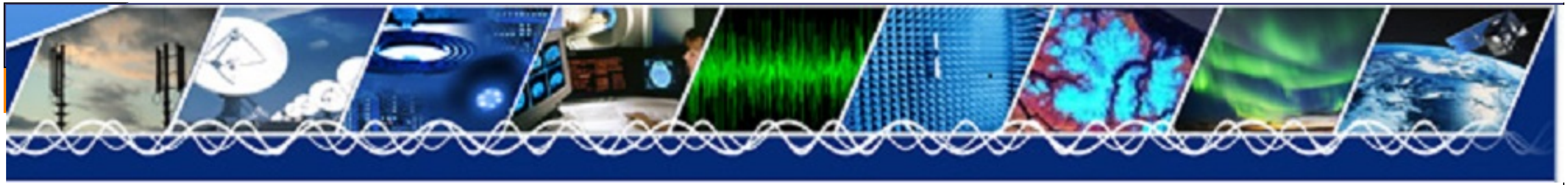


Benefits of space-time diversity for radar

“Diversity drives the architecture”

F. Le Chevalier

Emeritus Professor, Radar Systems Engineering, TU Delft

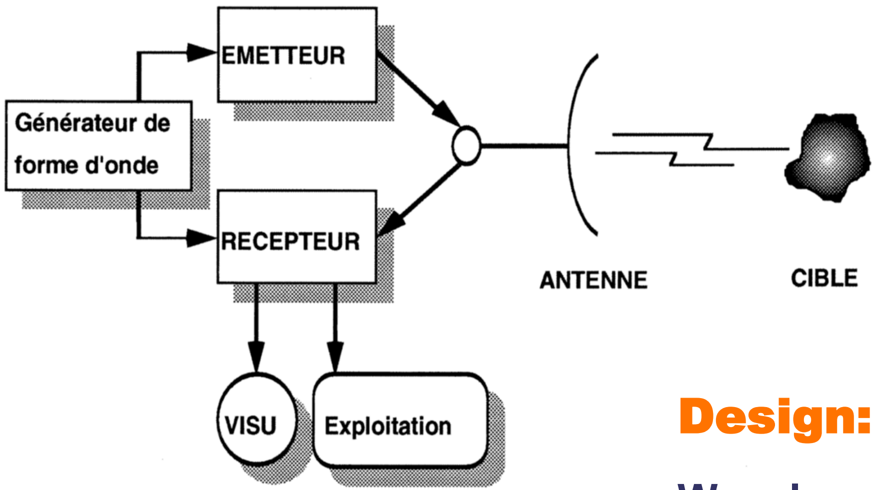
Chief Scientist (retired), Thales Land & Air Systems

N. Petrov

PhD Researcher, TU Delft

Motivations

- When designing a new radar system, standard resolution trade-offs play a major role, providing the basic parameters of the radar, such as size, update rate, and range.



Limitations

Propagation

Clutter

Thermal noise

Target

Jamming

Design: selection of

Wavelength

Power

Waveform

Signal processing

Antennas

Designing a surveillance radar

- **Critical feature : the "illumination time", a.k.a. "time on target"**
  - this time duration should be long enough to allow Doppler analysis, and to gain a sufficient signal to noise ratio (SNR),
  - but also sufficiently small to allow a fast update rate, required by the user.

Designing a surveillance radar

- **Critical feature : the “illumination time”, a.k.a. “time on target”**
  - this time duration should be long enough to allow Doppler analysis, and to gain a sufficient signal to noise ratio (SNR),
  - but also sufficiently small to allow a fast update rate, required by the user.
- **This well-known trade-off between update rate and velocity resolution also involves**
  - the antenna beamwidth: the wider the beam, the better the velocity resolution, for a given update rate
  - the clutter rejection capability: the wider the beam, the higher the clutter level
- **and has also direct consequences on the power budget**
  - the wider the beam, the lower the antenna gain, but also the higher the integration gain, for a given update rate

These intricate relations between beamwidths, velocity resolution, and power budget involve the fluctuation characteristics of the targets and clutter

- performances can be improved through an increased averaging of clutter and target echoes
  - averaging in frequency, or aspect angle, or polarization, etc.
  - requires widening of the beam, or longer illumination time, or wider bandwidths

Such improvements arise through modifications of the clutter and targets distribution functions

- more complex than mere mean or standard deviation modifications

Diversity has direct consequences on radar architectures

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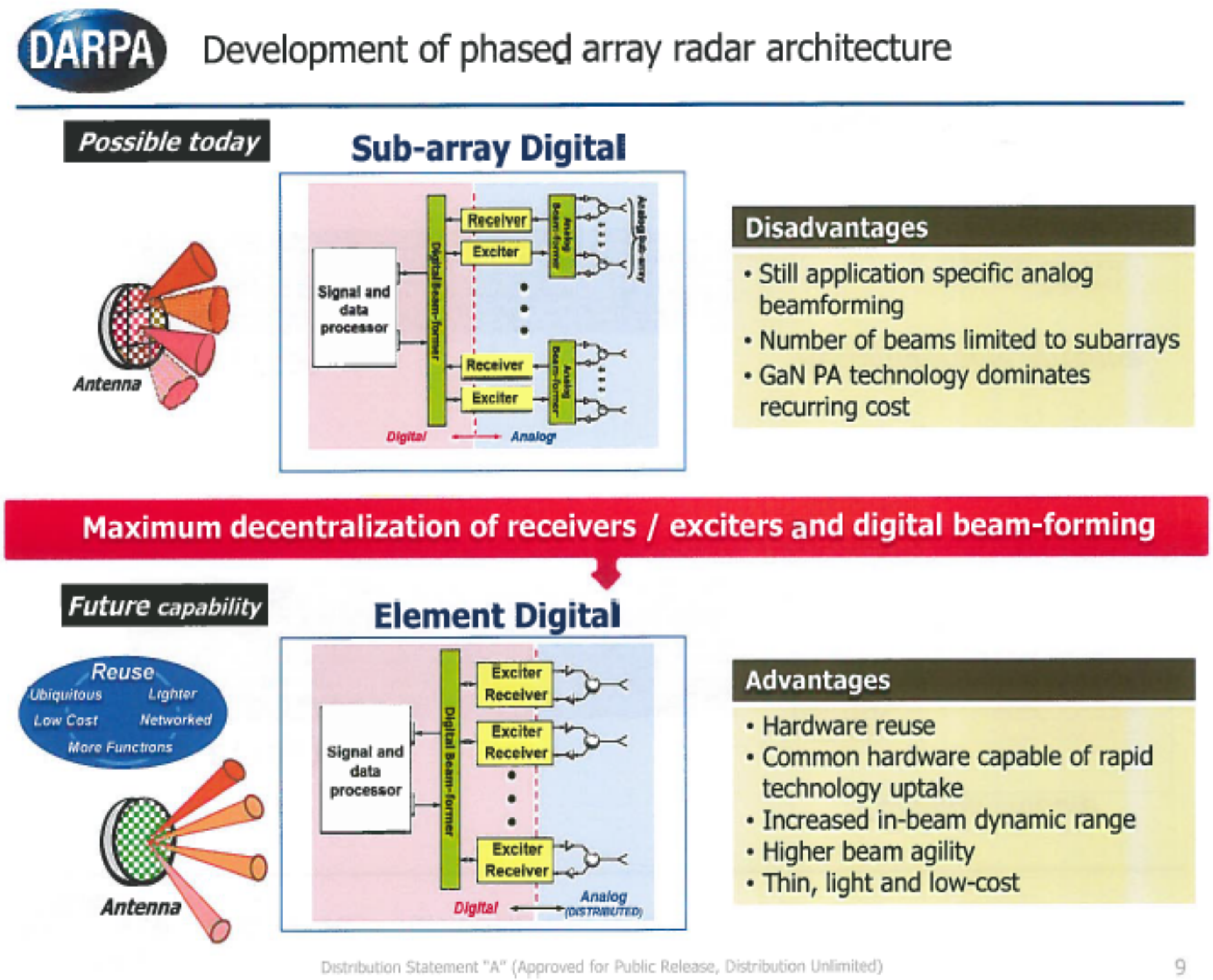
Evolution of radar architectures

