PRESENT AND FUTURE APPLICATIONS OF THE INFORMATION DENSE ANTENNA

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ABSTRACT

The basic theory of the Information Dense Antenna (IDA) is discussed. It is shown how the theory can be applied to direction finding (DF) of both wide band and non-stationary signals. Different modulation techniques based on the IDA theory is presented. It is also discussed how multiple input multiple output (MIMO) signal combining techniques can be applied to IDA and how noise measurements can be used for DF. The concept of absolute phase is introduced. Some qualitative results from multipath communication experiments are given. Radar applications, including topside sounding and ground penetrating radar is presented. The possible use of IDA to detect intelligent signals using polarization and the use of non-planar waves in stealth applications are briefly described. In the discussion, an account of frontline IDA research projects are given.

1 INTRODUCTION

The authors invented the Information Dense Antenna, IDA for short, in 1996. Their motivation was to construct an inexpensive and compact device for direction finding (DF) of remote high frequency (HF) radio sources for their space physics research.

IDA measures the full three-dimensional electric or magnetic wave vector field, denoted by $\mathbf{E}$ and $\mathbf{B}$, respectively, and it is in terms of these fields that IDA is decribed. The triaxial antenna itself, that constitutes the IDA sensor, is not a particularly new invention [1]. In fact, IDA has little to do with the actual hardware used in its implementation, which is more of a consequence of the underlying physics. Instead, it is the profound mathematical description of physical electromagnetic fields that forms the basis of IDA [2]. What signifies IDA, and makes it unique compared to similar concepts [3], is its ability to handle many different kinds of radio waves. IDA has the capability to handle not only quasi-monochromatic waves, but also wide band and non-stationary waves. IDA will never suffer from polarization mismatch: IDA intercepts radio waves of any polarization and from any direction, without loss of precious signal power. Fading elimination and interference rejection are other strong capabilities. Furthermore, using an array of IDA, it is possible to go beyond the planar wave field description, traditionally used in antenna theory, and also utilize non-planar waves [4]. Practical applications of non-planar waves has previosly, more or less, been reserved to quantum optics [5] but has recently been proposed also for astrophysical observations in the optical region [6]. The capability of an IDA array to cope with non-planar waves makes it possible to exploit and utilize the more exotic properties of the electromagnetic field, also in the radio regime of the electromagnetic spectrum. This possibility should be of great interest, not only for radio research, but also for stealth radar and communication applications.

As a transmitting antenna, a single IDA is capable of delivering a specified polarization in any given direction. This is particulary useful if the radio channel involves reflections. One can think of at least two different scenarios; either the radio channel is symmetric, and both transmitter and receiver use IDA, or the radio channel is asymmetric, and the transmitter use IDA but the receiving end has only a single polarized antenna. In the first case all three antenna elements can be used independently of each other, in what in essence is a MIMO (Multiple Input Multiple Output) channel. Experiments in office environments have shown that it is possible to triple the capacity compared to that of a radio channel with single polarized antennas at the ends [7] [8]. In the second case the polarization of the transmitting IDA is adaptively changed in order to maximize the signal intensity at the receiving antenna, without increase of the tranmitted power. Similar techniques could also be used for stealth applications. By using very low power and changing the polarization in a quasi random way, IDA could be made to blend with the background noise. In stealth applications, IDA would be very difficult to locate without active means and messages transmitted using quasi random polarization encoding would be very hard to intercept. IDA can, of course, also be used to detect traditional, polarized, radio transmitters, without prior knowledge of the modulation scheme.

In an array of IDA, the possiblity to adjust the polarization of every IDA independently makes beamforming extremely flexible. The IDA array can, for instance, be operated to form a virtual dish antenna with an electronically adjustable focus. The most interesting aspect of an IDA array is, however, the possibility to launch radio beams with highly non-planar wavefronts. In a stealth radar application, such beams can be tailored to become practically invisible for the target or at least very difficult to locate. It should also be possible to use the non-planar wave properties as a new means for radio communcation.

2 PRESENT APPLICATIONS

2.1 POLARIZATION MEASUREMENTS

By polarization, we mean the second order statistical properties of the field. Hence, taking the time-dependent electric field $\mathbf{E}(t)$, as shown in Fig.1, as an example, we want to study the Hermitean forms

$$\langle \mathbf{E}\mathbf{E}^{\dagger} \rangle_t \tag{1}$$

where the direct product of $\mathbf{E}$ with its Hemitean conjugate[1], $\mathbf{E}^{\dagger}$, is implied. The bra-kets denote time average.

