The use of dielectric materials to enable electrically small antennas

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This paper provides an overview of antenna radiation physics and introduces Helix Geospace's dielectric-based approach for achieving high-performance electrically small antennas.

Emphasises the need for electrical isolation autonomous radiation, and highlights the significant advantages in modern wireless devices and GNSS positioning systems, crucial for predictable control of antenna arrays and spatial multiplexing in wireless communications.

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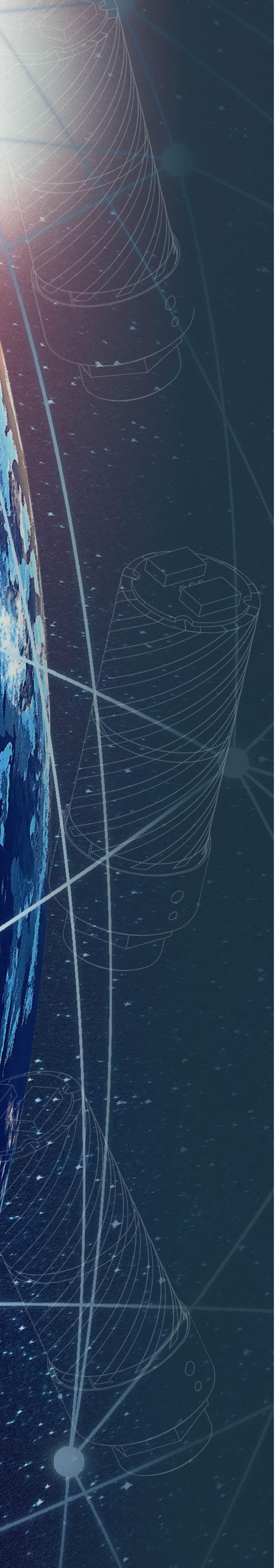


Abstract

The paper reviews the physics of antenna radiation: the displacement via solenoid fields from resonance fields that are induced by the antenna. The use of highly efficient dielectric materials to reduce the volume occupied, and outreach of, the dense resonance fields is described as the method that Helix Geospace uses to harness materials technology, to modify the natural free-space field operation in a manner that realises high-performance electrically small antennas. Some example antennas are described with respect to size, multiple frequency operation, and gain times bandwidth characteristics. The presentation shall emphasise that the pure form of electrically small antenna requires electrical isolation from the device platform so that the electrically small antenna radiates autonomously. Finally, the presentation shall set out some important system advantages that can be delivered by electrically small antennas in modern mobile wireless devices and GNSS positioning systems. The antenna radiating volume must be small compared the separation distance is critically important to the predictable control of arrays of antennas and therefore key to the development of spatial multiplexing as a mean of providing higher information density capabilities in wireless communications.

Point Source Antennas in Ideal Wireless Systems

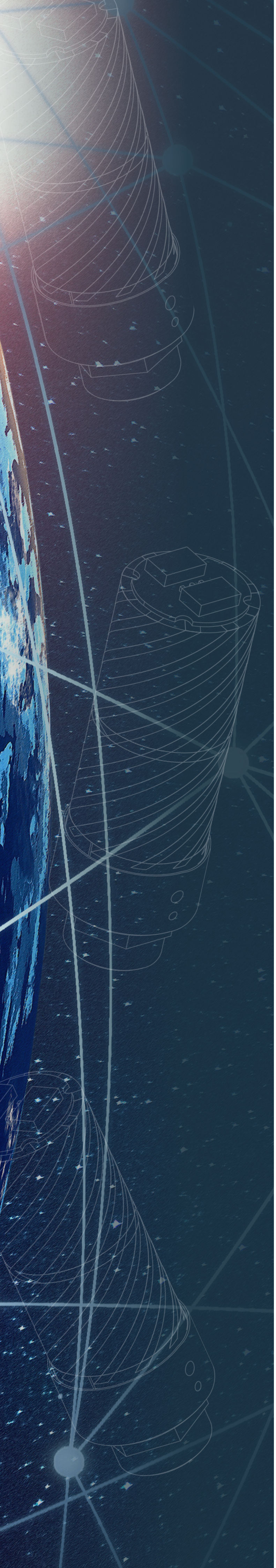
In an imaginary world, antennas could be made infinitesimally small, yet with operating as efficient radiators and manufactured so that each is identical to the other. It is interesting to consider the benefits of such antennas operating at frequencies where the wireless signal carrier wavelengths are comparable to the dimensions of the wireless terminal device. This exercise can provide a useful physical simplification which enables the performance characteristics of modern wireless systems that are built with ideal point source antennas.

The use of point source antennas removes the constraints of antennas dimensions. This enables the wireless terminal to be made much smaller than the signal carrier wavelength.

Wireless systems are developing to employ smart-antenna systems which exploit the space-domain to invoke higher power efficiency, faster data-rates and resilience against in-band interference. Space-domain smart-antenna systems can focus beams to concentrate signal-power in the link-path, or extract more information when information is distributed in space and prevent in-band interference from disrupting vital infrastructure or safety critical navigation systems.

The performance of spatial-domain wireless systems depends on the degree to which the antenna array can be predictably controlled. An ideal array of point-source antennas may be proposed as one in which each antenna does not pass signals to adjacent antennas in the array. The composite radiation pattern of such an array is then a linear superposition of the vector fields of the individual antennas in the array [2].

Conversely the statistical properties of the ensemble of signals that are collected by the point source antennas would express the degree of statistical independence that reflects the spatial correlation of those point locations in receiver space. This distinctiveness



determines the sensitivity and information capacity of MIMO receivers that are designed to receive the highest possible information quantity per unit of spatial volume [3] [4].

Considering the Characteristics and Limitations of Real Antennas

The direct impact on the performance of modern spatial-domain wireless systems can be examined by considering the properties of a more realistic model of a small antenna. As this physical description delves into electromagnetic detail it may be helpful to start by mapping the essential features and confounding effects of these real antenna properties.

Conventional antennas are not electrically small [5]. To deliver bandwidth and efficiency they are often designed to radiate from the entire terminal envelope.