- Modularity of antenna systems, waveform generation, etc.
- Wider bandwidths becoming affordable

More stringent requirements

- Detection, tracking, imaging/classification on-the-fly – simultaneously!
- Difficult targets: slow (a few m/s), low RCS (-20dBm^2), low altitude
- Difficult environment: clutter, urban, coastal, high sea states – and jamming...



[Dr W. Chappell, DARPA, Keynote address, IEEE International Radar Conference, USA, October 2015]

Detection, Diversity

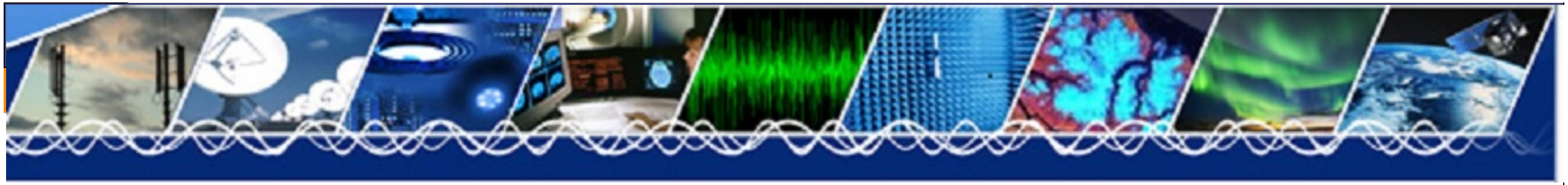
Wideband non-ambiguous radar

- Diversity / resolution gains for targets
- Diversity gains for clutter

Space-time coding for diversity

- Principles
- Ambiguity functions
- Diversity gains

Discussion : baseline examples



Detection vs Diversity

Basics

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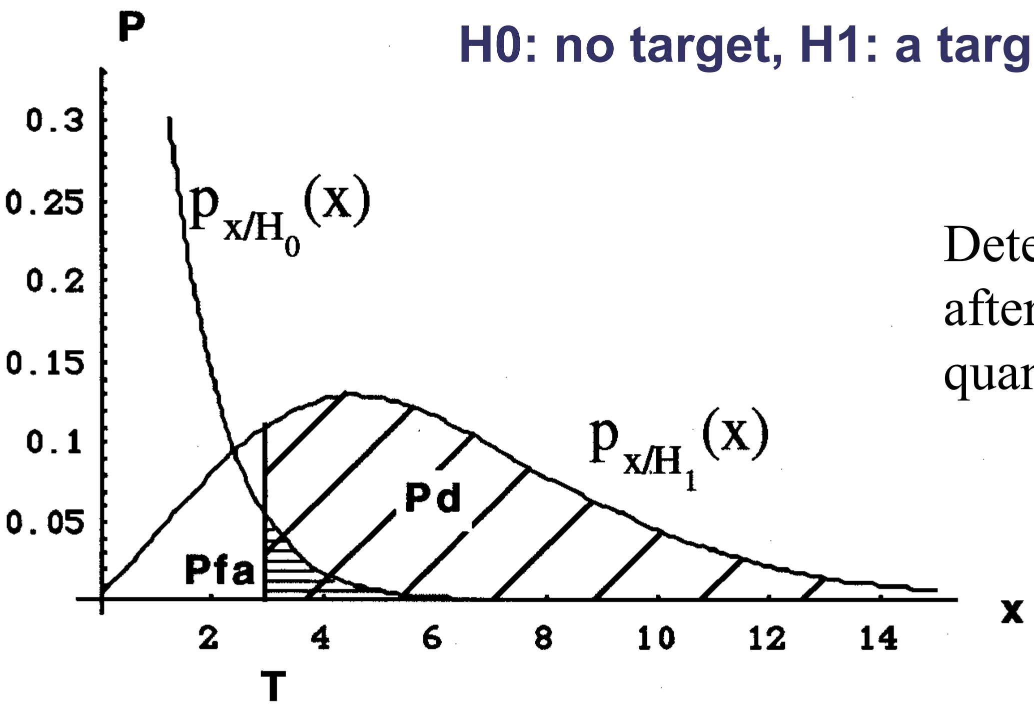
Detection as a 2-hypothesis problem

Compare a certain quantity **X**, function of the received signals and of the expected situations (e.g. energy of the output of a matched filter), to a threshold depending on the required probability of detection **Pd** and probability of false alarm **Pfa**

