

# Superresolution for HF Radar: Comparison of Performance with Simulated and Real Radar Data

A D Chadwick  
Roke Manor Research Ltd  
Romsey, Hampshire, SO51 0ZN, UK

## Abstract

*HF radars require large arrays to achieve narrow beamwidths, and are required to discriminate targets with low Doppler shifts compared to microwave radar. Superresolution processing can discriminate signals at separations much less than the beamwidth or conventional Doppler bin width (or conversely, achieve a given minimum resolvable separation with a smaller array or less time-on-target where SNR remains sufficient). Simulation results and analysis of real radar data presented here show at least a two-fold improvement compared to conventional processing, assuming ideal manifolds. A polarization-sensitive superresolution algorithm applicable to skywave HF radar is also discussed.*

*Keywords: HF Radar, Superresolution, IMP, POLIMP*

## Introduction

HF radar exploits surface wave and skywave propagation in the 3-30 MHz frequency band to enable target detection beyond the conventional line-of-sight horizon, at ranges of hundreds or even thousands of kilometres. However, HF arrays typically require apertures measuring hundreds of metres across to achieve the narrow beamwidth required to resolve multiple targets in azimuth. Furthermore, the relatively low Doppler shifts of targets at HF mean that long observation times (tens or hundreds of seconds) are required to resolve targets in velocity.

Angular superresolution processing is potentially able to resolve targets at separations much less than the array beamwidth and could therefore significantly reduce the cost and physical size of an array for a given minimum resolvable separation. Likewise, velocity superresolution can be used to discriminate targets within the

natural bin width of conventional Fourier Transform processing, and could therefore significantly reduce observation time whilst maintaining high Doppler accuracy.

This paper describes the results of angular and velocity superresolution processing using the Incremental Multi-Parameter (IMP) algorithm, and an extended polarization-sensitive algorithm known as POLIMP, in simulations of HF radar and applied to real data from an HF Surface Wave Radar (HFSWR) array operated by BAE Systems Integrated System Technologies (Insyte).

## Superresolution Using IMP

IMP is an approximate maximum likelihood method, in which the received data is compared to a set of calibration responses (the gain manifold) and signal detections reported at the parameter value or values at which the best fit occurs. An iterative signal nulling process is then used

to refine the parameter estimates and make further detections, until all significant signals have been found, i.e. the residue is essentially noise only.

Note that whereas subspace based methods such as MUSIC only work properly with decorrelated signals, IMP is largely unaffected by signal correlation. IMP is therefore ideal for the radar target superresolution application, where the signals to be resolved are all copies of the transmitted waveform and hence highly correlated.

The accuracy of the gain manifold is fundamental to the performance of IMP. In the case of velocity superresolution, the parameter to be estimated is the target Doppler, from a series of pulses received over a period of time. The timing of the data samples is invariably well-controlled and so an ideal theoretical manifold (set of baseband sinusoids) can always be assumed.

In the case of angular superresolution, the parameters to be estimated are azimuth and/or elevation, based on data snapshots collected across the  $N$  channels of the array. In microwave phased array radar, best results are typically obtained using a measured manifold comprising the responses to a known calibration signal source scanned across the array. Calibration of an HF array is more difficult due to the physical size of the array and individual elements; the variable coupling between elements; and the effects of the surroundings e.g. ground plane conductivity. Alternative approaches include numerical modelling of the array, e.g. using the NEC2 prediction code; measurements on a scale model of the array in a controlled environment; or simply assuming ideal theoretical element gain patterns and geometry in the absence of more reliable information. A comparison of measured, NEC2 modelled and ideal

manifolds for an HF array in [1] found that: (i) measured element gain patterns tend to be much more accurate than either modelled or ideal patterns, so measured manifolds are recommended wherever feasible; and (ii) modelling can give very good results in some directions of arrival, but may in fact give larger errors than a simple theoretical manifold in others.