Construction of arrays with such antennas is of little practical value because electrically large antennas have dimensions which comparable to the separation distances that are required by smart-array solutions.

It is important to recognise that the radiating fields of an antenna are formed by the resonance fields in space surrounding the antenna by the currents and voltages present in the antenna circuit. These resonance fields extend beyond the antenna and have much higher energy density than the radiating fields. Particularly when antennas are electrically large and placed closely together, the density of these resonance fields greatly increase the degree of coupling above that which would occur if only radiating fields were present.

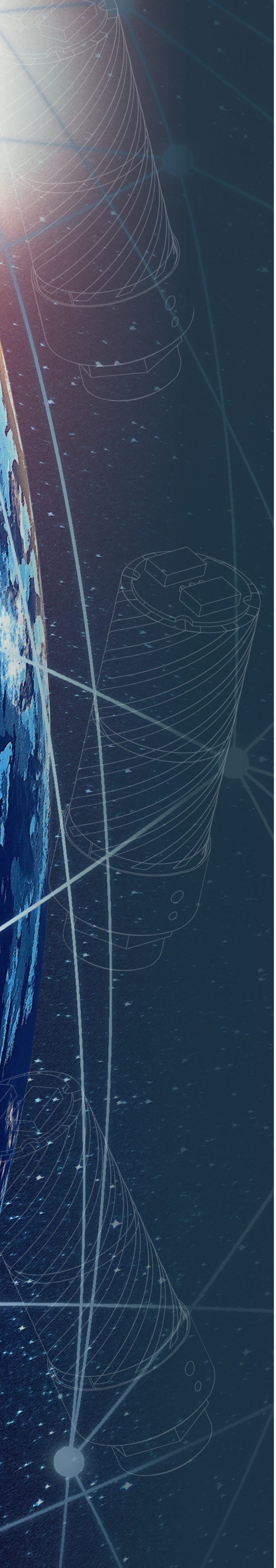
Coupled signal power is not contributing to the wireless link. It is simply dumped into the load of the adjacent antennas in the array.

Simplified Field-Analysis of an Antenna

Being passive devices, antennas obey the physical law of reciprocity. This implies that the same performance properties occur in either the transmitting or receiving directions. By convention antenna physics is described in the context of the transmitting direction: although many antennas are designed for receiving functions only.

When an antenna is stimulated by an electrical signal at the frequency of resonance, the resonance energy is mainly stored in electromagnetic fields in surrounding space. These moving magnetic and electric resonance fields are induced by currents and voltages respectively, that are present in the antenna network. From Faraday's, law the changing magnetic field through a surface induces a time-varying electric field at the boundary of that surface. In turn, a changing electric field creates a magnetic field (according to the Ampère's Law augmented to include changing electric fields). This is the process by which an electromagnetic wave is propagated away from an antenna.

The volume surrounding the antenna contains mainly resonance fields and at a distance further from the antenna it can be understood that wave propagation fields are radiating away from the antenna. The dispersal of radiation can be characterised by a pattern representing the energy densities at different directions from the antenna in comparison to a lossless radiation source that radiates energy equally in all directions.



Between the antenna and far-field where the propagating wave has formed there is a boundary that can be referred to as the near-field to far-field transition zone. The near-field region is a volume containing mostly electromagnetic energy that is stored in space and the far-field is in space beyond this region where most of the energy is far-field energy radiating away from the antenna. A thorough description of electromagnetic field distribution around an antenna can be found in [6].

For radio communications the far-field behaviour is key because this "connects" the signal from the transmitter to the receiver. Device designers try to optimise the far-field radiation pattern of the antenna to achieve the best radio-link performance for the wireless device. Far field performance is critically driven by the near field: a loss in near field energy will lead to a direct loss of far-field efficiency and therefore impair communications performance. The dense fields present in the near-field region determine that field interference in this region have particularly significant physical effects on the antenna performance and wireless channel.

The meaning and physical action of the near and far-field regions can be appreciated by considering the case of a very simple elemental (point dipole) antenna (see figure 1). The analysis is couched in a polar co-ordinate system so that the angle f denotes the angle concentric to the direction of the dipole and the angle q represents the angle around planes that are bisected by the direction of the dipole. The size of the antenna is small enough to permit the assumption that the angle from a point to one pole is not significantly different from that point to the other pole; such that both paths have angle q.

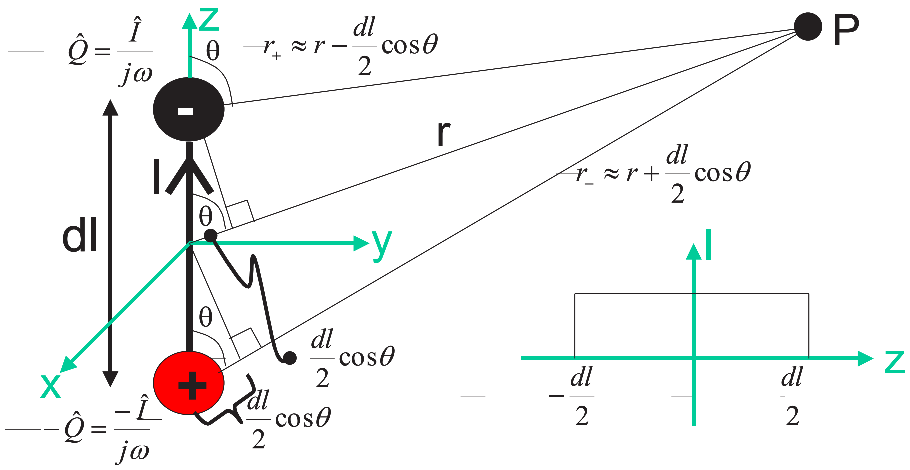
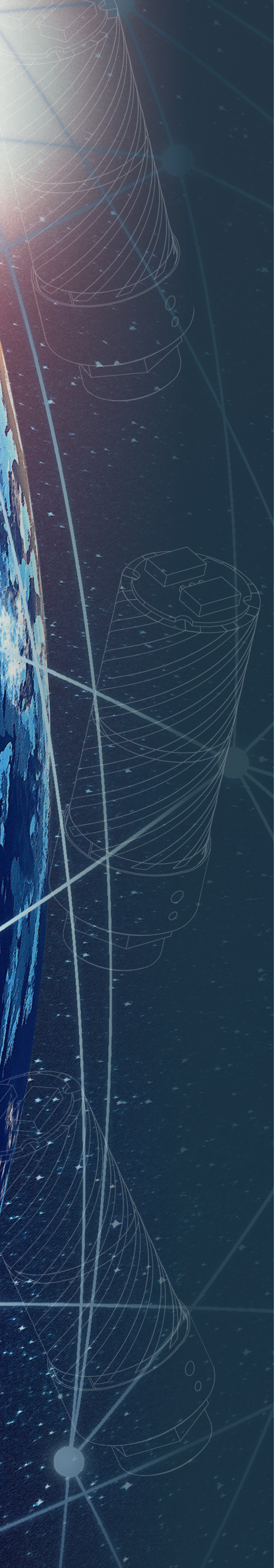