H0: no target, H1: a target



Detection and False alarm, after thresholding of the quantity X with threshold T

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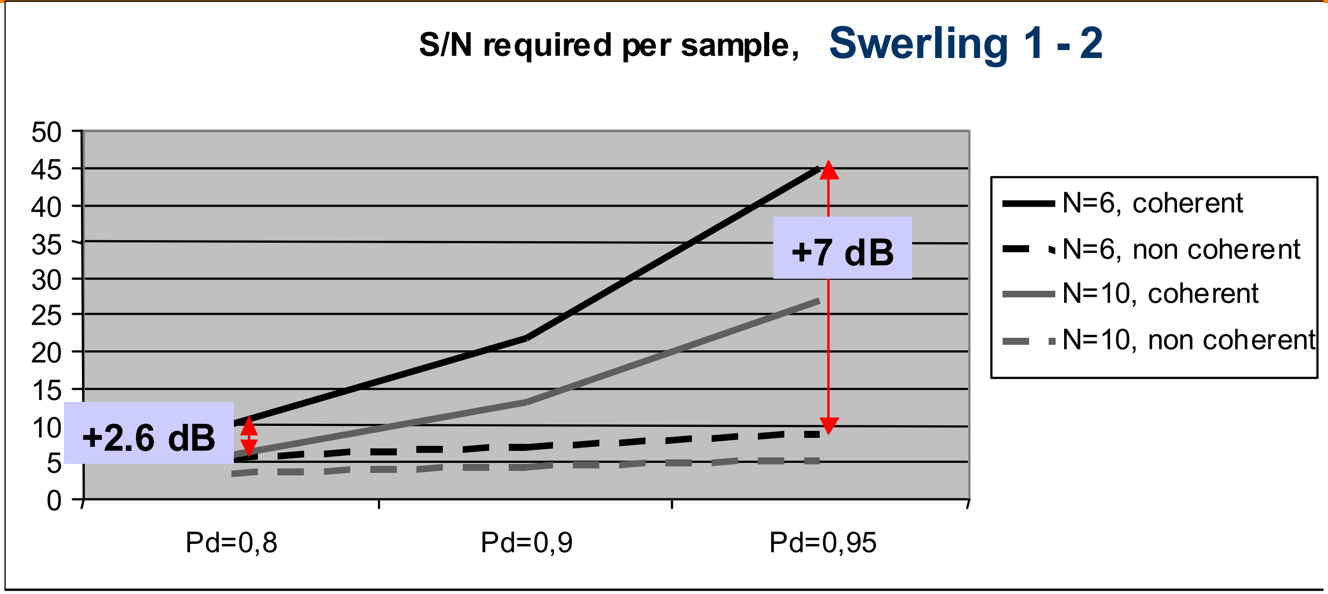
Coherent vs Non-coherent integration

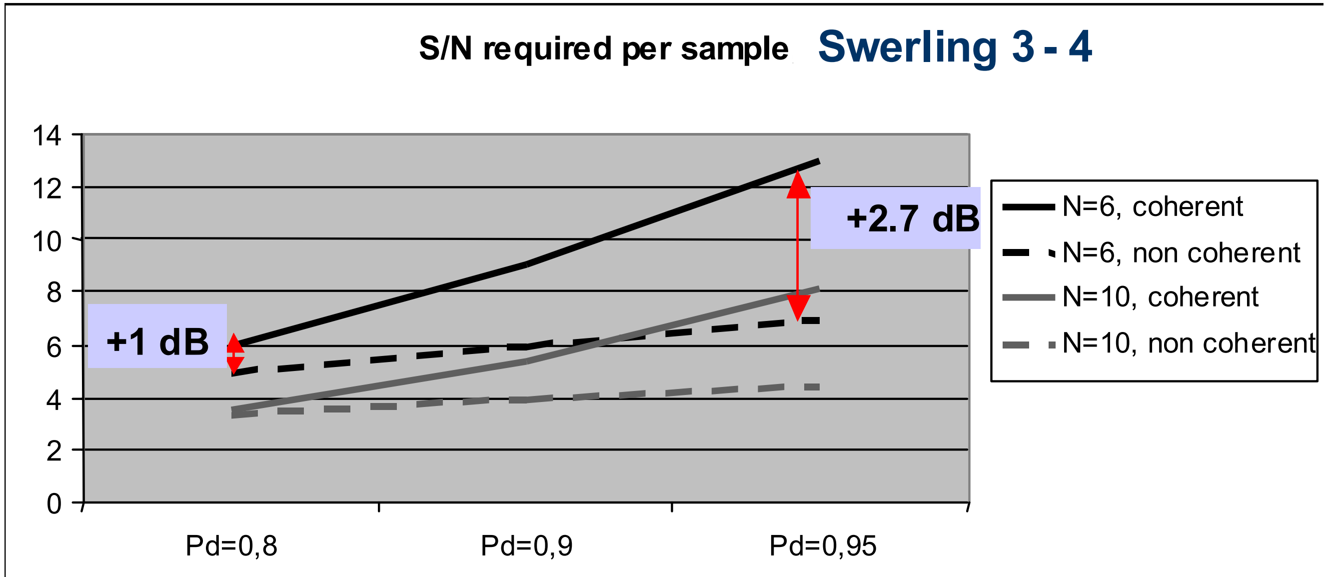
Shape of the probability density functions p(x/Hi) is critical

Using diversity is a means to improve the separation:

- **Averaging quantities reduces the spread of each probability density function, and brings it closer to a Gaussian (central limit theorem)**
  - Successive bursts at different carrier frequencies
  - Different aspect angles with different transmitters / receivers
  - Successive scans, with sufficient time separation
- **Using coherent integration, or more generally matched filtering, increases the mean value of X under hypothesis H1**
- **Both techniques thus improve the separation, in different ways: our objective here is to clarify these effects, and their consequences, for typical situations**

Coherent vs Non-coherent integration, fluctuating target





Effect of the number of bursts for fluctuating target detection. The traces show noncoherent versus coherent integration for a $Pfa = 10^{-6}$.

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How to integrate on fluctuating targets?

Swerling 1 targets are more difficult to detect than SW 3

- Even more true for higher required Pd

For high Pd, « some » non-coherent integration is preferable

- Not to get trapped in a low RCS zone
- Especially for highly fluctuating targets (SW 1)
- Only for low values of Npulses

How to integrate on fluctuating targets?

