The Development of a Professional Antenna for Galileo

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BIOGRAPHIES

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Robin graduated from Southampton University in 1999 with a Masters Degree with Distinction in Electronic Engineering, then started work at Roke Manor Research Ltd where he is currently a Senior Engineer in the Antennas and EM Solutions group. His work on antennas and electromagnetics includes designing a multiband Planar Inverted 'F' Antenna for the Siemens CX75 mobile phone and a 4.25Gbit/s non-contact rotary data link for Siemens Medical Solutions.

Peter Readman BSc, MPhil
Peter Readman graduated from Imperial College London in 1986 with an upper second class honours degree in Physics. He began working for Farnell Instruments in 1986 developing test equipment, gaining an MPhil in conjunction with Huddesfield Polytechnic ("Analysis and Design of Local Oscillators for a Wideband Spectrum Analyser") in 1991. He continued working at Farnell Instruments until 1994 before moving to GEC Marconi to develop RF systems for the Eurofighter. He joined Roke Manor Research Ltd in 1995 and has worked on a wide range of projects designing RF circuits including Power Amplifiers, LNAs, oscillators, filters, synthesizers and antennas.

Stephen HW Simpson BSc, PhD
Steve Simpson graduated from the university of Salford with first class honours in electronics in 1974 and went on to post graduate studies in microwave scattering at the university of Sheffield, from where he obtained his PhD in 1979. He spent a short time at British Aerospace (Dynamics) before moving to Roke Manor Research Ltd in July 1979. Steve has held a wide variety of posts at Roke, including Group Leader positions in: Air Traffic Management and Navigation, Computational Electromagnetics and Antennas and Electromagnetics, which is his current position.

ABSTRACT

With the availability of the Galileo system rapidly approaching, industry is developing technology to exploit the new signals. This paper describes one such activity aimed at the professional user segment. The Galileo Joint Undertaking, Area 1B "Technological Development", as one of its initiatives, has entered into contract for the development of advanced receiver technology for Galileo called "Advanced Receiver Terminal for User Services" (ARTUS).

The ARTUS project, as a whole, addresses the development of technology for a complete receiver system for Galileo. However, this paper concerns the design and development of a "professional antenna" for high-precision ground-based geodetic applications.

The paper will address the extra technical performance issues concerned with accessing the Galileo signal as compared to the GPS signal. The need for wide-band performance coupled with high phase centre stability results in a very demanding requirement, satisfied by only a few antenna technologies.

The relationships between gain and phase patterns and antenna aperture distribution are examined and it is explained how these theoretical parameters relate to the phase centre stability and the mechanical layout of the antenna's radiating structure. By doing this much physical insight is gained into why some antenna technologies can be expected to perform better than others.

Significant use has been made of both numerical simulation tools and anechoic chamber measurements of prototype hardware, and a post-processing environment has been developed to visualise the movement of the antenna's apparent phase centre with signal direction of arrival and frequency.

In the final analysis, usability and suitability as well as cost and production issues are real world factors that impinge on a practical solution, and the case is made for a new GNSS professional antenna.

INTRODUCTION

This paper describes an antenna development activity aimed at the professional user segment. The Galileo Joint Undertaking, Area 1B “Technological Development”, as one of its initiatives, has entered into contract for the development of advanced receiver technology for Galileo called “Advanced Receiver Terminal for User Services” (ARTUS). The ARTUS project, as a whole, addresses the development of technology for a complete receiver system for Galileo. However, this paper concerns the antenna.

A professional antenna, in the current context, is one that exhibits geodetic grade performance, which is itself described in more detail in the next section. This is not the sort of antenna that would be suitable to the low-cost mass-market part of the industry.

A key decision, from a technology and design criterion, is whether a ‘multi-band’ antenna technology can cover all the carriers necessary in a modern GNSS, or whether a true ‘wide-band’ technology needs to be developed. A second layer in the decision is whether the mechanical and resultant electrical symmetry of the antenna is sufficient to provide the phase centre stability with direction of signal arrival necessary for geodetic grade performance.

These issues are addressed in the following sections and the relative merits of different technologies are discussed before a more detailed analysis of the down-selected candidate is presented.

PERFORMANCE REQUIREMENTS

The two main ARTUS requirements from the antenna view point are: that all the Galileo and GPS carriers should be catered for; and secondly, the antenna needs a very stable phase centre at all the carrier frequencies.

