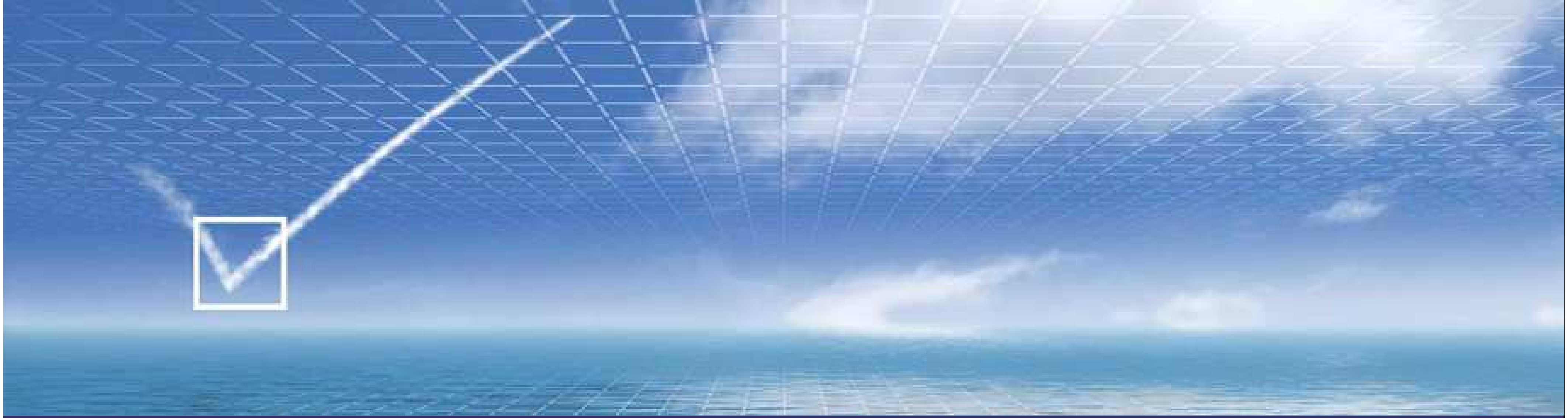


www.thalesgroup.com

Systèmes de « Sense and Avoid » pour drones basés sur Radar

Stéphane KEMKEMIAN

GT UAV le 24 mai 2012

THALES

Outline

1.Why and What is “Sense and Avoid” ?

2. System Requirements

3. Focus on the Radar

4. Data Fusion

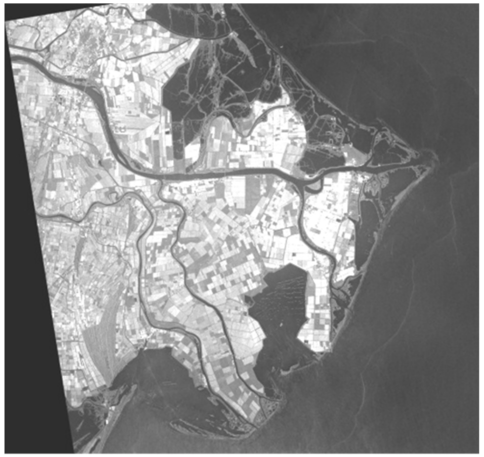
5. Simulations

6. Conclusion & Perspectives

THALES

Why is "Sense&Avoid"

- **UAS can carry various payloads (optics imagery, radar imagery)**



- **Up to now UAS are mainly used for military purposes:**
  - Easily deployable;
  - They can approach closely and safely a threat;
- **However, civilian security applications are emerging:**
  - Fire, Pollution surveillance;
  - Telecom relay;
  - Border / Costal customs surveillance;
  - Anti-terrorism surveillance

But UAS cannot be inserted into the General Air Traffic (GAT), so far:

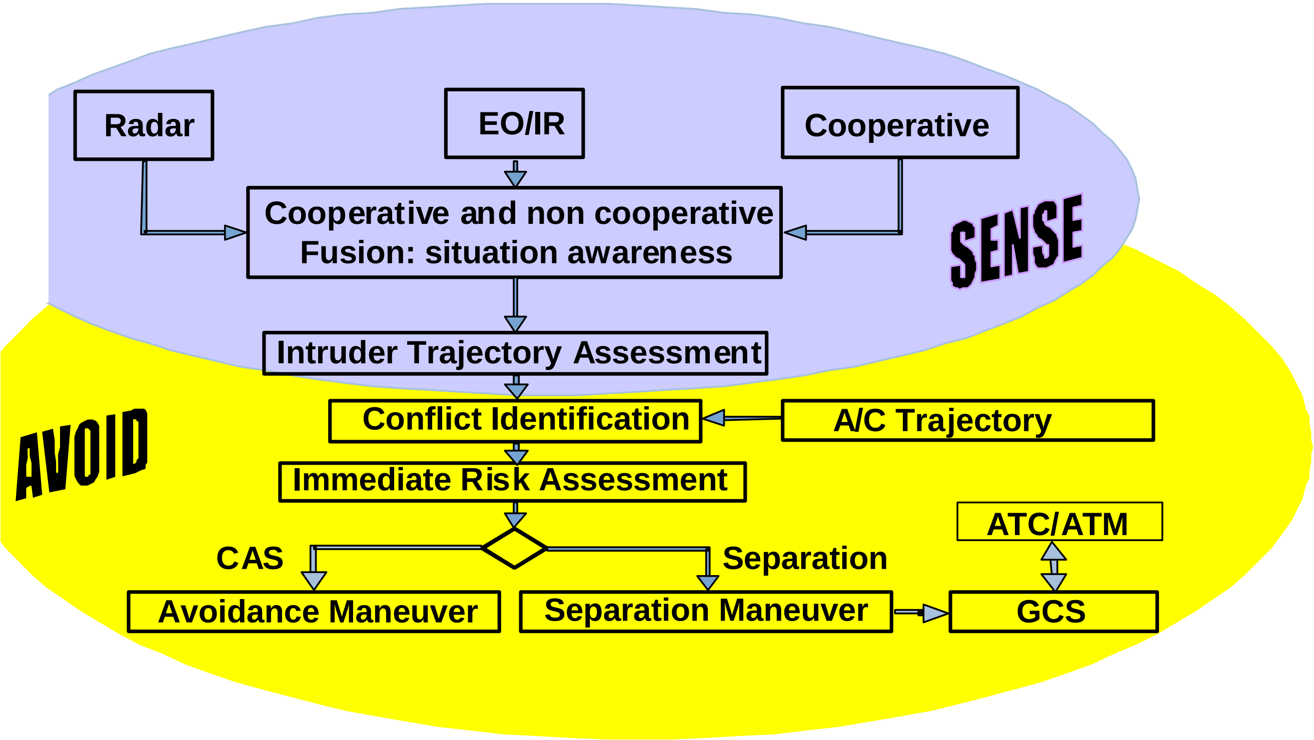
→ **For training purposes, they need to be operated in "Restricted (Segregated) Areas".**