Figure 1: Fields around a point dipole.

According to Maxwell's laws the magnetic fields surrounding the point dipole can be calculated from the curl of the magnetic vector potential (Â) of the point dipole.

$$\widehat{\mathrm{H}} = \frac{1}{\mu}\nabla \times \widehat{\mathrm{A}} = = -\mathrm{i}_{\varphi}\frac{\hat{\mathrm{I}}\mathrm{dl}}{4\pi}\mathrm{k}^2 \sin\theta\left(\frac{1}{\mathrm{jkr}} + \frac{1}{(\mathrm{jkr})^2}\right)\mathrm{e}^{-\mathrm{jkr}} \qquad (1)$$



Similarly, the electric fields surrounding the point dipole can be calculated from the curl of the magnetic field.

$$\begin{aligned} \hat{E} &= \frac{1}{j\omega\varepsilon}\nabla\times\hat{H} = \qquad (2) \\ &= -\frac{\hat{I}dlk^2}{4\pi}\sqrt{\frac{\mu}{\varepsilon}}\{i_r\left\{\left[2\cos\theta\left(\frac{1}{(jkr)^2}+\frac{1}{(jkr)^3}\right)\right]\right. \\ &\quad \left. +i_\theta\left[\sin\theta\left(\frac{1}{jkr}+\frac{1}{(jkr)^2}+\frac{1}{(jkr)^3}\right)\right]\right\}e^{-jkr} \end{aligned}$$

From 1 and 2 the field structure of the point dipole can be represented in terms of a polynomial in $^1/_{jkr}$ where k is the wavenumber ($k = {}^{\omega}/_{c}$). It is interesting to examine the physical basis of these terms. In line with the right-hand rule for a z-directed current the magnetic field circulates concentrically around the dipole and is therefore oriented purely in the f direction. The term in $^1/_{(jkr)^2}$is called the induction field or near-field because it is the dominant constituent of magnetic field close to the antenna. The magnetic field term that is responsible for the radiation function of the antenna is that in $^1/_{jkr}$ which dominates at distances far ($kr\rangle\rangle1$) from the antenna. This term can be shown to be responsible for the time-average power-flow from the source.

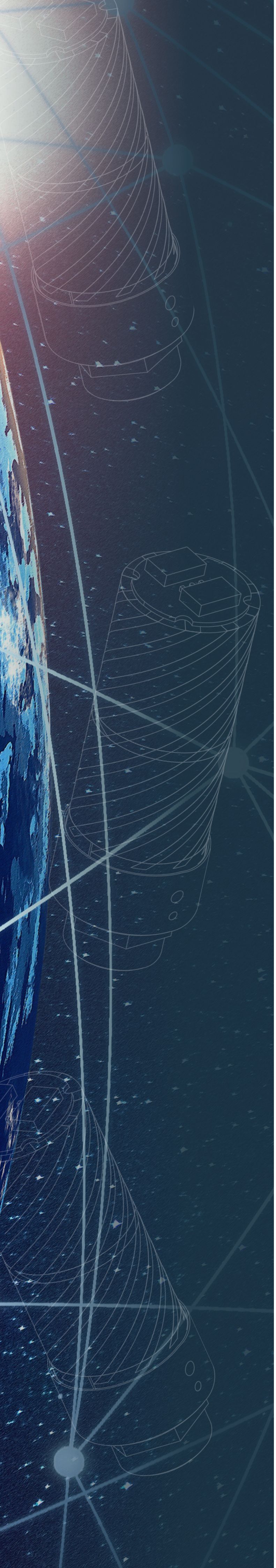
An examination of the electric field terms tells a similar story. The terms in $^1/_{(jkr)^3}$are electric dipole field terms which are often called the electrostatic solution because they are present at zero frequency. These together with the intermediate $^1/_{(jkr)^2}$ terms are dominant near the dipole and are near-field terms. For the function of the antenna the most important term is once again the $^1/_{jkr}$ field term in $i_\theta$which is a radiation field term and is the dominant constituent of electric field at a distance that is far from the antenna.

The near-field terms do not contribute directly to power-flow from the antenna. They can be visualised as stored energy in the magnetic and electric fields and therefore are often referred to as the reactance fields. Antennas are surrounded by dense electromagnetic fields associated with the resonance of the currents and voltages on the antenna. Further away from the antenna a radiation field predominates. These two regions are referred to the near field region where stored electromagnetic fields predominate, and the far-field where displacing radiation fields predominate.

