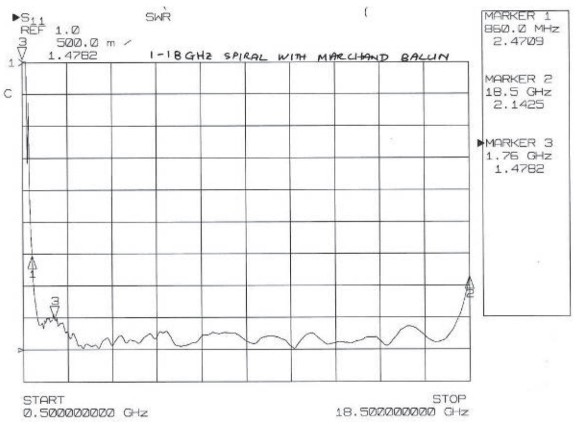


Figure 2: Measured VSWR of 1 to 18 GHz spiral antenna (black) and terminated balun (red).

For the more than 30% reduction in the diameter of the antenna there is a price to pay; this is in the gain as shown in Figure 3. The gain is in dBli for vertical and horizontal polarizations. The gain rolls off to about -11 dBli at 1 GHz which is in part due to the shallow cavity. The gain tracking between the V and H polarizations is good over the entire frequency range. This is desirable for DF systems.

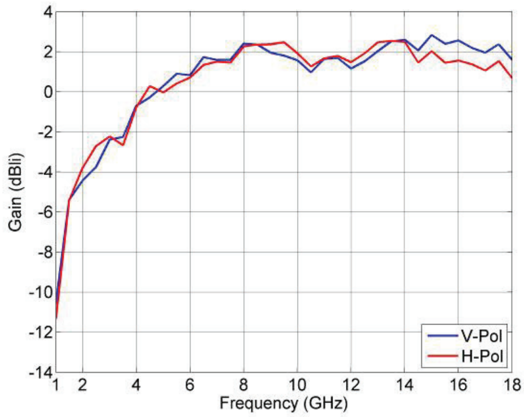


Figure 3: Measured gain of 1 to 18 GHz spiral antenna for V and H polarizations.

Figure 4 shows measured axial ratio (AR) patterns at 1 and at 18 GHz using a rotating linear source. The free-space back lobe at 1 GHz is relatively high (6 dB) because the antenna is electrically small. At any angle the peak-to-peak ripple is the AR in dB at that angle. The off-boresight AR at various angles to 80° is shown in Figure 5. Out to 60° the AR is nominally less than 2 dB and even to 80° the AR is typically less than 4 dB.

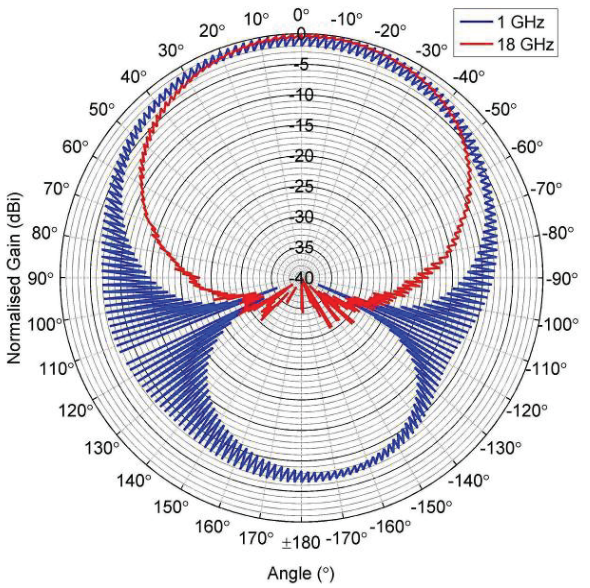


Figure 4: Measured axial ratio patterns at 1 GHz (blue) and 18 GHz (red).