Goal of a Sense & Avoid System: To allow the insertion of UAV into the General Air Traffic.

1.Why and what is "Sense&Avoid"

It is a system that replaces the Pilot' eyes in the cockpit.

- **Safety and reliability are the watchwords. To do that, parallel sensors are fused.**
- **Sense function:**
  - Situation Awareness.
  - Trajectories prediction.
- **Avoid function:**
  - **In normal operation:** Traffic Separation with Man in the loop **(SEP)**;
  - **Emergency operation:** Automatic Collision Avoidance **(CAS)**.



2. Systems requirements

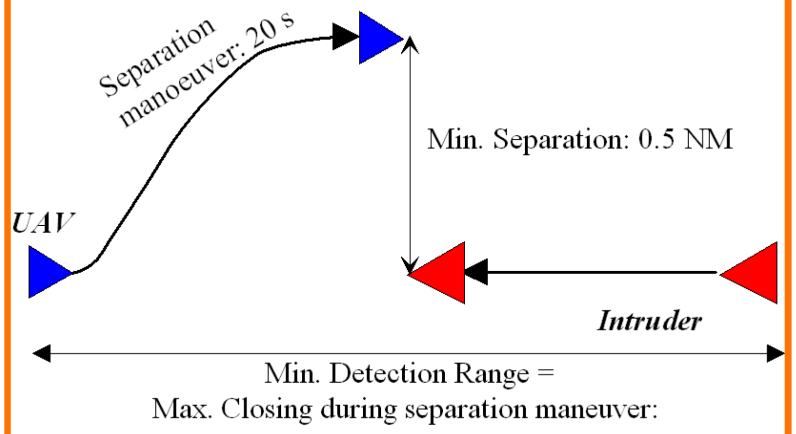
General System Requirements

Wide Field of View (FOV): 2sr

- Approximately that of a pilot in a cockpit: ±110° in AZ. and ± 15° in EL.

Accurate trajectory assessment, especially in Z:

- Traffic Separation requirements are: ΔXY > 0.5 nm or Δ Z > 500 ft.
- The fastest separation manoeuvre is most often in the horizontal plane.
- **But the critical parameter for the decision to avoid is the vertical spacing measurement.**



About 8 km with a maximim closing rate of 400 m/s.

Required range is proportional to the closing velocity.

"Long" detection range for Sense:

- Warning time is the sum of:
  - **The manoeuvre duration itself (about 20 s)**;
  - Data-link delays + GCS decision (some sec.).

The Sense task is the key driver for the sensors (accurate localization at long range ☞ the most demanding requirement for the traffic separation).

General System Requirements

There is no formal regulation, so far:

- Only generally admitted hypothesis based on current Air Rules.

The reliability of such a system is of prime importance:

- So, cooperative and non-cooperative sensors are merged.

As some A/C are not fitted with cooperative sensors, non-cooperative sensor is mandatory.

The different Sensors Involved in S&A

Co-operative sensors:

- These are mainly transponders or squitter messages receivers**:**
  - The transponders send a request for an answer from a potential intruder
  - The squitter messages are unsolicited. **The message receiver onboard the own ship is the co-operative sensor**.
- **But a co-operative sensor cannot be used alone for safety reasons:**
  - **All Aircraft are not equipped, and the integrity of transmitted data must be checked.**

Autonomous sensors:

- **Radar is an essential active sensor for Sense and Avoid, indeed:**
  - **Radar is "all weather", day and night.**
  - It provides basically **Direction, Closing velocity and Distance of targets**.
  - **So, it provides itself all "Sense" tasks (and also the avoid task).**
- **A complementary autonomous sensor can be a passive E/O one.**
  - In favourable conditions, **to enhance the angle measurements**.

Passive E/O Sensor

1. E/O sensor alone may provide some avoid functions:

- It provides accurate angular measurements, **but it is not “all weather”;**
- It may detect targets on a collision course, criterion: $\frac{d\theta}{dt} \approx 0$
- It may assess the Time To Go (accuracy is questionable):
    - **From the growth rate of a target image at short/medium range** unless a very Hi-Res. optical sensor system is used (> 6000 pixels in H for a 5m target @ 5nm).
    - **From the angle variation rate at short/medium range**.