Wide band signals are handled by using a mathematical transformation of the time dependent vector field. In principle, any kind of transformation can be used. It is practical to use the windowed Fourier transform, which is computationally efficient and has components that are easy to interpret. We define the windowed Fourier transform of the field as

$$\tilde{\mathbf{E}}(t,\omega) = \int_{-\infty}^{\infty} \mathbf{E}(t-\tau) w(\tau) e^{\mathrm{i}\omega\tau} \mathrm{d}\tau \tag{2}$$

[1]Hermitean conjugate (†) means transpose (T) and complex conjugate (∗), $\mathbf{E}^{\dagger} = (\mathbf{E}^{\mathrm{T}})^{*} = (\mathbf{E}^{*})^{\mathrm{T}}$

where $w(\tau)$ is the windowing function. Omitting the time average, the Hermitean form becomes

$$\tilde{\mathbf{E}}\tilde{\mathbf{E}}^{\dagger} = \begin{pmatrix} \tilde{E}_x\tilde{E}_x^* & \tilde{E}_x\tilde{E}_y^* & \tilde{E}_x\tilde{E}_z^* \\ \tilde{E}_y\tilde{E}_x^* & \tilde{E}_y\tilde{E}_y^* & \tilde{E}_y\tilde{E}_z^* \\ \tilde{E}_z\tilde{E}_x^* & \tilde{E}_z\tilde{E}_y^* & \tilde{E}_z\tilde{E}_z^* \end{pmatrix} \tag{3}$$

We call this tensor *the spectral density tensor*. Usually the coherency tensor is used to analyze the polarization properties of the field in the time domain, while in the frequency domain, the corresponding tensor is the spectral tensor. Usage of these tensors requires that the field in question is quasi monochromatic. When the spectral density tensor is used, there are no limitations on the field.

The $\mathbf{E}$ field vector can be described using six real numbers; three amplitudes and three phases. An alternative, but equivalent, set of parameters that better reflects the physical properties of the field can be found by studying the properties of the spectral density tensor. It is, however, allways possible to multiply the $\mathbf{E}$ field vector with an arbitrary phase factor, without changing the spectral density tensor. Therefore, the number of independent parameters can be only five. The intensity, $\mathcal{I}$, of the field is just the trace:

$$\mathcal{I} = |\tilde{E}_x|^2 + |\tilde{E}_y|^2 + |\tilde{E}_z|^2. \tag{4}$$

To the antisymmetric part of a tensor, a dual pseudovector is associated. We introduce a similar vector, $\mathbf{V}$, which by definition is real. It can be shown that this vector is perpendicular to the plane of polarization, and hence parallel to the wave vector $\mathbf{k}$, as depicted in Fig.1.

$$\mathbf{V} = -2\,\mathrm{Im}\left[E_y E_z^*\hat{\mathbf{x}} + E_z E_x^*\hat{\mathbf{y}} + E_x E_y^*\hat{\mathbf{z}}\right] \tag{5}$$

The normalised magnitude $\mathcal{V} = |\mathbf{V}|/\mathcal{I}$ describes the degree of circular polarization. It is zero for linear polarization and unity for circular polarization. Values between those numbers correspond to elliptical polarization. Using spherical polar coordinates, viz

$$\frac{\mathbf{V}}{\mathcal{I}} = \mathcal{V}\left(\sin\theta\cos\varphi\hat{\mathbf{x}} + \sin\theta\sin\varphi\hat{\mathbf{y}} + \cos\theta\hat{\mathbf{z}}\right) \tag{6}$$

the direction of arrival (DOA) in terms of the polar angle, θ, and the azimuthal angle, φ, can be calculated. The fifth polarization parameter is the tilt angle, α, describing the spatial orientation of the polarization ellipse. In two dimensions, it is usually given as the angle between the major axis of the polarization ellipse and the x axis. To recover it in the three-dimensional case, the coordinate system is first rotated, so that the $\mathbf{V}$ vector becomes parallel to the new z axis.

2.2 DIRECTION FINDING

Direction finding (DF) of remote radio sources was the original application of the Information Dense Antenna (IDA), by which it was conceived. The underlying idea is quite simple. By measuring either the three-dimensional electric field vector $\mathbf{E}(t)$ or magnetic field vector $\mathbf{B}(t)$, both functions of time, t, it should be possible to estimate the so-called polarization ellipse and hence the direction of arrival (DOA), which for transverse fields is always perpendicular to the plane of polarization; as shown in Fig.1.

