HF Radio Direction Finding

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Siemens:
High
Performance
Partner

GB ROWING

Contents

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Overview of HF DF

- High frequency band nominally 2-30 MHz, 10-150 m wavelengths
- HF band still used for broadcast, marine, aviation, military, diplomatic, and amateur purposes
- HF radio direction finding is needed to monitor and control the spectrum:
  - Identifying interfering sources (civilian)
  - Locating enemy forces (military)
  - Signals intelligence
- Also need to be able to separate out cochannel signals
- Need to be able to handle the unique HF environment
  - Groundwave and skywave propagation
  - Potential for correlated multipath
  - Time-varying ionospheric conditions, fading, polarization changes
  - External noise is not spatially white

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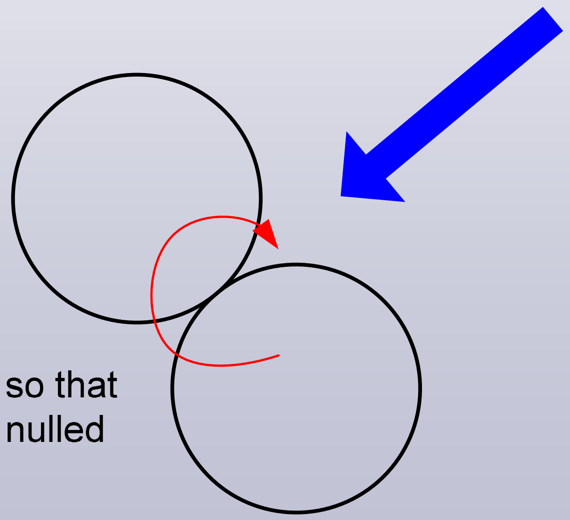
Traditional approaches to DF – directional antenna

- Simplest approach for DF is to mechanically rotate a directional antenna
  - A peak in the response indicates the approximate signal direction
  - Not easy to rotate directional HF antennas due to large size
  - Can use an electrically small loop
    - Not high accuracy
    - Problems with polarization – no good for skywaves
    - 180° ambiguity
  - Only needs a single receiver



Loop rotated so that the signal is nulled

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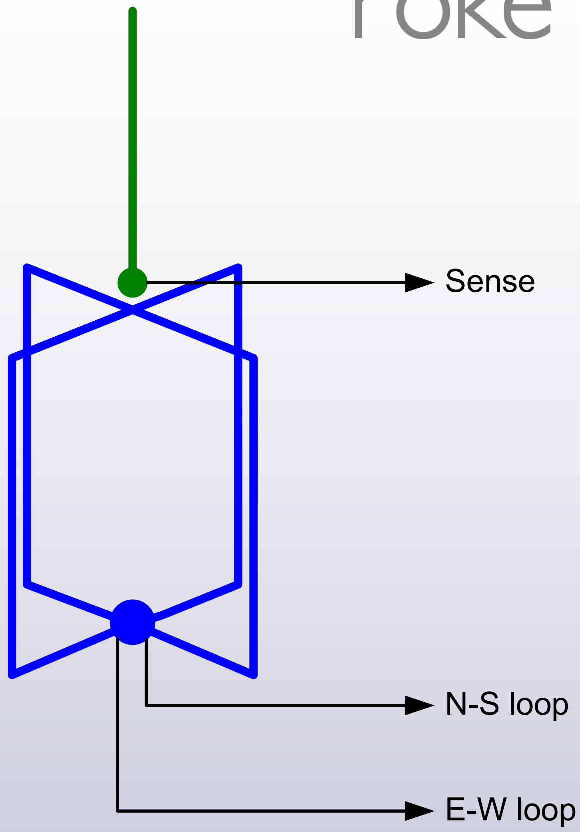
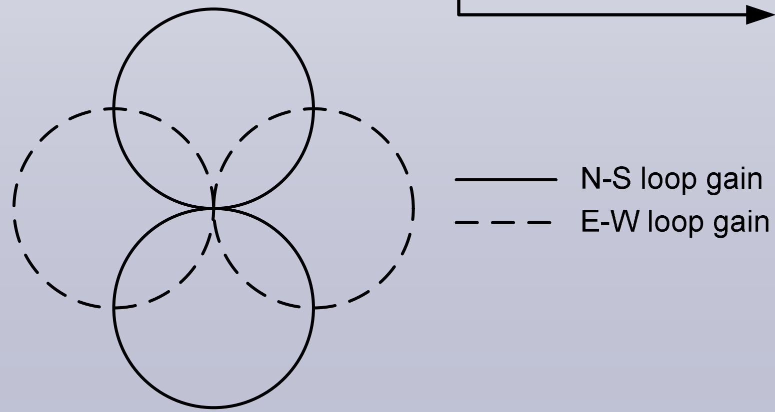
Traditional approaches to DF – Watson-Watt with loops

- Two orthogonal loop antennas
  - 'Figure of 8' responses
  - Cosinusoidal for N-S loop
  - Sinusoidal for E-W loop
- Direction is the arctangent of the ratio of the E-W signal to N-S signal
- 180° ambiguity can be resolved using a third omnidirectional antenna
- Needs 3 coherent receivers
- Small physical size
- Can have ~5° accuracy for groundwaves
- Very poor performance for skywaves with significant horizontal polarization





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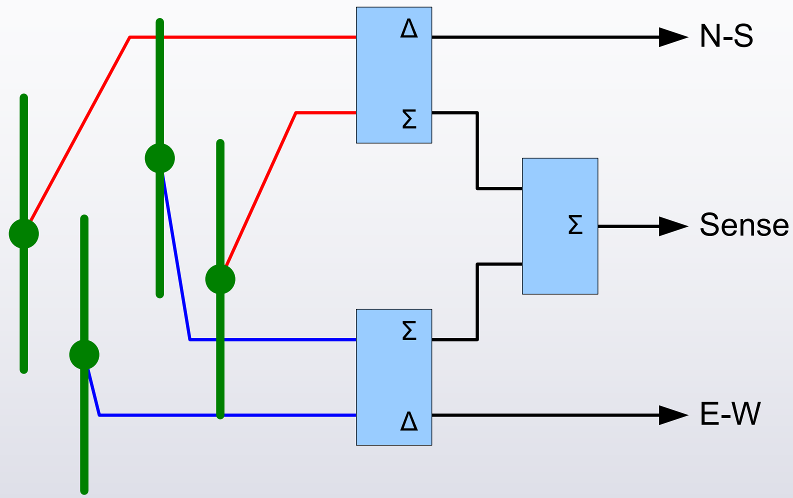
Traditional approaches to DF – Watson-Watt with Adcock antenna

- Adcock antenna can use the Watson-Watt principle
  - 4 antennas: monopoles or dipoles
  - 2 difference combiners are used to generate the N-S and E-W cos and sine patterns
  - Omni sense signal can be generated by an in phase combination of all antennas, or a fifth antenna
- 3 coherent receivers needed
- Accuracy still ~5° but much better than loops for skywaves



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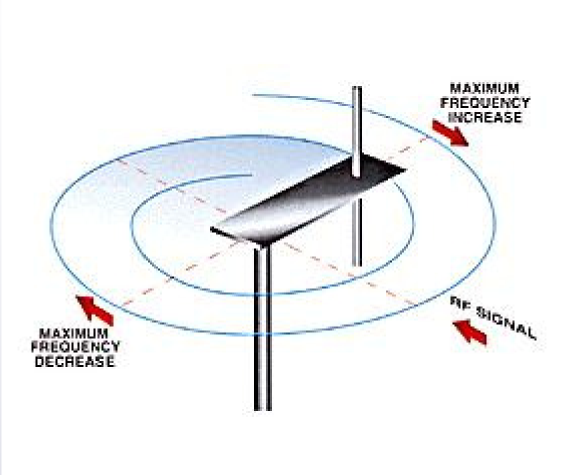
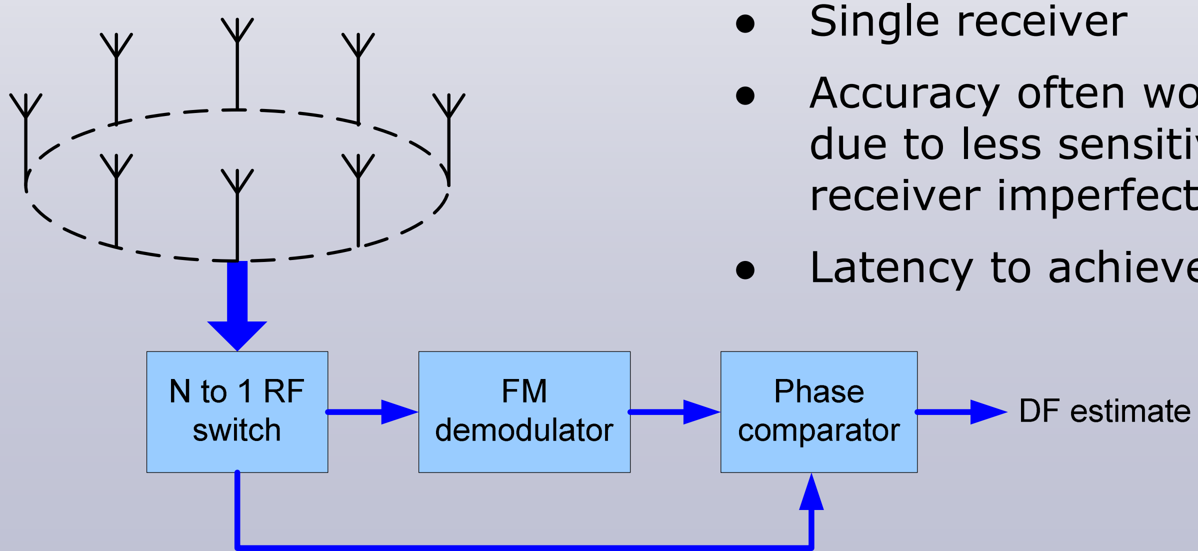
Traditional approaches to DF – pseudo-Doppler