2. E/O sensor is unable to provide itself a situation awareness :

- neither range nor velocity.

3. E/O sensor can only be used with other sensors to do that:

- **With Radar, to enhance the angular accuracy through data fusion.**
- **With a co-operative sensor, to check the integrity of the received data.**

E/O sensors alone may provide Avoidance function at “short or medium” range but never itself the Sense function.

Co-operative Sensor: ADS-B

ADS-B (Broadcast):

- **Stand for:**
  - **Automatic**: no interrogation is needed to start the squitter coming from surrounding aircraft/intruders.
  - **Dependent**: It relies on other aircraft/intruders navigation and broadcast means.
  - **Surveillance**: Automatic surveillance and traffic coordination.
- **An ADS-B equipped aircraft automatically broadcasts:**
  - Its position/velocity and ID. at a 2 Hz rate.
  - Geodesic position is derived from GPS.
  - Barometric altitude comes from anemometric sensors.
- **An ADS-B receiver on board the own ship provides localizations:**
  - Which are much more accurate than any other autonomous sensor;
  - Available "All weather" and at long range.

The main issue with ADS-B (or similar co-operative systems) is to check the integrity of received data

3. Focus on the radar

3. Radar Design - Operating Band, Architecture Enablers

Up to S (even C band), the angular accuracy is not fulfilled with a "reasonable" overall size of the antennas system.

Wavelengths in Ka band and above are too much weather sensitive.

- **So, operating frequencies in X or Ku band are a good tradeoff.**
- **Moreover, many "COTS" are available in X-Band.**

Both the required angular accuracy and the angular coverage:

- Make unrealistic mechanical scanning (too high rotation rate);
- Make problematic "pure" E-SCAN (too short dwell time).
- Full "classical" E-SCAN is also a costly solution.

DBF-based methods are convenient and cost effective for wide angular coverage systems in X or Ku bands.

THALES

3. Radar Design – Power Budget Tradeoffs

Detection Range depends only on the product:

$$\underbrace{P_{AVG}}_{\text{Average Power}} \times \underbrace{A_R}_{\text{Antenna Surface on Receive}} \propto P_{AVG} \times \underbrace{\lambda^2}_{\text{wavelength}} \times \underbrace{N_R}_{\text{Number of Receiving Elements}}$$

- For a given couple (P_D, P_{FA}).

Detection Range does not depend directly on wavelength;

Cost increases with the transmitted power and frequency;

Cost increases also with the number of receiver channels for DBF

Trade-off between transmitted power & number of receiver channels has to be found

3. Radar design – MIMO radar

Transmission and Vertical localization use a fixed vertical array:

- Directive in Elevation;
- Non directive in Azimuth;
- Vertical localization through Space Coloring on transmit.

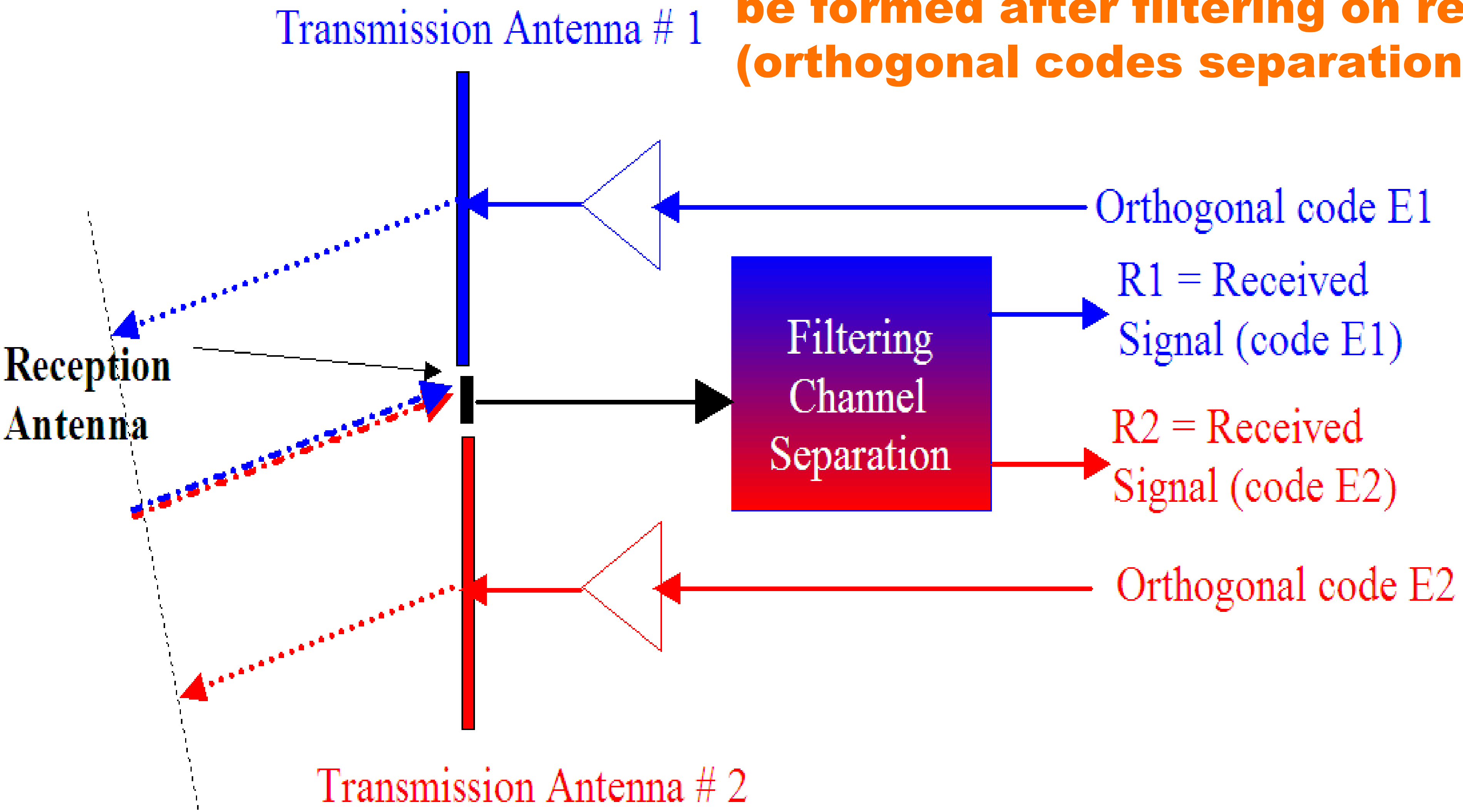
Reception and Horizontal localization use fixed horizontal array:

- Horizontal localization thanks to DBF;
- Receiving array pattern covers exactly the Elevation domain.

A cost effective solution is thus composed of 2 perpendicular separate arrays (T&R) implementing coherent MIMO principles.

3. Space Coloring Waveforms: The “Mono-pulse” on Transmit”

Two “equivalent (Σ, Δ) channels” can be formed after filtering on receive (orthogonal codes separation).



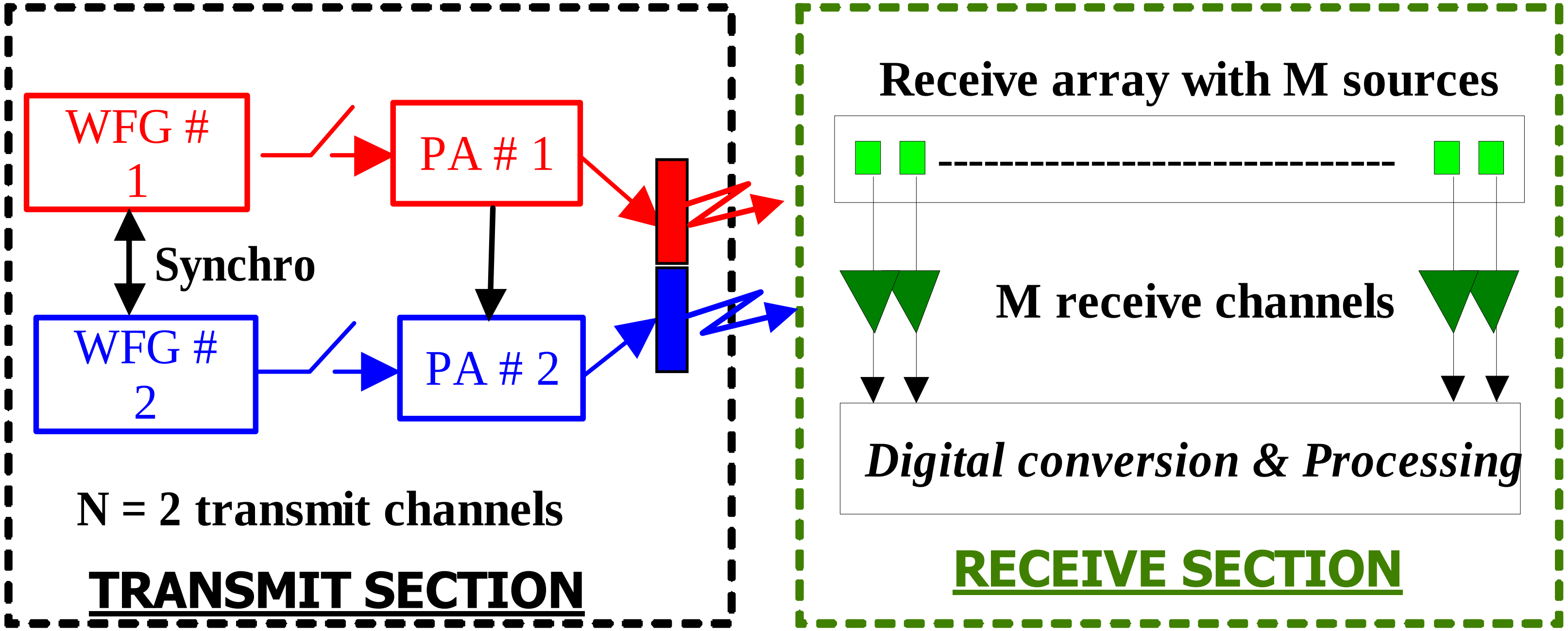
Equivalent elevation “Monopulse” with only one horizontal array on receive.

3. 1st step : Initial radar architecture

One linear array on receive: DBF in Azimuth (El. Coverage:±15°);

One "small" vertical linear array on transmit (El. Coverage:±15°);

- Azimuth coverage: Wide (several tens of degrees)
- Each half antenna radiates an orthogonal code with the other.