To fulfill the first of these requirements, the necessary bandwidth is prohibitively large, or at least difficult to achieve, for some antenna types, including the Patch commonly used for GPS. In fact, at the outset of the work it was unclear as to whether a multi-band approach could meet the requirement, or whether a true broadband design would be necessary.

The geodetic requirement is arguably more difficult to meet than the bandwidth requirement. The current generation of geodetic grade receivers are able to correct for phase centre movement with elevation, by *a priori* knowledge of the antenna’s characteristics. However, it is not usual for azimuthal variation to be corrected, hence the azimuthal variation must be sufficiently low that calibration is unnecessary. A target value for this azimuthal variation is directly related to the positioning accuracy required of the system as a whole.

A summary of the ARTUS performance requirements is given below:

- Azimuthal Phase Centre Variation (PCV) to be less than 5mm at any elevation above ten degrees above horizon. Below ten degrees it is difficult to keep the PCV small due to the relatively rapid roll-off in gain at low elevation angles which tend to magnify the mechanical asymmetry effects.
- Elevation PCV to be less than 20mm from 10° above horizon to zenith.
- Bandwidth is required to be a little wider than the signal bandwidth in order to ensure gain flatness at the band edges, and to prevent PCV becoming an issue. Typically, 1100 – 1600 MHz is required.
- Gain should be greater than 3dBic at zenith, rolling off by less than 15dB at 10° above the horizon.
- Gain below the horizon should be as low as possible, and at least 10dB lower than zenith (front-to-back), as this would risk allowing reception of multipath signals.
- Physical parameters of size and weight should be compatible with a man-portable system.
- The overall design should be suitable for production and maintenance free.

IMPLICATIONS OF THE PHASE CENTRE STABILITY REQUIREMENT

The phase centre can be thought of as the apparent point from which radio waves emanate, in the case of a transmitting antenna. This point is often located near to or inside the antenna’s structure but can sometimes be some distance away. A stable phase centre is one that does not move significantly with frequency or, particularly, angle of arrival.

Waves emanating from a point source have spherical phase fronts. In the far-field, the phase relationship between source and measured signal will remain constant as the antenna is rotated around its phase centre. Thus the far-field phase pattern contains a combination of the various effects of phase centre displacement relative to the centre of rotation of the antenna. In reality, no realisable antenna has a phase centre which is confined to a single point, but it is possible to design antennas which exhibit good stability over a limited range of frequencies or a certain portion of the radiation pattern.

Radiation pattern amplitude (gain) is related to phase in that a constant gain is usually necessary for constant phase [1]. Hence, for good stability, a geodetic Galileo antenna must have a smooth, preferably constant gain pattern over 360° in azimuth and almost 90° in elevation.

REVIEW OF CANDIDATE ANTENNA TECHNOLOGIES

This section reviews antenna technologies that have sufficiently broadband characteristics to meet the bandwidth requirement. There are three main groups under consideration: The spiral, the dipole/bow-tie turnstile and the crossed exponential flare or crossed Vivaldi. The judgments presented are based upon a combination of numerical simulation of basic structures and open literature data.

Turnstile Antennas

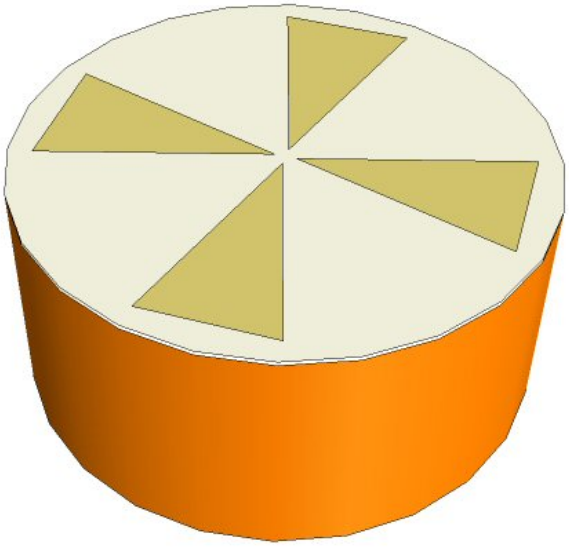

Figure 1. Arrangement of conductors comprising a crossed-bowtie Turnstile antenna

A Turnstile antenna, in its simplest form, is shown in Figure 1. Wideband performance, necessary for Galileo operation, is achievable through the use of wideband elements such as a bow-tie dipole. This design requires a cavity backing to give hemispherical coverage, potentially introducing a narrow band constraint (the cavity should be $\lambda/4$ deep) which must be treated carefully.