It was shown in the previous section how the DOA, in terms of the $\mathbf{V}$ vector, could be calculated from the measured $\mathbf{E}$ field. There is, though, an 180° ambiguity in this description. The $\mathbf{V}$ vector is parallel to the DOA; but it could equally well be *anti-parallel*. Using the IDA technique blindly, it is not possible to distinguish between a right-hand circularly polarized

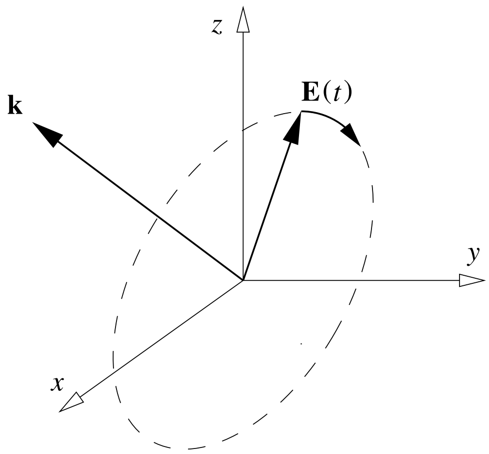

Figure 1: Polarization ellipse

wave coming from one direction and a left-hand circularly polarized wave coming from the opposite direction. To do so requires additional information, besides what is given by IDA itself. There are several possibilities: In many cases, IDA is located on the ground, the radio signals must then come from above the ground; and not from below. Another possibility is to measure *both* the $\mathbf{E}$ and the $\mathbf{B}$ fields and use the Poynting vector, $\mathbf{E}\times\mathbf{B}$, to determine the DOA. A third alternative is to use several distributed IDA and employ interferometry. If the source is stationary it is also possible to use a mobile IDA, forming a synthetic aperture antenna.

Another weak spot when using IDA for DF is that the accuracy of the measurements decreases with decreasing degree of circular polarization. When the source is exactly linearly polarized, it is only possible to determine the direction to within a plane. Using the ground does not help very much in this case as it only helps to turn the plane into a half-plane. However, the other alternatives listed above, for the remedy of the $180°$ ambiguity, can also be used in this case. It should be noted that an exactly linearly polarized source is only a mathematical construct. On the other hand, so is the the concept of infinite dynamical range. When the amplitude of the signal corresponding to the minor axis of the polarization ellipse becomes equal or less in magnitude to that of the noise floor the problem persists.

IDA measures the local electric wave vector field with very high accuracy. The local field is often built up from many contributions, according to the principle of superposition. On the ground these contributions involve at least the direct wave, $\mathbf{E}_\mathrm{d}$, and the reflected wave, $\mathbf{E}_\mathrm{r}$. For DF applications it is the DOA of the direct wave that is of interest. One therefore needs a quantitative method to extract the part of the local field that corresponds to the direct wave. In the case of a perfect ground plane it is possible to carry out analytical calculations. Lets denote the total electric field by $\mathbf{E}_\mathrm{tot} = \mathbf{E}_\mathrm{d} + \mathbf{E}_\mathrm{r}$, as measured by IDA at height h, above a perfectly conducting infinite plane. Using the technique of virtual images it is not difficult to show that

$$\begin{aligned} E_\mathrm{tot,x} &= 2\mathrm{i}\sin(kh\cos\theta)E_\mathrm{d,x} \\ E_\mathrm{tot,y} &= 2\mathrm{i}\sin(kh\cos\theta)E_\mathrm{d,y} \\ E_\mathrm{tot,z} &= 2\cos(kh\cos\theta)E_\mathrm{d,z} \end{aligned} \tag{7}$$

where k is the wave number. From the $\mathbf{V}$ vector, Eqs. (5) and (6), the azimuthal angle φ of the direct wave $\mathbf{E}_\mathrm{d}$ can be calculated from the total field $\mathbf{E}_\mathrm{tot}$, given by Eq. (7)

$$\tan\varphi = \frac{V_y}{V_x} = -\frac{\mathrm{Im}\left[E_{\mathrm{d},x}E^*_{\mathrm{d},z}\right]}{\mathrm{Im}\left[E_{\mathrm{d},y}E^*_{\mathrm{d},z}\right]} = -\frac{\mathrm{Re}\left[E_{\mathrm{tot},x}E^*_{\mathrm{tot},z}\right]}{\mathrm{Re}\left[E_{\mathrm{tot},y}E^*_{\mathrm{tot},z}\right]} \tag{8}$$