### **Polarization-Sensitive IMP (POLIMP)**

A key distinction between surface wave and skywave propagation is that, whereas surface waves are always essentially vertically polarized, the polarization of received skywaves is random and unpredictable, due to the effects of ionospheric reflection. For a single mode HF array on an uncluttered site, this is not necessarily a problem: co-polarized signal components are received as normal and cross-polarized components ignored, resulting only in an average loss of sensitivity of 3dB for skywaves.

For a single mode array on a cluttered site, however – which is more likely at HF than microwave frequencies, given the size of array required – significant mode conversion may occur, so that incoming cross-polarized signals result in co-polarized components at the array elements. These extra signals will not generally fit the manifold (defined for true incoming co-polarized signals) in *any* signal direction [2], thus leading to errors and a loss of sensitivity when the standard IMP algorithm is applied. Similar problems would be encountered if conventional IMP was applied to a true mixed mode array, since received signals will not in general fit a manifold defined at a single polarization only.

An important aspect of the current work was therefore to demonstrate a polarization-sensitive version of the angular IMP algorithm, known as POLIMP. In

conventional IMP, the aim is to maximise the signal-plus-noise to noise ratio given by:

$$f(\alpha, \varepsilon) = \frac{\mathbf{m}(\alpha, \varepsilon)^H \mathbf{Q} \mathbf{R} \mathbf{Q} \mathbf{m}(\alpha, \varepsilon)}{\mathbf{m}(\alpha, \varepsilon)^H \mathbf{Q} \mathbf{m}(\alpha, \varepsilon)} \quad (1)$$

where  $\alpha$  is azimuth,  $\varepsilon$  is elevation,  $\mathbf{m}$  is the manifold gain vector in this direction,  $\mathbf{Q}$  is a signal projection matrix and  $\mathbf{R}$  is the data covariance matrix. For POLIMP, the manifold vector becomes the sum of gain vectors at two orthogonal polarizations:

$$\mathbf{m}(\alpha, \varepsilon) = s_1 \mathbf{v}_1(\alpha, \varepsilon) + s_2 \mathbf{v}_2(\alpha, \varepsilon) = \mathbf{V} \mathbf{s} \quad (2)$$

and the aim is to first maximise the POLIMP function over polarization:

$$f(\alpha, \varepsilon) = \max_s \left\{ \frac{\mathbf{s}^H \mathbf{V}^H \mathbf{Q} \mathbf{R} \mathbf{Q} \mathbf{V} \mathbf{s}}{\mathbf{s}^H \mathbf{V}^H \mathbf{Q} \mathbf{V} \mathbf{s}} \right\} = \max_s \left\{ \frac{\mathbf{s}^H \mathbf{X} \mathbf{s}}{\mathbf{s}^H \mathbf{Y} \mathbf{s}} \right\}$$

It can be shown that this simplifies to:

$$f(\alpha, \varepsilon) = \lambda_{\max} \quad (4)$$

where  $\lambda_{\max}$  is the largest eigenvalue of the 2 x 2 matrix  $\mathbf{Y}^{-1} \mathbf{X}$ . In this way, rather than explicitly searching over all possible polarizations, the maximum POLIMP function value at each direction ( $\alpha, \varepsilon$ ) can be found directly and economically, with little more than twice the computation of conventional IMP. The corresponding eigenvector  $\mathbf{s}$  gives an estimate of the signal polarization.

## Simulation Results

### Angular Superresolution

A baseline simulation of an 8 element, vertically polarized linear array, with two co-polarized signals at zero elevation (i.e. surface waves) and at 12dB SNR at the element after Doppler filtering, demonstrated successful resolution of signals down to 5° (approx 1/3<sup>rd</sup> beamwidth) separation using conventional

IMP operating in azimuth only. See Figure 1.