Crossed Tapered-Slot Antennas

This class of antennas is capable of extremely wide band operation. The flare, or tapered slot, can be linear, exponential or a fractal combination of any of these [2].

The Vivaldi antenna is a subset of a group of planar, ‘tapered-slot’ or ‘notch’ antennas. In particular, the flare geometry of a Vivaldi is defined as exponential (as opposed to linear tapered slot antennas, and other curved-flare variants). A typical Vivaldi element (in this case a stripline-fed antipodal design) is illustrated in Figure 2.

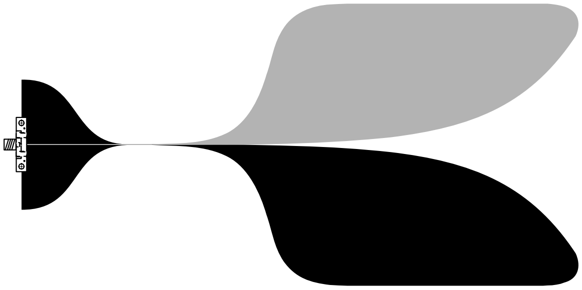

Figure 2. Typical Vivaldi element construction - the grey and black regions indicate different layers in a PCB structure

Circular polarization is achieved using a crossed pair of elements. In order to maintain rotational symmetry, the two orthogonal elements must be co-axial which leads to a complicated mechanical arrangement of feed structures so that they do not interfere with each other. The patented technique which Roke has developed [3] involves bending the triplate transmission line section of one element away from the centreline whilst within the slot region of the other element. A photograph is shown in Figure 3. The technique has been shown experimentally to work well, with many tens of decibels isolation between the elements.

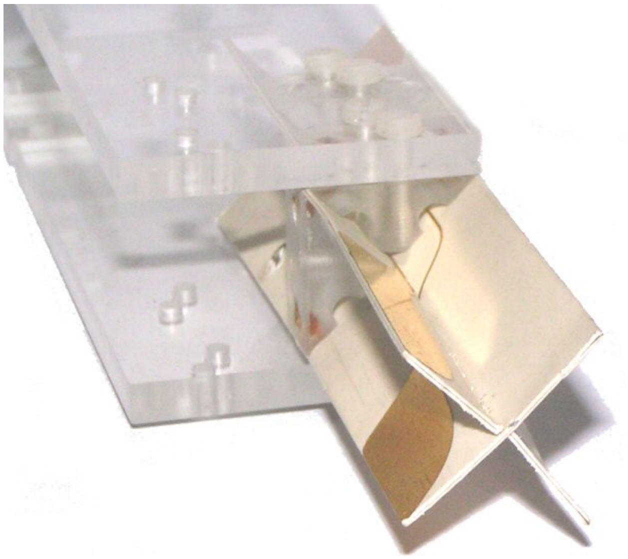

Figure 3. Two 'crossed' Vivaldi elements

Spiral Antennas

The spiral antenna is essentially frequency independent; a broadband antenna. If the antenna’s dimensions extended infinitely the antenna would exhibit no lower frequency limit. A practical antenna will exhibit low frequency cut-off, but above the cut-off frequency the radiation pattern and impedance characteristics are relatively independent of frequency.

Spiral antennas can be realised on a flat surface forming a Planar Spiral antenna, as shown in Figure 8, or alternatively on a conical surface forming a Conical Spiral antenna as shown in Figure 4. The Conical Spiral antenna produces single-lobe radiation, with the maximum along the axis of the cone. The Planar Spiral produces double-lobe radiation, i.e. one lobe is towards the ground making it unsuitable for GNSS applications without a ground plane placed behind to form a cavity backing.

Figure 4. A Conical Spiral antenna

Axial ratio performance of a spiral is strongly influenced by its azimuth (rotational) symmetry. Rotational symmetry is dependent upon the number of spirals and the number of turns on the spirals. For example, preliminary simulations of spirals with two arms showed only 3dB axial ratio which worsens considerably at low elevation angles. A similar spiral with four arms (fed in quadrature like a quad-helix antenna) quite easily achieves almost 0dB axial ratio on boresight, thus it can be assumed that a spiral needs at least four arms to produce good CP. Of course, this complicates the feed arrangement somewhat.