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Golden rule

- First improve S/N (coherent integration), then mitigate the low RCS zones (frequency agility on a few steps, or multistatic diversity)
- The price to pay is lower Doppler resolution (because of shorter coherent bursts)

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Coherent / Non-coherent integration

Coherent integration (summation along the burst, or along the array, before detection)

- Requires no target fluctuation
- Doppler or spatial summation
- → Signal to noise improvement = $N_{samples}$
- → Best against noise

Non-coherent integration (summation after detection)

- From scan to scan, or from receiver to receiver (multistatic)
- From pulse to pulse, or burst to burst, with frequency agility
- → Poor against noise (the non-linear detection degrades S/N ratio)
- → Best against target & clutter fluctuations

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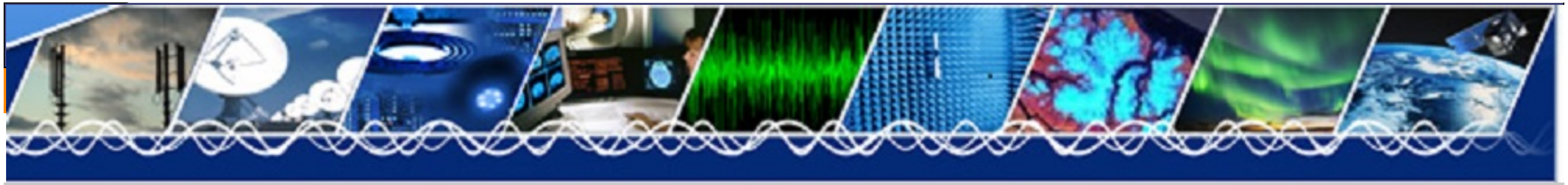


Wideband non-ambiguous radar

- Diversity/resolution gains for targets
- Diversity gains for clutter

Supported by STW – Users Committee: Thales NL, Christiaan Huygens Laboratorium (CHL), TNO, MetaSensing, ISAE Toulouse

Ambiguities, Blind speeds

Conventional radars

- Instantaneous relative bandwidth < 1/1000, range resolution > 15 m
- Agility bandwidth 1/10
- Ambiguities (High, Medium, Low PRF)

$$V_a \times D_a = \frac{\lambda \times c}{4}$$

Blind speeds and velocity ambiguity

- Due to the fact that Doppler is measured as a phase shift from pulse to pulse, modulo 2π
- Mitigation: sending successive pulse trains of periodic waveforms (with different periods) $\Rightarrow$ shorter coherent duration for each train

Wideband coherent radar

Conventional radars

- Instantaneous relative bandwidth < 1/1000, range resolution > 15 m
- Agility bandwidth 1/10
- Ambiguities (High, Medium, Low PRF)

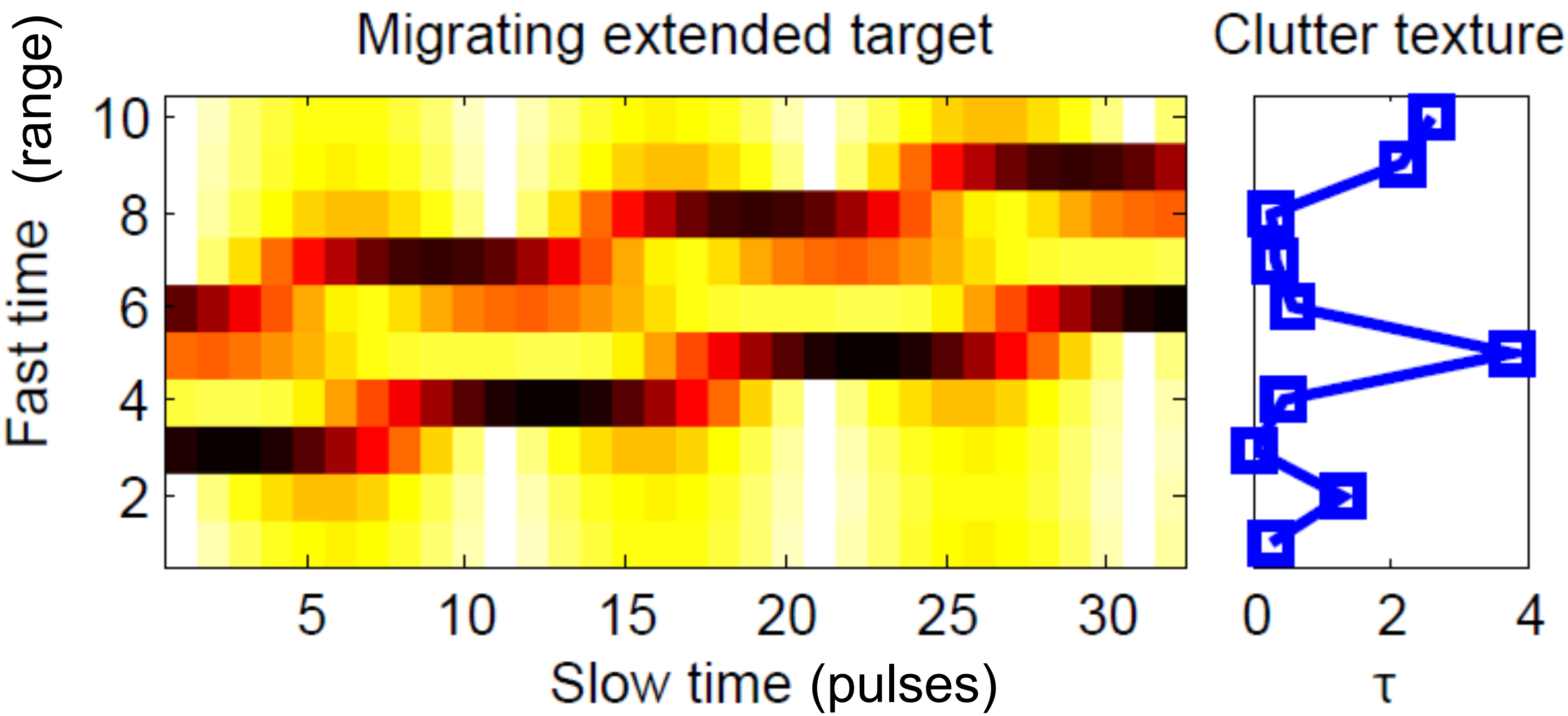
$$V_a \times D_a = \frac{\lambda \times c}{4}$$

Wideband coherent radars

- Instantaneous bandwidth ~ 1/10, range resolution ~ 10 λ
  - Non-negligible rangewalk during the pulse train
  - Varying Doppler across the bandwidth
  - One low PRF burst, unambiguous in range