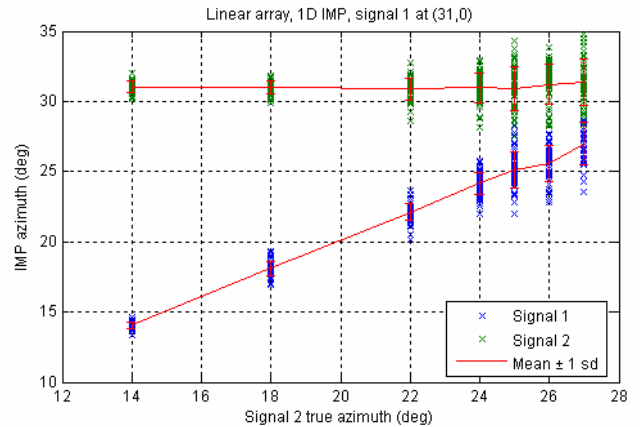


Figure 1: Resolution vs azimuth separation using 1D IMP

Further simulations carried out using an 8 element arc array demonstrate two-dimensional resolution in both azimuth and elevation. For a single mode array and co-polarized signals as before, Figure 2 shows accurate resolution of a surface wave at 0° elevation and a skywave at 30° elevation (approximately half an elevation beamwidth separation) at only 1° azimuth separation.

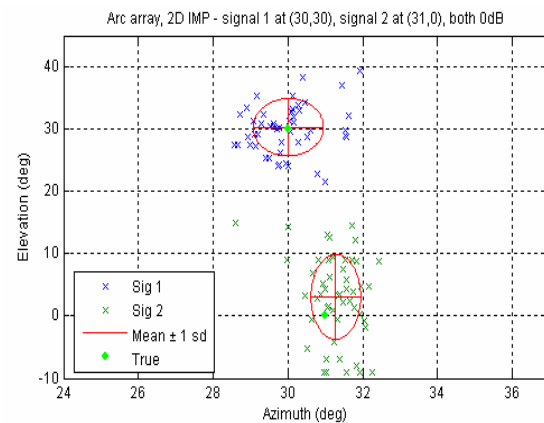


Figure 2: Resolution of signals using 2D IMP

To introduce polarization diversity, a modified arc array comprising loop and monopole elements inclined at various angles was defined. Simulation results for conventional IMP using a vertically polarized manifold demonstrate that, while purely vertically polarized signals (e.g. surface waves) are still detected correctly, arbitrarily polarized signals (e.g. skywaves)

result in spurious (but consistent) detections at the wrong positions. POLIMP, however, is able to correctly and accurately resolve all signals. See Figure 3.

Moreover, exploiting the extra dimension for resolution where signal polarization diversity is present can actually give better overall performance (reduced minimum separation, increased detection accuracy) compared to identically polarized signals in the same directions. Figure 4 shows that, for two vertically polarized signals at  $3^\circ$  azimuth and  $10^\circ$  elevation separation, the distributions of estimated positions from both IMP and POLIMP overlap considerably, making it difficult to correctly associate detections. Where one signal is circularly or (in particular) horizontally polarized, the distributions for both signals are much tighter and the respective mean positions can be estimated to within  $0.1^\circ$  azimuth and  $2^\circ$  elevation.

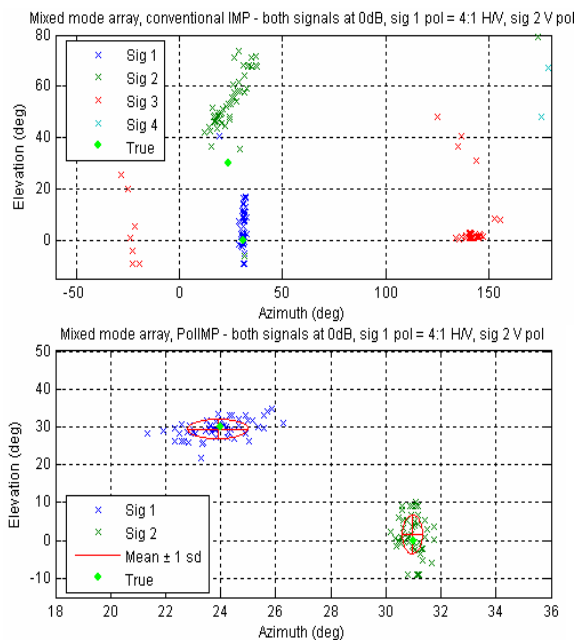


Figure 3: Resolution of mixed mode signals with IMP (top) and POLIMP (bottom)

