

Airborne Radar and the Communications Revolution

An adaptation of the IET Watson-Watt Lecture
2007

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Scimus

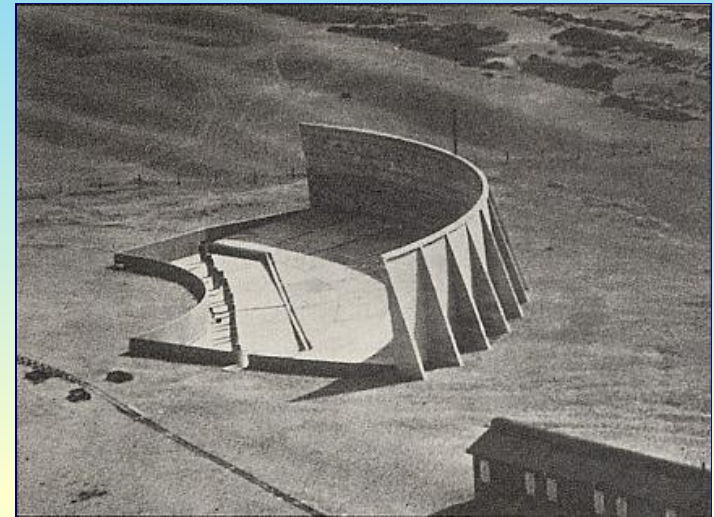
Thesis

- ❑ Radar is such an attractive subject precisely because of the diverse technical scope it contains. Using DC to light, all the disciplines of electrical science are involved in radar.
- ❑ It is not surprising that this comprehensive subject, privileged by military expenditure should be a candidate for cross-fertilisation with other subjects, but, in fact the connections between radar and communications today are more profound than they seem.
- ❑ The motivation for looking more deeply at them is that to do so stimulates invention. If we understand the path we have travelled we may better find the path that lies forward.
- ❑ In the next 45 minutes I will very briefly sketch the origins of radar in the UK, and move to the contemporary connections between radar and communications – what I call the “virtuous circle”. I will use this as a basis for pointing out some directions for

The Background to wartime radar

- ❑ In the first world war, the bomber aircraft was largely ineffective. By 1935, as Germany re-armed under National Socialism and another war in Europe seemed likely, it was well recognised that improvements in speed, load capacity and endurance would make the bomber a formidable weapon in any new conflict.
- ❑ It was impractical to keep fighter interceptors in the air continuously and even if it were possible, they still couldn't find the bomber target.
- ❑ The only means of detecting bombers were visual or acoustical – concave concrete sound mirrors up to 200ft in length, listening to the sea.
- ❑ With conflict looming, Britain did what it always did – it formed a committee. It happens to have been the most effective committee ever. The terms of reference were;
“to consider how far recent advances in scientific and technical knowledge can be used to strengthen the present methods of defence against hostile aircraft”

Early Warning before the "Chain Home" radar fence



1904, The TELEMobiloscope, Patent 165546 Christian Hulsmeyer, Dusseldorf

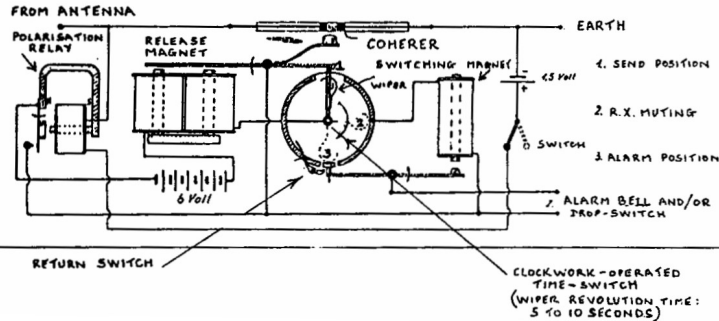
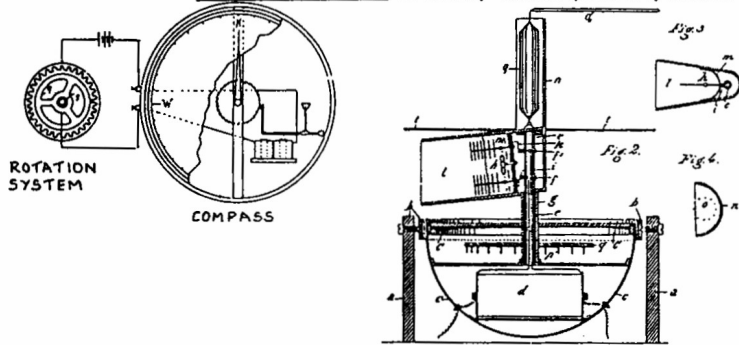
THE TELEMobiloscope 1904

OF CHRISTIAN HÜLSMEYER, DÜSSELDORF, DRP. 165546, 169154



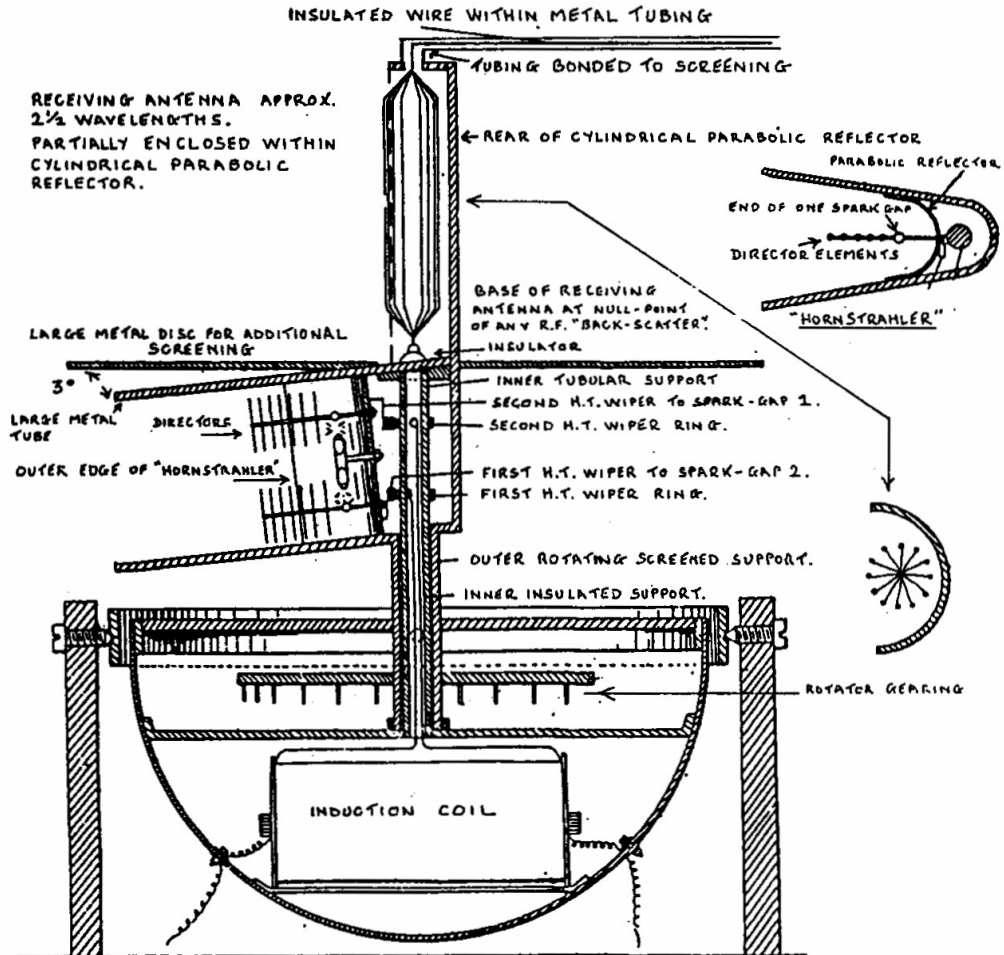
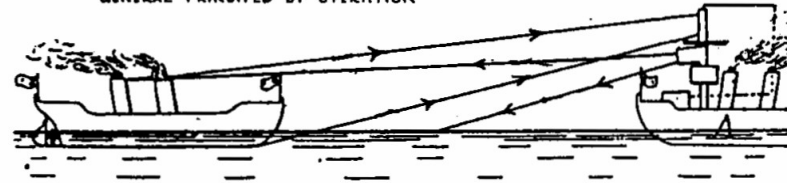
APPARATUS FOR DETERMINING POSITION AND RANGE OF NEARBY MOVING METALLIC OBJECTS (SHIPS, WRECKS, SUBMARINES, ETC.) THROUGH AUDIBLE AND VISUAL SIGNALS.

GERMAN REG. PATENTS No 165546, 30.4.1904, 6.169154, 11.11.1904.

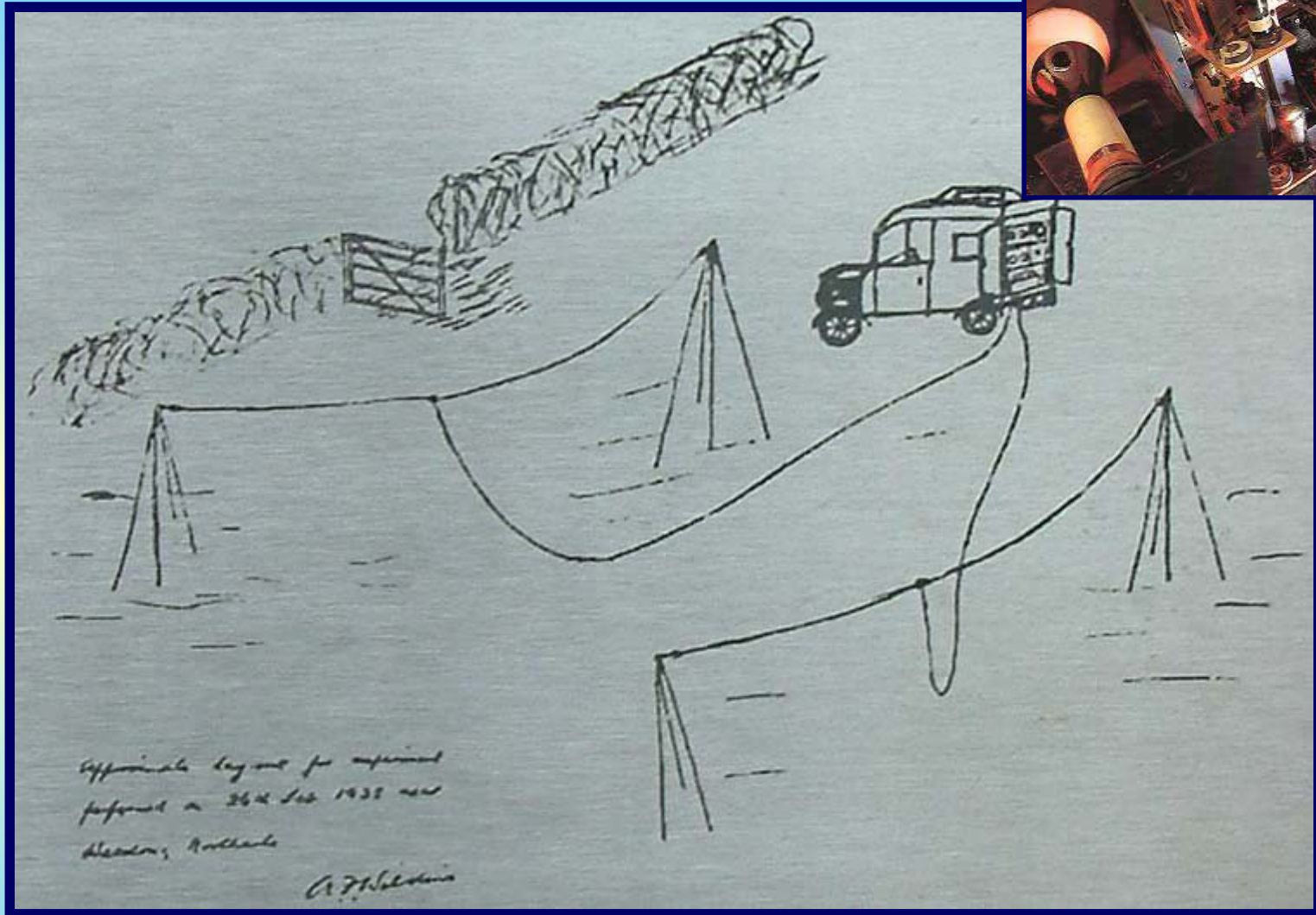


- ❑ Gimballed assembly
- ❑ Spark-gap transmitter
- ❑ ~50 cm wavelength
- ❑ "Yagi" transmit antenna
- ❑ Cyl. Parabolic Receive antenna