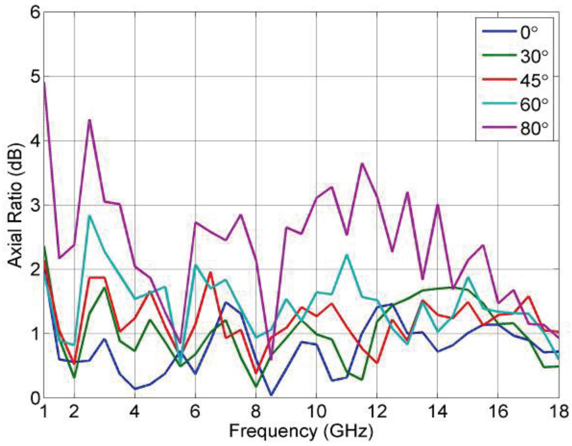
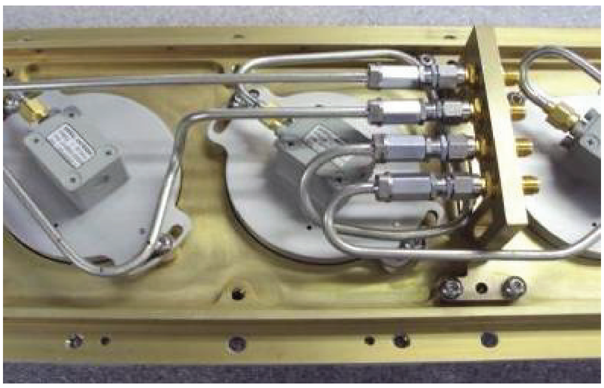


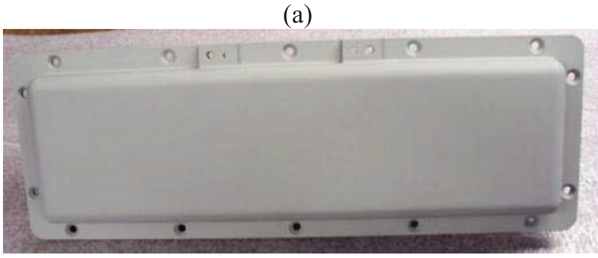
Figure 5: Measured axial ratio of 1 to 18 GHz spiral antenna at off-boresight angles out to 80°.

5 INTEGRATED DF PERFORMANCE

The main purpose of the antenna development was for application in low-profile DF systems. Figure 6(a) shows a partial rear view of a four element interferometer panel. The coax cables with phase shifters which run from the antennas to the receiver interface are clearly visible. Figure 6(b) shows the front of the 1 to 18 GHz interferometer panel with its radome. The panel is 134 mm wide and 383 mm long, the radome extends 24.3 mm above the mounting surface and the mass of the entire assembly is 1.3 kg.



(a)



(b)

Figure 6: (a) Rear view of 1 to 18 GHz interferometer panel and (b) front view showing protective radome.

Figure 5 shows the installed phase and amplitude tracking between antennas on boresight as measured at the receiver interfaces, i.e. through the radome and at the ends of the interface cables. Antenna no. 1 in the set is taken as reference and a S_{21} calibration is done between a transmit antenna and antenna no. 1 to obtain reference traces at 0 ° phase and 0 dB amplitude. The test port is then moved to antenna no. 2 and the antenna is rotated about its axis to eliminate systematic phase offsets and the phase shifter is adjusted to reduce slope in the phase characteristic. At any frequency the phase tracking between the four antennas is better than 4° peak and below 0.5 dB peak amplitude tracking.

The interferometer DF panel was installed in an anechoic chamber and DF measurements were made over a ± 30° field of view using four pulse receivers. The system operates over a ± 60° field of view but parallax errors in a 3 m anechoic chamber introduce large systematic errors. The peak DF errors of Figure 8 show that excellent DF is achieved for the compact interferometer panel.

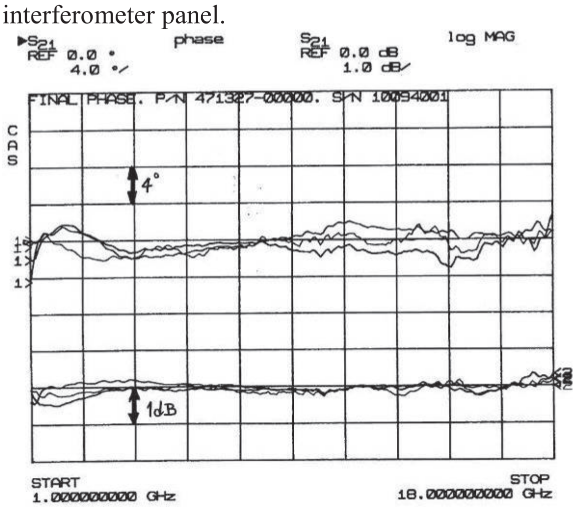


Figure 7: Installed phase (upper curves) and amplitude tracking (lower curves) between four antennas.