Lack of elevation selectivity ⇒ strong ground clutter

Small transmission antenna ⇒ Lack of accuracy in elevation

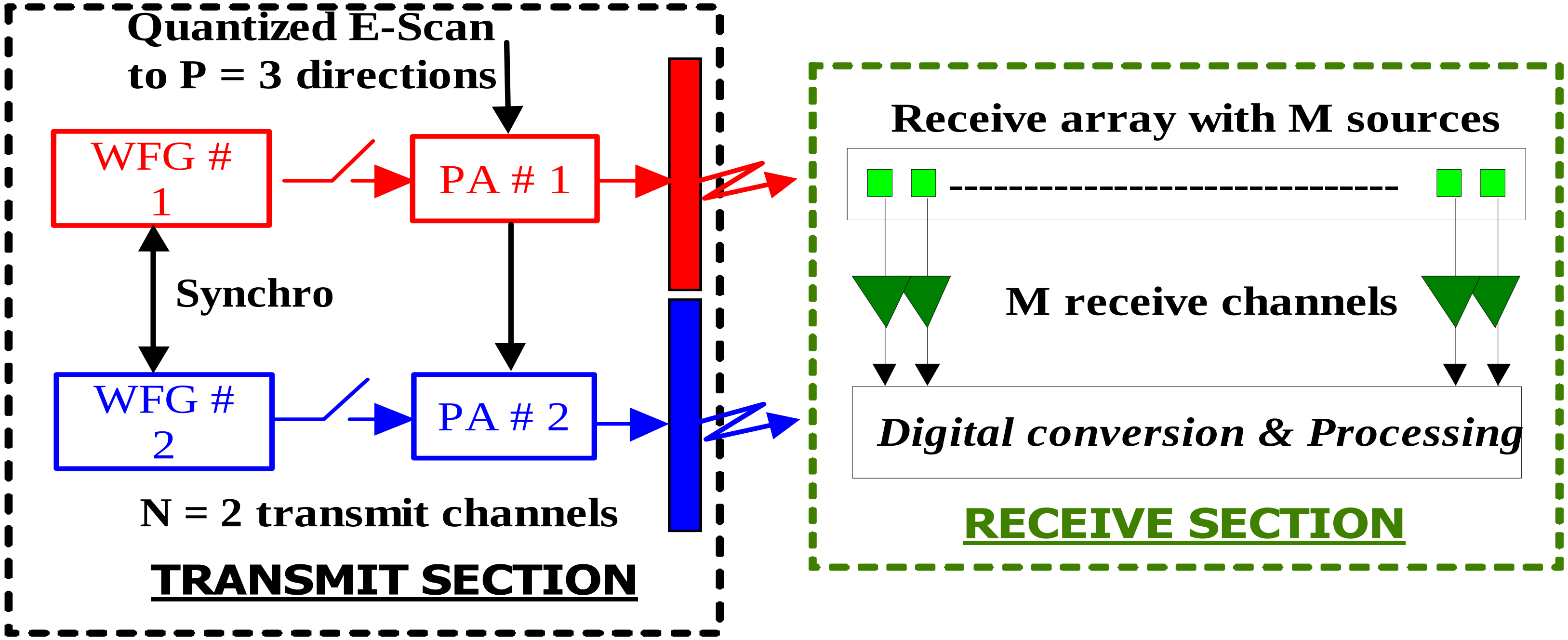
3. 2nd step: Improvement of Elevation Selectivity

Same receiving array & processing on receive (El. Cov.: ±15°);

One "large" vertical linear array on transmit (El. Cov.: ±5°);

⇒ Additional quantized E-Scan on transmit (3 states) is required;

⇒ Ground clutter reduction due to "narrow" elevation beam at transmission ;



Quantized E-Scan
to P = 3 directions

WFG # 1

PA # 1

Synchro

WFG # 2

PA # 2

N = 2 transmit channels

TRANSMIT SECTION

Receive array with M sources

M receive channels

Digital conversion & Processing

RECEIVE SECTION

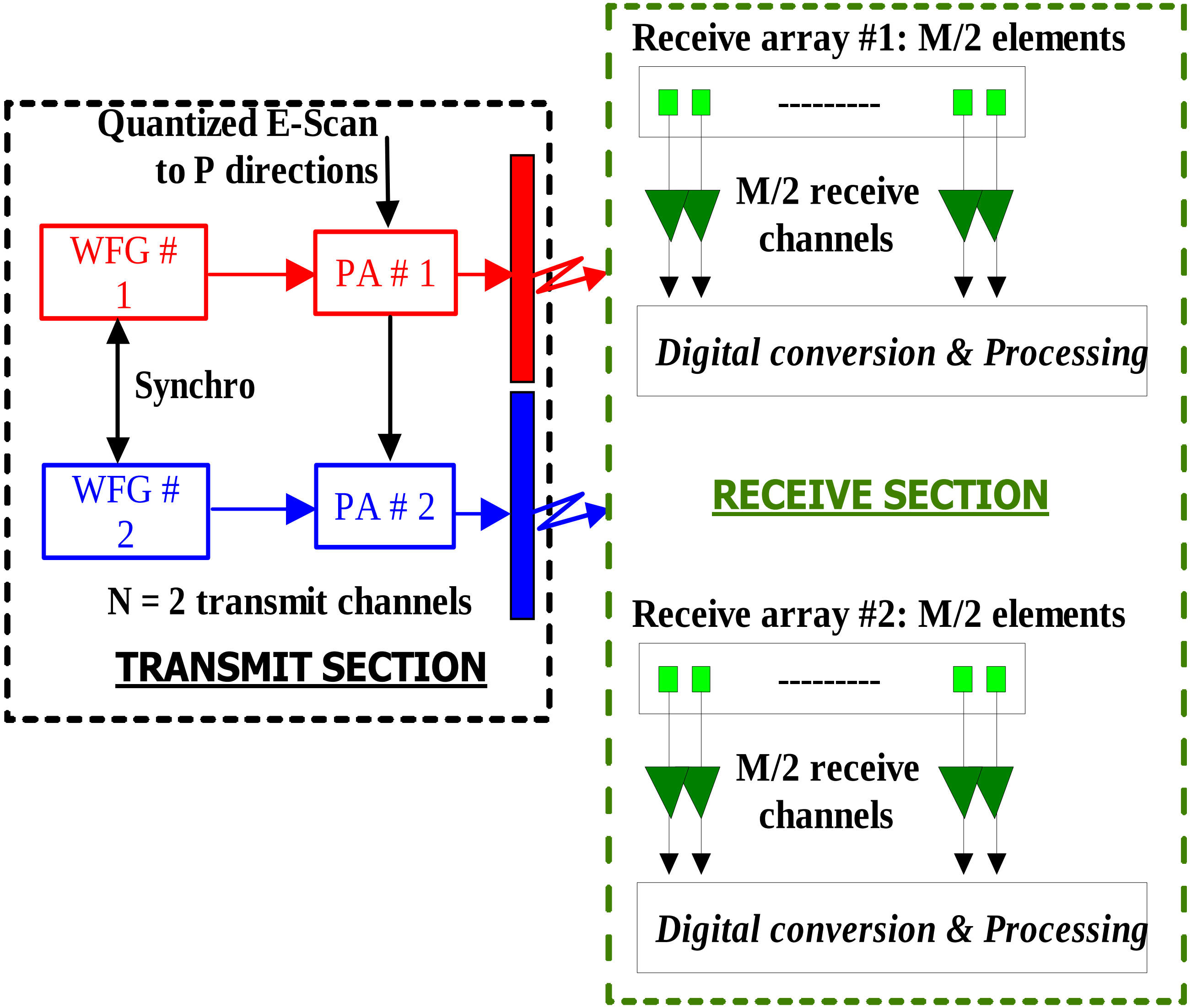
Better elevation selectivity ⇒ Ground clutter reduction;
Better accuracy in el. BUT does not meet requirements.