GENERAL PRINCIPLE OF OPERATION



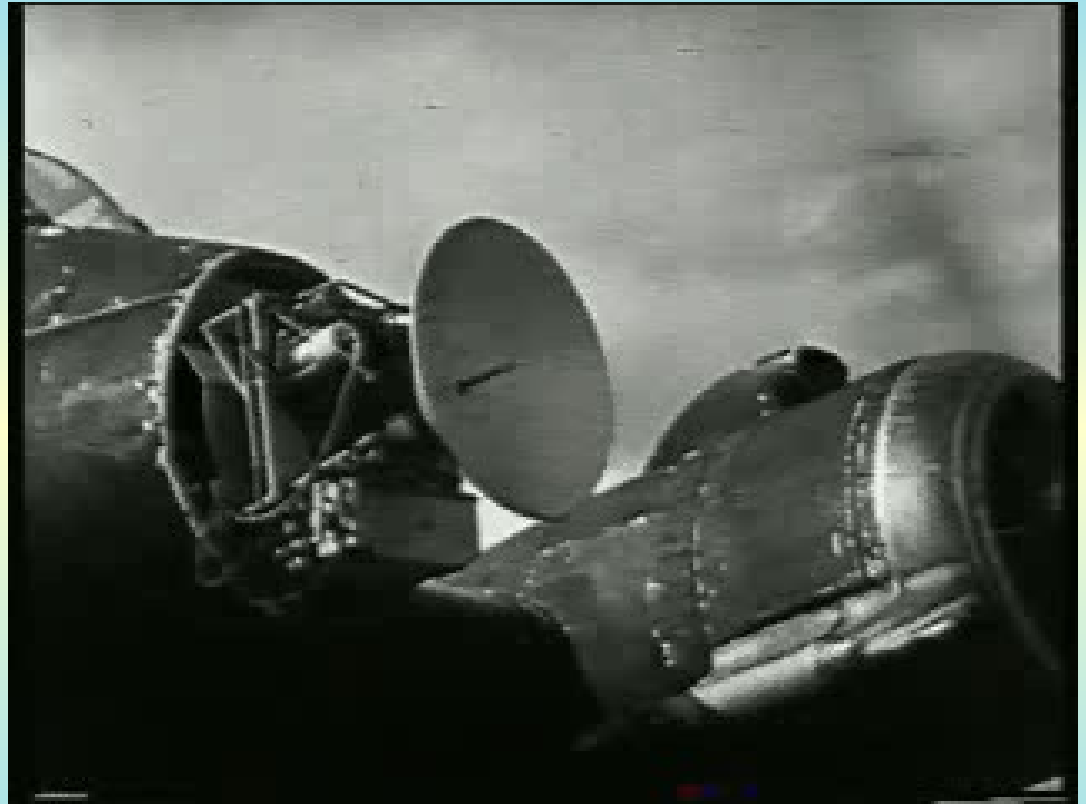
The Daventry Experiment, 26th February 1935



- ❑ BBC Empire Radio transmitter at Daventry gave a useful test beam of 30° Azimuth x 10° elevation on 49m wavelength,
- ❑ The beat caused by a Heyford bomber was clearly detected at 8 miles distance.

A.I. radar began as a means of guiding fighters - 1945

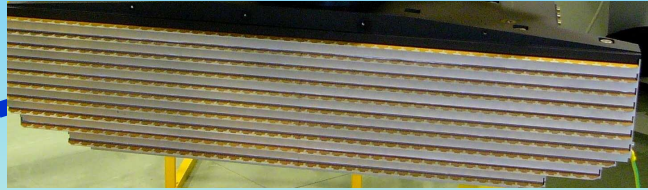
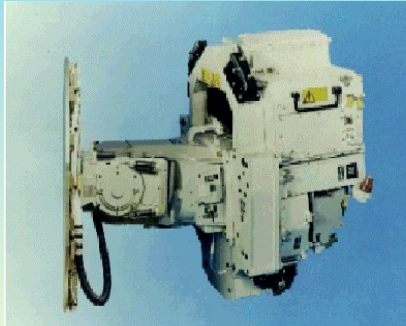
- ❑ Night interception of bombers is impossible without radar guidance.
- ❑ By 1941, fixed-beam VHF systems were installed on night fighters on both sides.
- ❑ Following the invention of the magnetron and the Tizard mission to the US, microwave radars of US manufacture were available.
- ❑ By the end of the war, we begin to see microwave radars fitted as standard.
- ❑ Short pulses (1 μ sec at a PRF of 1kHz.) and some bizarre scanning arrangements.



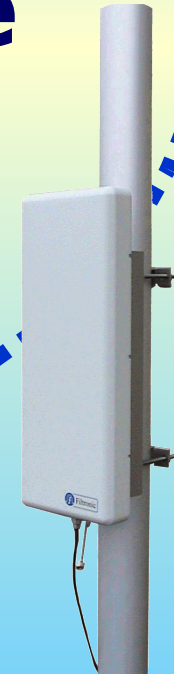
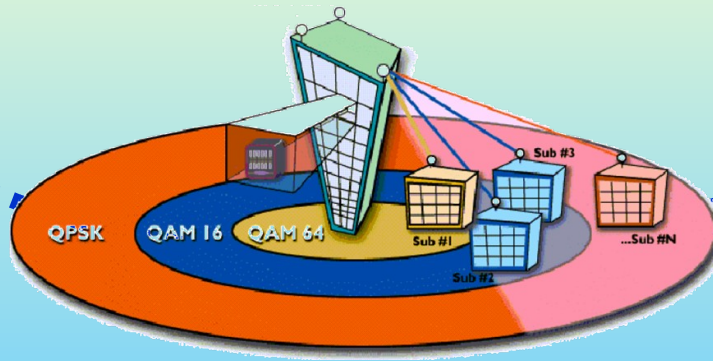
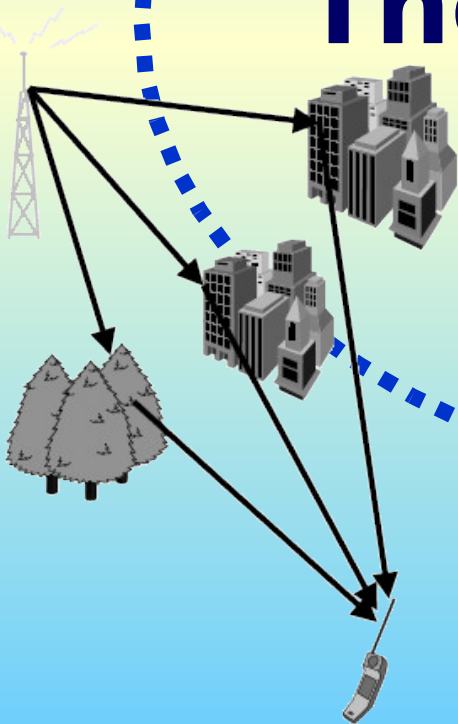
A.I. Mk 8

MIT Lincoln Labs, JPL and Malvern

- ❑ The British wartime effort fuelled developments in the US. The British development of the magnetron saw the formation of the Radiation Laboratory, later the Lincoln Laboratory at MIT and technical progress as swift as in Los Alamos on the nuclear bomb.
- ❑ The 1950's saw the publication of much of the classified wartime effort, the Matched Filter, the Weiner Filter, and Claude Shannon's monograph on Information Theory with application to communications.
- ❑ In the 1960's, prior to accessible digital technology, major US programmes for planetary mapping and ballistic missile tracking laid the practical framework for modern communications,
 - ❖ Pulse compression – spread spectrum.
 - ❖ Coherent signal integration.
 - ❖ M-sequence codes, Golomb, Viterbi and Gold codes.
 - ❖ The concepts of correlation detection.
 - ❖ False alarm control and automatic detection
- ❑ In this framework Philip Woodward at Malvern invented the Ambiguity Function and put radar resolution and accuracy of measurement on a sound basis and theoretically linked radar and communications.
- ❑ As airborne radars needed Doppler processing to suppress ground echo, the relevance to modern communications emerges.



The Virtuous Circle



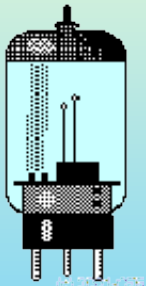
Active electronic component evolution

Analogue

Digital

Better, Cheaper, Faster,
Smaller

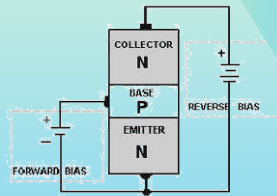
Vacuum Tube



1905

Sony's vision for the pocket radio heralds the growth of solid-state electronics.

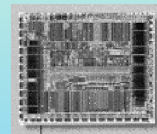
Transistor



1947

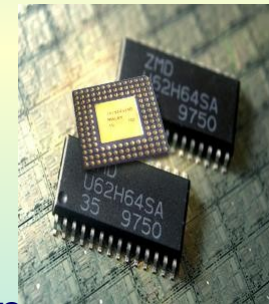
The end of the vacuum era as integrated circuits come into sight.

Microchip



1971

CMOS VLSI



PlayStation 3



80

90

00

"Moore's Law" era

200

07-05-15

10

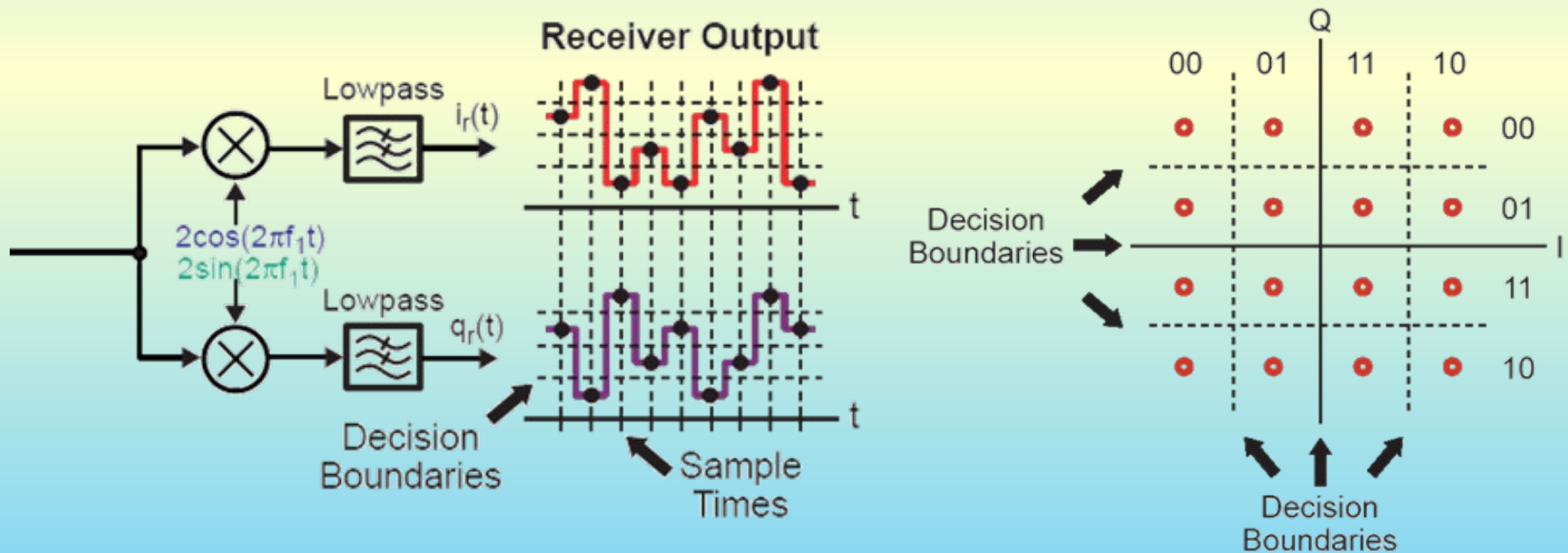
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The commercial drive – communications overtakes military

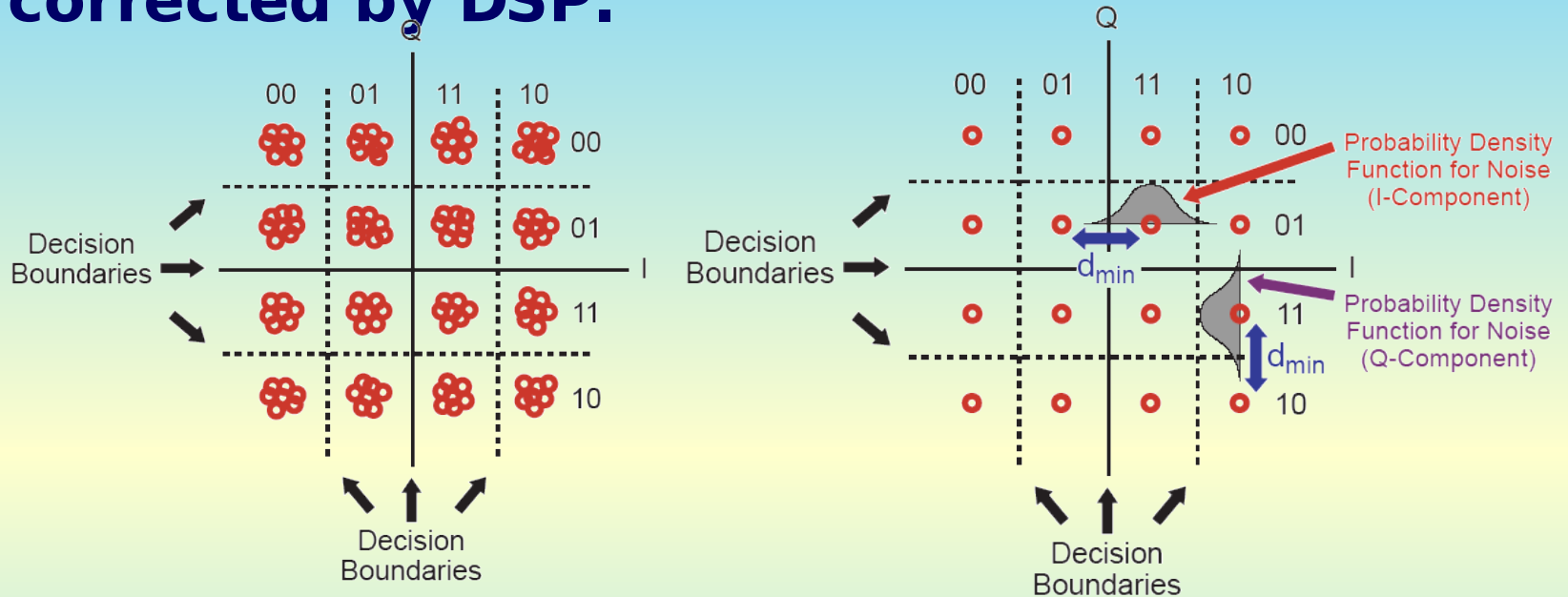
- ❑ Military focus on spectral analysis, spread-spectrum and detection of pulses in noise/clutter provided a conveniently established technology for commercial exploitation in communications.
- ❑ This was driven at systems level by Qualcomm and in practice by the major Communications OEMs world-wide.
- ❑ Very many features of Radar signal processing mapped directly into communications, examples,
 - ❖ I – Q vector receive channel architecture.
 - ❖ BPSK Pulse-compression into Direct-Sequence Spread spectrum.
 - ❖ Ambiguity Diagram, Delay – Doppler description of signals and propagation channels.
 - ❖ Matched filtering, Correlation detection.
 - ❖ Pilot tone calibration – extended to include the propagating channel.
 - ❖ Array antennas and adaptive smart antennas.
 - ❖ Detection theory – hypothesis tests, BER versus FAR.
 - ❖ MIMO (Multiple Input, Multiple Output), Space-Time Adaptive Processing.
- ❑ And in consequence, today, there is a reverse flow of technology from communications impacting costs in military equipment.