Conclusion

Whilst all three antenna classes are expected to be capable of meeting the ARTUS bandwidth requirements, early radiation pattern simulations of typical designs suggested that it would be easier to meet the PCV target with a spiral type design. From the point of view of size and manufacturing complexity, this choice was then reduced to the cavity-backed Planar Spiral, as opposed to the Conical Spiral.

THE SPIRAL ANTENNA

The Spiral can be thought of as a travelling-wave antenna: currents in neighbouring turns which flow in the same direction add in phase and tend to radiate, whereas those currents which oppose each other tend to cancel in the far-field. The pattern of areas of co-phased currents depends on the exact phase of each conductor at its feed and determines the far-field radiation pattern [4]. For any *N*-conductor spiral, there are *N*-1 distinct ‘modes’ (current distribution patterns) and, unless the phasing of the feeds is perfect, the spiral typically radiates in one or more modes simultaneously. Mode 1, for example, is excited when the phase of each feed advances by 90° in the direction of the spiral and (in the presence of a cavity backing) produces a single broad beam. The ‘active’ region of the spiral where the currents are in phase takes the form of an annular ring with a circumference equal to the wavelength. Thus, the outer diameter of the antenna places a limit on the lowest frequency of operation. The size of the feed structure, on the other hand, dictates the upper frequency bound.

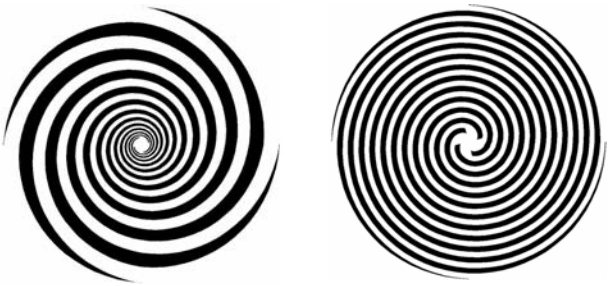

Figure 5. Examples of Equi-angle (left) and Archimedean (right) self-complementary spirals.

A common spiral design employed for wideband applications is the Equi-angle Spiral – so named because the relative angles and proportions of the conductors are maintained at all radii, i.e. regardless of frequency (which is the key to its broad bandwidth). The equation for the equi-angle spiral function, in cylindrical coordinates, is given by

$$r = r_0 e^{a\phi}$$

where r_0 is the radius for $\phi = 0$ and the constant a determines the flare rate [5]. The same curve, rotated, defines both edges of each conductor. When the pattern of conductors is the same as the pattern of spaces between conductors, the design is said to be *self-complementary*. Such designs tend to be frequency independent and offer the best bandwidths. However, the requirement to preserve angles results in very wide conductors towards the outer edge of the spiral; its circular nature is progressively dominated by a strong four-fold symmetry.

A better alternative, for this application, is the Archimedean Spiral, defined by

$$r = r_0\phi$$

This design does not suffer the same problem of loss of circular symmetry (as long as there are sufficient turns) since the flare rate is effectively linear [6]. Bandwidth is generally not as good as for the equi-angle spiral, but is sufficient for this application.

A common problem, especially for spirals working near the lower frequency cut-off, is that of how best to terminate the ends of the conductors. Reflections from unterminated ends propagate backwards around the spiral, effectively exciting an alternative mode (called Mode 3 in the particular case of a four-arm, Mode 1 design) which degrades the wanted-mode performance.

SIMULATION ENVIRONMENT

Computer simulation was a key part of the design process, particularly in the early stages, in order to develop insight into the effects of the many design parameters without the need for time-consuming and costly prototypes.

It had been hoped to use Ansoft HFSS v10.1 primarily, especially to model the more subtle effects of the radome and other dielectrics. However, it soon became apparent that the spiral shape necessarily required a complex mesh of many hundreds of thousands of tetrahedra owing to its curved nature and dense packing of conductive and non-conductive regions. The available computing resource was not sufficient to simulate the entire model, though some progress was made using the ‘low order solution’ option requiring only four parameters per tetrahedron rather than the usual twelve. HFSS also proved invaluable in the design of the feed structure.