- Pseudo-Doppler DF comprises
  - Circular array with a commutating RF switch to approximate the circular motion of a rotating antenna
  - The antenna signal is frequency modulated at a rate equal to the rotational frequency
  - After FM demodulation the rotational tone is recovered
  - The phase offset of the recovered tone compared to the original tone equals the direction of arrival
- Single receiver
- Accuracy often worse than Watson-Watt due to less sensitivity and intolerance to receiver imperfection
- Latency to achieve DF result



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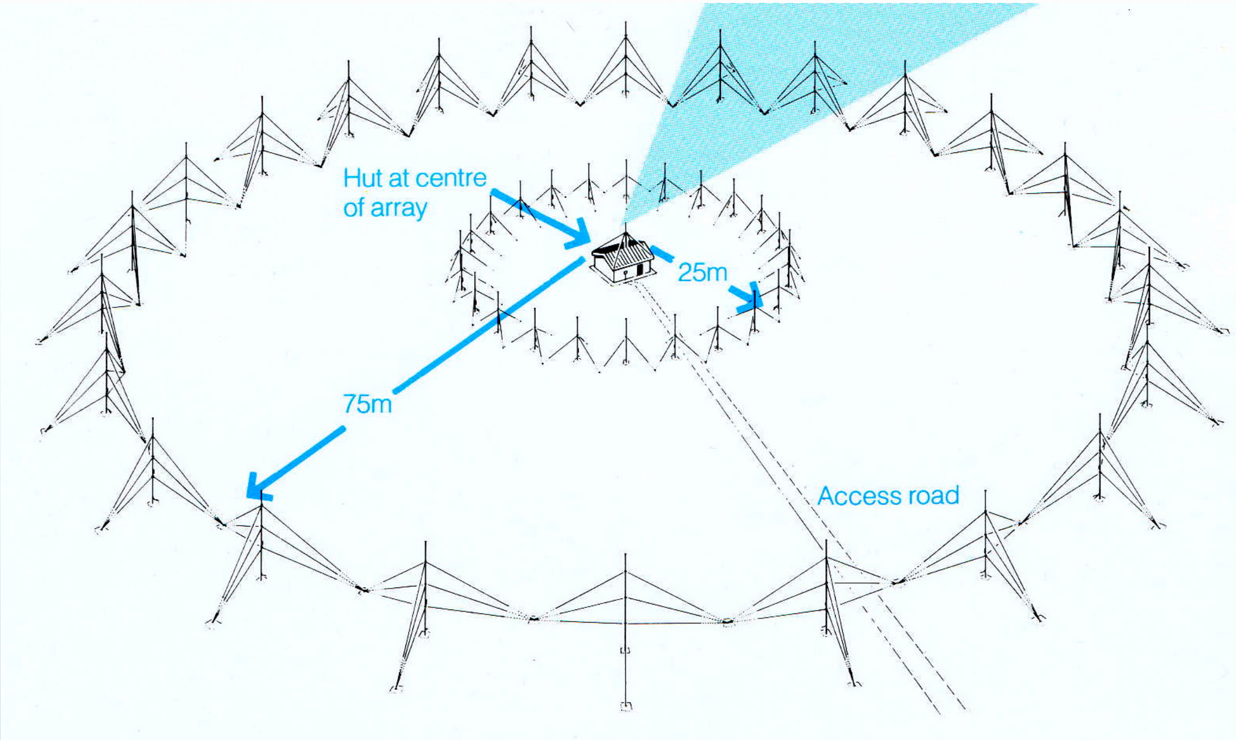
Traditional approaches to DF – array goniometer



- Pusher CDAA shown
- 24 antennas per ring
- Outer ring 3-10 MHz
- Inner ring 10-30 MHz
- Mechanical/analogue goniometer used to sweep a beam around 360° azimuth
- Single receiver
- Lots of equipment / expensive

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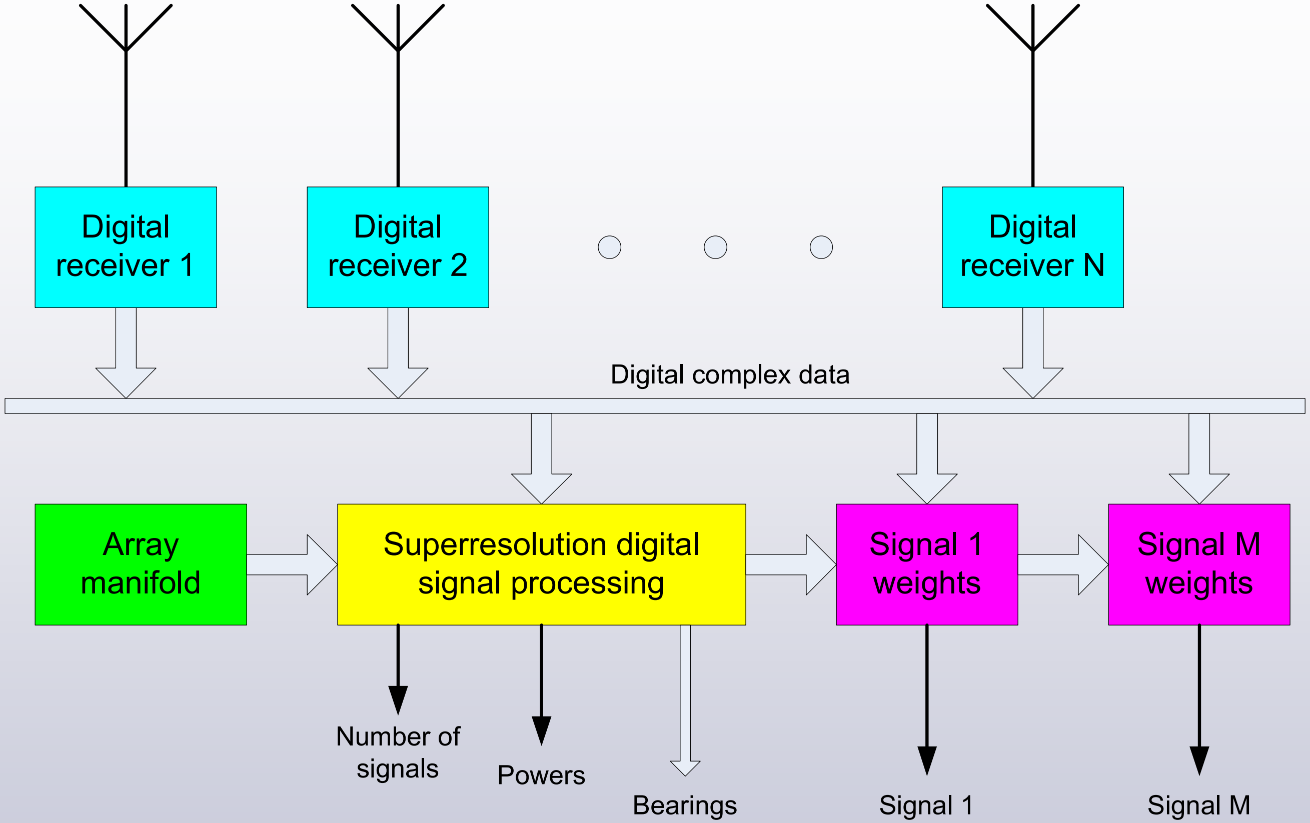
Superresolution DF – block diagram



- A good SRDF/ADBF system can solve the following:
  - Detection problem
  - Estimation problem
  - Reception problem

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Superresolution DF – for and against

- Superresolution means two signals can be resolved which are less than one beamwidth apart
- An antenna array is needed with multiple synchronous receivers
- Subspace techniques are applied to achieve superresolution
  – Requires knowledge of the array manifold
  – Multiple antennas and receiving equipment
  – More sophisticated digital processing
  + Order of magnitude increase in resolution
  + Increased DF accuracy (< 1° error)
  + Azimuth and elevation DF
  + Simultaneous DF of multiple cochannel signals
  + Operation with very few data samples
  + Not fixed to a particular array geometry
- The array manifold characterizes the antenna array and fundamentally sets how good it will be for DF
  - It is the known array calibration function against which the unknown signals are compared to find the lines of bearing