The difficulty that conventional antenna physics presents for device designers is that the storage of electromagnetic energy is dependent on the properties of the materials that occupy the same volume as the near-field region. This is physically because the energy density (v) of an electric field is proportional to the dielectric constant: $e=e_oe_r$ (equation 3 below)

$$\varpi = \frac{1}{2}\varepsilon E^2 \qquad (3)$$

Thus, the near-field energy will transfer to any medium which has a higher propensity to store it than air (free-space). Unfortunately, human tissues typically store near-field energy approximately 40 (er»40) times more densely than free-space as blood rich



tissues are mainly composed of salty water. As mobile devices are often used in close proximity to humans this has the impact of draining the energy of the resonance-field into human tissues where it is dissipated as heat. This, in turn, leads to poor performance as energy has been lost from the radiation function of the antenna. For instance, a mobile telephone antenna design could readily be optimised to attain as much as 65% radiation efficiency in the absence of body loading. Unfortunately, the very same device is likely to achieve only 5% or less when it is used close to the body in the intended use scenario. [7] Though such impairments can be absorbed by deployment of robust cellular telephone infrastructure (many base-stations) there is no such opportunity with satellite-based systems which are constrained by power and cost. It is well known that use of such antennas which resonate with the housing of the product to make a dipole between the antenna and the housing (and are therefore termed single-ended antennas) are typically impaired by 5-15dB when hand-loading is present. The extent of the gain impairment is determined mostly by the size of the housing.

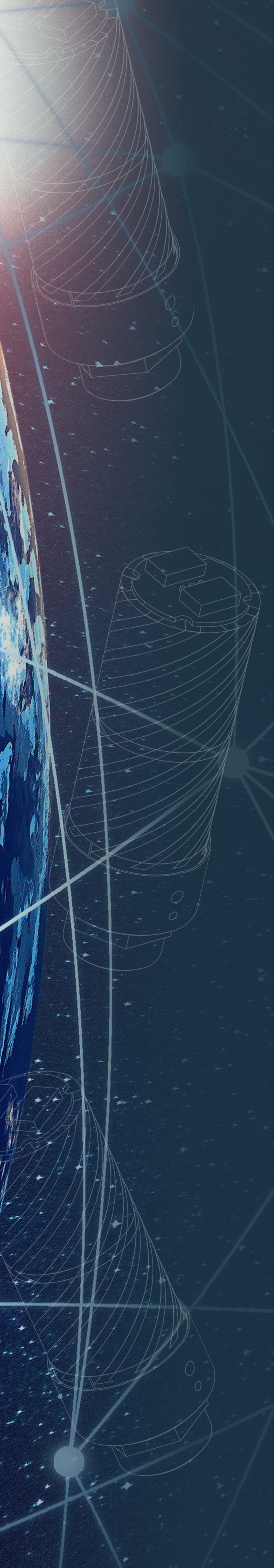
The high energy density of resonance fields is usefully applied to wireless payment products which require the user to transact payments by intentionally close coupling the handset to the vendor transaction terminal. However, as previously stated, for smart-antenna arrays such dense coupling of resonance-fields is highly undesirable. Conversely if the array-space contained only the radiating fields then, the management by superposition, to generate a desired array characteristic would of course be relatively simple and much more effective. In the next section, methods modifying the fields of the conventional antenna, using microwave materials to greatly reduce the outreach of resonance fields, shall be considered.

Modifying Fields to Implement an Electrically Antenna Using Low-loss Dielectric Materials.

Using microwave materials of appropriate electromagnetic properties, it is possible to engineer antenna solutions with electrically small size dimensions and with low resonance field outreach, whilst retaining the radiation efficiency of the unmodified antenna. There is a great diversity of structures employing dielectric [1] or magnetic materials, depending on the particular frequency of use, and the properties of available materials at that frequency. In this treatment a dielectric-loaded multi-filar helix antenna structure [8] [9] [10] [11] shall be described, and the system advantages it brings to space-domain antennas shall be illustrated, with some examples.

Helix Geospace has continued the development of dielectric-loaded multi-filar helix antennas which employ a dielectric-core to intensify resonance field energy density within the antenna element and conversely to reduce resonance energy density and outreach in surrounding space. These antennas are designed to radiate with circular polarisation and to be suitable for operation in modern spatial domain array applications.

The operation and performance of the Helix Geospace dielectric-loaded multifilar-helix antennas has been extensively reported (references). These antennas are printed as copper artwork patterns on the outer surface of a cylindrical dielectric core that has a relative dielectric constant of between 21<ε_r<110 so that the resonance electric fields are



held mainly within the dielectric medium. Embodiments have been produced with quadrifilar, hexafilar, octafilar and decafilar topologies. Generically the basic operation of this series of antenna topologies is illustrated in figure 2 below:

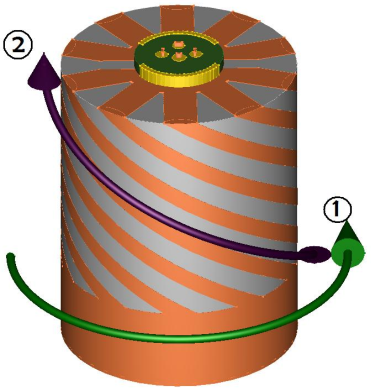


Figure 2: Basic operation of the Helix Geospace multi-filar antennas is a synthesised combination of two resonances. (1) Full guide-wavelength ring-resonance of the sleeve balun rim organised so that equal-amplitude phased currents are distributed to individual helices according to the mechanical angle of connection to the balun-rim. (2) Each individual helix resonates with a guide half-wavelength so that the ensemble of helices resonates in a phased sequence that commutate in manner that synthesises the spinning dipole that is required for circular polarisation.

The design of the antenna is such that the electric-field dipole is always loaded by the dielectric core as it is caused to spin about the cylindrical axis such that at any instant it straddles the instantaneous positions of opposing voltage maxima across the centre of the radiating section (see figure 3).

The antenna is back-fire fed by means of a feed-system that is shown in figure 3. In the longitudinal direction the antenna is structured as a juxtaposition of a sleeve-balun section with a multi-filar radiating section. The antenna is connected to the wireless device at the bottom but is nevertheless an end-fire topology with a co-axial feed cable passing through the axial centre of the core.