Condition for non-ambiguity: Bandwidth 5-10%, 50-100 pulses

Coherent processing of 1 burst, compensating for migration



Range migrating extended target in spiky clutter

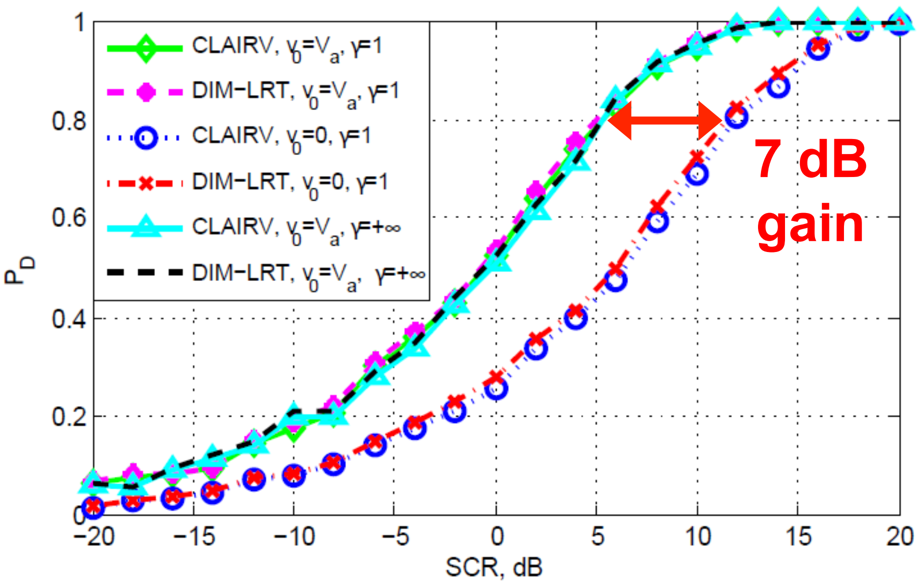
Diversity gains for wideband radar

Detection: extended target situation

- Specific integrator-detector
- Classification potential

2 kinds of diversity gains

- Against target fluctuations, through wideband observation
- Against clutter fluctuations, through target migration
- Obtained without any cost in Doppler resolution (1 burst)



Detection probability of range migrating target in CG clutter with: v = 0 m/s and v = 15 m/s, SCR is the power of clutter after whitening, exponential correlation in range with $\gamma = 1$ and $\gamma = +\infty$; PFA = 10^{-5}. Radar parameters: f_c = 10 GHz, B = 1 GHz, δ_R = 0.15 m, T_r = 1 ms, M = 32.

Diversity for wideband radar

For wideband radars, coherent integration time needs not be reduced to obtain diversity gain

- summing the bursts in each range cell of a narrowband agile radar is equivalent to summing the samples of the range profile of a high range resolution radar

Target detection performance

- depends on target extent and velocity ("spread of the signature")

Detection gain for the target with velocity v_0 = 15 m/s,

- which obeys a range-walk of about 3 range cells during the CPI
- is about 7 dB in K-distributed clutter with shape parameter ν = 0.5

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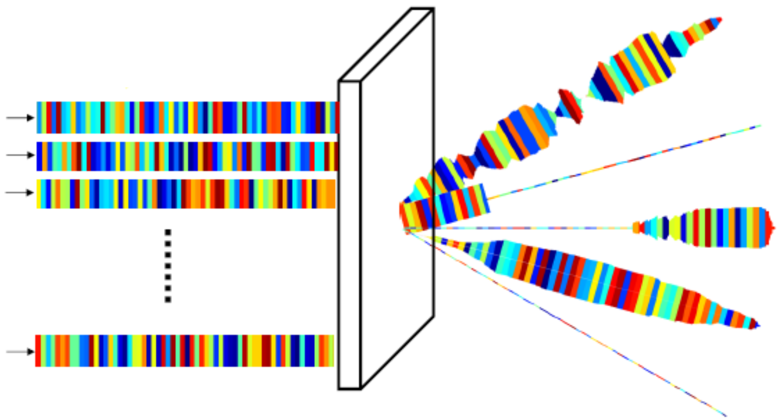
Space-time coding (MIMO) for diversity



Sidelobes diversity

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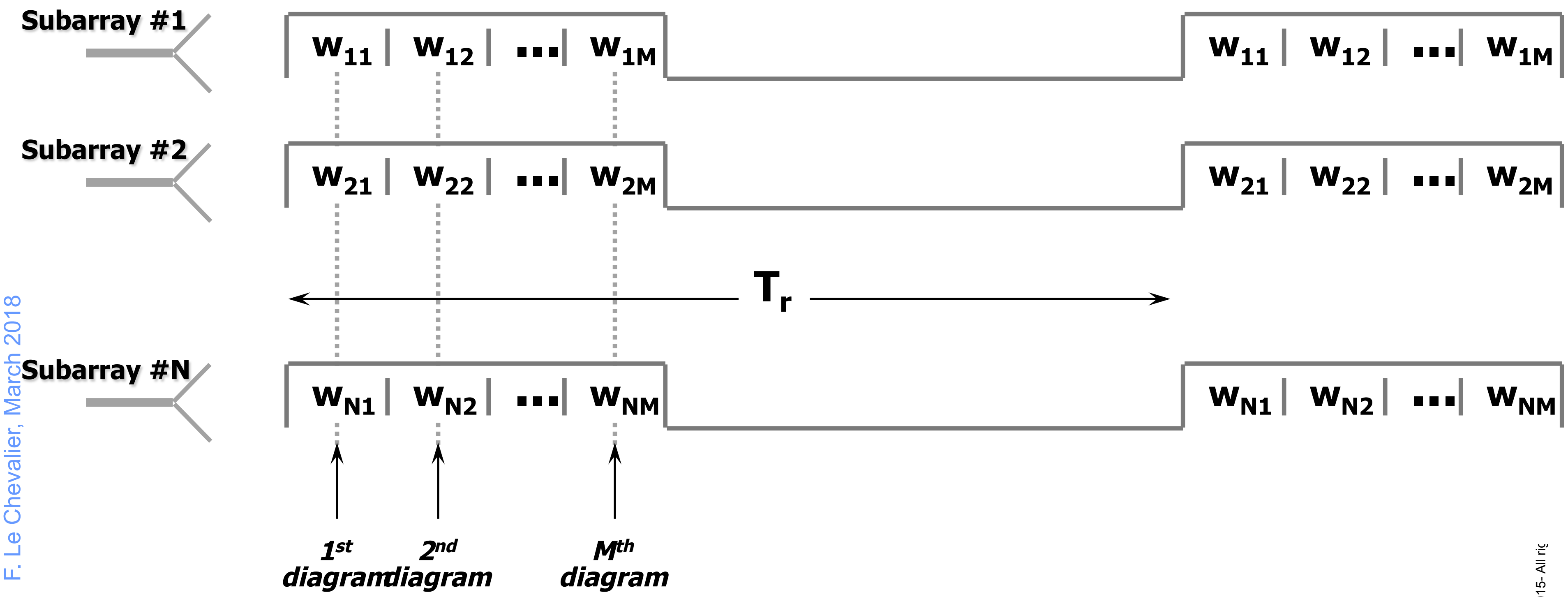
Space-time omnidirectional coding on transmit: wide instantaneous angular coverage

Recovery of transmission directivity by signal processing on receive



F. Le Chevalier, “Space-Time Transmission and Coding for Airborne Radars”, *CIE Journal on Radar Science and Technology*, Vol. 6, N 6, Dec 2008