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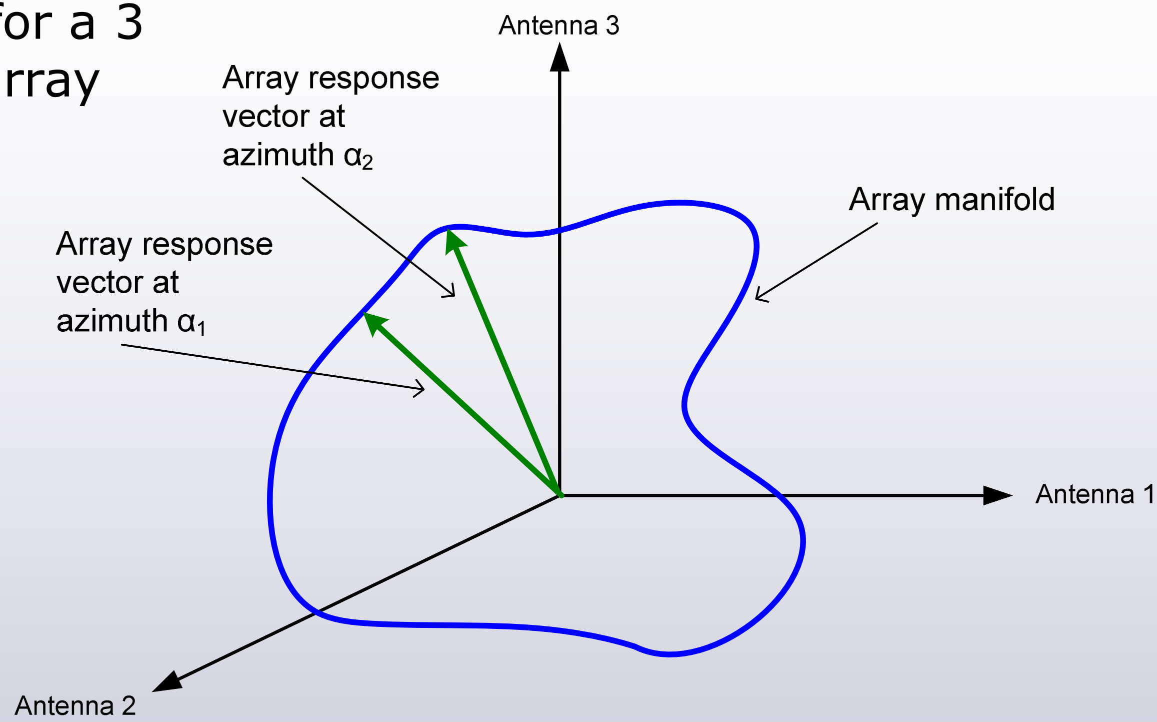
Superresolution DF – the array manifold

Example for a 3 element array



- For a signal arriving at the array from a particular direction, the set of relative gains and phases at the antennas defines an array response vector
- The array manifold is the locus (curve) of the complete set of array response vectors for all directions

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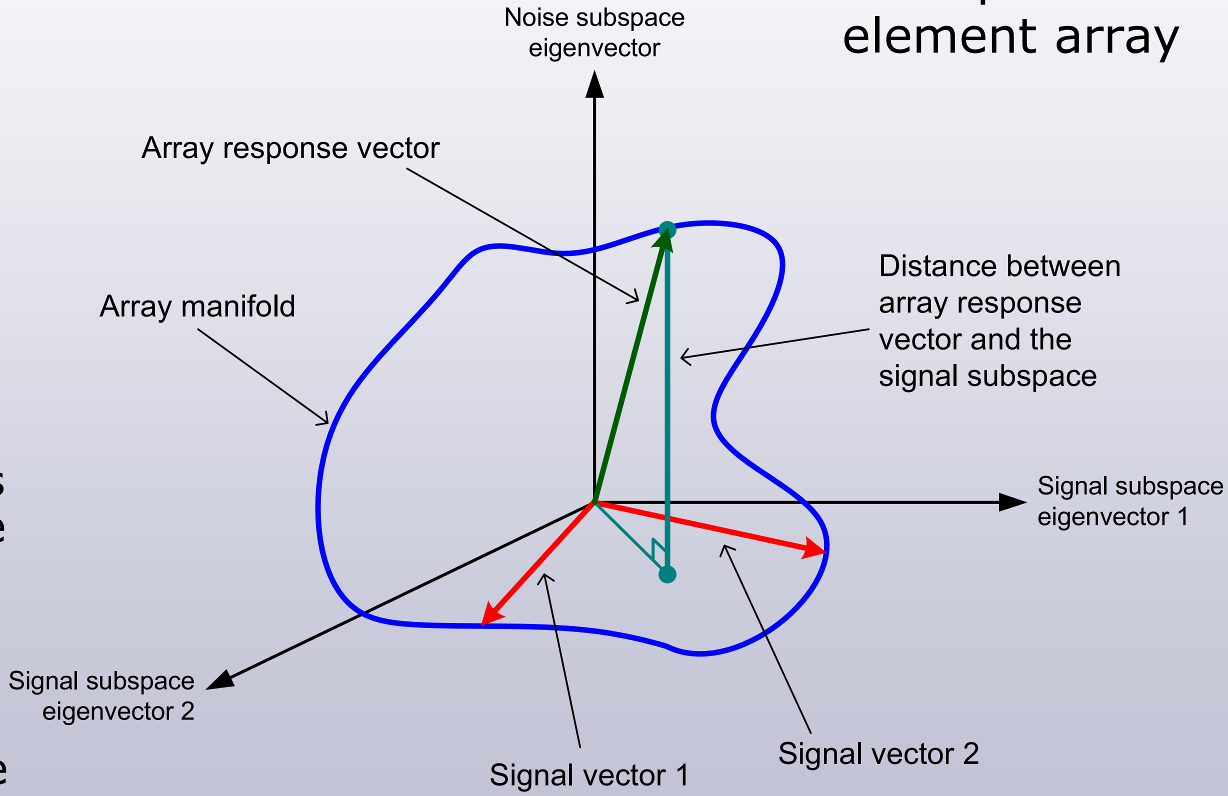
Superresolution DF – MUSIC algorithm

- There are many algorithms – Capon, MUSIC, ESPRIT, IMP …
- MUSIC is the most well known of the subspace techniques

1. Correlate the IQ data from each element with every other element to form the data covariance matrix
2. Eigendecompose the covariance matrix
3. Separate the noise and signal subspaces
4. Calculate the projection of the array response vectors for all directions into the signal subspace
5. Look for nulls in the projection function – when the distance between an array response vector and the signal subspace is at a minimum we have found a signal

Example for a 3 element array



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Antenna array design

- Array design is critical to DF performance – defines the array manifold
- Need an array which exhibits low levels of ambiguity
  - DF ambiguity occurs when an array has a similar response to signals which arrive from distinct directions
  - Grating lobes are perfect ambiguities, large sidelobes are also a problem
  - Ambiguity patterns are used to analyze different layouts
- Ideally arrays of aligned antennas are set up in clear sites to avoid polarization effects
- For difficult electromagnetic environments, additional array calibration and polarization processing are needed

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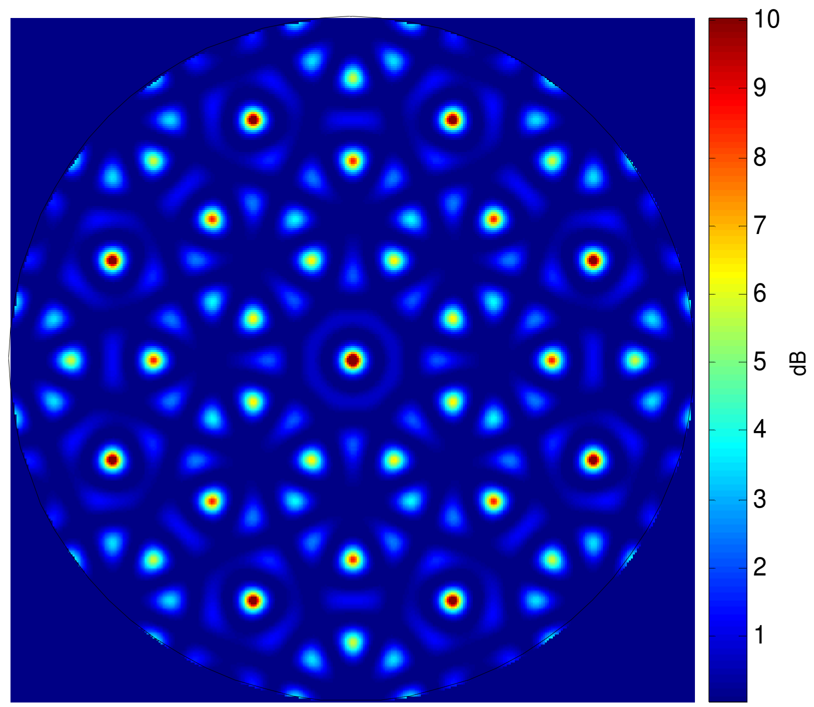
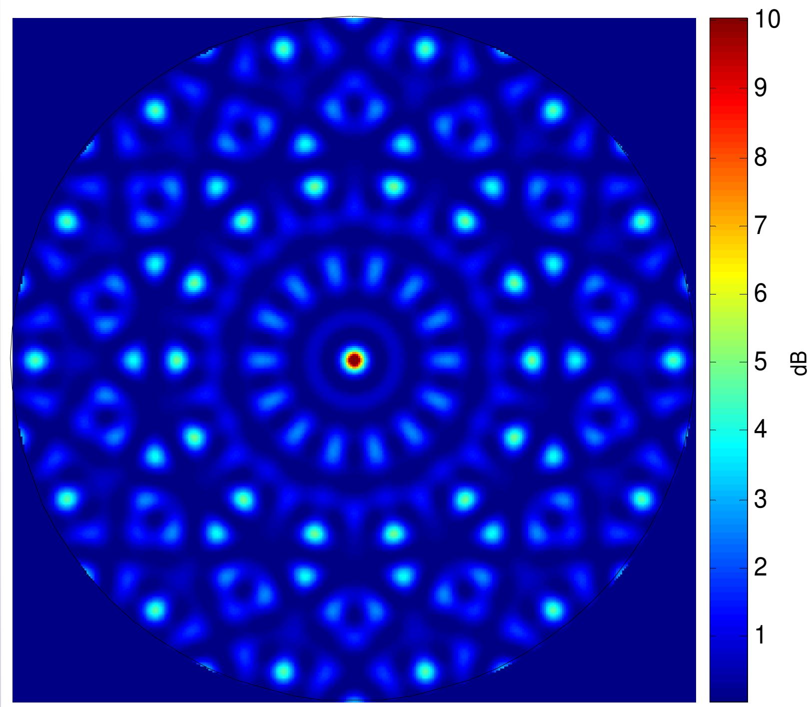
Antenna array design - clear array site ambiguity patterns