The Vector Receiver (I,Q) structure used in radar suits Communications signals, Example QAM(16)

- I,Q samples can be represented on a 2-D co-ordinate system which also shows the decision boundaries between message words. Using Gray code assignment minimises the impact of error.



Practical equipment and real propagation channels cause errors that have to be corrected by DSP.



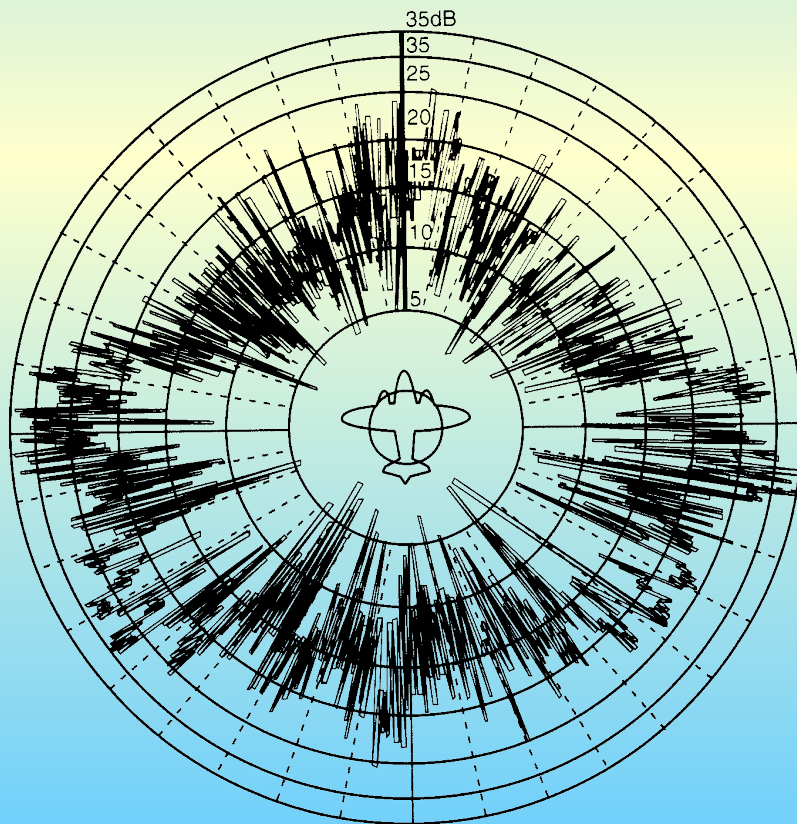
- ❑ Errors that must be corrected include,
 - ❖ I – Q mismatch in gain and phase.
 - ❖ Channel to channel gain and phase, i.e. Sum, Difference, Guard etc.
 - ❖ Propagation, including multi-path scattering.

The reciprocity of influence

- For the next part of this lecture I will examine in more detail a selected set of examples where radar knowledge or technique has been of service to communications.
- This is a personal choice – that's what lectures are about. I make no attempt to disguise prejudice here. Each is entitled to his view.
- The few examples I choose from many possible are,
 - ❖ Target fluctuation models and their influence on modelling the communications channel.
 - ❖ Range tracking and its equivalence in the delay-lock loop of communications.
 - ❖ Pulse compression, its connection to direct-sequence spread-spectrum communications.
 - ❖ Monopulse and I,Q channel matching and their relationship to propagation channel equalisation.

Target Fluctuation models

- ❑ Conceived by Marcum, extended by Swerling, the statistical description of radar targets has served the radar community since the Rand Memo 753 was declassified.
- ❑ The statistical approach was seen as a pragmatic way to describe the complex scattering that takes place on the detail of the target surface, and the reinforcement and cancellation of waves scattered from specific facets.



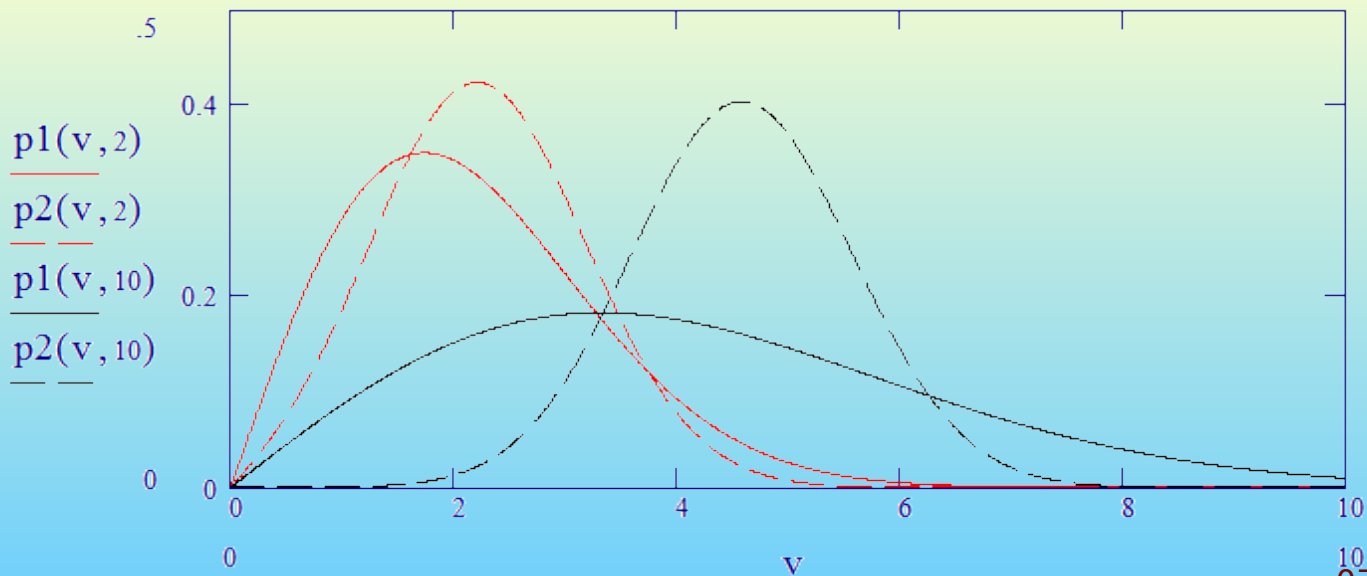
- ❑ Figure shows cross-section of an aircraft target at $\lambda = 10\text{cm}$ as a function of azimuth angle.
- ❑ Small angular change dramatically affects the scattered return because the target dimensions are \gg wavelength.

Target Fluctuation Models

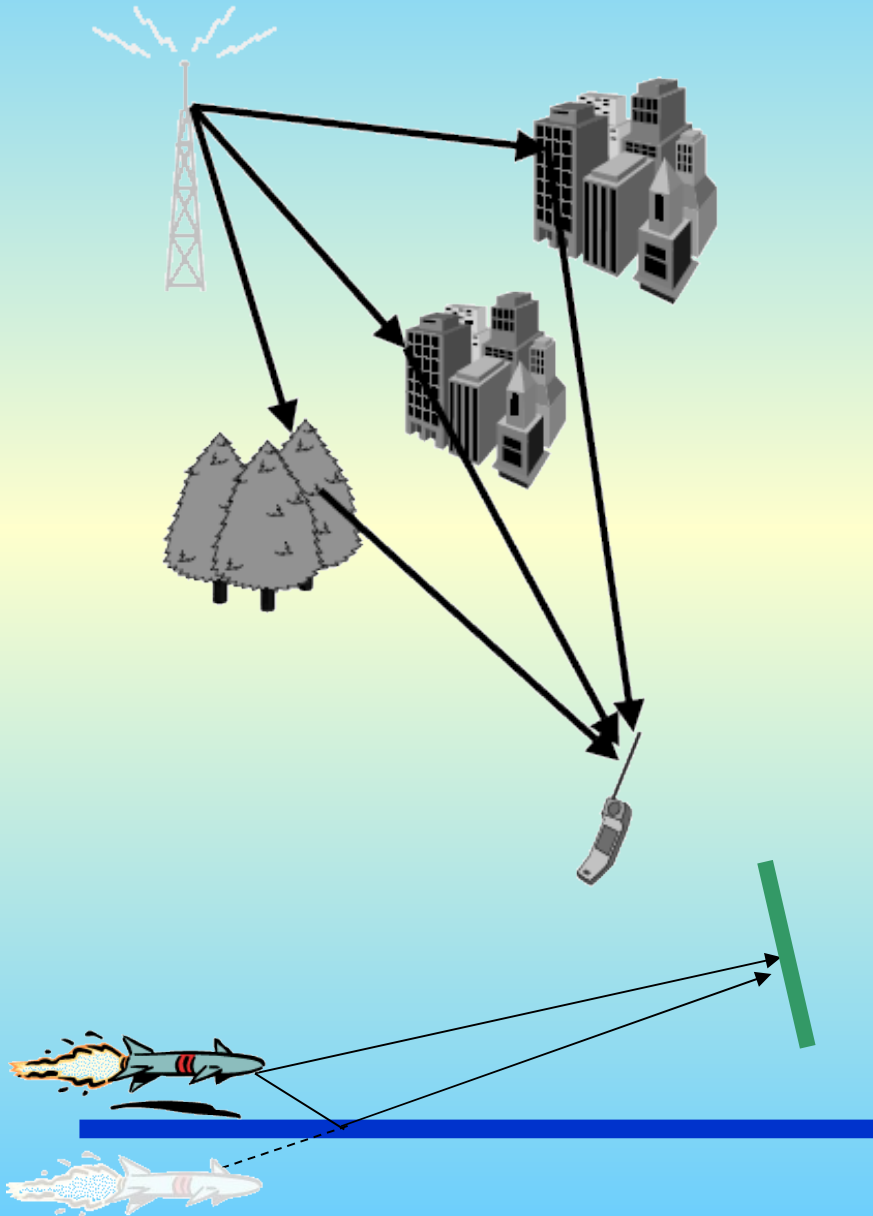
- Two models are particularly useful:
 - ❖ Rayleigh – aggregate of small scatterers.
 - ❖ Ricean – a dominant scatterer in an aggregate of smaller scatterers.

$$p1(v, S) := \frac{v}{(1+S)} \cdot \exp\left[\frac{-v^2}{2 \cdot (1+S)}\right] \quad \text{Rayleigh}$$

$$p2(v, S) := v \cdot \exp\left[-\left(\frac{v^2}{2} + S\right)\right] \cdot I_0(v \cdot \sqrt{2 \cdot S}) \quad \text{Rice}$$



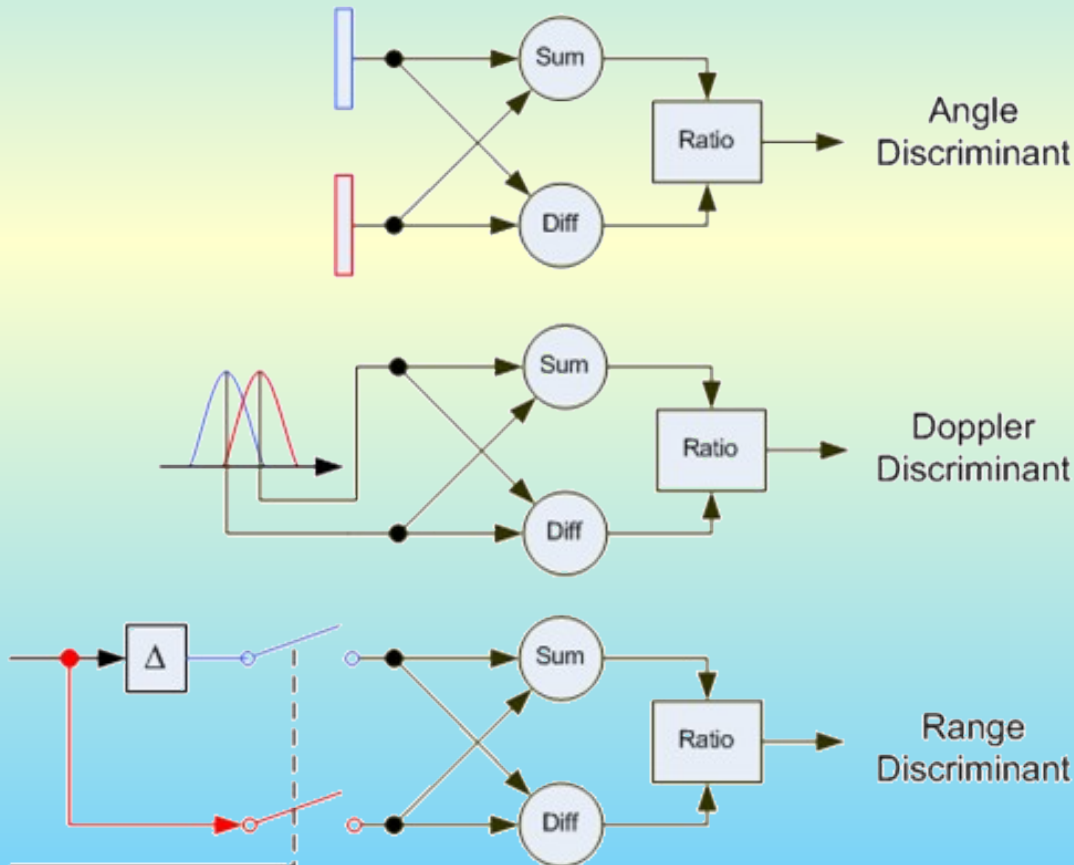
Channel multipath



- ❑ Cellular communications is multipath limited. Two basic models are used, Rayleigh and Rice, as in radar.
- ❑ The same physical mechanism of vector addition applies.
- ❑ But cellular has gone a step further than radar and seeks to extract the energy from multiple paths by assigning an independent matched filter to each. The filter delay timing is maintained by a delay-lock loop (range-tracker) and coefficients are assigned to maximise received energy, i.e. to compensate the multipath.
- ❑ This is called a RAKE receiver. The name relates to the spectral appearance of the channel prior to processing.