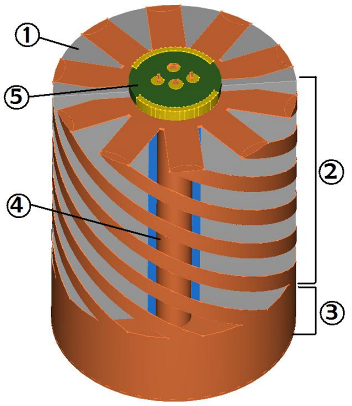
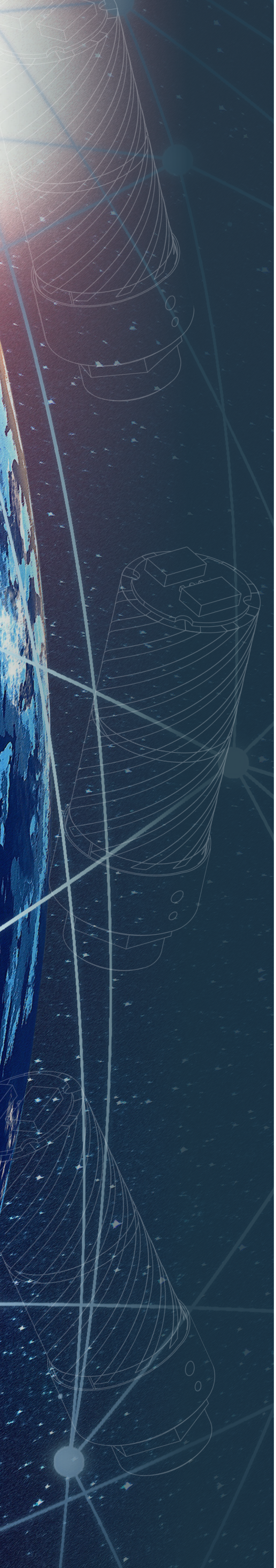


Figure 3: Feed structure of the generic Helix Geospace multi-filar antenna topologies. (1) Dielectric core (shown halved to reveal co-axial feed). (2) Radiating section comprising of a multiplicity of phased resonant helical tracks. (3) Sleeve balun section which projects balanced current feed at the top plane of the antenna and isolates the radiating section from the device housing. (4) 50W co-axial feed cable. (5) Reactive match tile to match antenna to 50Ω characteristic impedance.



The resonant operation of the antenna is illustrated, using simulated surface currents, in figure 4. The overall purpose of the dielectric loading scheme is to significantly reduce the resonant volume of the antenna with respect to the free-space equivalent and to provide an antenna whose resonance fields will not be preferentially stored in biological tissues. The use of a low-loss dielectric medium to store the resonance fields in a concentrated and managed way provides an antenna which operates predictably, with stable radiation patterns, in the presence of environmental clutter and bio-loading.

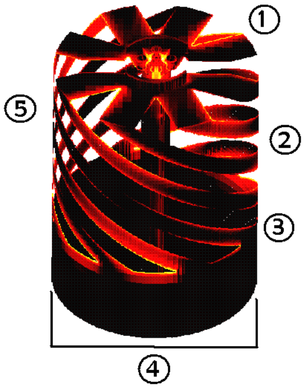


Figure 4: Resonance operation of an octafilar embodiment of the multi-filar antenna. (1) Balance feed point through 50Ω match transition at back-fire feed-plane. (2) Plane of spinning voltage maxima. (3) Rim of balun operating as a resonant ring supporting a continuous anti-clockwise flowing standing wave. This current path completes the loop between the balanced terminals of the feed-point. The functional purpose of the arrangement is to distribute equal-amplitude currents to the individual helices of the multi-filar radiating section. (4) The sleeve balun provides electromagnetic isolation between the radiating section and the device housing. (5) The currents are concentrated onto the edges of conductors due to striction of currents (by associated induced magnetic fields).

In summary this Helix Geospace format of antenna has addressed the need to be electrically small (dimensions <0.05-0.07λ) and to be electrically isolated from the platform. These antenna ideas have been adapted for multi-band operation and can more generally be engineered to implement complex frequency responses as may be required by modern wireless systems which may employ signal amalgamation over many channels to provide broad-band operation. In this context is it important to recognise frequency stability (due to low resonance-field interaction with the diverse near-environment use scenarios) as another crucial advantage of dielectric loading.

A GNSS Anti-jamming Array as an Example of a Spatial-Domain Application.

One important application for smart-antenna technology is that of eliminating interference from Global Navigation Satellite System (GNSS) signals that are used for transport positioning and telecommunications synchronisation. These critical infrastructure services must be maintained effective and resilient for the benefit of economic efficiency. However, as GNSS signals are transmitted from satellite spacecraft they have low power and therefore these critical services are vulnerable to malicious or accidental interference from terrestrial jammers. The function of a GNSS anti-jamming array is to provide excellent reception of GNSS signals, whilst projecting pattern nulls in the directions of the interference sources.

Helix Geospace has developed GNSS anti-jamming array solutions of various configurations. One simple example comprising of three full-wave decafilar-helix elements is illustrated in the photograph that is shown in figure 5. Following the principles that have been described, the elements are designed to constrain the outreach of resonance fields so that near-field coupling is not an important cause of intra-element coupling. The dielectric core also causes the dimensions of the antenna to be significantly reduced with respect to the free-space wavelength. Therefore, the radiating- fields passing between two neighbouring antennas in an array are small – approximately the ratio of the aperture of a second antenna to the area of a spherical surface centred on the first antenna and touching the centre of the second. For a system that relies on wave-interferences or angle of arrival measurement the separation between elements should nominally be a half carrier wavelength.