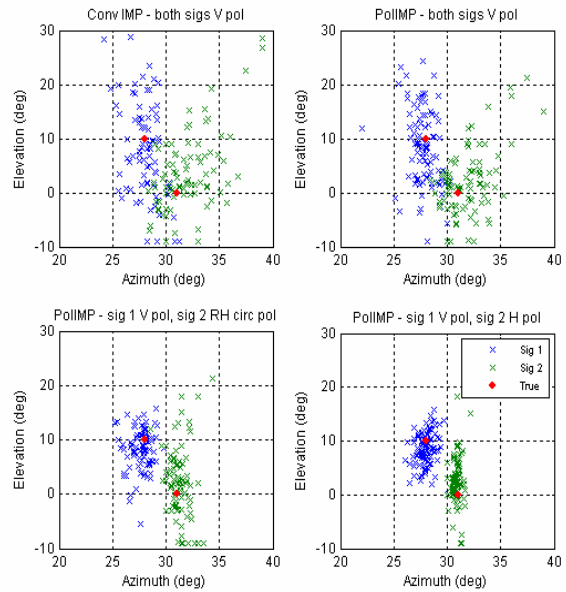


Figure 4: Improved resolution exploiting polarization diversity with POLIMP

Note that the results presented above were all generated using a perfect array manifold. Further simulations for signals at half a beamwidth separation, incorporating random manifold errors at a typical level (similar to those reported in [1]) of  $1\text{dB} / 5^\circ$  RMS showed that, while the accuracy of detections was reduced by 20-40%, the proportion of runs in which the correct number of detections were made was not significantly affected.

### Velocity Superresolution

The performance of velocity superresolution using IMP and conventional FT processing were compared, again using simulations of an 8-element HF array. A typical result featuring three simulated aircraft targets at radial speeds of  $-350$ ,  $-150$  and  $+300$  m/s and  $0\text{dB}$  SNR at the element is shown in Figure 5. Whereas 32 samples are required to resolve the targets using conventional processing, superresolution using IMP requires only 7 samples. Furthermore, the IMP results are accurate to within about  $\pm 1.5\text{Hz}$ , compared to  $\pm 3\text{Hz}$  (the bin width) for the FT. Repeated simulations with varied target parameters suggest that, where performance is not SNR-limited, superresolution reduces the

required observation time (i.e. number of samples) by at least a factor of 4. Where performance is SNR-limited, superresolution does not reduce the time-on-target but is still able to outperform standard processing in accuracy and resolution.

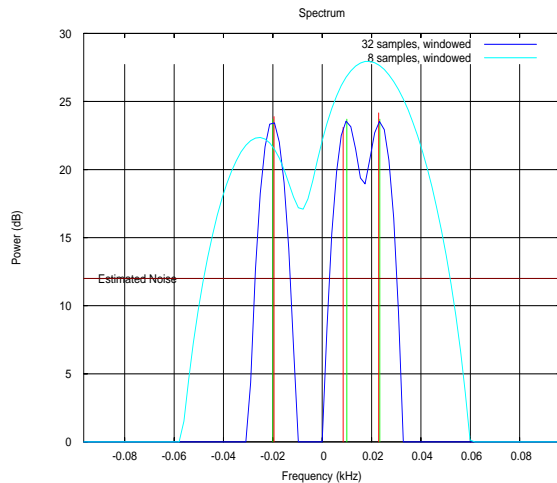


Figure 5: Velocity superresolution (8 pulses) vs FT (8 pulses and 32 pulses) with 3 targets

### Analysis of Real HFSWR Data

To validate the simulation findings, recorded data from an operational HF Surface Wave Radar located at Bradwell, England was supplied by Insyte and analysed using conventional IMP. The HFSWR array was a uniform linear array of 8 elements (since extended to 16 elements), each element comprising a pair of tetrahedral antennas phased to provide rear lobe cancellation and forward reinforcement. A measured array manifold was not available, but the array site was known to be uncluttered with a highly conductive ground plane. For simplicity, an ideal theoretical manifold was therefore assumed based on the known array geometry, an omnidirectional gain pattern for each tetrahedral antenna and no mutual coupling.