Delay-lock loop

- One of the most important discoveries of radar was mono-pulse angle measurement. This technique generalises to cover range and Doppler as well. It is the basis of delay and Doppler tracking in communications.



Error model:

For all measures,

$$(\sigma_x)^2 = \frac{k \cdot (\Delta x)^2}{\text{SNR}}$$

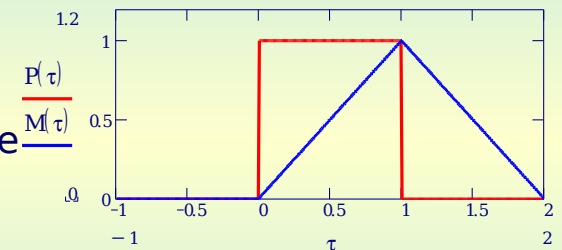
Where Δx is resolution.
Best find, k, by simulation

Pulse compression – matched filtering

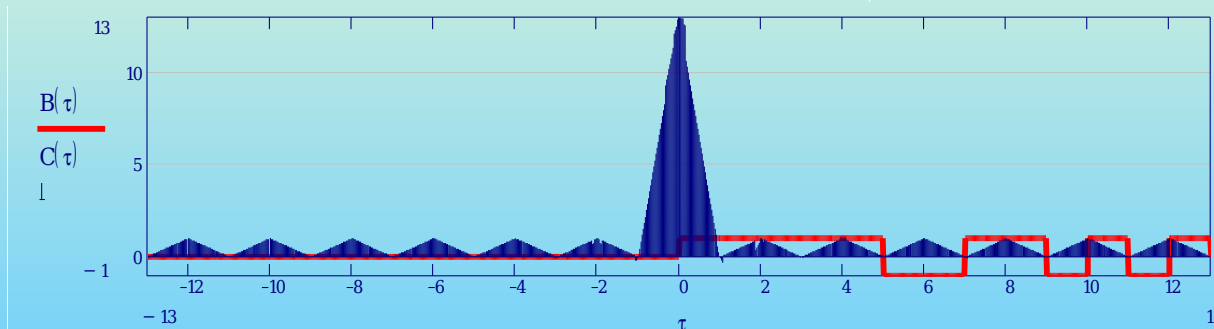
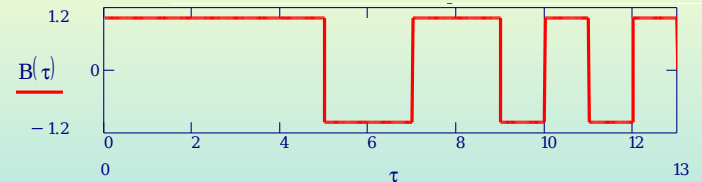
- The matched filter is the filter that maximises signal to noise ratio. It has an impulse response that anticipates the signal – it is the time reversal of the signal.
- It is mathematically equivalent to correlation detection. For example, observe the matched filter output for a pulsed sinusoid signal.

$P(t) := (\Phi(t) - \Phi(t-1))$ Define a unit pulse as difference of two step-functions

$$M(\tau) := \left(\int_0^1 P(t) \cdot P(\tau - t) dt \right) \text{ Calculate matched filter response}$$

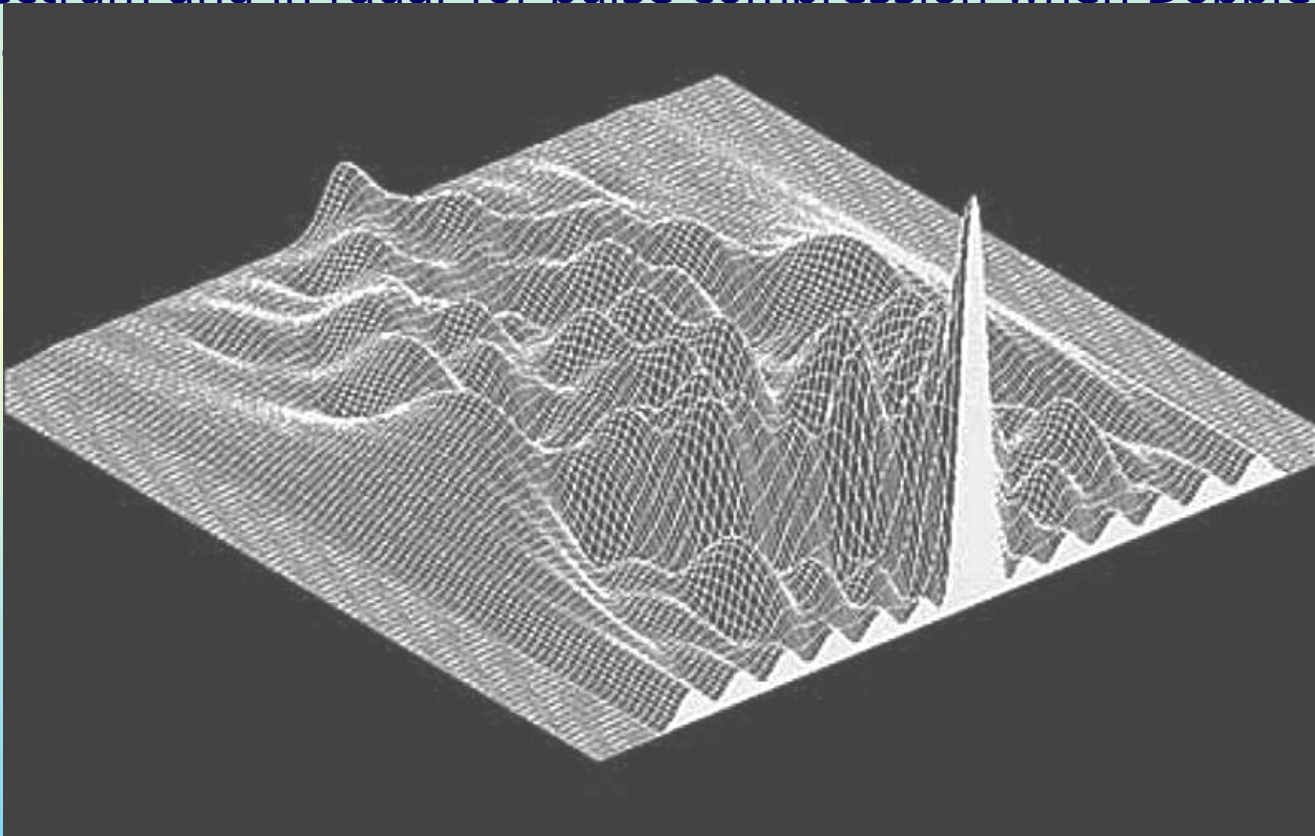


Define a Barker code $a_n = \{1,1,1,1,1,-1,-1,1,1,-1,1,-1,1\}$



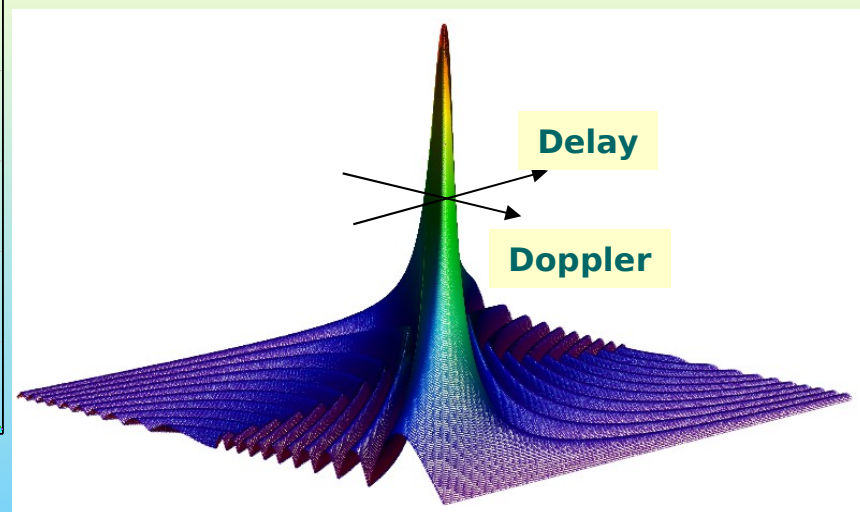
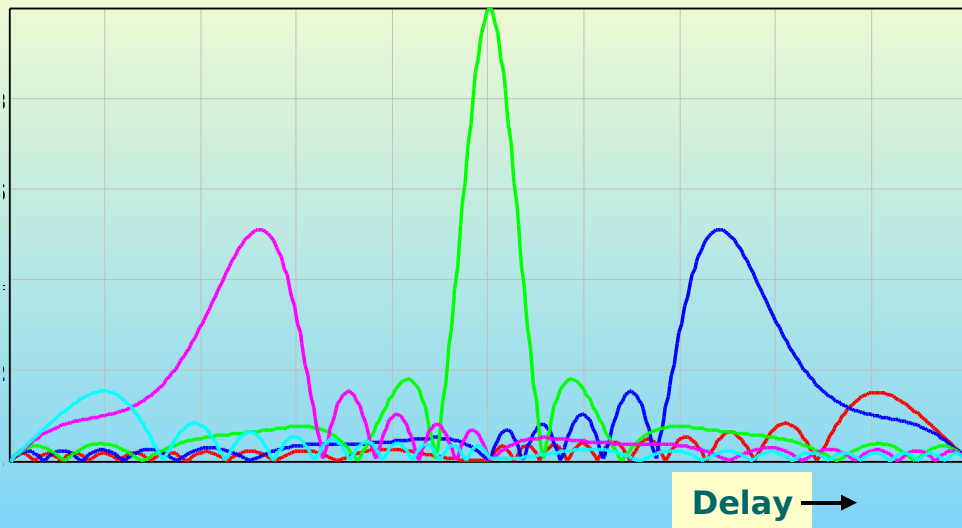
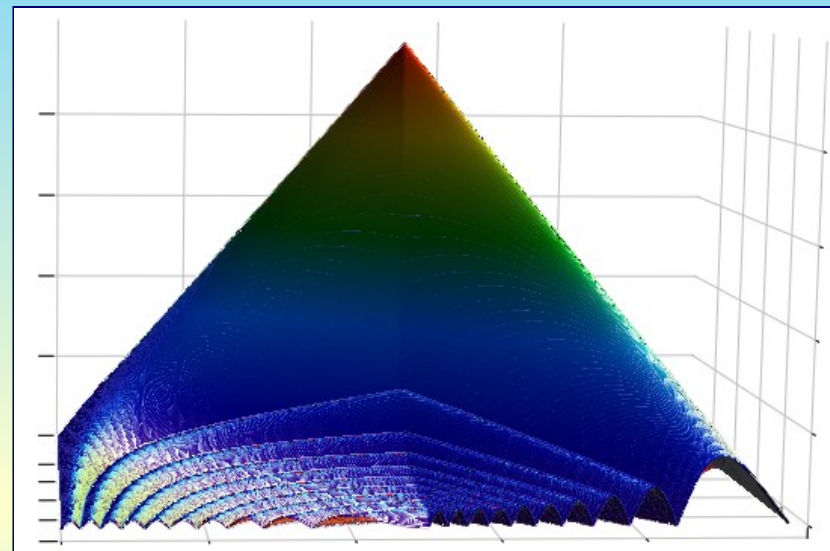
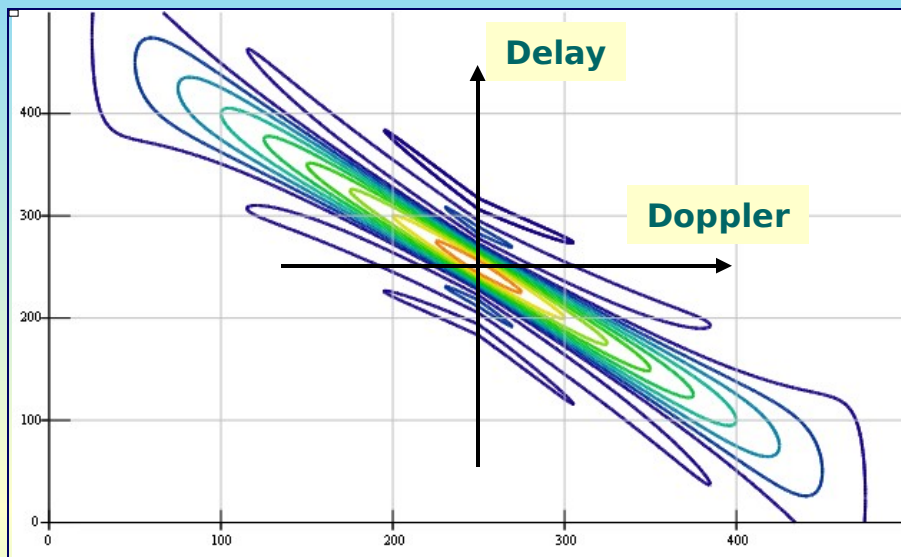
Ambiguity Function – an extension of matched filter response

- ❑ Includes effect of Doppler mistuning.
- ❑ Communication links can track carrier and minimise Doppler offset.
- ❑ Barker codes are used in Wireless LAN to spread the data spectrum and in radar for pulse compression when Doppler is small.