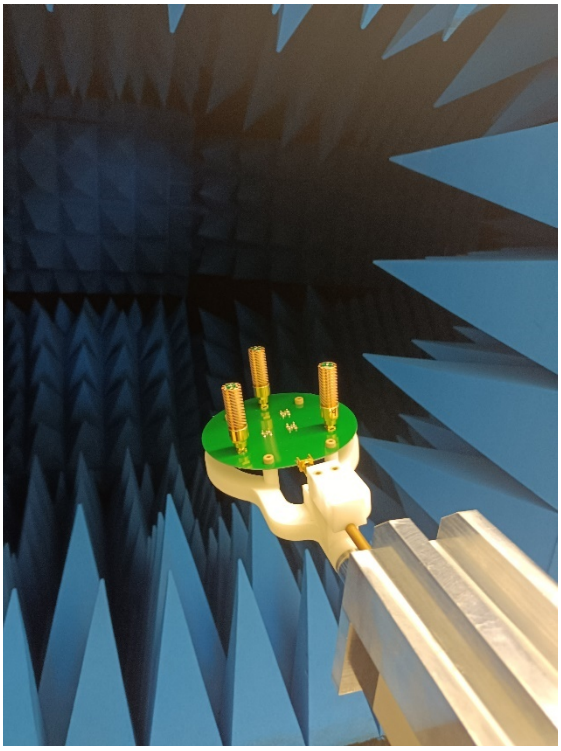
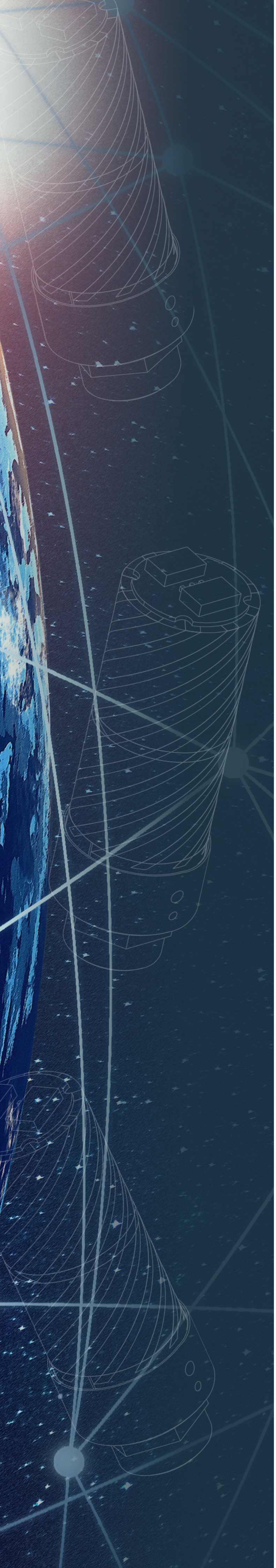


Figure 5: An example three-element GNSS anti-jamming array in an anechoic test-chamber.

The GNSS anti-jamming array passes a GNSS signal to the GNSS receiver as the combined output of the elements of the array. A control system seeking the minimum interference in this combined-output sets the phase delay of each signal from an antenna element to the combination point so that the combination of interference-signals sums to zero. Thus, the composite array pattern is managed to present a null only in the directions of arrival of interference sources and to combine constructively to generate high gain in the GNSS signal directions.

The optimum array-control method for GNSS anti-jamming arrays depends on the details of the use-case. In a static-system exemplified by that of a GNSS synchronised telecommunications clock node the pattern management may be managed by a slow-acting but refined algorithm. Conversely, a more dynamic system designed for the positioning of an autonomous vehicle positioning system operating within the complex propagation environment that is present at street level within the cityscape may need



much more rapid radiation-pattern adaptation. Whether the goal is to achieve the deepest pattern null in the direction of arrival of interference signals or alternatively to adapt the pattern most rapidly for lowest interference in dynamically changing use-scenarios the possible algorithm performance is ultimately limited by hardware characteristics.

The elimination of intra-antenna coupling enables effective, fast acting, deterministic management of antenna patterns using simple trigonometry. Helix Geospace have developed very advanced laser-lithography antenna patterning processes that enable the accurate manufacture of elements of identical characteristics so that the effective spatial processing can be undertaken without the need for array calibration. Figure 6 shows the interference power output for a Helix Geospace demonstrator array which shows how specific phase settings cause nulls of lowest interference power.

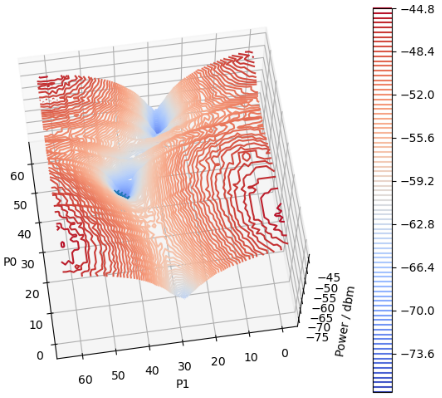


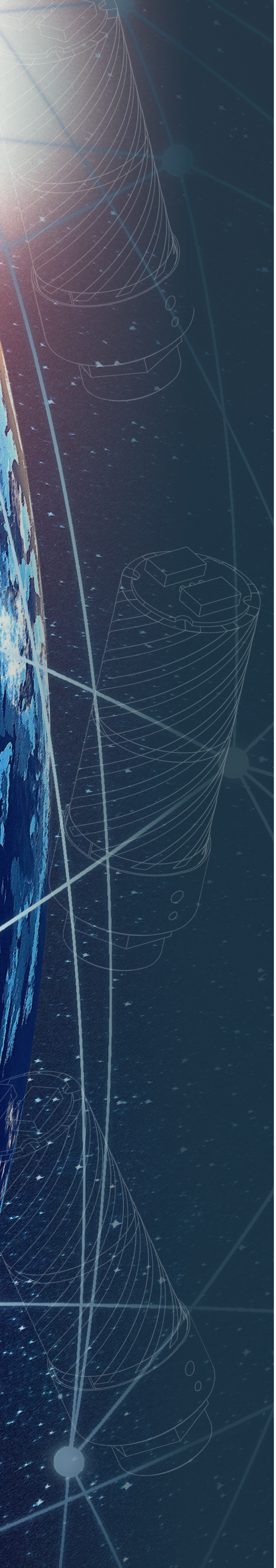
Figure 6: Graph of phase-shift settings and output power showing the effect of phase-shifter adaptation to generate deep interference nulls.