The data set comprised approximately 7 minutes of continuous data, collected using a simple pulse waveform. Initial Doppler

analysis revealed fast-moving aircraft targets in a number of range cells, in addition to a strong band of clutter and slow-moving targets present in every cell. Of particular interest were the three tracks highlighted in Figure 6, which were found to converge in both azimuth and Doppler, and hence ideal for analysis using both angular and velocity superresolution.

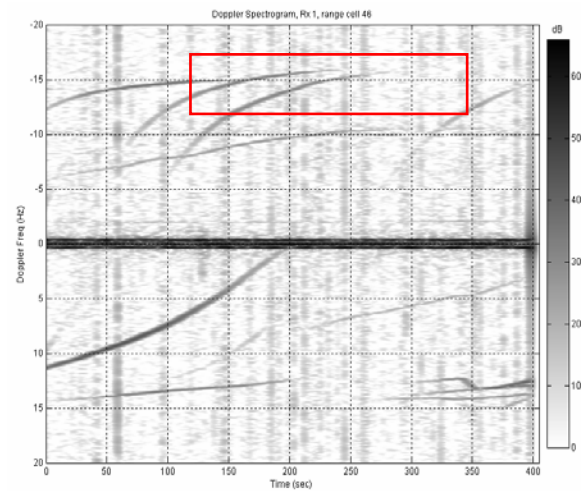


Figure 6: Doppler spectrogram of HFSWR data

### Angular Superresolution

Applying conventional fixed beamforming to the selected data segment (taken from a 2Hz wide Doppler bin to remove clutter and other targets) shows only a single smeared target track. Ripples in the track suggest beating between multiple Doppler targets, but the target azimuths cannot be distinguished. The IMP results, however, show clear resolution of targets where these are present simultaneously, down to a minimum separation of approximately  $8^\circ$  or  $\frac{1}{2}$  an azimuth beamwidth where highlighted. Given the simple assumed manifold, this is an excellent result and compares well with the minimum resolvable separation of  $\frac{1}{3}$ <sup>rd</sup> beamwidth seen in simulation.

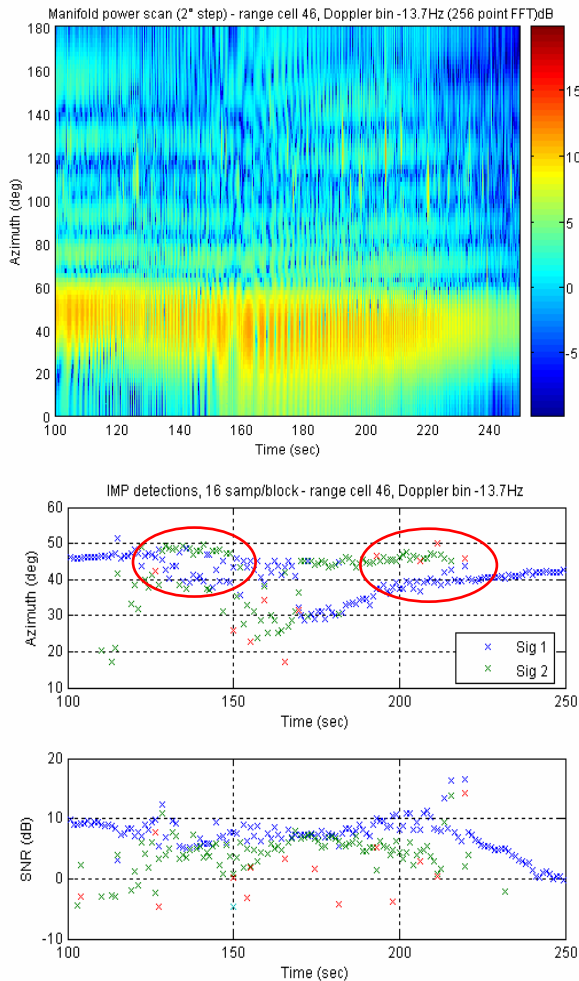


Figure 7: Beamforming (top) vs 1D IMP (bottom) for converging tracks in HFSWR data