C8 array, 5λ aperture



C7 array, 5λ aperture

- Highly symmetrical C8 array has very poor performance
- C7 array is superior even with less antennas
- Array layout optimization is possible – simulated annealing

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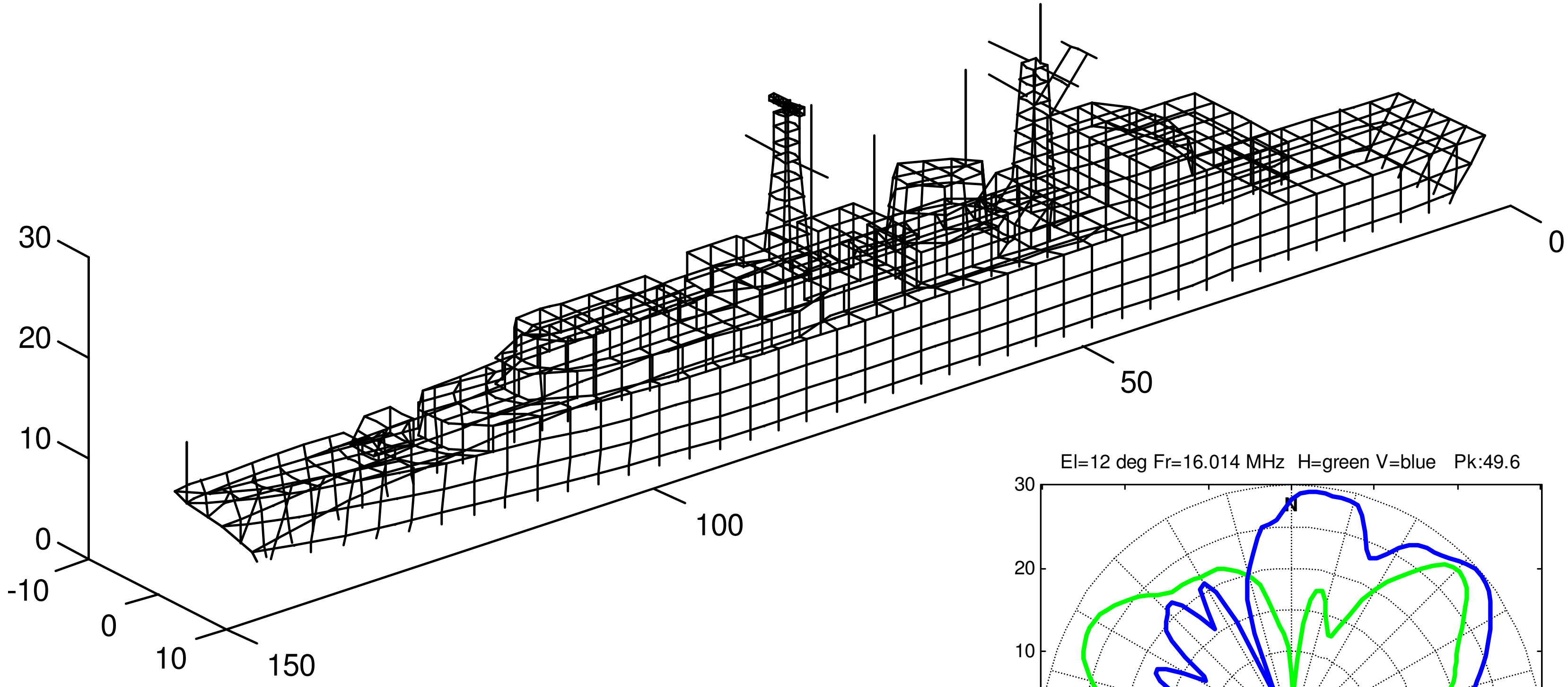
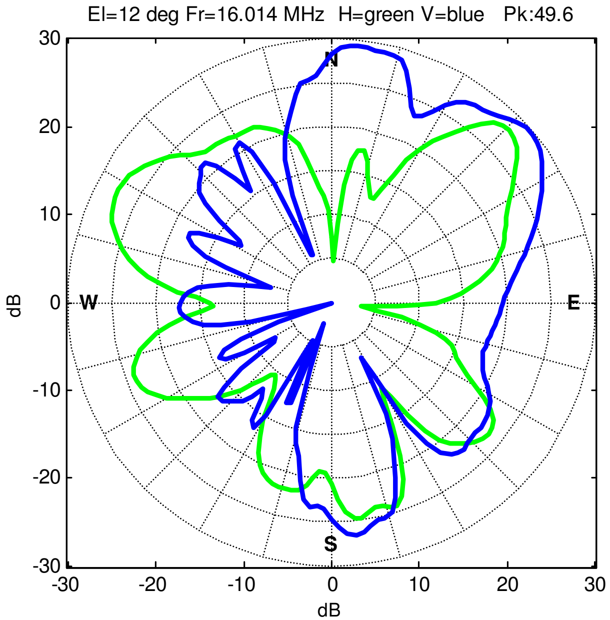
Antenna array design – EM modelling for difficult environments



- NEC model of a Type 22 frigate
- Radiation pattern for a deck edge loop antenna @ 16 MHz
- Diverse V and H polarization response
- Skywaves usually have unknown polarization



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HF array elements

- Antennas can be passive or active
- Generally inefficient antennas are used for DF
  - Keeps the size down
  - Low mutual coupling – reduced effect on the array manifold
- Monopoles are more practical than dipoles
  - Smaller physical size
  - Monopoles need to work against the ground plane, no need to elevate
- Loops can also be used
  - Good for higher elevation skywaves
  - Suitable for NVIS

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HF array elements – Sarsen crossed loop

- Sarsen antenna for strategic fixed sites
  - Requires a poured concrete footing
  - Feed cables typically run underground and enter the antenna underneath the main pillar
- Omnidirectional, broadband elements (1-30 MHz)
- Simultaneous or switched vertical monopole and cross loop outputs (RHCP and LHCP)
- Monopole primarily for 0-45° elevation, cross loops for 25-90° elevation
- Ground mesh and 8 ground radials with ground rods ensure a good ground for the elements to work against

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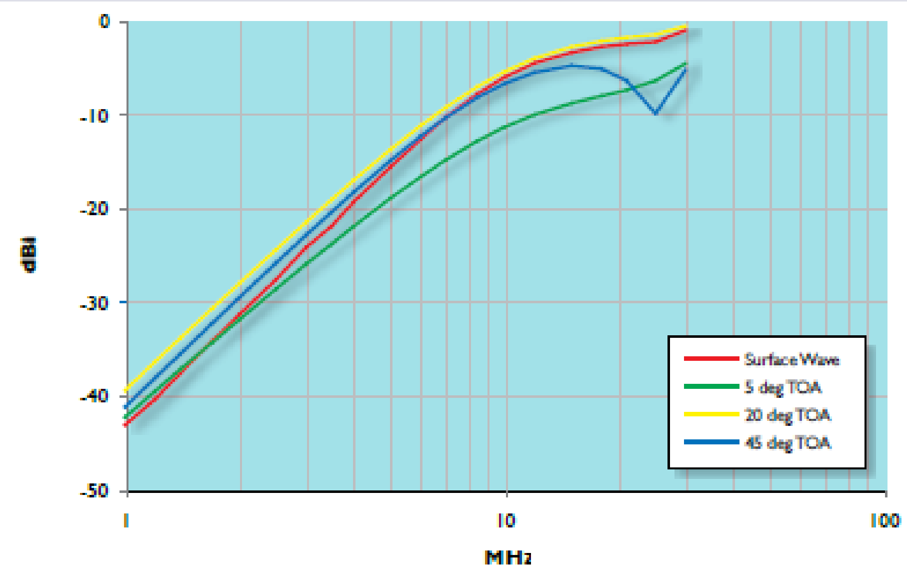
HF array elements – Quadrant crossed loop