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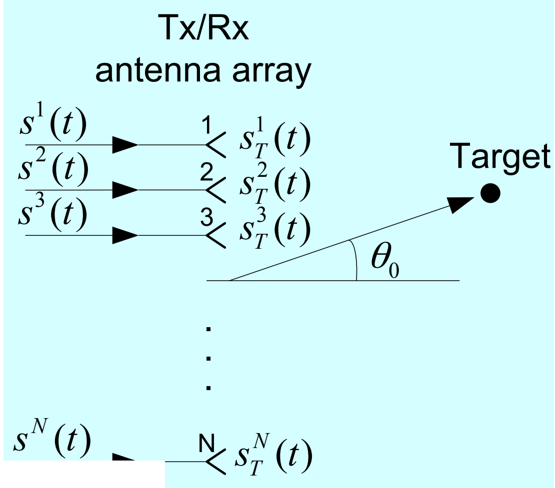
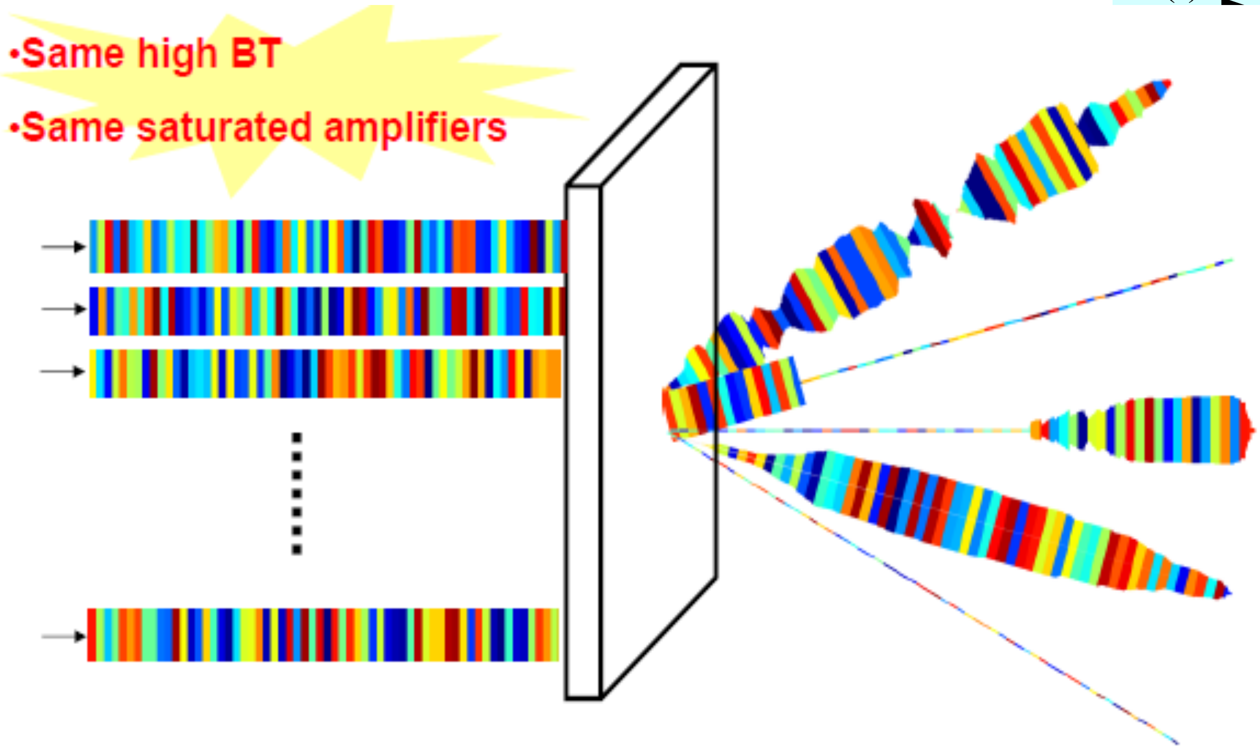
Space-time signals

The signal transmitted in a given direction θ_0 is the sum of all transmitted signals, with appropriate phase shifts corresponding to this direction