3. 3rd step: Improvement of Elevation Accuracy

Same transmitting section as in 2nd step.

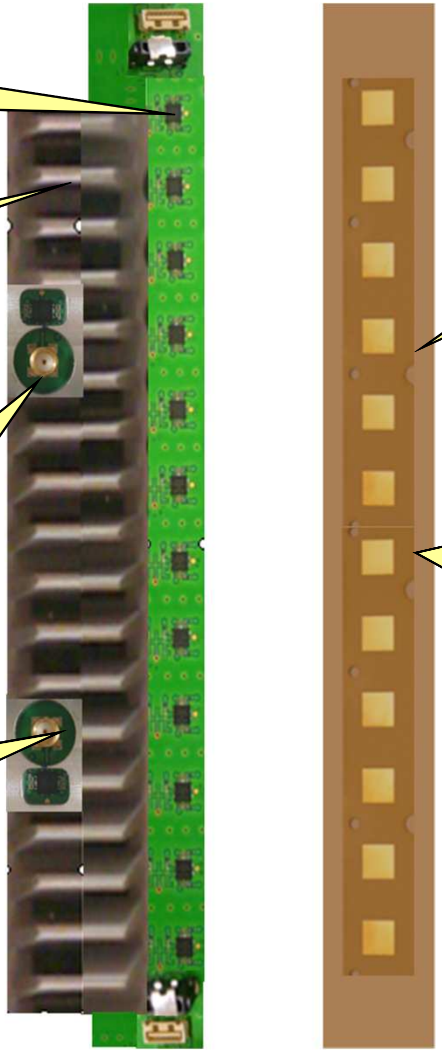
Receiving array is split into two parts.

- The two parts form an accurate interferometer;
- Interferometer is angle ambiguous in Elevation;
- Ambiguities are removed thanks to Space Coloring on transmit.



Excellent accuracy in el. : the proposed architecture meets the requirements.

4. Low Cost Technology Utilized – Transmit Section



COTS X band HPA: ≈ 2W average power

Heat-Sink (moved for drawing readability)