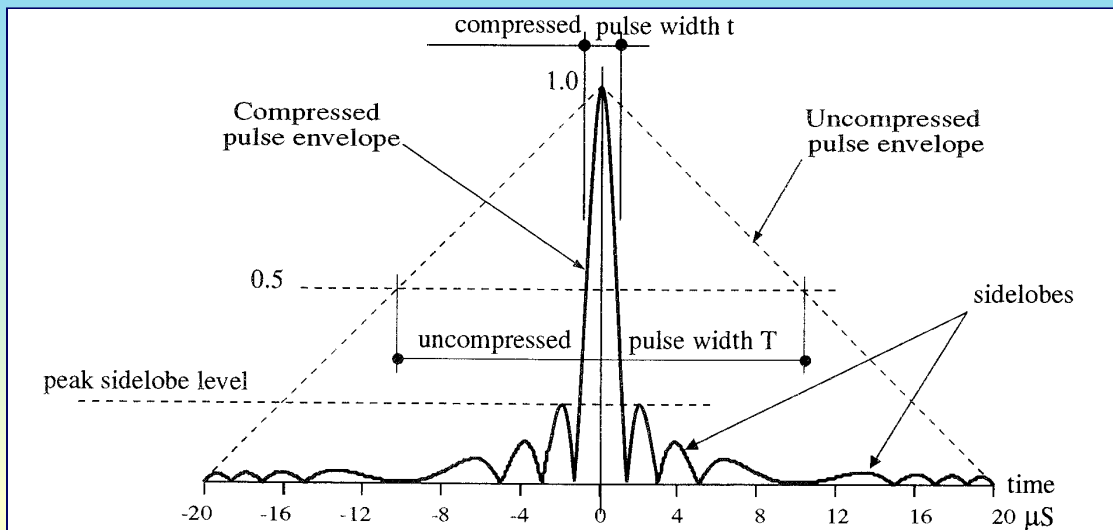


$$a_n = \{1,1,1,1,1,-1,-1,1,1,-1,1,1\}$$

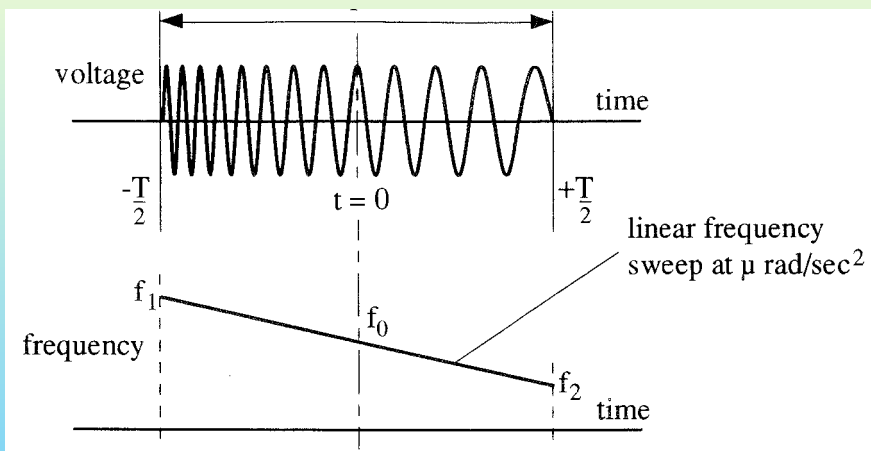
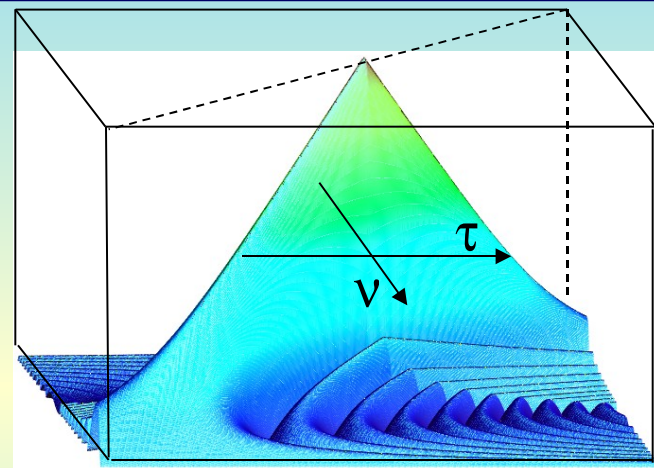
Ambiguity Diagram for a LFM (Chirp) Pulse – $TB = 10$



Properties of LFM Pulse (Chirp) Compression



$$E(t, \omega_d) = \frac{\sin\left[\left(\frac{\omega_d + \mu t}{2}\right) \cdot (T - |t|)\right]}{\left(\frac{\omega_d + \mu t}{2}\right) T}$$



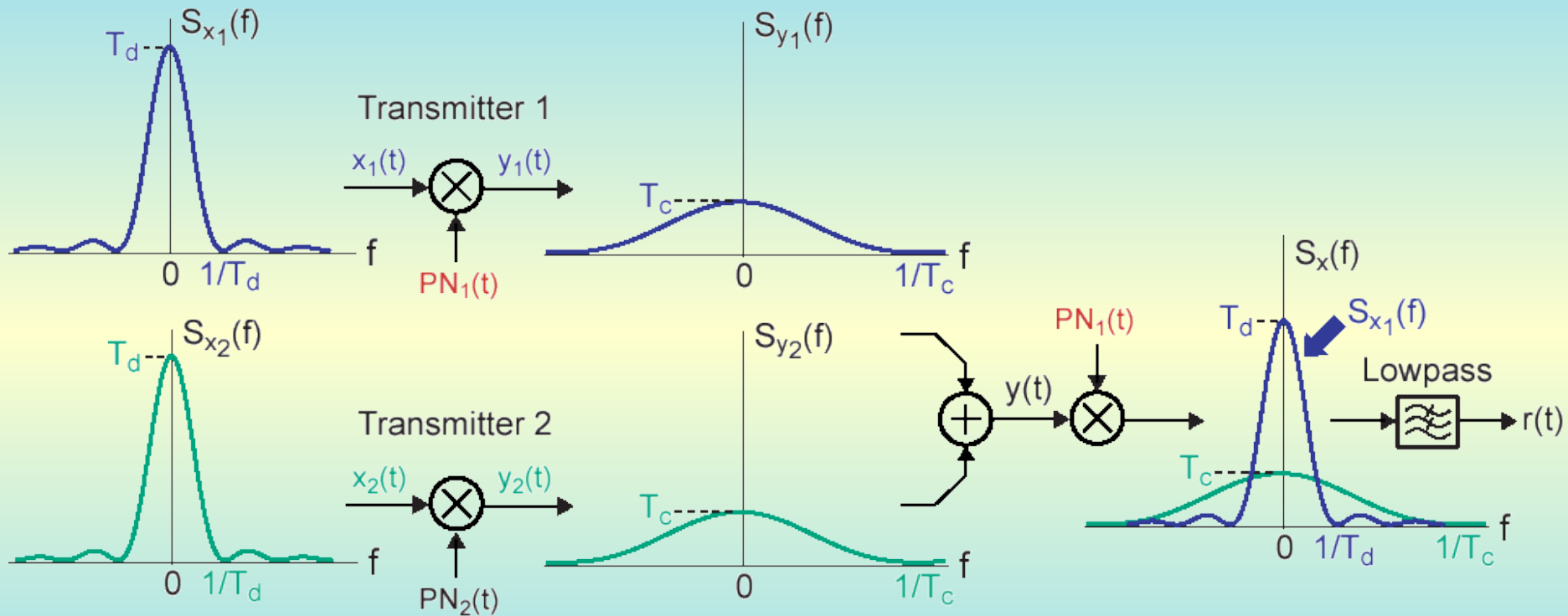
- The extremes of the frequency sweep are:

$$\omega_1 = 2\pi \cdot f_1 = \omega_0 + \mu \cdot T/2 \text{ and } \omega_2 = \omega_0 - \mu \cdot T/2$$

- Sweep Bandwidth,

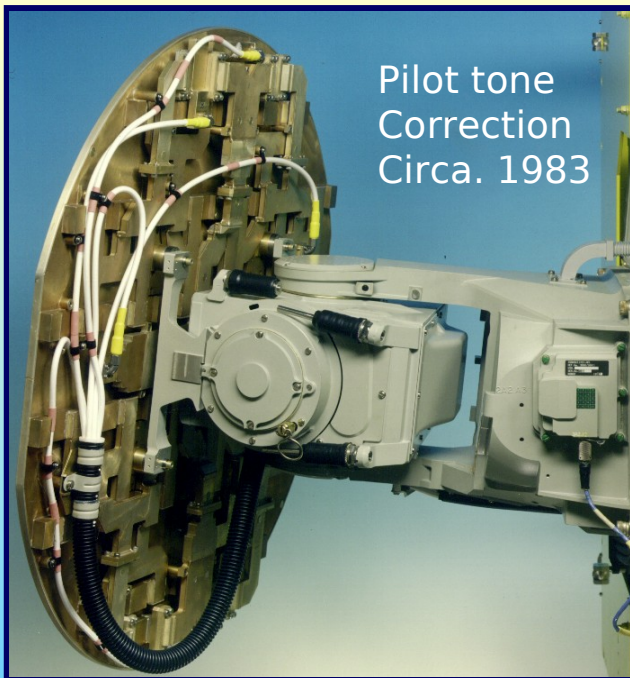
$$B = \mu \cdot T / (2\pi) \text{ Hz.}$$

Spectral interpretation of CDMA - DSSS

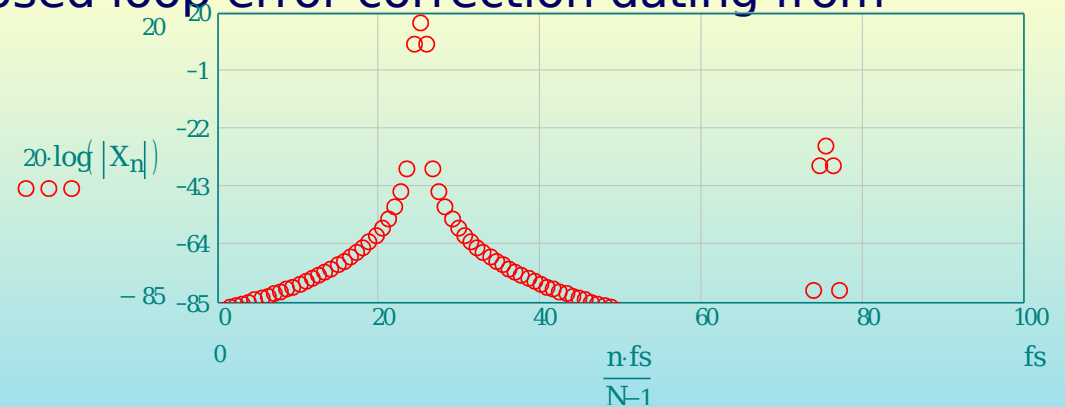


Monopulse and I,Q match and relationship to channel equalisation

- ❑ The channel matching requirement in radar was technically solved by pilot-tone injection, error measurement and digital correction.
- ❑ Prior to this, high gain analogue amplifiers had to be kept at common temperature so that gains and phases would track.
- ❑ Monopulse error discrimination is sensitive to gain and phase errors.
- ❑ I,Q channel gain and phase errors create spectral images.