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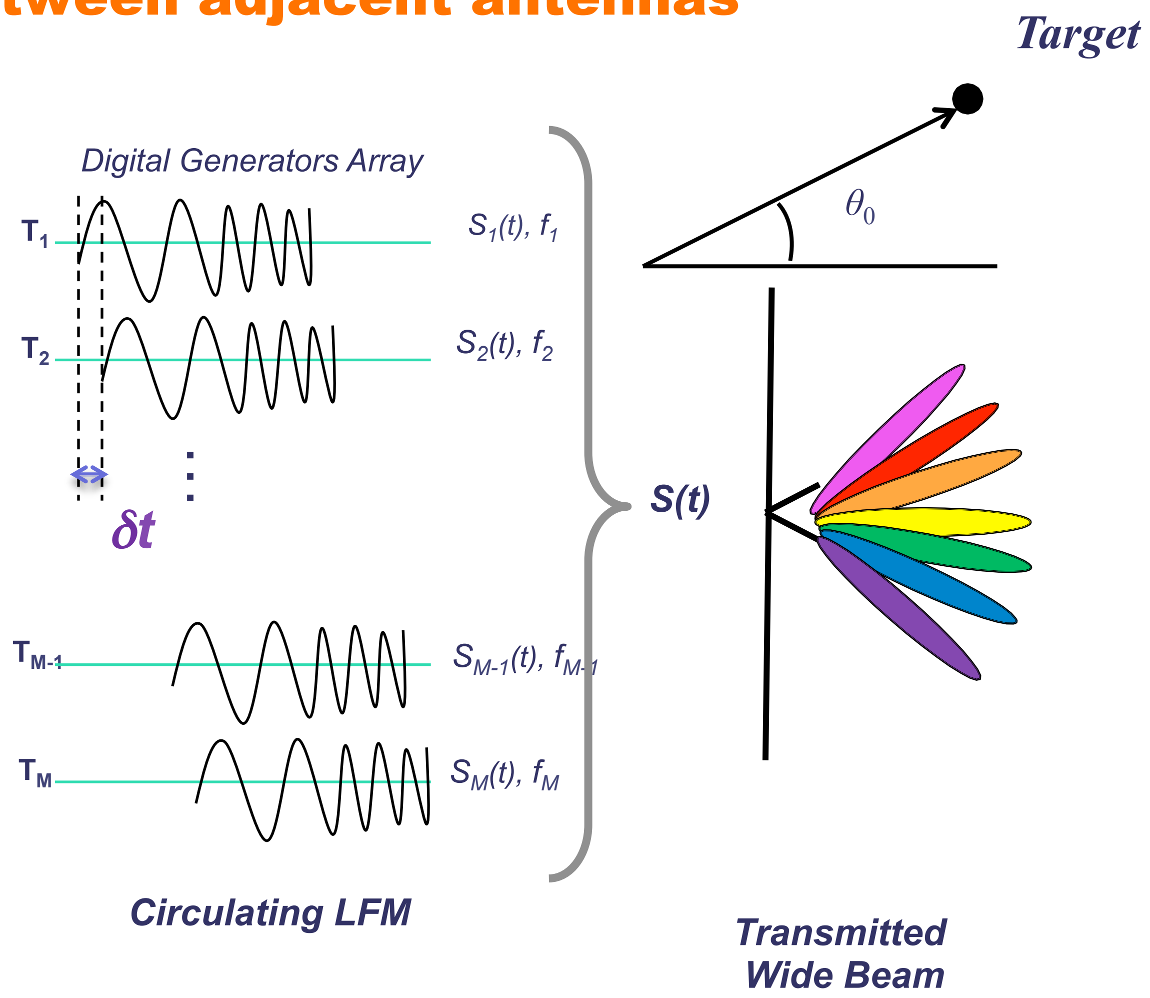
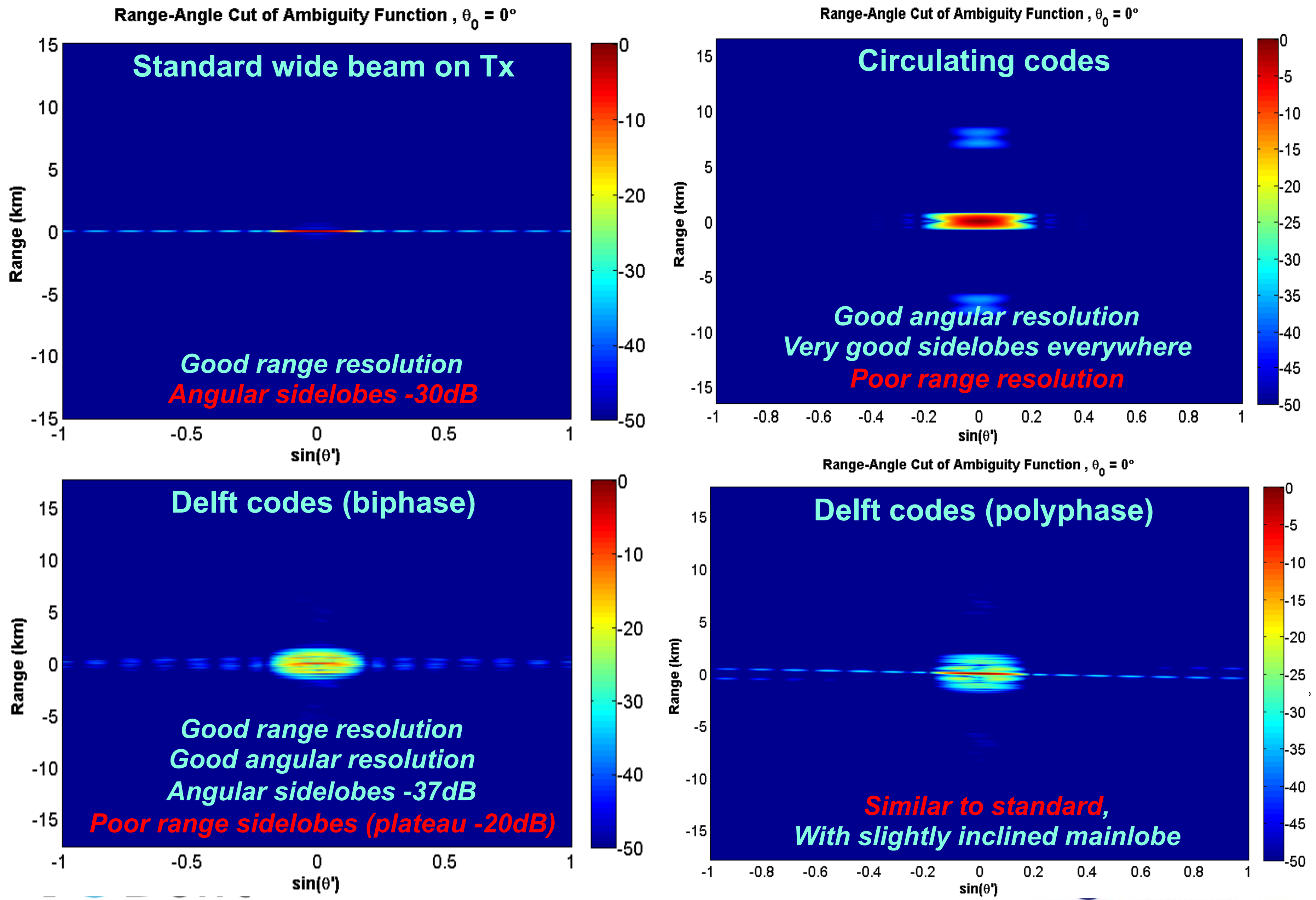
Delay δt between adjacent antennas



Range-angle diversity, mismatched receiver, loss < 1.5 dB

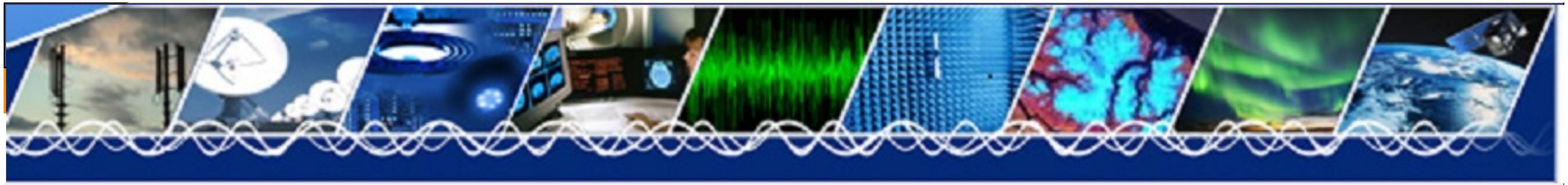


Space-time coding for surveillance

- The increased degrees of freedom provided by space-time coding on transmit open the way to adaptive systems where range and angle resolutions can be traded, depending on the mission and the actual environment (knowledge aided)

- Compared with modern wide beam DBF Systems, space-time coding provides an improvement in both accuracy and resolution larger than 2, for 2-dimensional antennas.

- For application to modern radar systems with multiple bursts, space-time coding provides an additional diversity, comparable to – and compatible with – frequency diversity



Discussion

F. Le Chevalier
Emeritus Professor, TU Delft
Chief Scientist (retired), Thales

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How to combine diversity effects when using agile waveforms?