The polar angle becomes more complicated

$$\cot^2\theta = \frac{V_z^2}{V_x^2+V_y^2} = \frac{\left(\text{Im}\left[E_{\text{d},x}E^*_{\text{d},y}\right]\right)^2}{\left(\text{Im}\left[E_{\text{d},y}E^*_{\text{d},z}\right]\right)^2+\left(\text{Im}\left[E_{\text{d},x}E^*_{\text{d},z}\right]\right)^2}$$
$$= \frac{\cot^2(kh\cos\theta)\left(\text{Im}\left[E_{\text{tot},x}E^*_{\text{tot},y}\right]\right)^2}{\left(\text{Re}\left[E_{\text{tot},y}E^*_{\text{tot},z}\right]\right)^2+\left(\text{Re}\left[E_{\text{tot},x}E^*_{\text{tot},z}\right]\right)^2} \tag{9}$$

This is an example of a transcendental equation, which does not have any solution in terms of elementary functions. Therefore it must be solved numerically, using for instance Newtons method. Some might think that using the Poynting vector, measuring $\mathbf{E}\times\mathbf{B}$, would simplify the DF calculation process. It is not so; while still useful for waves with a high degree of linear polarization, such measurments will normally only make things worse, with even more complicated equations for the DOA angles. An interesting application of the above discussion is to use a known source to actually measure the ground reflection coefficient.

2.2.1 Instantaneous direction finding

The Fourier transform separates different frequencies and is therefore suitable for broadband quasi-stationary signals. For non-stationary and band-limited signals there is no need for this frequency separation. In these cases the Gabor representation [9], which assigns instantaneous values of amplitude and frequency to the signal, is much more suitable. From a real time series $u(t)$, an analytical complex valued time series $v(t) = u(t) + \mathrm{i}\,u_H(t)$ is formed, where $u_H(t)$ is the Hilbert transform of $u(t)$. Instantaneous values for amplitudes $A(t)$ and phase $\phi(t)$ are defined by $v(t) = A(t)\exp[\mathrm{i}\phi(t)]$ and the instantaneous frequency, $f(t)$, is the time derivative of the phase

$$f(t) = \frac{1}{2\pi}\frac{\mathrm{d}\phi(t)}{\mathrm{d}t} \tag{10}$$

Consider an electric field vector $\mathbf{E}(t)$ in vacuum, tracing a polarization ellipse with time as shown in Figure 2. Ampère's law in vacuum $\nabla\times\mathbf{B}(t) = \frac{1}{c^2}\partial\mathbf{E}(t)/\partial t$, implies that the change of the electric field with time, $\partial\mathbf{E}(t)/\partial t$, must be perpendicular to $\mathbf{k}$. Here c denotes the vacuum speed of light. Further, Gauss' law in vacuum $\nabla\cdot\mathbf{E}(t) = 0$, states that $\mathbf{E}(t)$ also must be perpendicular to $\mathbf{k}$. This means that both $\mathbf{E}(t)$ and $\partial\mathbf{E}(t)/\partial t$ lie in the plane of polarization and that $\mathbf{k}$ must be parallel to $\pm\mathbf{E}(t)\times\partial\mathbf{E}(t)/\partial t$, giving an instantaneous value of the direction of $\mathbf{k}$ for each time t.

For the case of wave propagation in a medium, the magnetic field should be used instead of the electric field, since it is, according to the Maxwell equation $\nabla\cdot\mathbf{B} = 0$, always perpendicular to the direction of wave propagation.

2.3 MODULATION TECHNIQUES

From a mathematical viewpoint, there is nothing special about any of the five polarization parameters, $\mathcal{I}$, $\mathcal{V}$, θ, φ and α described above. In the time domain, any of these parameters should be possible to use for modulation purposes. One of the simplest types of modulation is amplitude modulation (AM). In AM it is only the intensity $\mathcal{I}(t)$ that changes with time. IDA therefore provides a perfect, omnidirectional, AM antenna. It is easy to think of other possiblities. Modulating the parameter $\mathcal{V}(t)$, which describes circular polazation, one can, for instance, easily construct a radio for polarization modulation; maybe PM would be the right acronyme.