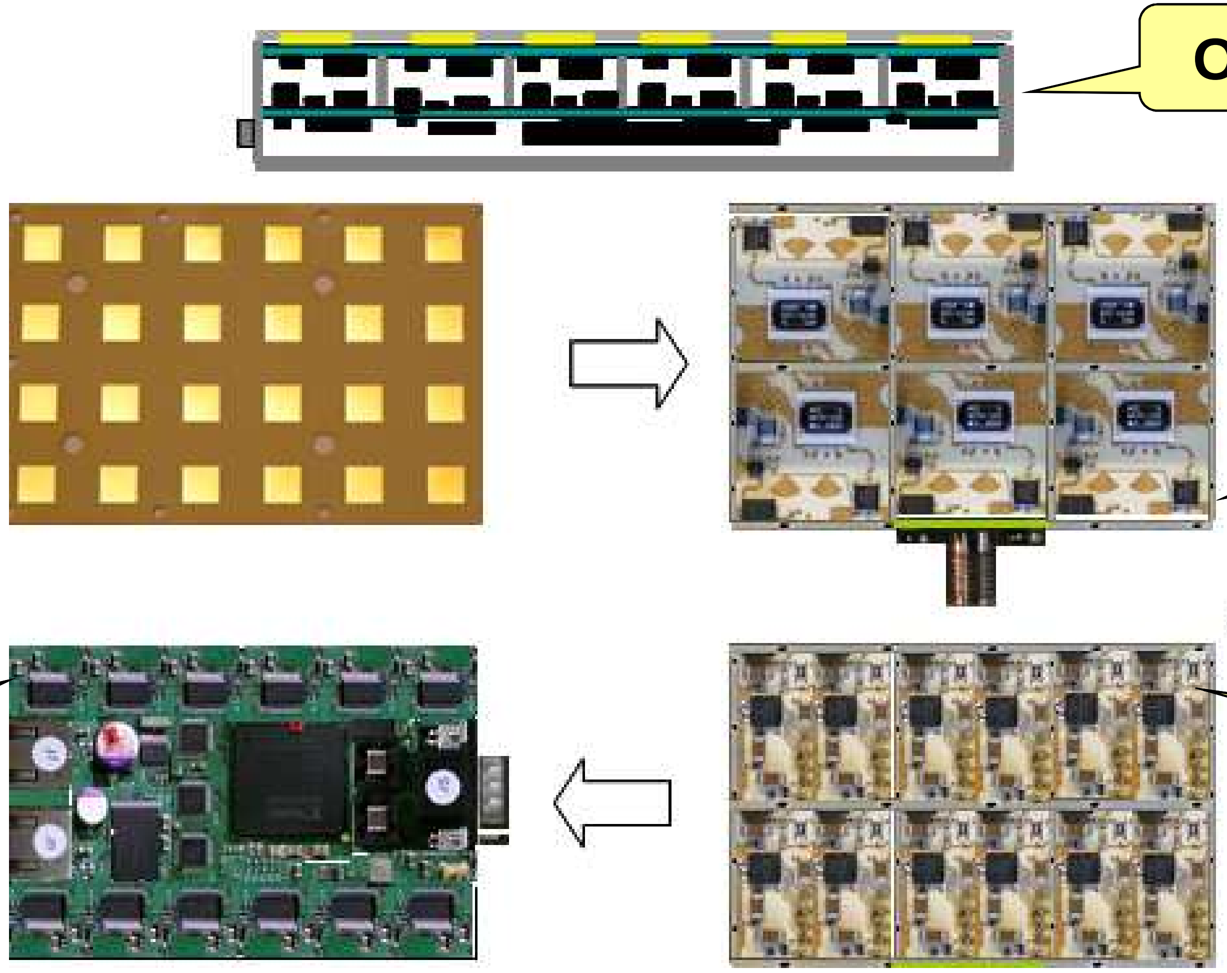
Two low level inputs (two orthogonal codes)

Front Side: Radiating Elements

Radiating array split into two halves (mono-pulse on transmit)

RF parts + radiating elements on a single printed board.

4. Low Cost Technology Utilized – Receive Section



One "tile" BB

Front Side: Radiating Elements

Back Side: LNA (one per column)

Front Side: Receivers (IF & base-band)

Back Side: ADC + FPGA (pre-processing

Each receiving array is a set of several building blocks.

5. Waveforms Scheme

Need for detection expressed in term of advance warning time:

- **Required detection range proportional to target’s closing speed**

1. Fastest targets that can be detected on thermal noise:

- Use of waveforms without Doppler ambiguity.
- The peak power is a cost driver for HPA ⇒ CW cost effective and unambiguous in velocity

2. Slow targets competing with clutter:

- Long range detection non longer needed
- Pulsed waveforms without range ambiguity more suited, for Space Time Processing implementation.

A two waveforms scheme (slow / fast targets) is used.

5. Waveforms – CW Issues

Main concern = Signal leakage from Tx to Rx.

Due to the vicinity of the T & R sections aboard the platform:

- Since transmitted power is relatively low, R.F. traps or special implementation can solve this issue.

The main issue is the strong coupling which may occur by close backscattering on heavy rains.

- We have to use a CW with range selectivity to remove closest echoes (a few tens of meters):
- Solution : FM-CW.

A FMCW without ambiguity (in range & Doppler) is not feasible in X-band and above (on fast targets up to several km).

A special range-ambiguous non-interrupted FM-CW is used.