- **Baseline example, with a typical modern radar using**
  - digital beamfoming in elevation only,
  - chirp waveform with pulse length 100 μs, pulse repetition frequency 1 kHz

Any designer would like to benefit from:

- **High Doppler resolution, for visibility of slow and weak targets;**
- **High angular resolution, in elevation (for altitude measurement) and azimut (for tracking);**
- **Diversity on the target, for improved detection in noise;**
- **Diversity on clutter, for improved detection in clutter.**

Requirements analysis

High Doppler resolution

- **long coherent integration time**
  - but anyway this coherent integration time is limited by the fluctuations of the aspect angle of the target, typically to less than 100ms

High angular resolution

- **narrow beams on transmit and receive**

Diversity on target

- **different carrier frequencies, or different aspect angles (multistatic system), or integration along a high resolution range profile**

Diversity on clutter

- **target superposed to different patches of clutter**
  - either through range migration or range extent of the target
  - Or through multi-bursts with different range ambiguities (so that the target folds over different clutter patches).

Standard solutions

These requirements tend to eliminate standard solutions

- **pencil beam with low range resolution**
  - ☹ limited velocity resolution due to a short time on target
- **standard digital beam forming with no ambiguity in range**
  - ☹ limited angular resolution due to the wide beam,
  - ☹ limited diversity on clutter

Several baseline solutions can be sketched

- **combining long time on target, high angular resolution, and diversity on targets and clutter**

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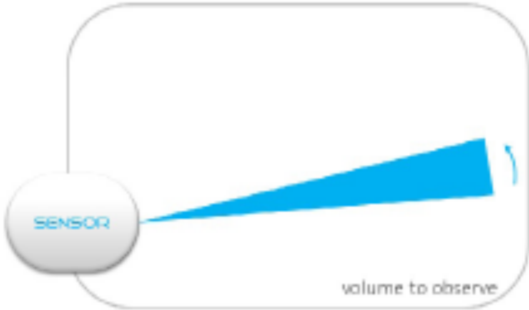
Baseline solutions with diversity

1. **Pencil beam, high range resolution, unambiguous in range (low PRF)**
   - satisfies all requirements if the available coherent integration time is sufficient
   - also provides valuable target analysis capabilities, with high resolution range-Doppler signatures.



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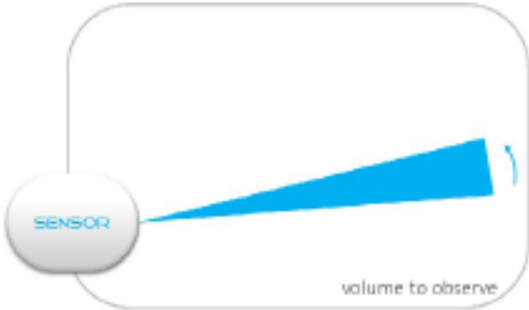
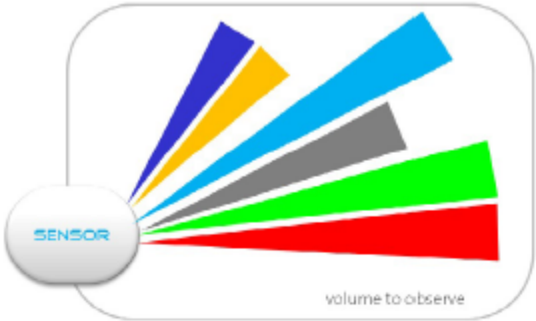


2. **Space-time coding, low range resolution, ambiguous in range (high/medium PRF)**
   - also satisfies all requirements
   - pure circulating codes could be a preferred solution in strong clutter, with very low sidelobes everywhere



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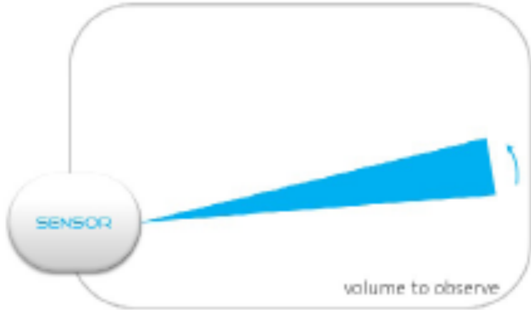

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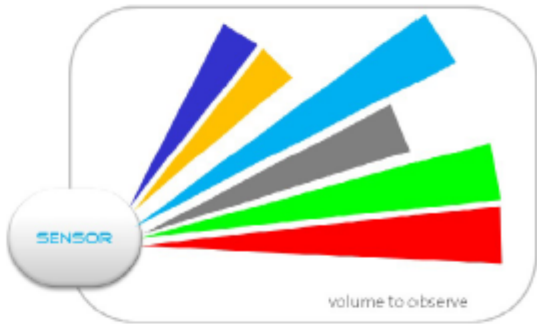

3. **Space-time coding, high range resolution, unambiguous in range (low PRF)**
   - low sidelobes, high diversity, and valuable target analysis capabilities, with high resolution range-Doppler signatures.

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Caveat

Baseline descriptions ≠ definitive solutions

- **Very complex task of defining a multifunction radar**
  - for instance, multistatic solutions could also make sense, possibly combined with space-time coding for solving the “rendez-vous” issue
- **The objective was rather, as outlined in introduction, to highlight and clarify some specificities of diversity effects which have to be considered when designing future systems**
- **Many other aspects, from complexity and cost to multifunction requirements, have also to be taken into consideration**
  - they should also bring out different advantages of high resolution and space-time coding for surveillance radars.

Diversity has direct consequences on radar architectures

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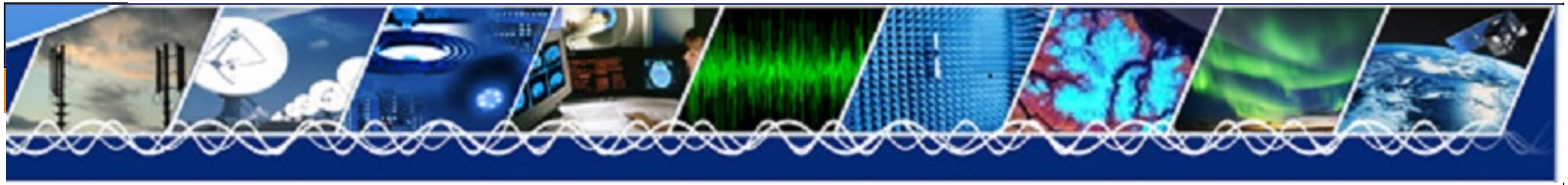

Thanks!

Any question, or comment ?

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