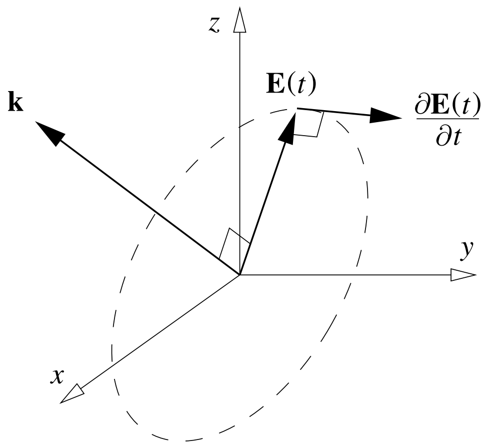

Figure 2: The electric field vector $\mathbf{E}(t)$ and the polarization ellipse shown together with the instantaneous change of the electric field $\partial\mathbf{E}(t)/\partial t$. Note that $\mathbf{E}(t)$, $\partial\mathbf{E}(t)/\partial t$, and $\mathbf{k}$ are perpendicular to each other.

The use of dual polarized antennas are common in fixed radio links to increase the capacity of the radio channel. Normally, either fixed vertical and horizontal polarizations or fixed left- and righthand circular polarizations are used independently. Using IDA, the additional two parameters would be $\mathcal{V}(t)$ and $\alpha(t)$, the tilt angle of the polarization ellipse.

2.3.1 Signal combining

In order to correctly handle frequency modulation (FM), or phase shift keying (PSK) modulation techniques, the intensity $\mathcal{I}(t)$ alone is not enough. One also has to recover the phase that was lost when the spectral density tensor was formed. There are several ways to acheive this. One way is to use the phase information from one particular antenna element of IDA. A better way is to monitor the signal to noise ratio (SNR) and use the phase from the the antenna element with the highest value. The same type of problem shows up in the MIMO radio channel, where so called *optimum ratio combining* is preferably used, as it gives the theoretically best value of the SNR. The same principle can be applied to IDA, by considering the corresponding eigenvalue problem.

In optimum ratio combining, the eigenvector corresponding to the largest eigenvalue is chosen. For IDA it is possible to make a physical interpretation of the corresponding three eigenvectors: The two eigenvectors with the largest eigenvalues correspond to the two possible signal vectors. The third eigenvector corresponds to noise.

Optimum ratio combining has the drawback of being computationally intensive, using for instance the singular value decomposition technique. On the other hand it gives the theoretically best signal, it gives the possibility to continuosly get a total measure of the noise level; and it gives the direction to the source.

2.3.2 Direction finding using noise

In MIMO systems, the eigenvector with the smallest eigenvalue corresponds to noise; and it is seldom used. For IDA, this vector has physical significance, because it must be perpendicular to the two signal vectors. Indeed, the three eigenvectors spans an ellipsoid in the tree-dimensional *complex* space $\mathbb{C}^3$. It turns out that the noise vector is parallel to the direction of propagation.

2.4 POLARIZATION FADING ELIMINATION

A similar technique to that used in optimum ratio combining, which essentally is a minimum variance method (least square) can also be used to separate the total field vector into three orthogonal vectors: two signal vectors and a noise vector. All three vectors are in general complex valued. By chosing either of the signal vectors, problems with polarization fading can be eliminated.

2.4.1 Interference rejection

Interfering signals can be filtered out using the same technique as described above by discriminating the signal vector corresponding to the interefering signal.

2.5 THE ABSOLUTE PHASE

A different way to recover the lost phase information is to use the *absolute phase*. A complex scalar signal $s(t)$ can be written $s(t) = s_0(t)e^{\mathrm{i}\phi(t)}$. It is then natural to define $\phi(t)$ as the absolute phase of the scalar signal. An electric vector field $\mathbf{E}(t)$ can likewise be written

$$\mathbf{E}(t) = E_1(t)e^{\mathrm{i}\phi_1(t)}\hat{\mathbf{e}}_1 + E_2(t)e^{\mathrm{i}\phi_2(t)}\hat{\mathbf{e}}_2 + E_3(t)e^{\mathrm{i}\phi_3(t)}\hat{\mathbf{e}}_3 \tag{11}$$