- Quadrant antenna for tactical sites
  - Self supporting
  - Fibreglass and aluminium construction, weight < 35 kg
  - Deployable in 90 s
- Monopole gain falls off at low frequencies – this is typical for broadband receive only antennas



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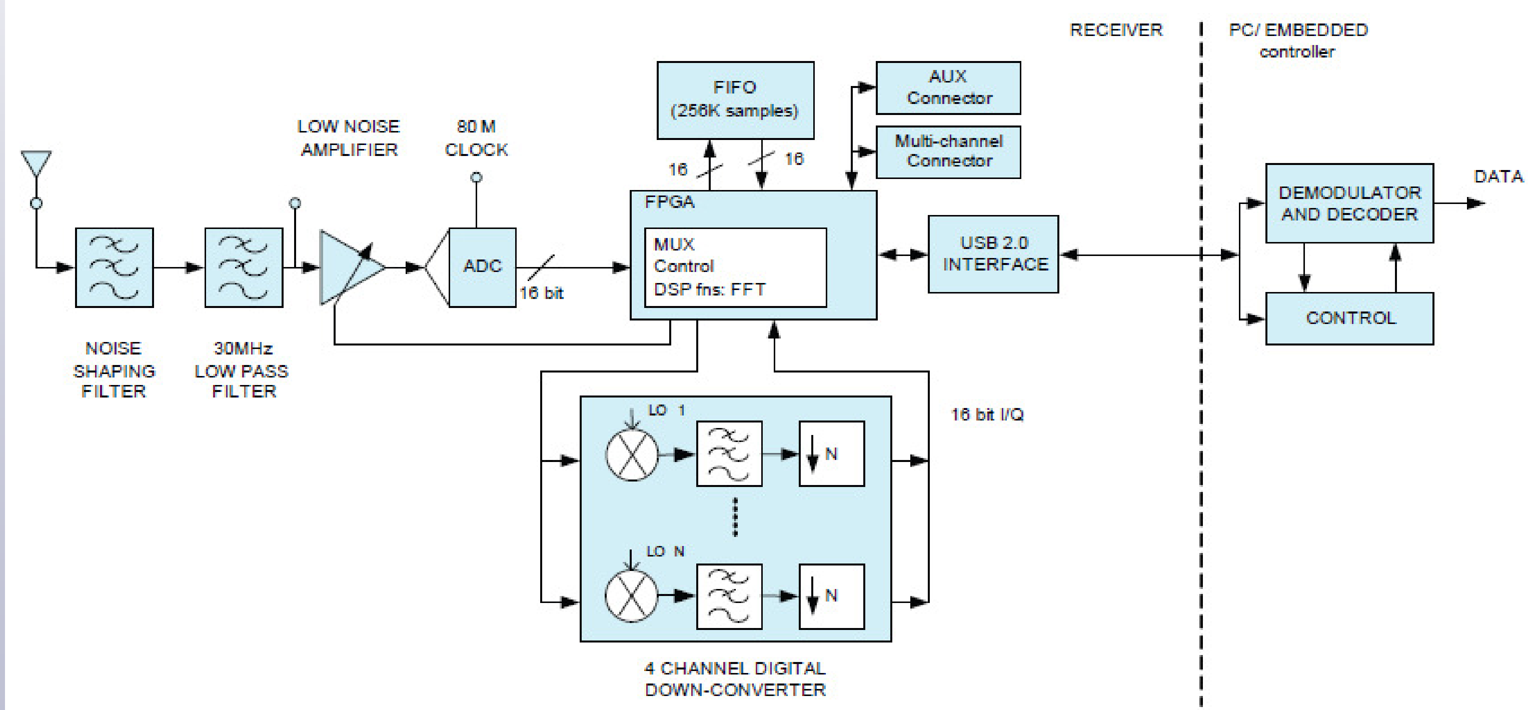
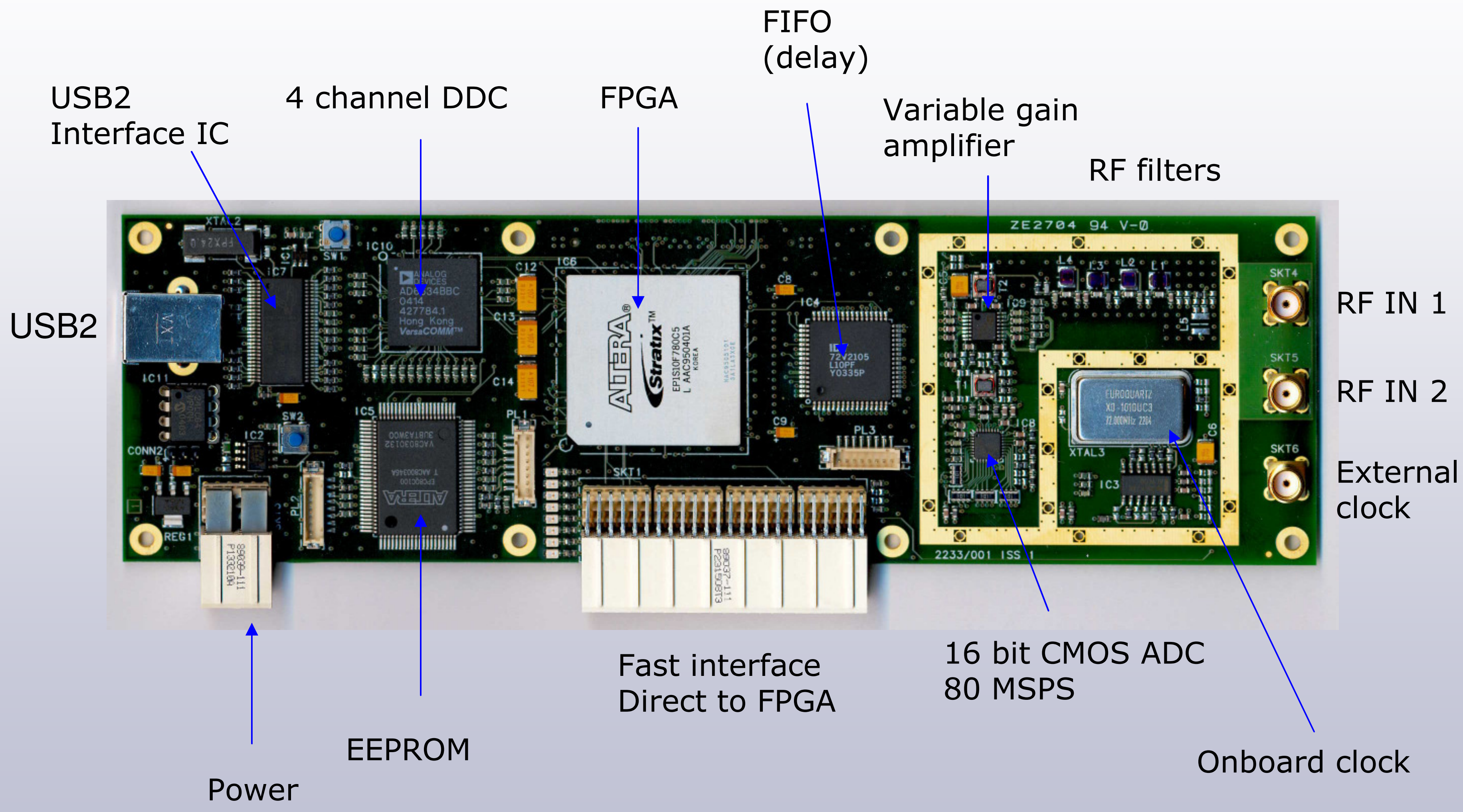
Digital receivers – DWR16

- 30 MHz wideband spectrum monitoring
- 4 independent DDCs each provide a 32 kHz narrowband channel
- RF in, sampled IQ data out over USB2.0
- High linearity, no images from LOs and mixers, high dynamic range



Digital receivers – DWR16 PCB



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Digital receivers – DWR16 GUI

- FFT and spectrogram displays
- DDR control
- Power level monitoring
- Software demodulation
- AGC settings
- Data recording and playback

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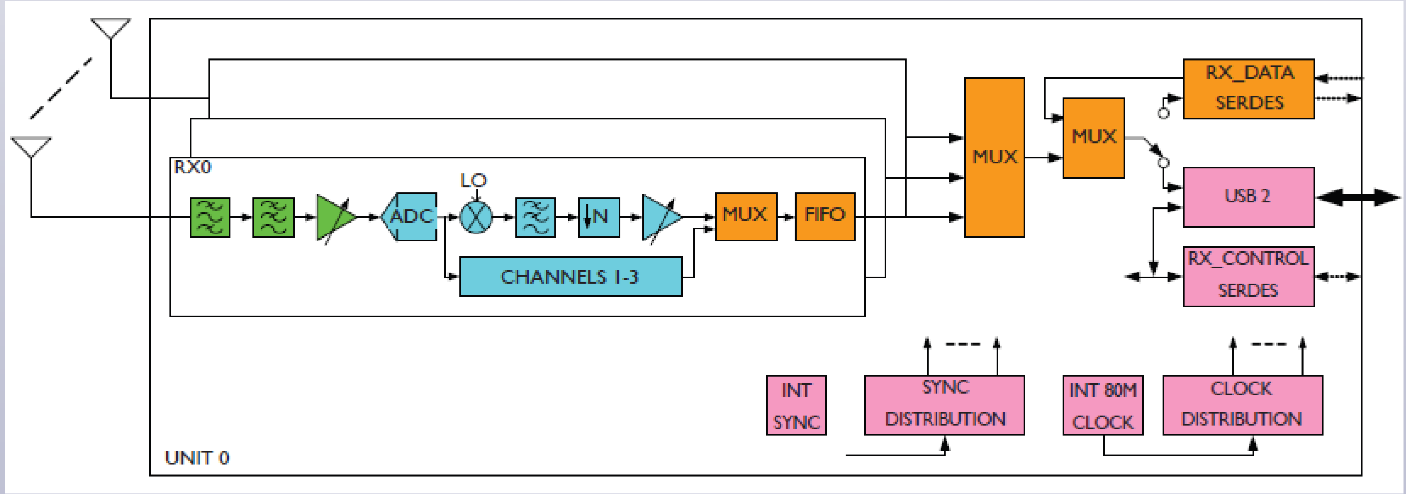
Digital receivers – MCDWR16