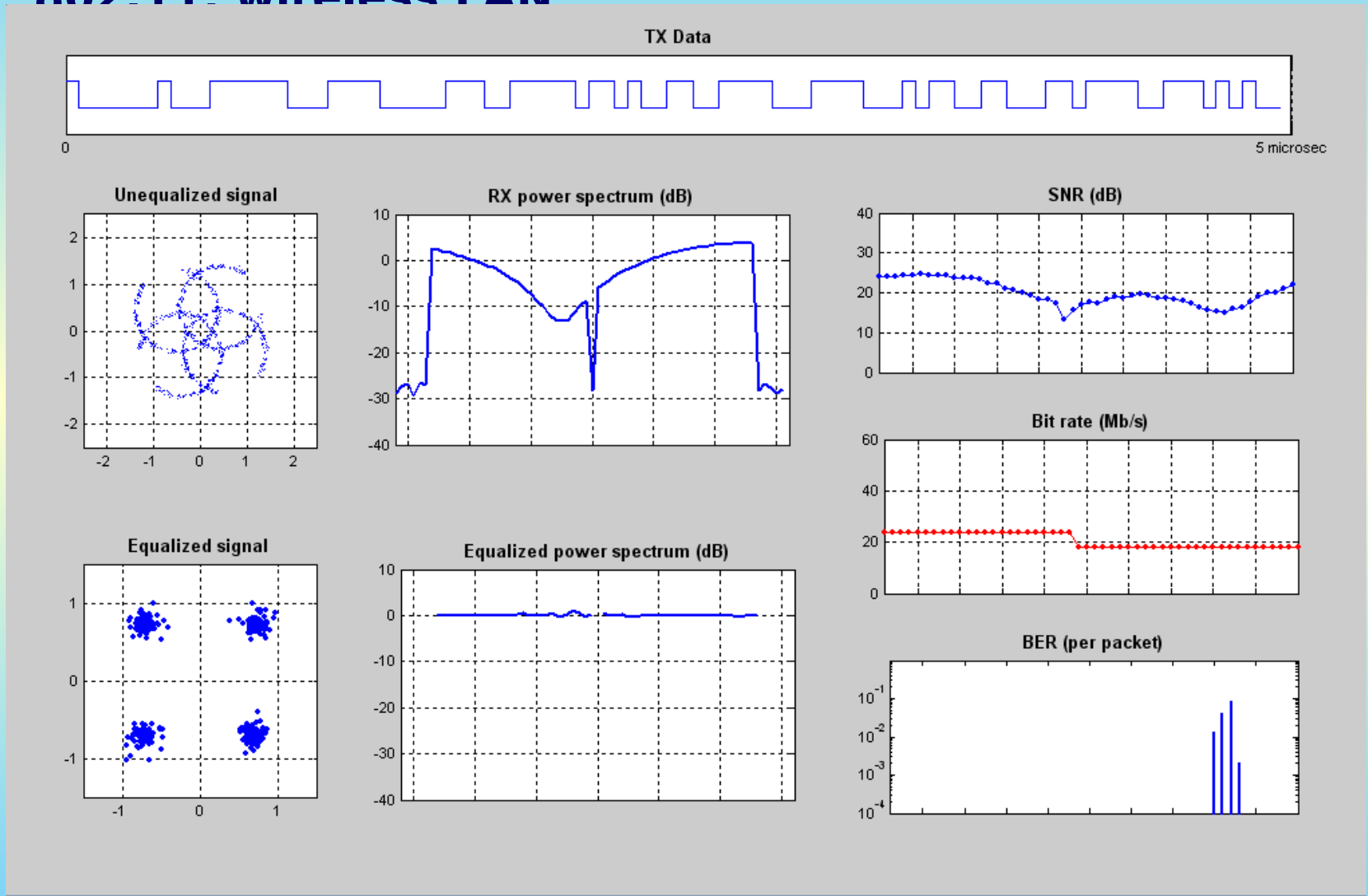


closed loop error correction dating from



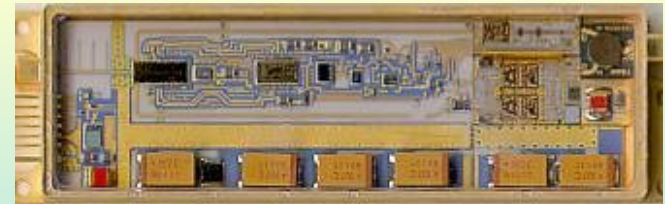
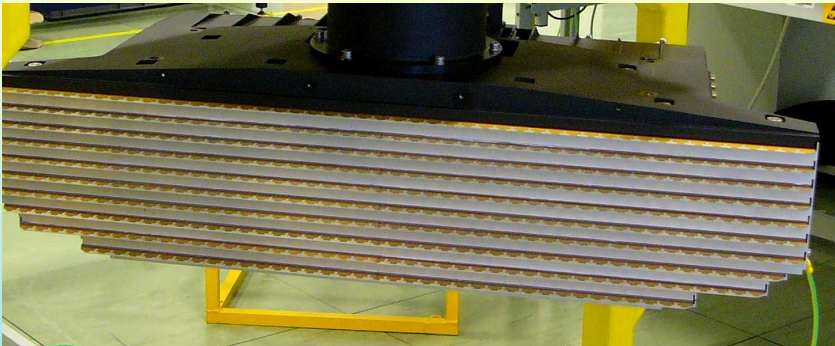
Spectral image resulting from 0.1dB amplitude error in I,Q

Channel Equalisation - The communications development of pilot tone correction – Example 802.11 wireless LAN



Current and Future influences of Communications on Radar

- The immediately discernable influences are,
 - ❖ Costs – particularly microwave active components.
 - ❖ Digitisation – achieving speed and dynamic range.
 - ❖ Processing throughput.
 - ❖ Programming convenience.
 - ❖ New and adventurous systems – UWB, MIMO as examples.

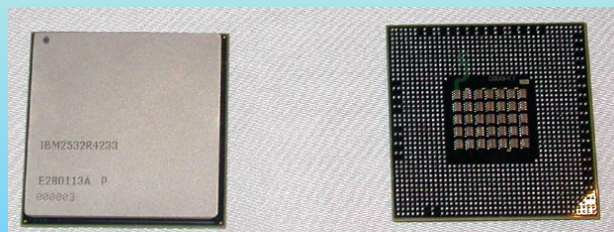
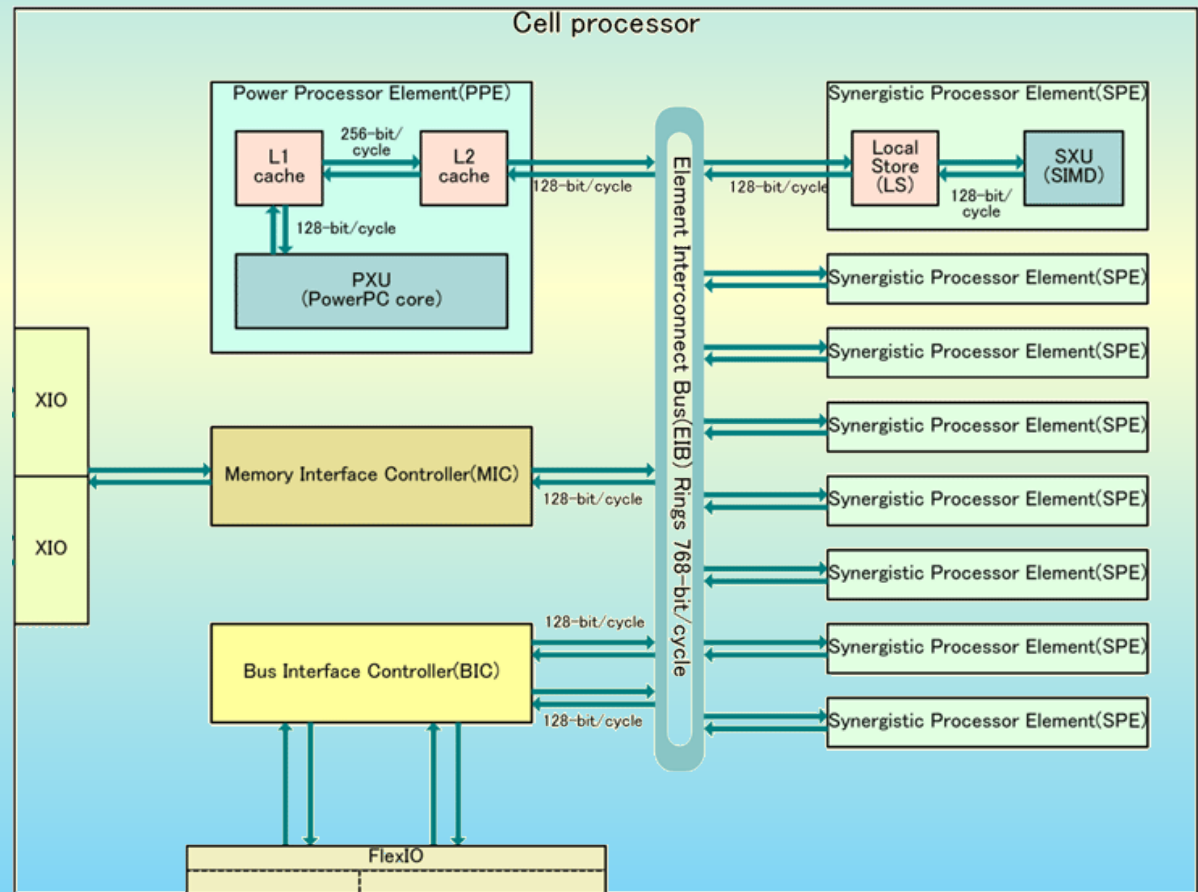
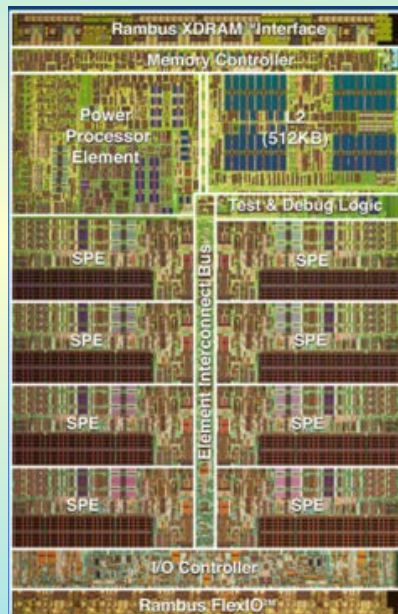


Low-cost X-band T/R module

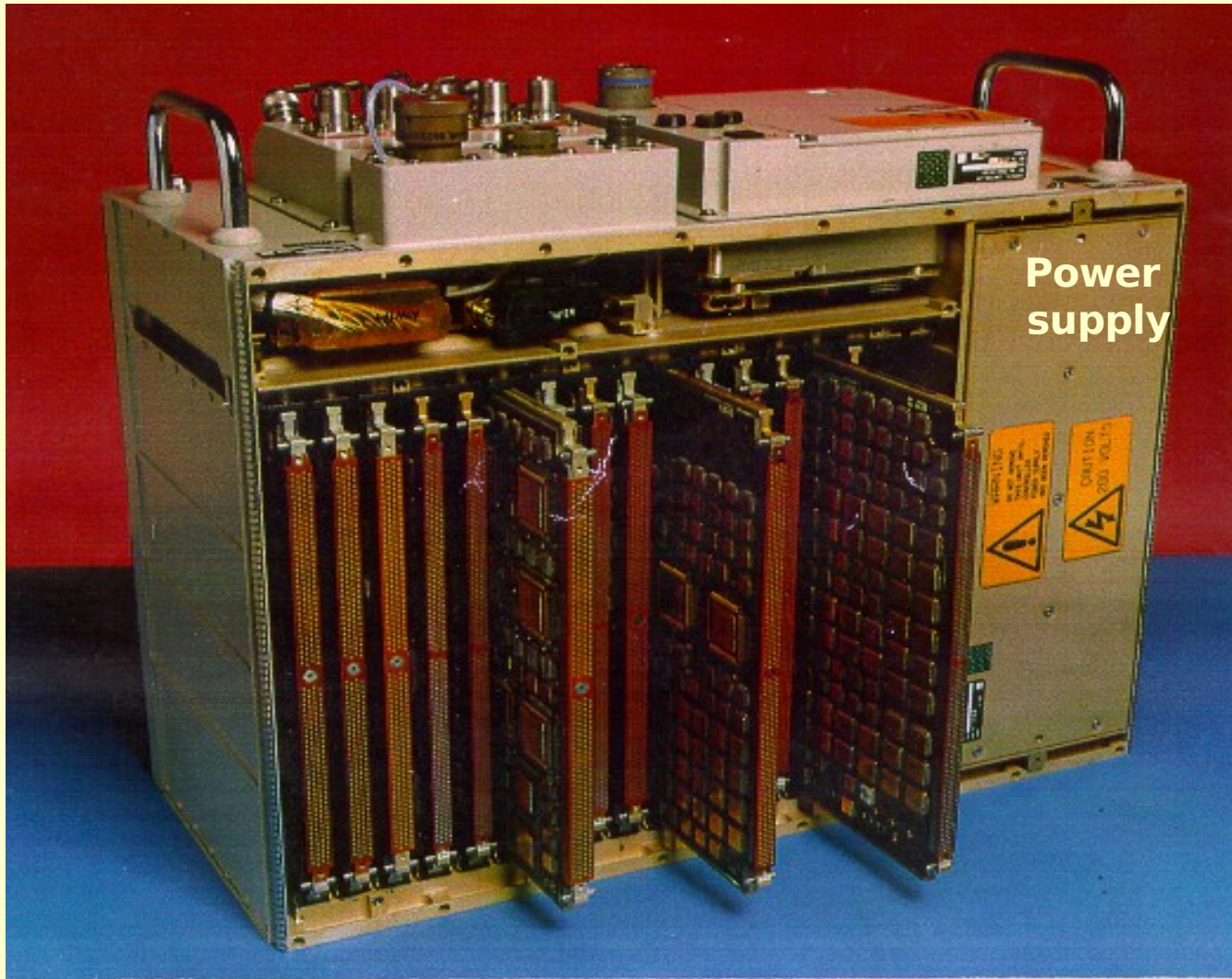
First airborne active array produced in UK and sold into the US. Uses GaAs components from the Communications market to achieve pricing competitive mechanically scanned systems.

Over 200 GFlops on a chip

- ❑ Produced by IBM for Sony's Play-Station 3, this has the favoured architecture of a radar processor.
- ❑ Available with GEDAE™ graphical programming support.