The wire-like nature of the spiral inspired the use of NEC-2D instead for simulation (Figure 6). A key difficulty was found in generating the model, and meshing it, since no CAD front-end was available. A program written in MATLAB was used to generate directly the NEC files based on parameters such as the number of turns, the inner and outer radii and the size and depth of the cavity backing. The meshing problem was avoided by ensuring an unnecessarily dense mesh of $\lambda/10$ or smaller. In later stages of the development, the NEC simulation results were confirmed by measurement to gain confidence in the models used.

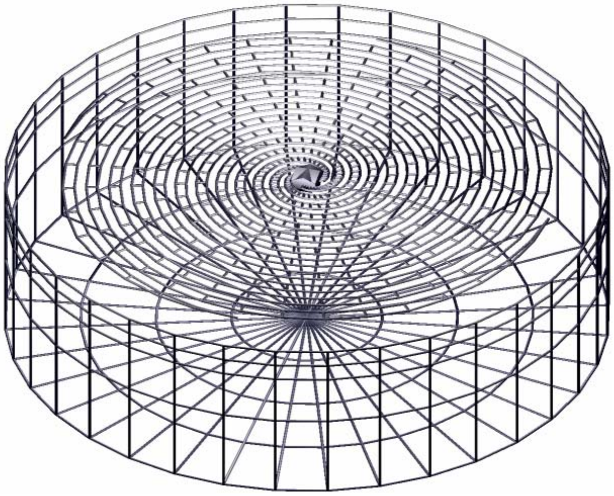

Figure 6. A visualisation of a typical NEC model

The simulations were primarily used to predict antenna impedance, radiation pattern, cavity backing effects and spiral arm termination effects, though the lack of any dielectric modeling capability meant that the results could only be used as a guide to performance.

A modified version of the same MATLAB program was also developed to generate Gerber data artwork files necessary for the production of the printed circuit spiral prototypes.

AWR Microwave Office was used to simulate the phase-forming network, impedance matching and spiral arm termination effects.

MEASUREMENT AND POST-PROCESSING

Radiation pattern and phase centre measurements were made in an anechoic chamber at the Roke site. The chamber itself is 7.3 x 3.7 x 3.7 metres, and suitable for measurements between 500MHz and 18GHz. It is equipped with a dual-polarisation quad-ridged horn, a Rohde and Schwarz ZVRE network analyser and a two-axis positioning system. A PC-based control system allows fully automated measurements. Angular accuracy of the positioners is very good (better than 0.2°) but the overall mechanical tolerance is quite poor, since the chamber was not designed for such high precision measurements. Alignment repeatability was improved by the use of lasers during setup: absolute positioning accuracy is estimated at +/- 2mm.

The antenna under test is mounted with its axis (normally directed upwards) oriented with the chamber centre line, and with the centre of the spiral at the centre of rotation (Figure 7). Rotations with azimuth and elevation are then achieved by moving the phi and theta positioners respectively.