- 9 DWR16s in a 2U, 19” box
- All channels are synchronized, coherent sampling
- Two units can be linked together to support 16 antenna DF systems
- Two USB2.0 outputs
    - Channels 1-8 narrowband DF
    - Channel 9 wideband monitor



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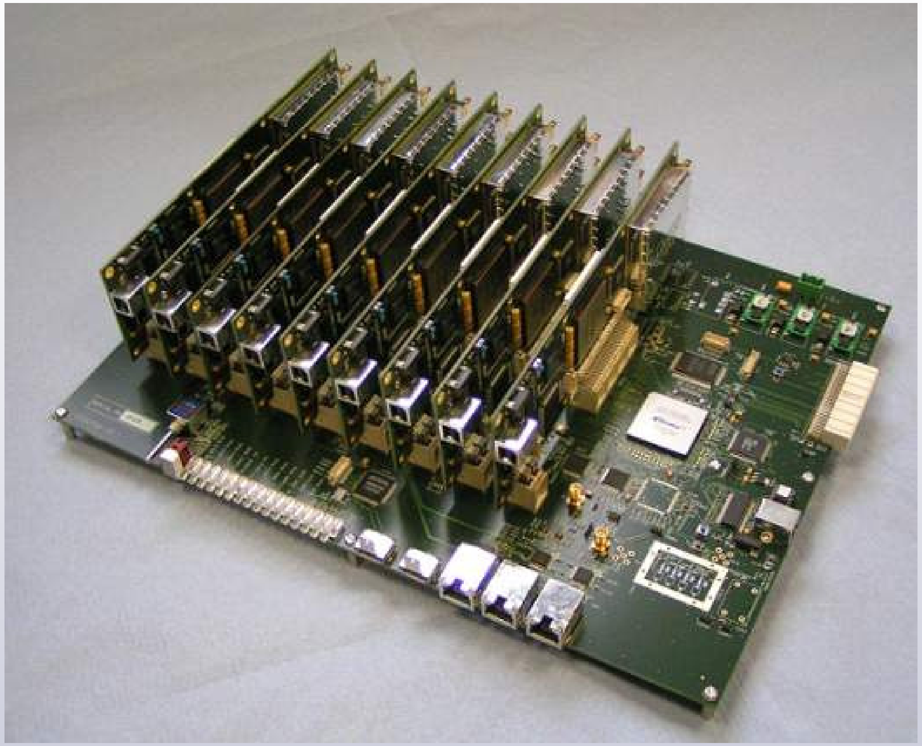
Digital receivers – benefits of N channel direct digitization

- Near instantaneous signal acquisition
- No calibration required
- No need for multiple coherent local oscillators
- Supports DF on short duration / frequency hopping signals
- Can support reconstruction of frequency hoppers



- Provides broadband beamforming without the need for large coaxial cable delay lines
- Supports ADBF for enhanced signal copy
- N channels provides 10logN dynamic range enhancement

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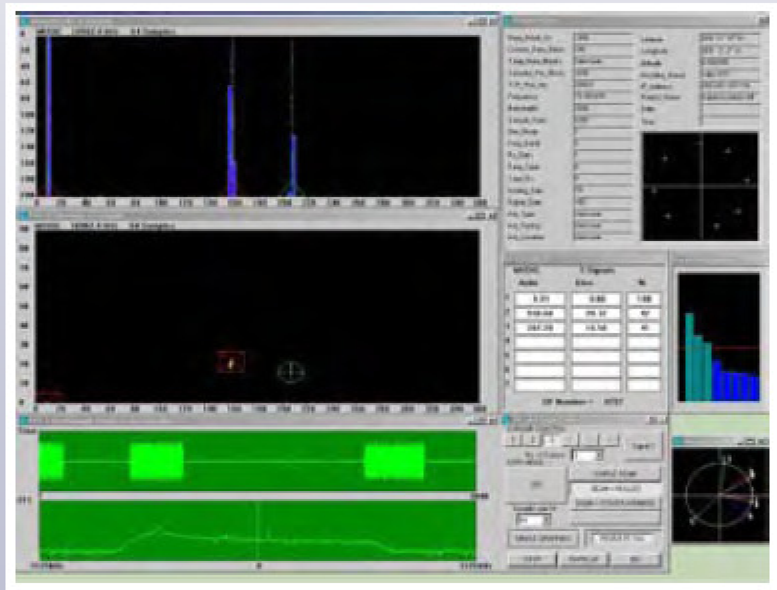
SRDF software

- DF processor is receiver independent, the data server handles the receiver interface and outputs packets over TCP/IP
- Up to 4 independent DF processors can run simultaneously – supports the 4 DDRs in the MCDWR16
- MUSIC DF algorithm for azimuth and elevation estimation of multiple cochannel signals
- 4 different ADBF algorithms