Signal processor for UK airborne pulse-doppler radar.



Prototype (1988).

Early surface mount,
ECL gate arrays.
Ericsson BYB format.

Fibre optic inputs.

Photo courtesy of :
Ferranti, Edinburgh

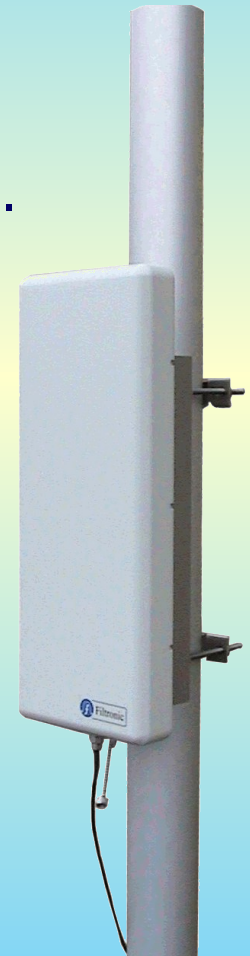
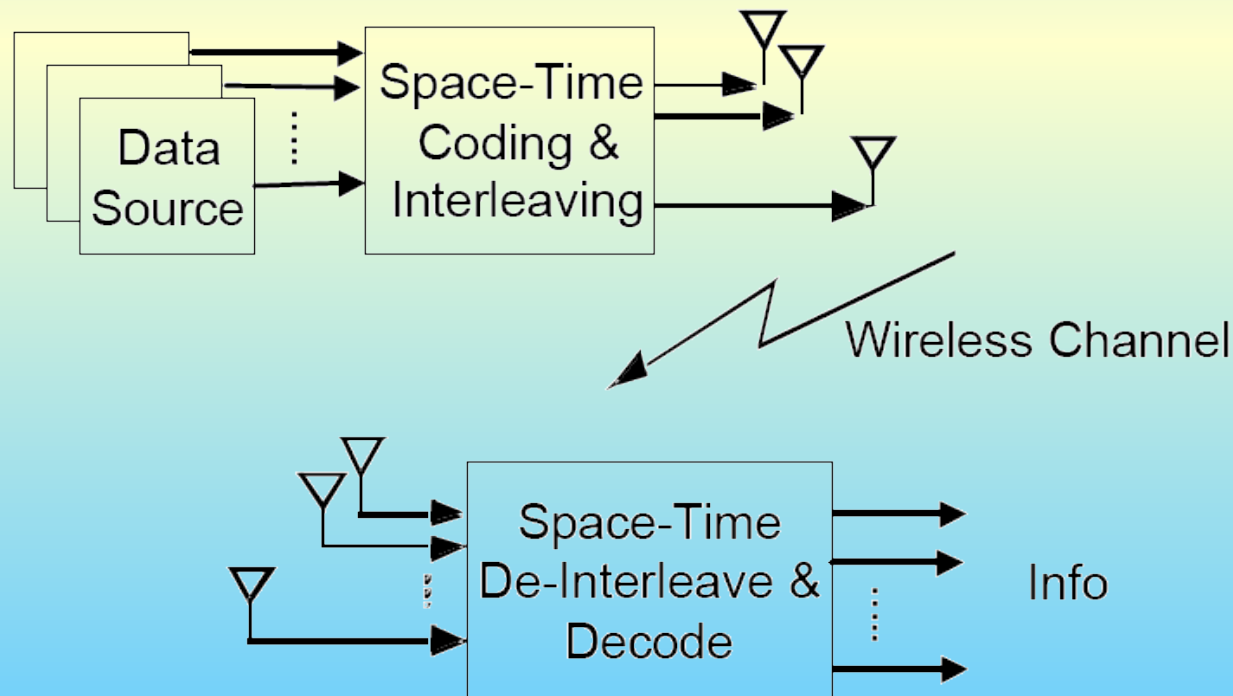
Looking ahead – after the affordable AESA

A lot of innovation, driven by the commercial need of communications.

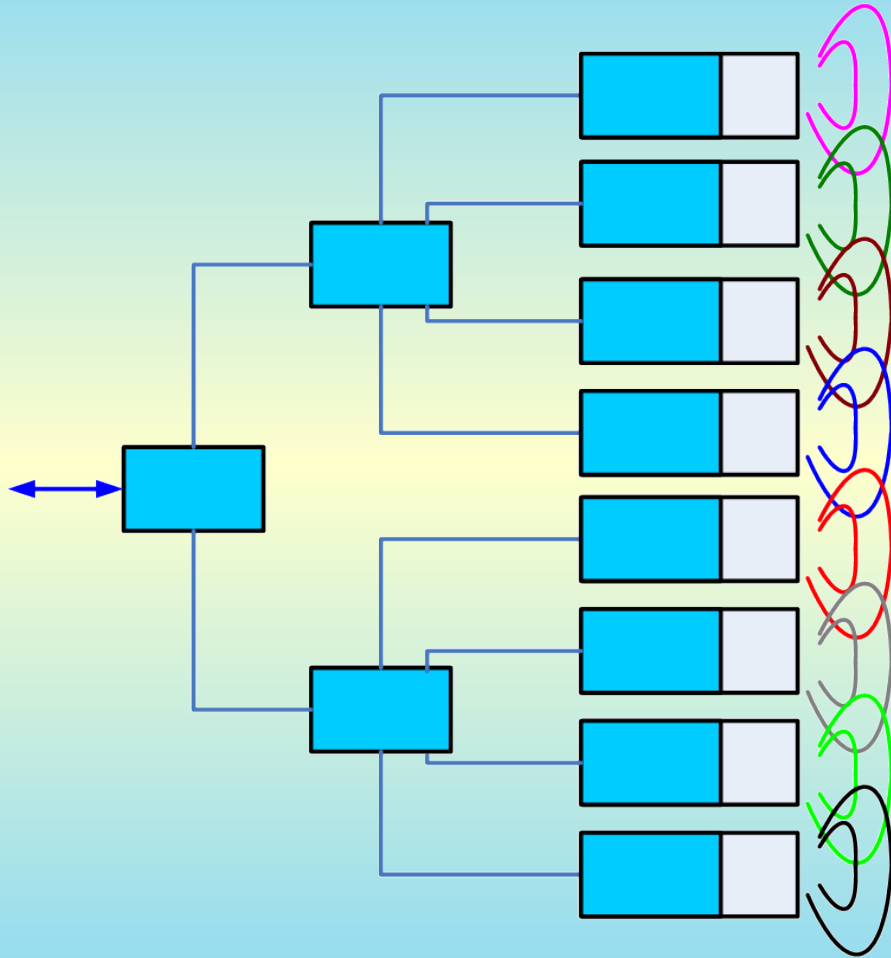
Two examples, MIMO and UWB

The active Transmit/Receive head facilitates “Smart Antenna” algorithms and “MIMO”

- ❑ Increased data rates due to multiple transmit and receive antennas.
- ❑ Assists in combating fading and multipath.
- ❑ More base-station capacity, improved link budget.
- ❑ Embedded in WiMAX standard, 802.16.



What is “MIMO” applied to radar?

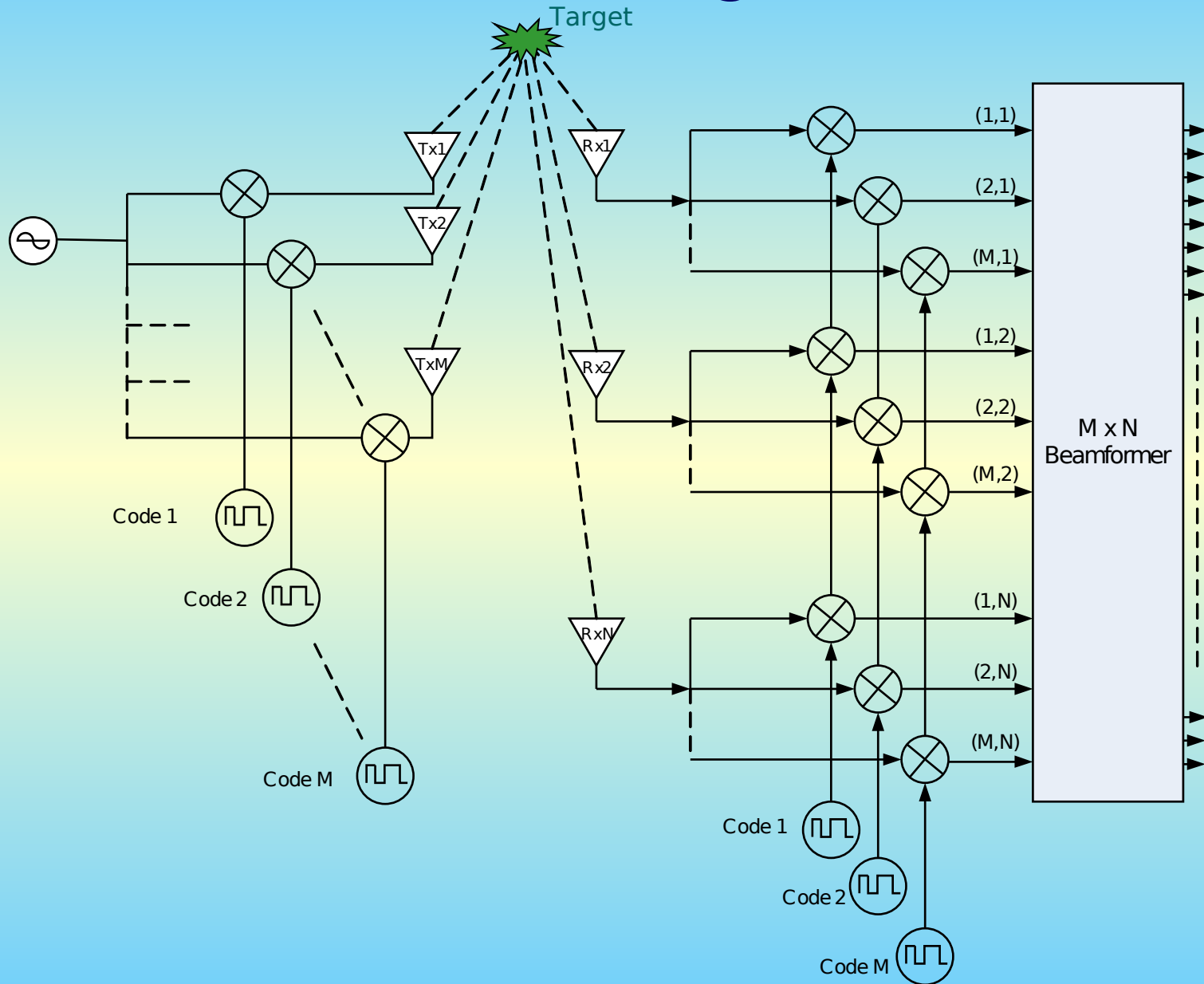


- ❑ Elements are effectively single radars in their own right.
- ❑ Their signals can be “coded” to avoid interference in space, so the energy addition can be controlled by signal processing.
- ❑ This leads to very many new freedoms in design and it is definitely the beginning of an era in radar architecture.
- ❑ Should see this as the next step after AESA – basically element digitised AESA.
- ❑ Tx and Rx elements need not be co-located.
- ❑ This makes sense because the MIMO hardware overhead is large and the synthesised array allows trade-off that reduces hardware. It is based on the “co-array” principle.