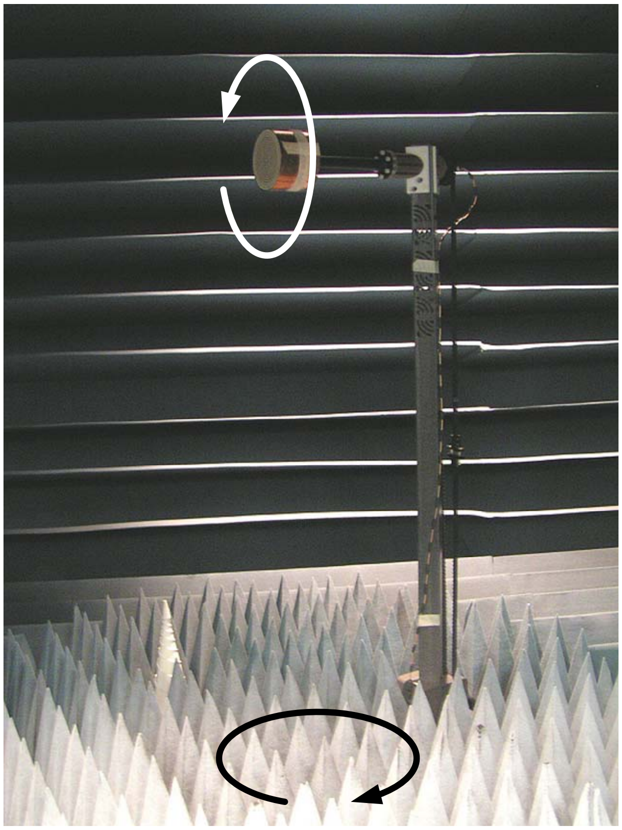

Figure 7. A view inside the anechoic chamber showing the axes of rotation

Raw measurement data, in vector form and for each polarisation – horizontal (H) and vertical (V) – is imported into MATLAB for post-processing using proprietary codes. Post-processing involves correcting for magnitude errors, using correction data from a reference antenna substitution measurement, and estimating the phase difference between the H and V channels by inspection of the data. The corrected data can then be analysed numerically to derive gain (both left-hand and right-hand circularly polarised), radiation pattern, axial ratio, phase pattern and the approximate location of the phase centre.

DEVELOPMENT AND RESULTS

Figure 8 illustrates the chosen design: a four-arm cavity-backed planar spiral. It measures 125mm in diameter and has a cavity 55mm deep. The spiral itself, approximately Archimedean in nature, is only 105mm across (approx. 1.2 wavelengths in circumference at the lowest frequency) but good operation down to 1.1GHz has been proven experimentally. Sufficient circular symmetry is obtained by approximately three turns per conductor, resulting in an axial ratio of less than 3dB over 120° of the beam and a RH-to-LHCP isolation ratio of some 30dB at zenith.

Figure 8. A photograph of the antenna

The bottom surface of the cavity is made from a second printed circuit board which also contains the phase forming network, interference rejection filters, a Low-Noise Amplifier (LNA) and power supply circuitry. The phase forming network comprises a 90° hybrid and two baluns, using commercially-available components in chip form. The balun phase imbalance is approximately 4° across the frequency band of interest, and this error is compensated by including a short delay line at one of the outputs. The result is a noticably straighter and more symmetrical beam pattern, and correspondingly lower azimuthal PCV. In fact, the mechanical symmetry of the antenna is to such a high degree that the dominating factor in the remaining phase centre variation is due to phase imbalance in the feed network [6].

At the end of each spiral arm is a short length of narrow line, wound more tightly than before, and terminated in an open circuit. As anticipated, the open circuit causes a reflection which has the effect of markedly changing the input impedance at frequencies which correspond to resonant lengths of the arm. The azimuthal PCV is also shown to be worse at these frequencies, but it is unclear whether this is a fundamental effect of the antenna or, more likely, the result of the impedance mismatch upsetting the hybrid and baluns. Various attempts to load the line with matched resistances led to poor axial ratio and PCV. Because of this, and for efficiency and complexity reasons, it was decided not to include any lossy components, coatings or layers. The resonance effect was mitigated instead by carefully designing the arm length such that the frequencies of interest do not coincide with those frequencies for which phase centre stability is poor.