where $\hat{\mathbf{e}}_i$, $i = 1, 2, 3$ denotes base vectors in $\mathbb{R}^3$. In this case it is not evident how the absolute phase should be defined. Radio waves are, however, transverse fields and in the transverse plane in general, $\mathbf{E}(t) = (\mathbf{a}(t) + \mathrm{i}\mathbf{b}(t))e^{\mathrm{i}\Phi(t)}$, where $\mathbf{a}, \mathbf{b} \in \mathbb{R}^3$ and $\mathbf{a} \cdot \mathbf{b} = 0$; and $\Phi(t)$ denotes the absolute phase. To recover $\Phi(t)$ we employ the scalar product $\mathbf{E} \cdot \mathbf{E} = (a^2 - b^2)e^{2\mathrm{i}\Phi(t)}$. Hence,

$$\Phi(t) = \frac{1}{2}\text{Arg}\,[\mathbf{E} \cdot \mathbf{E}] \tag{12}$$

A problem with the absolute phase is that a branch choice has to be made. Even so, it is our meaning that the absolute phase Φ constitutes the "lost" sixth polarization parameter.

Using similar arguments one can also construct the *differential absolute phase*, $\Delta\Phi$. Assuming the DOA to be stationary between two measurements, let $\mathbf{E}_1 = (\mathbf{a} + \mathrm{i}\mathbf{b})e^{\mathrm{i}\Phi_1}$ and $\mathbf{E}_2 = (\mathbf{a} + \mathrm{i}\mathbf{b})e^{\mathrm{i}\Phi_2}$ denote the field vectors at time t_1 and t_2, respectively. The differential absolute phase, $\Delta\Phi = \Phi_1 - \Phi_2$, is then obtained from the scalar product $\mathbf{E}_1 \cdot \mathbf{E}_2^*$, according to

$$\Delta\Phi = \text{Arg}\,[\mathbf{E}_1 \cdot \mathbf{E}_2^*] \tag{13}$$

2.6 MULTIPATH COMMUNICATION

IDA is an excellent antenna for multipath communication in highly reflective environments such as an indoor office. By taking advantage of the reflection paths it is possible to send and receive simultaneously using all three antenna elements independently of each other.

In an indoor radio transmission experiment that got very much publicity in 2001, a research group from Bell laboratories, transmitted a spectacular painting by Miro using a *tripole*. They subdivided its colours into red, green and blue, and used three perpendicular dipoles to transmit the separate colours [7]. In 2002 a similar experiment using IDA [8] was performed. Instead of transmitting paintings, a quasi-random bit sequence was used on top of the polarization parameters described earlier. The center frequency was 2.4 GHz and differential BPSK modulation was used. The SNR and the number of bit errors was measured at different locations in an office. The tripeling of capacity found by the Bell team was verified. Comparisons with a receiving antenna array of three vertical dipoles gave approximately the same result. Spatial diversity and polarization diversity antennas with the same number of elements had similar capacities. However, at certain locations or polarizations, the dipole array had very poor performance. IDA proved more rubust; it was much more compact and it gave the possiblity to measure the transfer matrix and hence the indoor IDA radio channel. The tranmitter could then be tuned by polarization alone to increase the SNR and lower the number of bit errors. Modulation using the five polarization parameters was proven.

2.7 SATELLITE BORNE RADAR APPLICATIONS

A satellite borne radar uses range and Doppler shift to distinguish different areas on the ground. By only minor additions in the traditional radar it is possible to also take advantage of the polarization. Making it possible to transmit arbitrarily polarized signals, the radar echo will include polarization signatures of the target. Including also direction finding, the left-right echo direction ambiguity can be resolved.

A conventional radar on board a satellite separates the ground below into concentric rings of different ranges with the center of the rings being in the nadir direction. Taking into account the different Doppler shifts, the ground can be further divided into stripes perpendicular to the flight direction of the satellite, as shown in Figure 3. The radar distinguishes between areas of different range and different Doppler shift, but there are areas to the right- and left-hand side of the flight direction having identical properties. When, for a certain frequency, there is