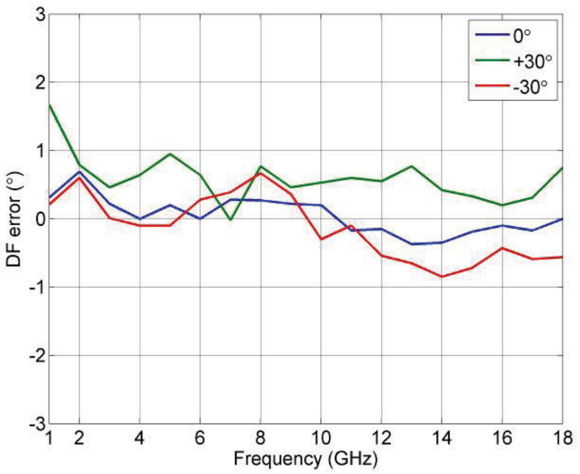


Figure 8: Full system peak DF errors for 1 to 18 GHz.

6 CONCLUSIONS

This paper has described a novel compact 1 to 18 GHz spiral antenna which has excellent electrical performance. The VSWR is low over the entire frequency range and pushes the limits of what can be achieved with a compensated Marchand balun. The measured gain is nominally 0 dBli from 4 to 18 GHz for V and H polarizations and rolls off to -10 dBli at 1 GHz. The gain roll-off occurs in part because the cavity is very shallow as required by the interferometer panel. Axial ratio performance is good, particularly in the size-reduced part of the frequency band. Phase and amplitude tracking sets of antennas were integrated into a fully functional interferometer DF panel and anechoic chamber measurements have demonstrated that excellent DF can be achieved. The compact 1 to 18 GHz spiral antennas are critical for achieving this DF performance.

REFERENCES

[1] D. E. Baker and J. Erasmus, "Compact, extended bandwidth 0.7 to 40 GHz spiral antenna with integrated diplexer," in *Proc. 8th SAIEEE AP/MTTS Symposium*, Stellenbosch, South Africa, Oct. 1994, p.237.

[2] E. M. Turner, "Spiral Slot Antenna," U.S. Patent 2 863 145, Dec. 2, 1958.

[3] R. Bawer and J. J. Wolfe, "The Spiral Antenna", *IRE Int. Conv. Rec.,* 1960, pp. 84-95.

[4] D. S. Filipovic and T. Cencich, "Frequency Independent Antennas", *Antenna Engineering Handbook,* 4th Ed., J.L. Volakis (ed.), New York: McGraw-Hill, 2007, Chap. 13.

[5] W. F. Patterson and E. T. Roland," Spiral antenna with zigzag arms to reduce size," U.S. Patent 3 454 951, July 8, 1969.

[6] T. E. Morgan, "Reduced size spiral antenna," in *Proc. 9th European Microwave Conference,* Brighton, England, Sept. 1979, pp. 181-185.

[7] J. W. Greiser, "Helix-Loaded Spiral Antenna," U.S. Patent 4 012 744, March 15, 1977.

[8] C. H. Walter, *Travelling Wave Antennas,* New York: Dover Publications Inc., 1970, pp. 332-333.

[9] I. Tzanidis, C-C. Chen and J. L. Volakis, "Low-Profile Spiral on a Thin Ferrite Ground Plane for 220-500 MHz Operation," *IEEE Trans. Antennas Propag.*, vol.58, pp. 3715-3720, Nov. 2010.

[10] C. Fumeaux, D. Baumann and R. Vahldieck, "Finite-Volume Time-Domain Analysis of a Cavity-Backed Archimedean Spiral Antenna," *IEEE Trans. Antennas Propag.*, vol.54, pp. 844-851, Mar. 2006.

[11] J. H. Cloete "Graphs of Circuit Elements for the Marchand Balun," *Microwave Journal*, vol. 24, pp. 125-128, May 1981.

[12] V. Trifunovic' and B. Jokanovic', "Review of Printed Marchand and Double *Y* Baluns: Characteristics and Application," IEEE Trans. MTT, vol. 42, Aug. 1994, pp. 1454-1462.