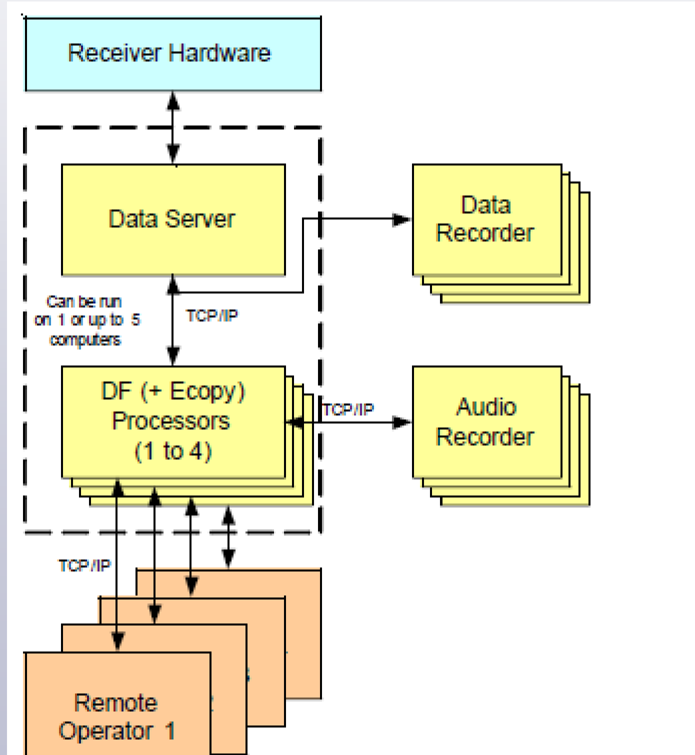


Figure 6: SRDF Software Architecture

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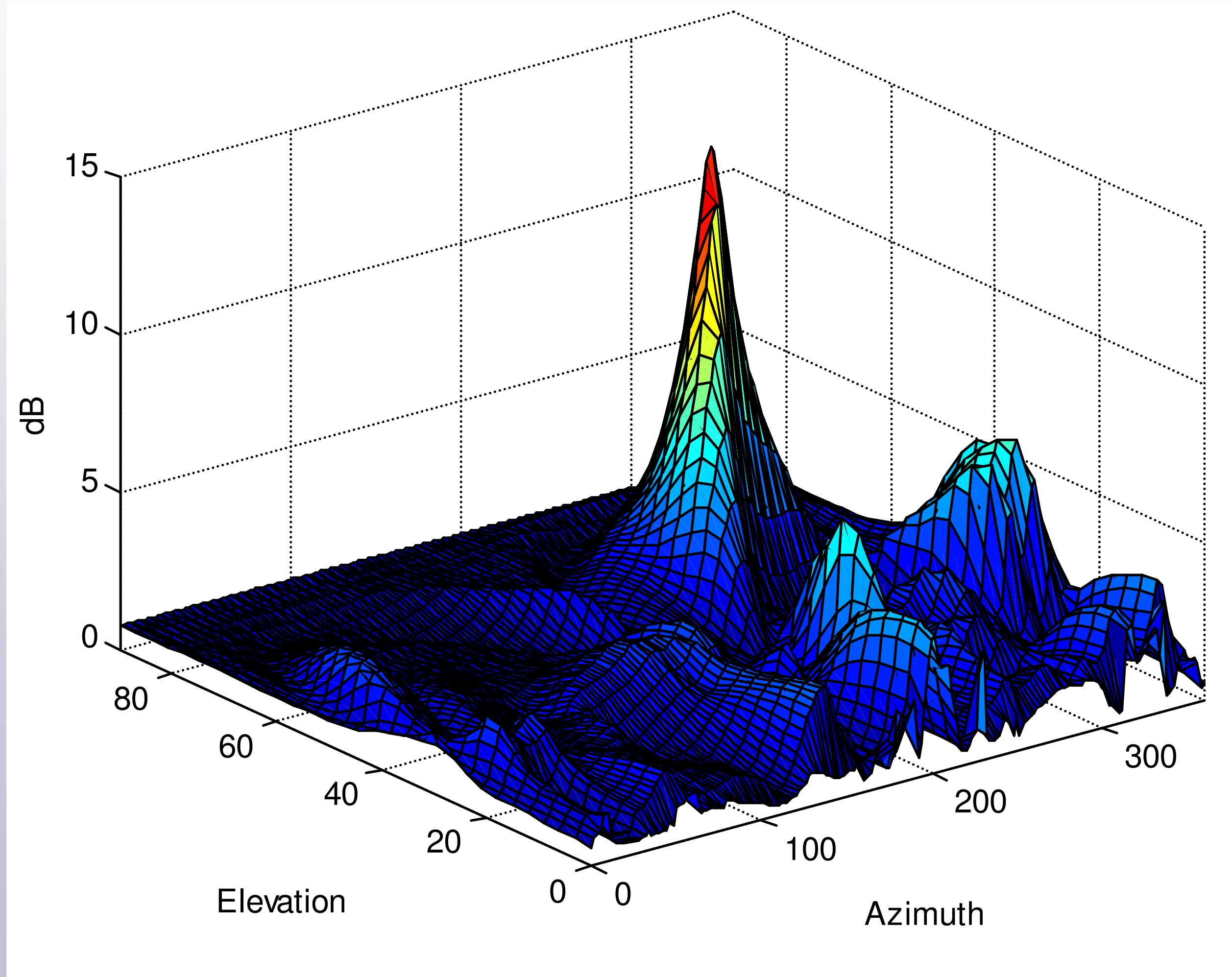
SRDF software – MUSIC result

- Single signal incident upon the array: 250° azimuth, 60° elevation
- MUSIC is akin to steering nulls rather than beams, so the resolution is greater



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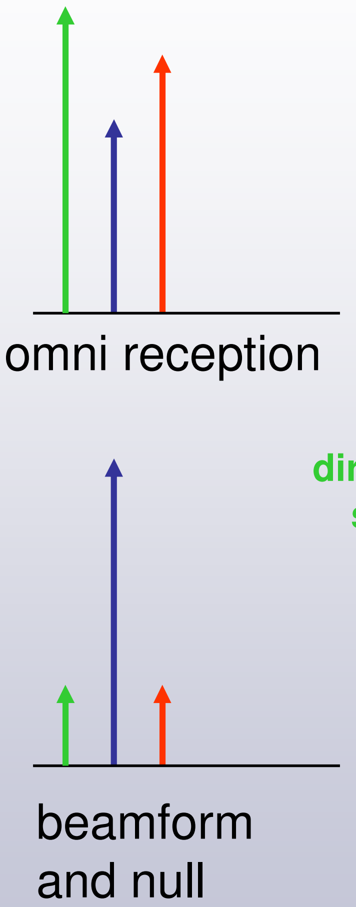
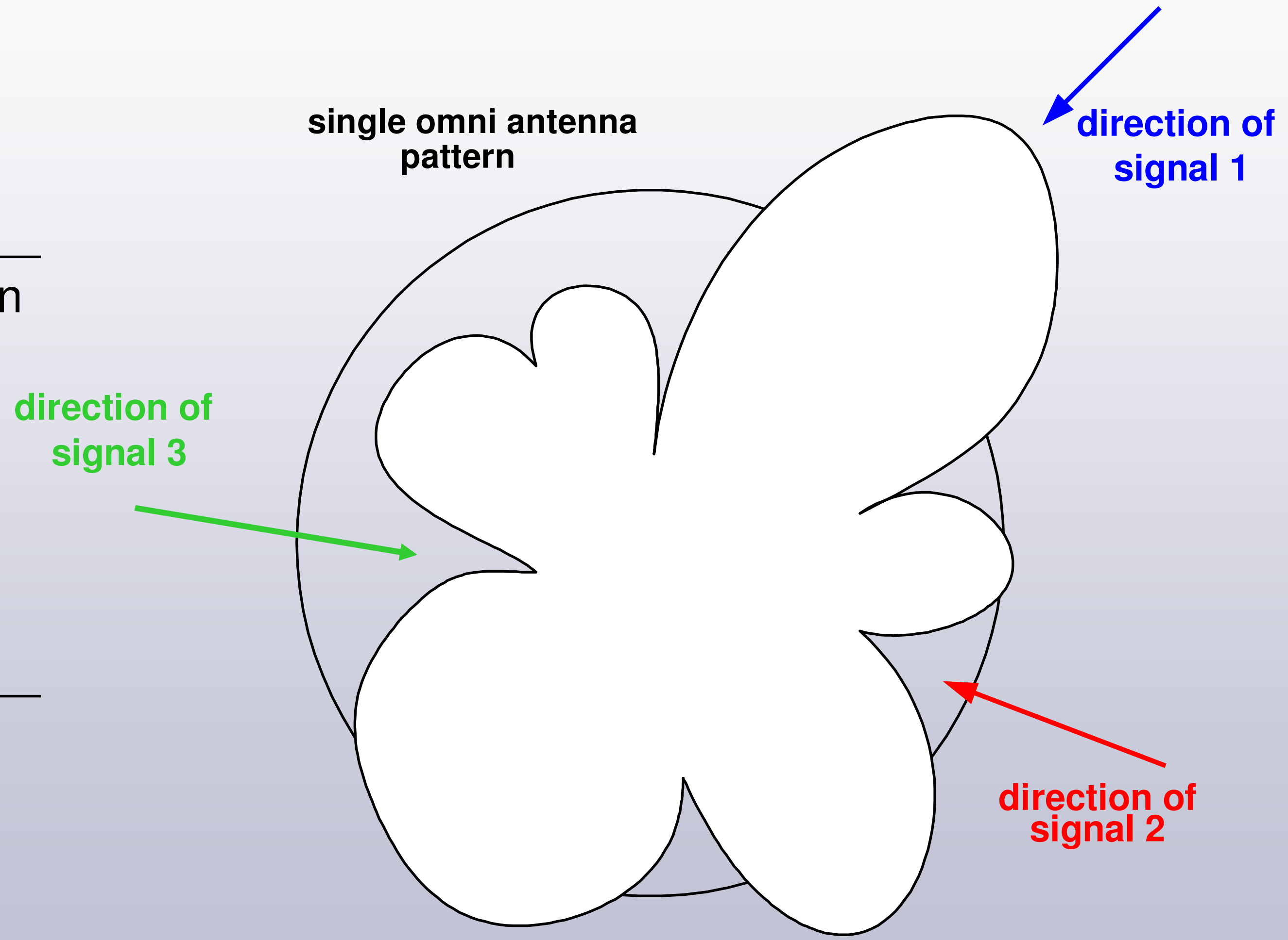
Adaptive beamforming for signal separation





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Adaptive beamforming for signal separation

- Conventional beamforming sets the array steering weights equal to the array response vector for the signal direction
  - 10logN improvement in the SNR for the wanted signal
  - Interferers reduced to the beam pattern sidelobe level
- Beam plus nulls takes the conventional beamforming weights and projects them to be orthogonal to the interferer subspace
  - 10logN improvement in the SNR for the wanted signal
  - Superresolution with regards to interferer cancellation
  - In theory very high levels of cancellation, in practice 15-20 dB occurs due to errors in the array manifold
- Steer a beam plus minimize the output power: Wiener-Hopf solution
  - 10logN improvement in the SNR for the wanted signal
  - Maximizes the SINR
  - Works best for strong interferers, can provide 40 dB of cancellation
  - Can attenuate the wanted signal if the beam constraint is erroneous
- Higher Order Statistics methods not based on DF results
  - Needs larger data blocks to accurately estimate the statistics
  - Good nulling even when there are significant DF errors

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SRDF and ADBF demonstration

8 element array in New Hampshire

3 cochannel signals centred on 16 MHz

1. Over-modulated AM jamming signal north of array (10° azimuth)
2. Morse signal from Havana Cuba
3. 75 baud FSK teletype from Fort-de-France