### Velocity Superresolution

Applying conventional Doppler processing to beamformed data from the selected segment, using a 256-point FFT, reveals four target tracks between -5 and -20Hz. However, targets can no longer be reliably resolved once they converge within the natural Doppler bin width of approximately 2Hz. Using the same number of samples, IMP is able to resolve all four targets to within 1Hz separation. See Figure 8. Where all targets are simultaneously present in the range cell, Figure 9 shows IMP accurately resolving all four using 224 samples; conventional processing with this many samples only gives two smeared detections, and in fact requires at least 576 samples – 2.5 times the time-on-target for IMP – to make four distinct detections.

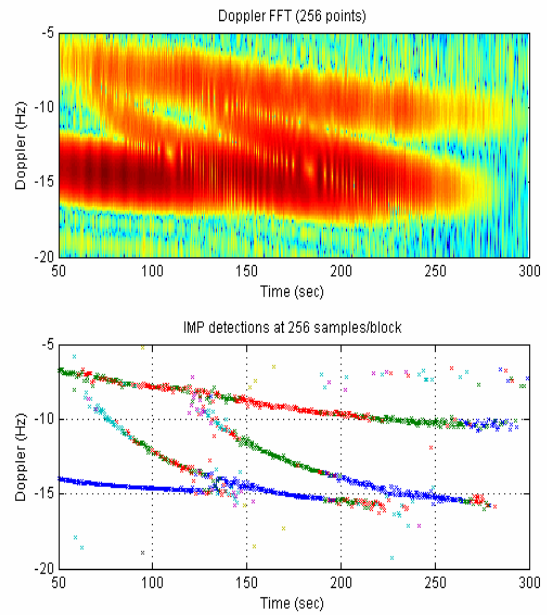


Figure 8: FFT (top) vs IMP (bottom) for converging tracks in HFSWR data

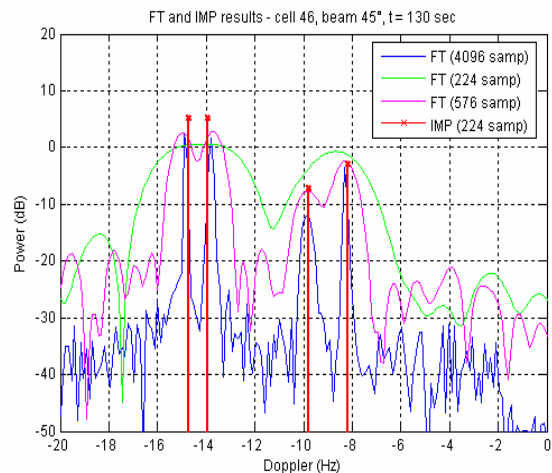


Figure 9: FFT vs IMP for HFSWR data with 4 targets present  
**Conclusions**

Superresolution processing has been shown to offer significant performance advantages compared to conventional target processing for HF radar, improving the discrimination of multiple targets in both angle and velocity where SNR permits. Simulations have shown improvements of up to 3 times in minimum resolvable azimuth separation (for a single mode linear array) and at least 4 times in time-on-target for resolution in velocity. Analysis of targets of opportunity

in real HFSWR data gives slightly more conservative results, but still shows at least a two-fold improvement in all respects.

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The success of the angular superresolution technique applied to the real data is particularly significant, as this demonstrates that a simple theoretical manifold can be sufficient to achieve accurate results for an HF array on a “good” site. Further work should address manifold requirements for more difficult sites, as well as implementation issues and the impact on other parts of the processing chain in a real radar system.

A polarization-sensitive variant of the IMP algorithm, POLIMP, has also been successfully demonstrated for use with mixed-mode arrays (or equivalently, single mode arrays where mode conversion occurs) when arbitrarily-polarized signals e.g. skywaves are present.

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### **References**

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