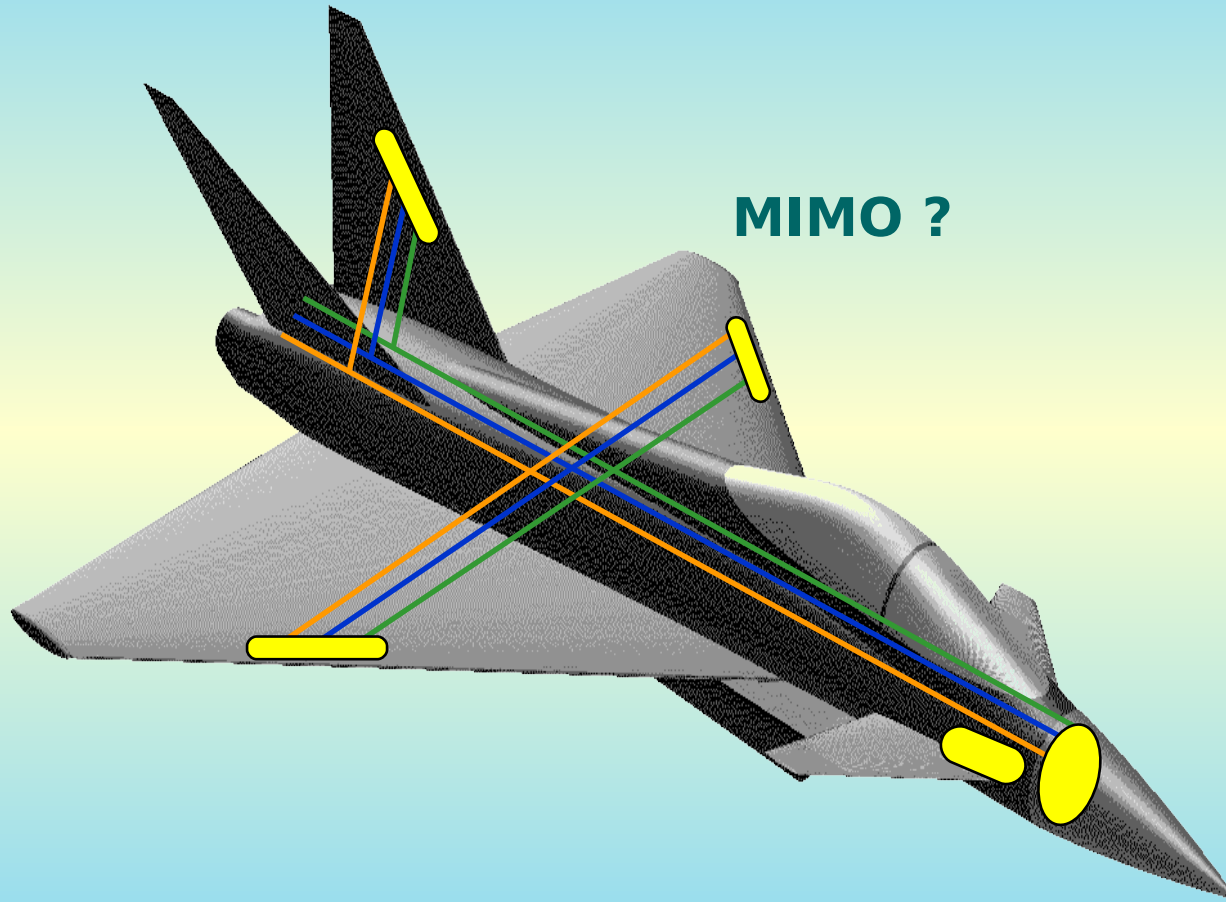
MIMO Research/Design Issues

- ❑ Codes have to show strong autocorrelation and low cross correlation. Orthogonality preferred.
- ❑ This has to be sensibly preserved,
 - ❖ In the presence of Doppler if targets move.
 - ❖ For long Delays involving multiple time around echoes.
- ❑ In coherent MIMO target decorrelation sets a time limit to processing.
- ❑ Ambiguity properties have to be acceptable.
- ❑ Pattern synthesis,
 - ❖ The single pattern is the Fourier transform of the single aperture distribution.
 - ❖ The product pattern is the Fourier transform of the convolution of the transmitting and receiving apertures.
 - ❖ The convolved apertures gives an effective aperture called the “co-array”.
 - ❖ In extremis, this allows a major trade-off on power-aperture while preserving angular resolution.
- ❑ Arrays can be 1D, 2D or 3D.
- ❑ Very flexible effective arrays can be synthesised.

Generic MIMO beam-forming

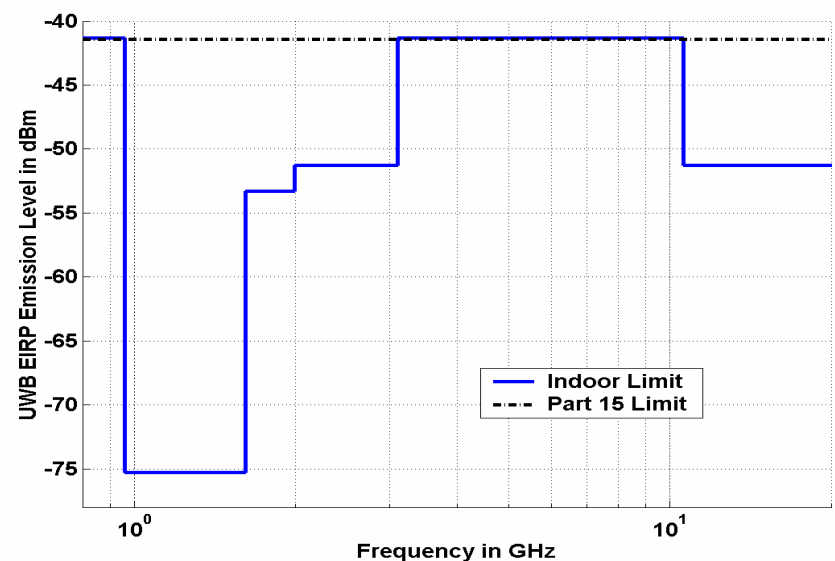
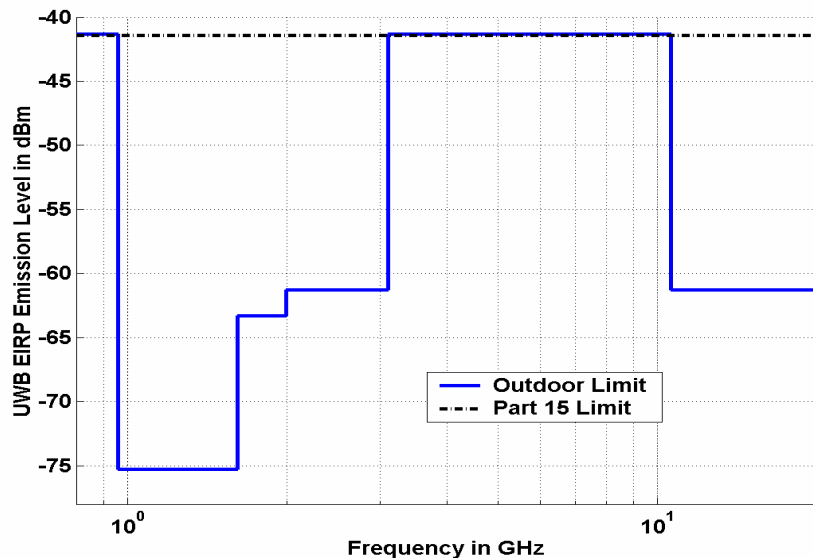


MIMO as the path to conformality

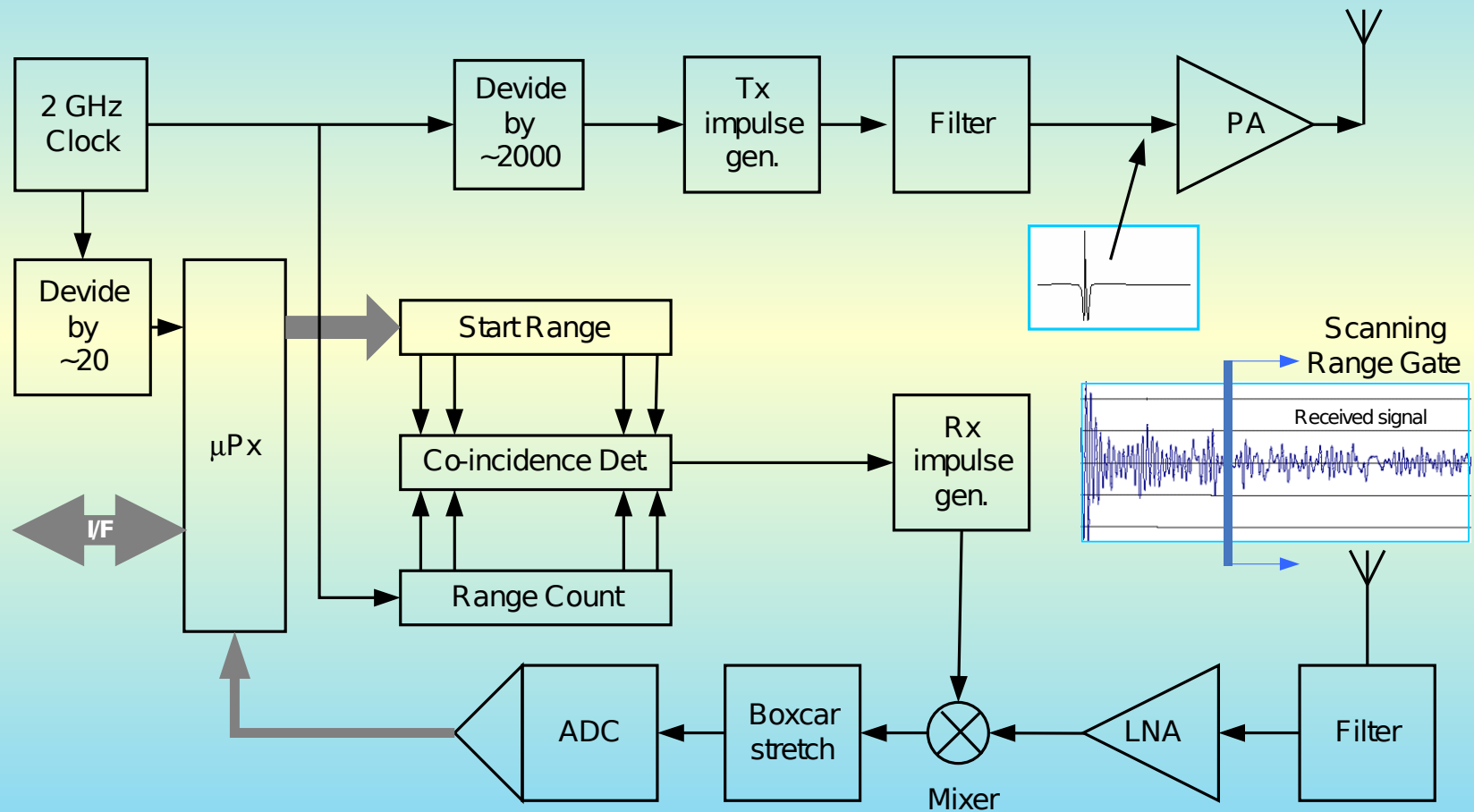


UWB Radar Applications – a field for innovation

- ❑ Allocation of the UWB spectrum has precipitated intense interest in short-range radar applications using communications components and very advanced processing, usually FPGA-based.
- ❑ Power levels are extremely low, but long integration times are possible and resolution in both range and velocity can be very high.
- ❑ Sampling may use boxcar techniques so that high bandwidth ADCs may not be needed

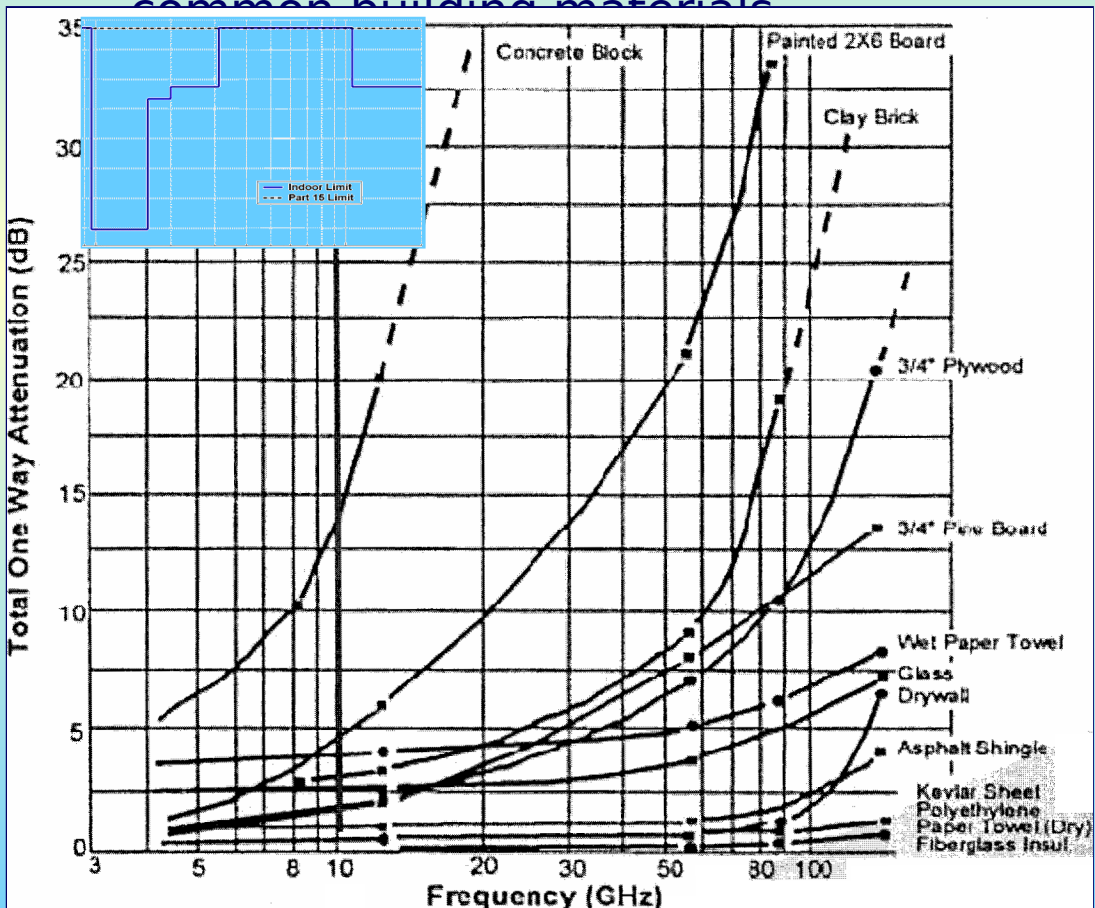


Ultra WideBand (UBW) Radar for range measurement



Through-wall UWB radar

- ❑ A video demonstration can be seen at this URL:
<http://www.cambridgeconsultants.com/prism200.shtm>
- ❑ One-way signal attenuation through common building materials



<http://www.camero-tech.com/>

Conclusion

- ❑ Radar began in earnest through war-time exigency and with reliance on the radio technology of the day.
- ❑ Its post-war development on military investment delivered major social payback by assisting cellular wireless.
- ❑ The massive market this entails and the commercial impetus it gives is continuously feeding back into radar today.
- ❑ Cellular communications is making the digitised array element a reality. This is the basis of MIMO radar and it is happening faster than any previous generation of technology. The successor to the AESA will be MIMO arrays.
- ❑ Rapid innovation is making strong impact in short-range, low power systems for special applications.
- ❑ The technology has never been more accessible That allows new players into the field with new ideas and creates healthy disruption