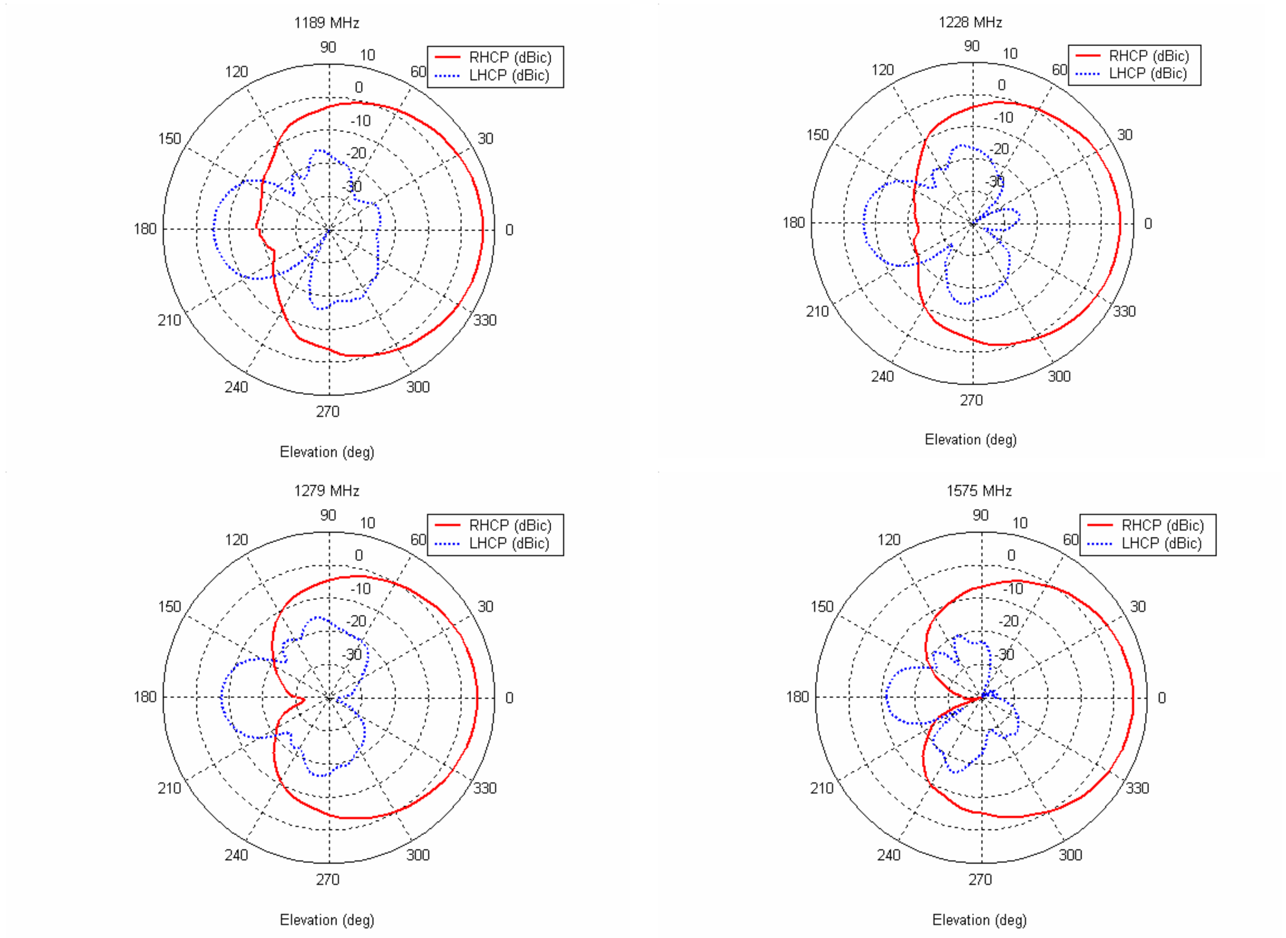

Figure 9. Plots showing antenna gain (elevation cut) for four different frequencies

Figure 9 shows the measured right-hand and left-hand CP gain for each of the four carriers listed in Table 1. The graphs in Figure 10 indicate an approximate measure of the PCV relative to a nominal reference point between 7 and 10mm below the spiral (actually inside the cavity). Alignment and position errors in the anechoic chamber setup prevent more accurate estimates to be made.

Table 1. Carriers supported by the antenna

Frequency (MHz)	*Band*	*GNSS*
1189	E5a&b	Galileo and GPS
1228	L2	GPS
1279	E6	Galileo
1575	E1-L1-E2	Galileo and GPS

FURTHER WORK

The antenna described in this publication has been shown to exhibit a highly stable phase centre over a frequency range sufficient to cover the Galileo and GPS bands. In order for this design to be suited to a wider range of practical applications, some attention must be paid to its multipath rejection characteristics. Multipath is one of the largest sources of error in GPS and Galileo. Most geodetic-grade GPS antennas are designed to operate against a large ground plane, often incorporating choke rings, to cut-off multipath from below a particular angle – usually just above the horizon. Futher work is planned to determine the necessary size and type of such a ground plane, and possibly investigate the use of Electromagnetic Band-Gap (EBG) surfaces and substrates as an alternative.

The measurement of phase centre variation (PCV) in our anechoic chamber has proved to be very difficult, most notably because of problems of positioning accuracy. Ideally, a stronger, less flexible positioner assembly should be constructed for future measurements, but this is a considerable task in itself. Instead, it is the intention of the authors to analyse the sources of mechanical error in more detail and develop techniques for measuring and correcting these errors during data post-processing.