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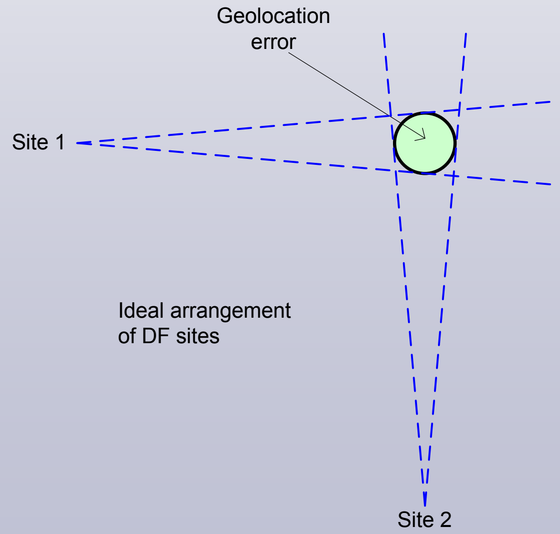
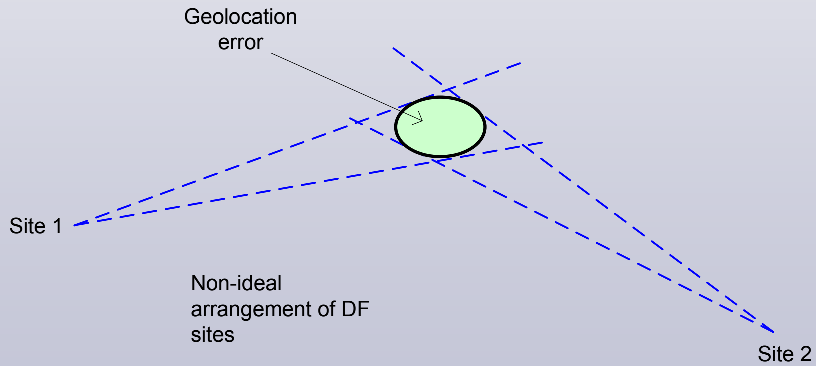
Geolocation systems - triangulation

- The intersection of lines of bearing from multiple DF sites defines a region where the transmitter is located
- Azimuth triangulation errors depend on
  - Lateral azimuth error on individual lines of bearing
  - Number of DF sites reporting
  - Locations of the DF sites relative to each other
- In general the 2 site geolocation error is an ellipse, defined by the lines of bearing RMS azimuth errors





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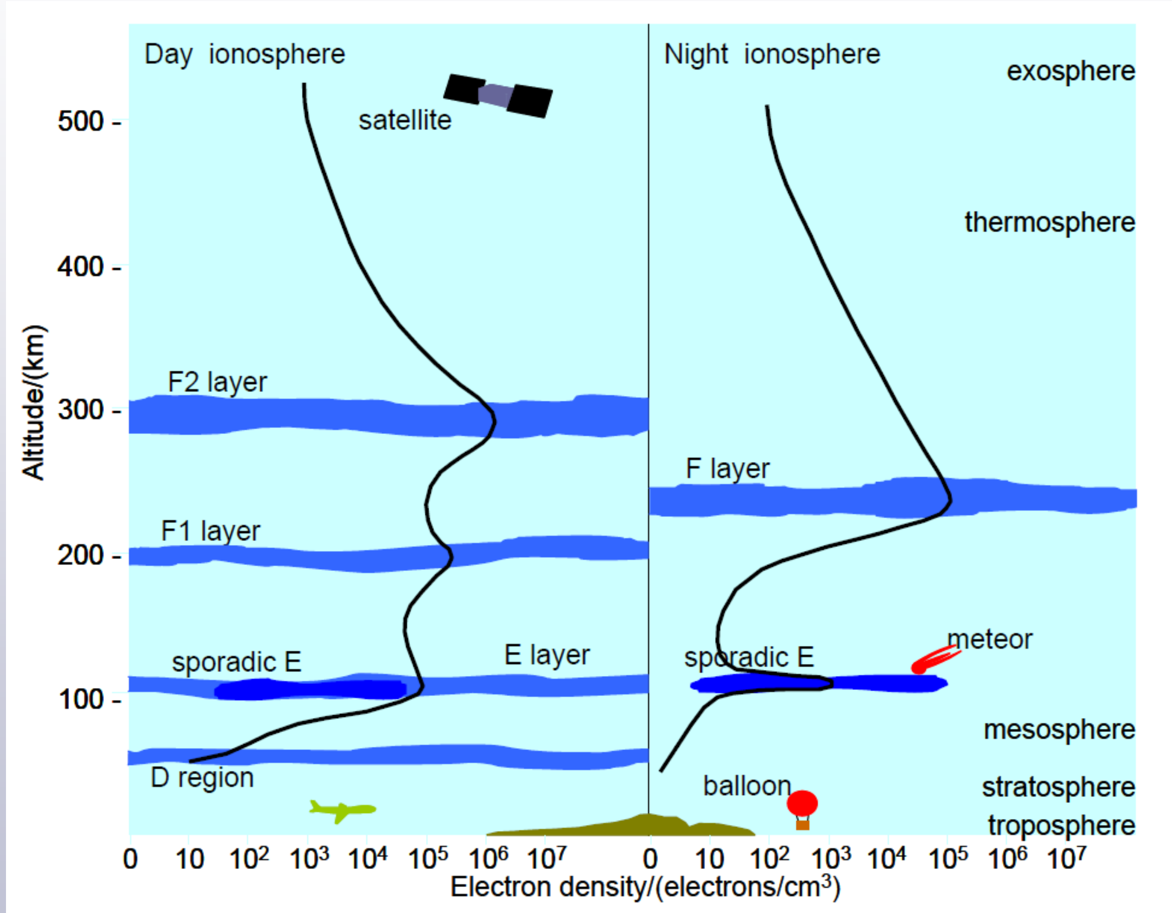
Geolocation systems – single site location

- Single site location of skywaves is feasible if there is knowledge of the ionosphere
- F2 layer is the most important for skywave refraction
- D layer tends to absorb HF waves
- Large variations between day and night
- Variation with the sunspot cycle
- MUF determines which layer is active for the signal of interest
    - Critical frequency
    - Elevation angle



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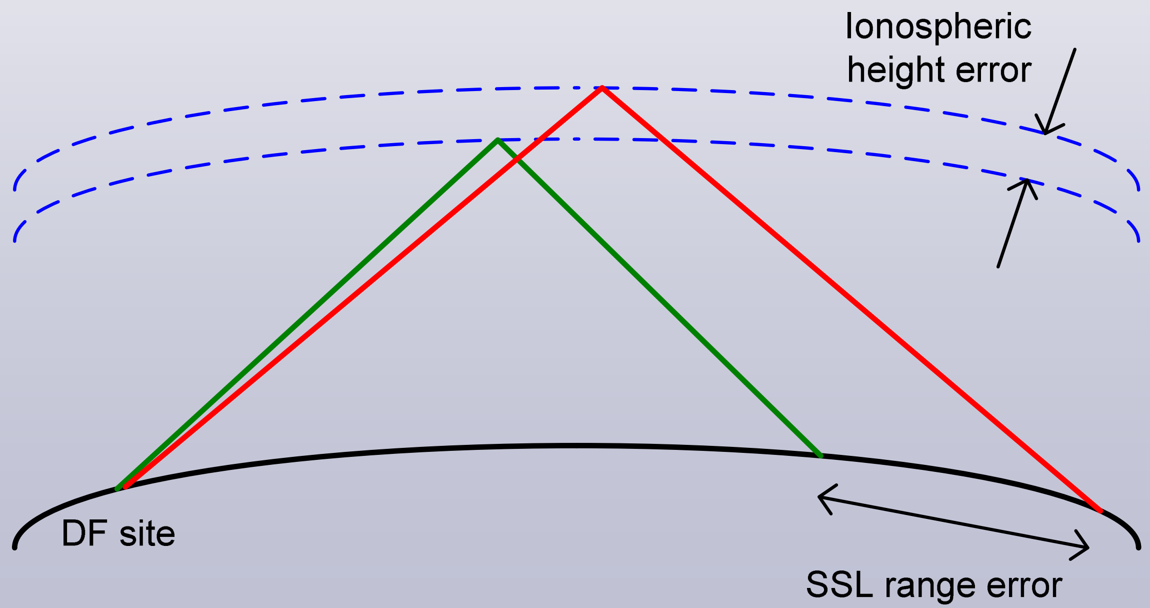
Geolocation systems – single site location

- Usual assumption is that a single hop has occurred, typically up to 1000 km range, but could be up to 3000 km range
  - Use an ionosonde to measure the ionospheric height
  - Use a model to predict the ionospheric height
- Geolocation accuracy depends on
  - Azimuth RMS error
  - Elevation RMS error
  - Ionospheric height error
  - Validity of the single hop assumption



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Concluding remarks

- Conventional HF DF techniques were developed during WWII
  - Simple amplitude comparison techniques
  - Adcock antenna to handle skywaves
- Superresolution processing first developed during the 1980s
  - Increased resolution and accuracy
  - Multiple signals
- Practical SRDF systems did not appear until the 1990s
  - More complete understanding of the array manifold and DF ambiguity
  - Array, cable and receiver calibration requirements
  - High quality digital receivers
- Current SRDF systems harness technology developments in
  - Optimized antenna array layout
  - Compact antenna designs with multiple elements
  - N-channel wideband digital receivers
  - Powerful signal processing in PCs and DSPs
- SRDF systems are far more capable than conventional systems and are increasingly cost effective

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Build a DF system

- Watson-Watt method with loops is simple but effective
- At a minimum need
  - 2 loop antennas, orthogonally mounted
  - 2 HF receivers, can be low cost COTS, needs a digital output
  - Simple DF processor implemented in software in a PC
- WinRadio or GNU radio? Direct PC interface
- Things to remember
  - Need coherent receivers – locked LOs/clocks
  - No AGC, or at least synchronized AGC across the receivers
  - Receiver calibration is needed if the RF filters are not consistent between receivers

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