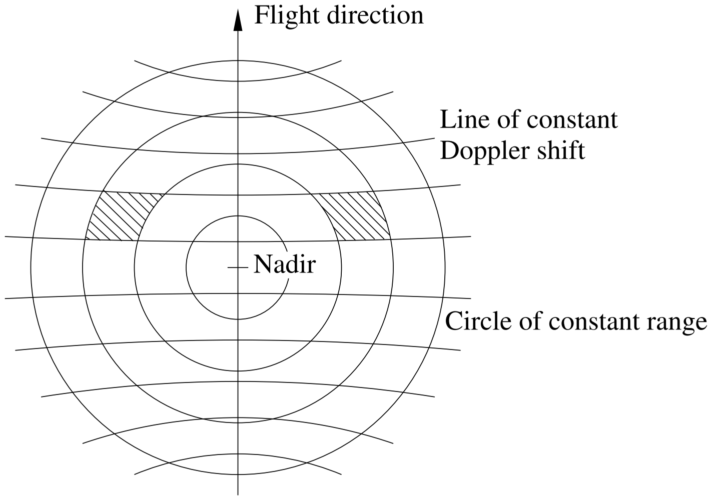

Figure 3: A conventional radar resolves the ground in concentric rings of equal range, and stripes perpendicular to the flight direction of equal Doppler shift, but it can not distinguish between left and right. The radar echo can therefore come from either side of the flight direction as indicated by the two dashed regions.

only one radiating source, the direction from where the signal comes can be determined, as described in Subsection 2.2. On tho other hand, two sources at the same frequency cannot be treated separately. Instead, there will be a superposition of the fields from the two sources and a resulting polarization ellipse will be formed. The orientation of the DOA calculated from the resulting polarization ellipse will give an estimate of how much of the total signal that comes from each of the two source regions.

2.7.1 Topside Sounding

In the case of topside sounding, IDA offers extra parameters compared to other topside sounders, which only measure range. These parameters are the degree of circular polarization and the DOA of the echo. The polarization of the wave is important when considering propagation in media since different wave propagation modes are most easily distinguished by their inherent polarization. For example, the ionosphere and the magnetosphere consists of magnetized plasma which is birefringent and therefore must be taken into consideration when radar signals with frequencies close to the plasma frequency are used. In this case the measurement of polarization can be used to distinguish between the ordinary and the extraordinary wave modes. The DOA gives additional information of from where the echo is coming and enables a more detailed mapping of the ionosphere and magnetosphere.

2.7.2 Ground Penetrating Radar

Having the possibility to transmit arbitrarily polarized signals the radar echo will include polarization signatures of the target, making it easier to determine the composition of the target. Including also direction-finding of the radar echo, the left-right echo direction ambiguity can be resolved and surface echoes can be sorted out so the radar can look straight down into the ground.

3 FUTURE APPLICATIONS

3.1 DETECTION OF INTELLIGENT SIGNALS USING POLARIZATION

The polarized nature of radio signals can faciliate identification of potentially intelligent sources. This is mostly due to the common use of polarized antennas for transmission. A reasonable strategy for detection of intelligent signals seams to search for peaks in the radio spectrum. However, this strategy might not work on spread spectrum signals. Unsuppressed carrier modulation has a strong carrier and sidebands and can be easily identified in a spectrum due to its peaks. Direct spread spectrum signals on the other hand are formed by modulating the baseband signal by a pseudo-random code. The spectrum becomes spread and without features and therefore appears as noise at a monitoring receiver.

By considering the *polarization intensity* $\mathcal{P}$ rather than the usual intensity $\mathcal{I}$ it can be shown that for an antenna generated signal $\mathcal{P} = \mathcal{I}$ while for the noise signal $\mathcal{P} = \mathcal{I}/\sqrt{n}$, where n is the number of dimensions; for IDA $n = 3$. Therefore, even if the SNR figure is one, the polarization intensity to noise ratio will be $\sqrt{3}$.

3.1.1 Stealth Communication

It is possible to intentionally create a seamingly unpolarized radio signal and yet transmit information.

3.2 NON-PLANAR WAVES

The standard theory of antennas relies heavily on the notion of the plane wave. One could say that it is the atom of EM wave modes. The concept of antenna gain for instance is expressed in terms of the antennas response to a wave with a particular $\mathbf{k}$, wave vector, direction.

3.2.1 The use of non-planar radio waves in stealth applications

It was recently realized by the authors that the ubiquitous assumption of plane wave has interesting possibilities for stealth radio and surveillance. We have found that certain types of nonplanar waves have properties that can aggravate undesired detection.

Specifically, our nonplanar waves have two features that make them interesting for stealth radio: they do not induce any signal in ordinary antennas under certain conditions and even when they do induce a signal it fools ordinary direction finding techniques by providing a false direction of arrival.

These nonplanar waves, which are handled incorrectly by ordinary antennas, can however be handled properly by arrays of IDA. Ultimate applications are for instance stealth radar since the detected radar signals cannot be traced back from the target aircraft.