At the time of writing, a full environmental enclosure has been designed but not tested. Prototype radomes of appropriate materials have, however, been tested and shown to exhibit almost no influence when placed more than about 10mm in front of the spiral. Thus, in the

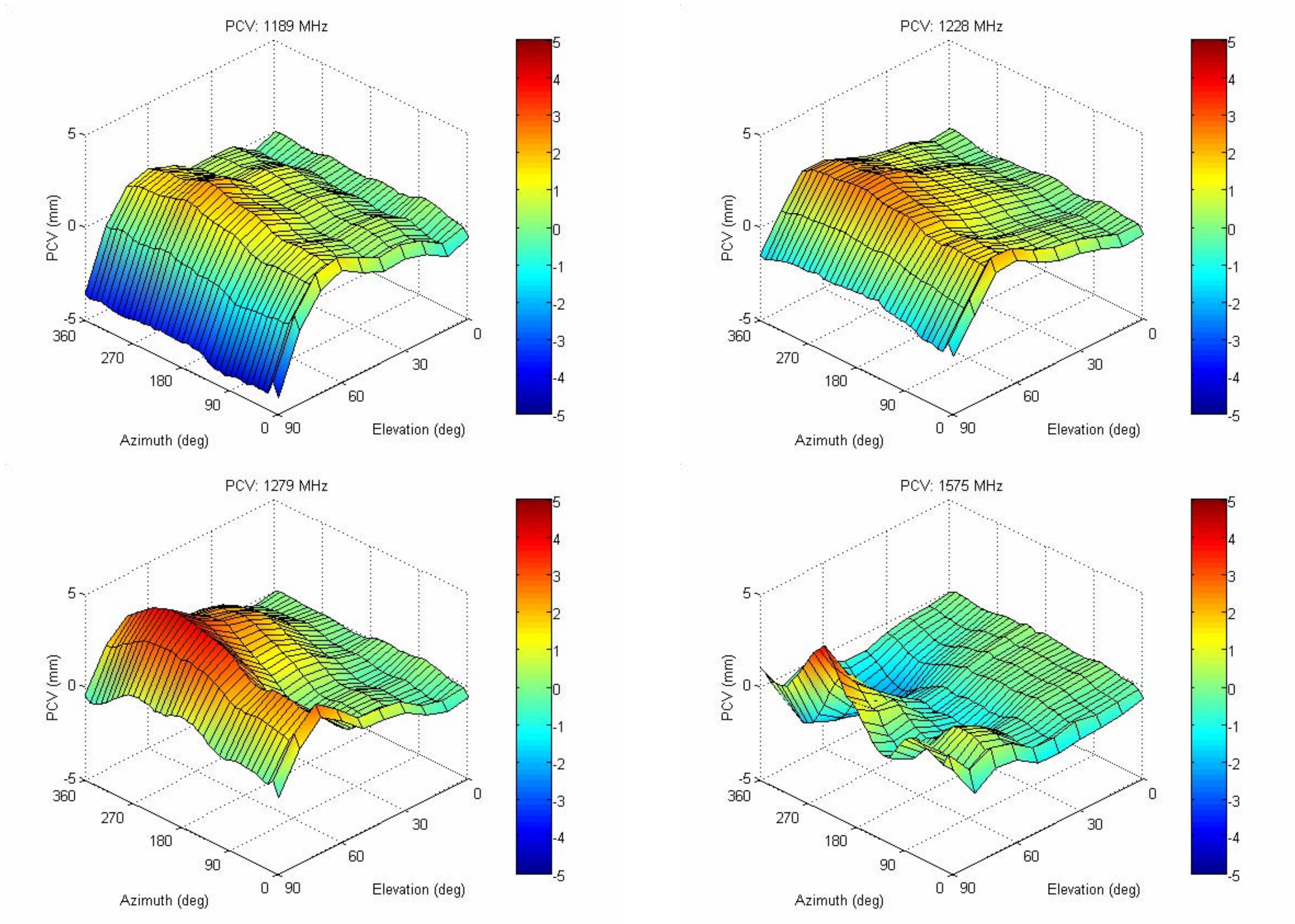

Figure 10. Plots showing PCV *versus* Angle of Arrival for four different frequencies

immediate future, it is planned to construct a complete, environmentally-sealed version for evaluation.

ACKNOWLEDGMENTS

The authors acknowledge the support of The Galileo Joint Undertaking, Area 1B “Technological Development” who, as one of their initiatives, has entered into contract for the development of advanced receiver technology for Galileo called “Advanced Receiver Terminal for User Services” (ARTUS).

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