The destructive interference between sine-wave signals can only arise over narrow bandwidth. In common with many modern wireless architectures GNSS positioning systems invoke resilience by operating over multiple frequency bands. The sparce occupancy of array space by electrically small dielectric-loaded mutifilar antennas provides an opportunity to interleave sub-arrays of antennas operating at different frequencies to implement multi-frequency interference cancelling.

Some Thoughts About Spatial-Domain Antennas.

System bandwidth in smart antenna arrays is managed as a combination of spatial separation distance and antenna element bandwidth considerations. Often, the wave-interference effect that is required to effect the desired array response can only be achieved at a narrow spot-frequency bandwidth with a particular separation distance and phase-shift manifold solution. In such cases the provision of bandwidth must be organised as a series of sub-array solutions with bandwidth contributions summing to the required composite bandwidth.

At Helix Geospace insights gained from the development of GNSS antennas for precise navigation applications are applicable to smart antenna applications. Precision navigation requires antennas which provide a known and stable position for the focal point which serves as the measured point in the position solution. Many spatial-domain



antenna arrays require the constituent elements to possess identical focus characteristics which are sharply defined. In array solutions this focal point defines the antenna element position and the difference between points of foci of two antenna elements: the separation distance. The performance of the array solution may depend on the consistent sharpness of the antenna foci together with the resolution of the phase-shifting method.

Materials Science and Spatial-Domain Antennas.

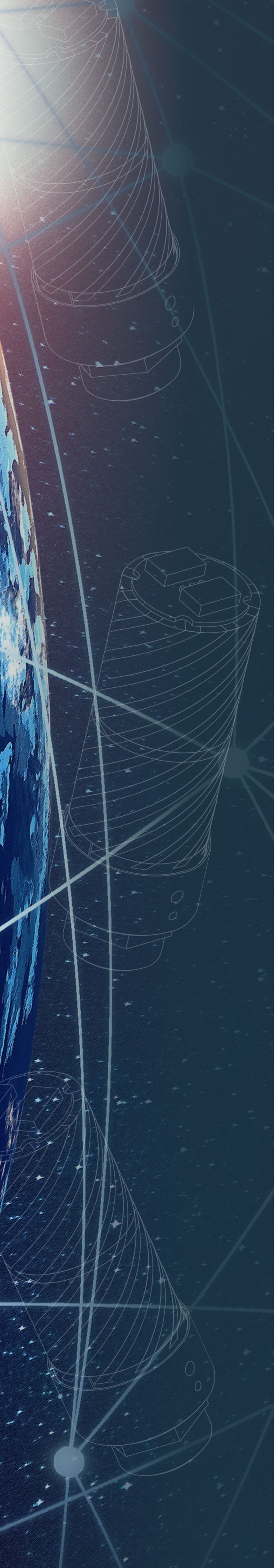
The resonator core of the multifilar-helix antennas has been produced using ceramic dielectric materials having very low losses, excellent temperature stability and medium relative permittivity (in the range $20 < \varepsilon_r < 100$). As previously reported in [12] the diverse properties of this class of materials facilitate a broad range of dielectric-loaded antenna solutions of various size and weight configurations as may be tailored for specific application requirements. A useful review paper [13] of material compositions that have been used as the dielectric material for resonators, including dielectric-loaded antennas contains the content of table 1.

Table 1: List of ceramic materials currently used in microwave resonator components.

Material	Abbrev'	ε_r	Qf_0 [GHz]
$BaMg_{1/2}Ta_{2/3}O_3$	BMT	24	250,000
$BaZn_{1/3}Ta_{2/3}O_3$	BZT	29	150,000
$Ba(CoZn)_{1/3}Nb_{2/3}O_3$	BCZN	34	90,000
$SrTiO_3$-$LaAlO_3$	STLA	39	60,000
$CaTiO_3$-$NdAlO_3$	CTNA	45	48,000
$ZrTiO_3$-$ZnNb_2O_6$	ZTZN	44	48,000
$Ba_4Nd_{9.333}Ti_{18}O_{54}$	BNT	80	10,000

Clearly, the ceramic materials that are listed in table 1 possess remarkably low dielectric losses (high Q-factors). It follows that dielectric-loaded multi-filar antennas can be made with high radiation efficiency (>70%) but the realisable performance depends on the interplay between several factors. To understand these physical relationships, it is instructive to consider a particular multi-filar antenna topology (e.g., half-wave decafilar as shown in figure 3) and to scale as loaded by different dielectric materials so that the resulting dielectric-loaded antennas operate at the same frequency. In this experiment the radiating volume is then controlled by the relative permittivity of the material used to implement the dielectric core of the antenna.

As has been mentioned before the energy density (v) of an electric field that is created by an electric field strength E is proportional to the dielectric constant: $e=e_o e_r$ (equation 3). The combination of increased energy density due to increased relative permittivity (ε_r) and increased dielectric losses also due to higher relative permittivity cause the dielectric losses to become more important as the size of the antenna is decreased by means of dielectric loading.



Copper-loss is also an important cause of performance impairment in dielectric-loaded multi-filar antennas, and this is also governed by the electrical size of the antenna. The dipole length (dl) of the dielectric-loaded multi-filar antenna is the diameter of the dielectric-cylinder that the artwork is printed on because the structure synthesises a spinning dipole. The dipole length of the multi-filar helix antenna is short with respect to the free-space wavelength it follows that the radiation resistance, R_{rad}, of the antenna can be estimated from a formula (4) that is readily derived from the concept of the point dipole:

$$R_{rad} = 80\pi^2 \left(\frac{dl}{\lambda}\right)^2 \qquad (4)$$

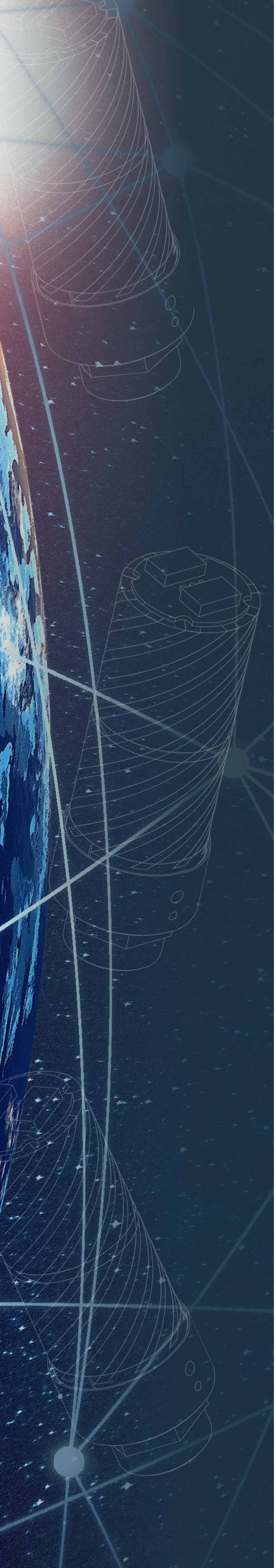
where dl is the length of the dipole and l is the free-space wavelength at the operating frequency.

From equation 4 the antenna radiation resistance drops rapidly as dielectric loading reduces the dipole length. For a particular antenna size, it is necessary to configure an impedance matching circuit to attain maximum power transfer to the antenna radiation resistance (Rrad). However, from Ohms law, the lower radiation resistance of the smaller antenna reduces the electric-field potential and increases the magnetic-field that is present. The peak of the voltage standing wave is reduced and the peak of the current standing wave is increased. This current increase with reducing size of the antenna has the effect of heightening the importance of resistive losses in the metal conductor pattern. If resistive loss, caused by an equivalent dissipation resistor R_{dis}, was the only cause of efficiency impairment then the efficiency (η) of that antenna is given by:

$$\eta = \frac{R_{rad}}{R_{rad}+R_{dis}} \qquad (5)$$

At high RF frequencies magnetostriction causes currents to be distributed most densely on the surfaces and edges of the antenna metallisation pattern. This current concentration at conductor edges constrains the scope for efficiency improvements by increasing the conductor cross-section because the interior portions of those conductors cannot carry large currents. A more effective approach to improve conductor efficiency is to increase the surface area of the metallisation pattern using a multi-layer metallisation scheme. One implementation method is described in [14]. This implemented a metal, insulator, metal multilayer stack using polyether ether ketone (PEEK) insulating layers which were deposited from aqueous colloid using electrophoretic deposition followed by heating.

Seeking to overcome the manufacturing challenges of forming accurately dimensioned ceramic parts, an alternative dielectric loaded technology: that of ceramic-loaded glass has been investigated [1], [15]. Glass-ceramic materials that have been reported are not as efficient ($Q_o f$: ceramic =45,000, $Q_o f$: glass-ceramic =10,000) but for antenna designs for which conductor losses are the main determinant of radiation efficiency it



has been demonstrated that antennas of comparable performance can be made in the same size (as from an equivalent ceramic-realised antenna).

Glass-ceramic material technology promises to provide some interesting opportunities to improve the mass-producibility of the dielectric-loaded multi-filar helix antennas. Following precise heat-treatment procedures ceramic-loaded glass can be processed to undergo ceramization to form quite attractive homogenous material properties in the cast-formed part. Ceramization is a controlled crystallisation of the desired paraelectric phases of the additive materials inside the glass. These materials have the advantage that they are intrinsically pore-free, and it is possible that they may offer the opportunity to provide the crystalline texture/relief that is required ensure secure metal adhesion. Differential rates of etching between intrinsic glass and crystals may provide a pathway to manage the surface texture without the need for surface machining.

Conclusions

This description of antenna physics expresses a universal truth applying to all smart antenna arrays operating at all wireless frequencies. The performance and controllability of arrays requires the antenna elements to be small relative to the separation distance. In this regard the meaning of electrically small refers to the region enclosing the resonance fields which stimulate radiation. This definition excludes the use of single-ended resonance because the resonance fields in such a system would encompass the housing. Rather it is necessary to constrain the outreach of fields by isolating the antenna from the housing which requires the antenna to be balanced. Microwave materials offer means of managing the outreach of resonance fields to deliver electrically small radiation sources from small but efficient antennas.

The useable frequency spectrum is finite, and it is therefore certain that wireless technologies will develop to exploit the spatial domain to maximise energy efficiency enable greater frequency reuse and to filter out interference. Microwave materials will provide the means of engineering antenna elements that realise the quality of smart antenna arrays that will be required. As these systems proliferate cheaper materials that emulate the properties of ceramic dielectrics will be necessary to enable scale of production. Glass-ceramics seem to be able to fulfil this need.

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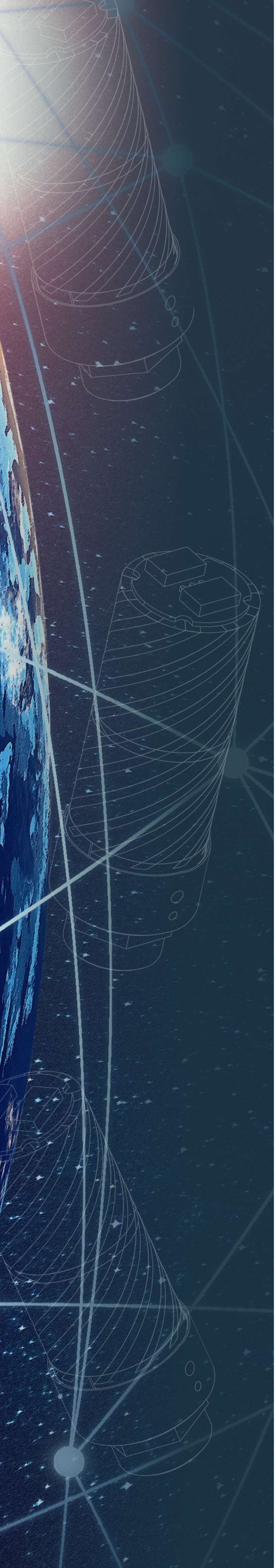

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