4 CURRENT SCIENTIFIC PROJECTS

4.1 ISS, HF SPECTROMETER

An IDA HF spectrometer for monitoring the local $\mathbf{E}$ and $\mathbf{B}$ fields in the vicinity of the International Space Station, ISS, is being built by the Swedish Institute of Space Physics in Uppsala, Sweden (electronics) and the Space Research Center in Warsaw, Poland (antennas). The instrument will also be used for remote sensing.

4.2 LOIS, A LOFAR OUTRIGGER IN SCANDINAVIA

LOIS is the first research project where arrays of IDA will be used, both for reception and transmission. LOIS aims at enhancing the atmospheric and space physics capabilities of the huge, new-generation digital radio telescope LOFAR (Low Frequency Array), currently being built in Netherlands and Northwestern Germany, by providing a software configurable sensor and emittor infrastructure distributed in southern Sweden with Växjö as hub. Primary target areas for LOIS are solar physics, ionospheric physics, and space weather as well as large-scale sensor, radio, antenna, telecom, and IT research.

4.3 NANOSPACE-1, ELECTRIC FIELDS

A miniature IDA receiver for electric fields is planned for the proposed Swedish nano-satellite, Nanospace-1, developed at the Ångström Space Technology Center, ÅSTC, in Uppsala, Sweden. The miniature receiver will have the size of an ordinary matchbox. This is acheived using so called *multi chip modules*, which are built up by so-called *bonding* of naked silicon chips.

5 DISCUSSION

The mathematical formulation of IDA has led much further than the authors believed when they applied for their first patent [10] in 1998. Presently, they are finalizing their research on a covariant formulation of polarization, which is based on the Maxwell field tensor and incorporates both the $\mathbf{E}$ and the $\mathbf{B}$ field [11]. They also study the properties of non-planar waves from a polarization perspective. Research is being made to extend their covariant polarization theory to media, including relativistic kinetic plasma theory into the description. In a near future they also hope to start an in-depth study of the polarization properties of gravity waves.

References

[1] R. T. Compton, The Tripole Antenna: An Adaptive Array with Full Polarization Flexibility, *IEEE Transactions on Antennas and Propagation*, Vol. AP-29, No. 6, 1981.

[2] T. D. Carozzi, R. Karlsson, and J. Bergman, Parameters characterizing electromagnetic wave polarization, *Phys. Rev. E*, **61**, 2024–2028, 2000.

[3] IMAGE RPI, Imager for Magnetopause-to-Aurora Global Exploration Radio Plasma Imager (2000), web site: `http://image.gsfc.nasa.gov`

[4] R. J. Beil, A Classical Photon Model, published in *The Present Status of the Quantum Theory of Light, Proceedings of a Symposium in Honour of Jean-Pierre Vigier*, Edited by S. Jeffers, S. Roy, J-P. Vigier and G. Hunter, Fundamental Theories of Physics, Vol. 80, 9–16, Kluwer Academic Publihers, 1997.

[5] G. Stix, Hands of Light, Moving particles with photons leads to a new form of nanomanufacturing, *Sci. Am.*, Aug. 2003

[6] M. Harwitt, Photon Orbital Angular Momentum in Astrophysics, *The Astrophysical Journal*, **597**, 1266–1270, 2003.

[7] M. R. Andrews, P. P. Mitra and R. Decarvalho, Tripling the capacity of wireless communications using electromagnetic polarization, *Nature* **409**, 316–318, 2001.

[8] Redsnake Radio Technology AB, Measurement specification Emil phase C and Measurement report Emil Phase C, *Technical reports on the capacity of the indoor IDA MIMO radio channel*, 2002. Held in deposit by Roger Karlsson, `rk@irfu.se`, Swedish Institute of Space Physics, Uppsala, Sweden.

[9] Cohen, L., *Time-frequency analysis*, Prentice-Hall, 1995.

[10] J. Bergman, T. D. Carozzi, and R. Karlsson, Metod och system för att erhålla riktning för en elliptiskt polariserad elektromagnetisk vågutbredning, *Swedish patent* `512 219`, (February 2000), Method and System for Obtaining Direction of an Electromagnetic Wave, *International Patent Publication* `WO99/66341`, (December 1999), *US Patent* `6,407,702`, (June 2002).

[11] M. Olofsson, Towards a covariant formulation of electromagnetic wave polarization, *Masters thesis*, IRF Scientific Report 273, 2001. (Swedish Institute of Space Physics, Uppsala, Sweden, 2001)