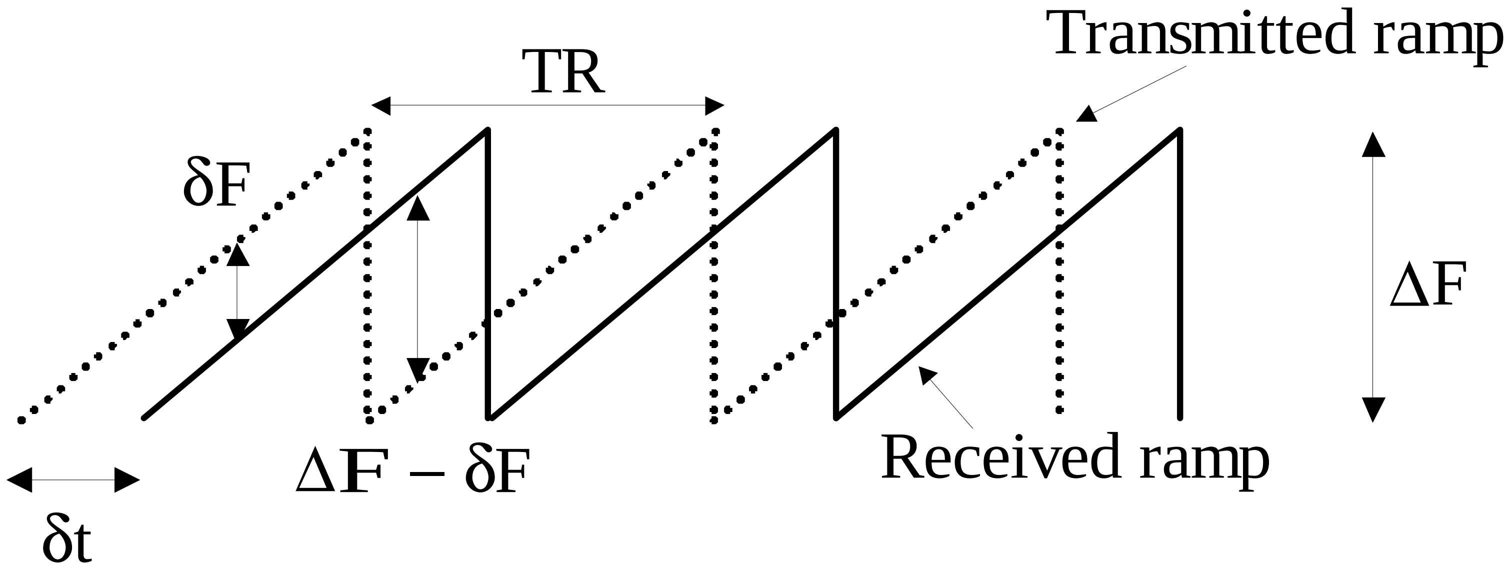
5. Waveforms – Range Ambiguous FM-CW

Conditions required for Doppler operation (Range ambiguous, Doppler non-ambiguous FM-CW):

Sampling frequency of beating signal exactly equal to ΔF.

Total phase rotation during a ramp: $\Delta\varphi = 2\pi.k$ (k integer).

- No phase discontinuity on the beating signal.



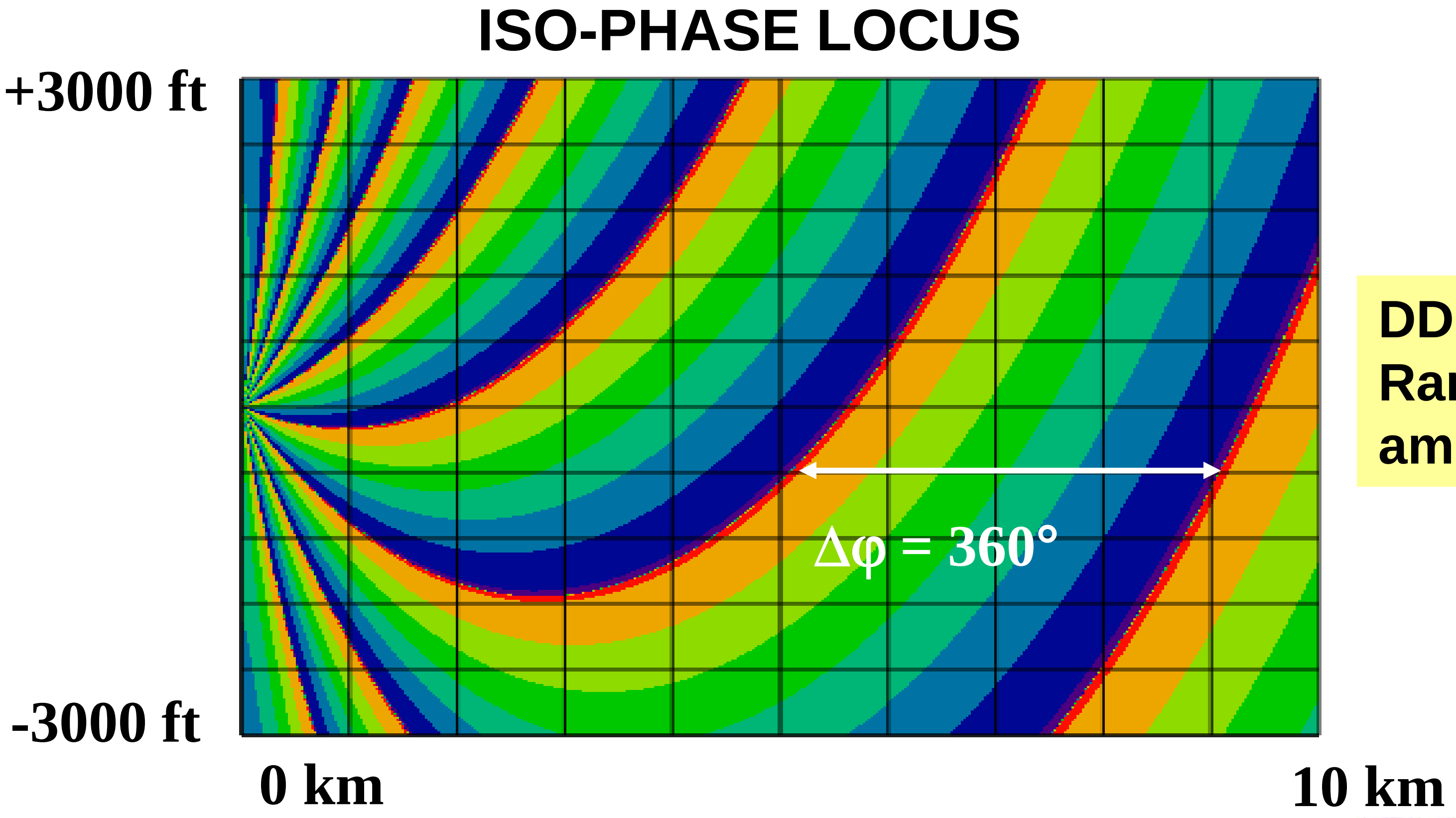
The 2 lines corresponding to each part are folded one over the other and added in phase.

5. Orthogonal Waveforms Used

The orthogonal codes used are based on Doppler Division Multiple Access (DDMA).

- Two ramps are radiated with constant frequency shift. Orthogonality for some judicious choice of the frequency shift.

DDMA induces a Range-Angle coupling, easily removed thanks to the range measurement issued from FM-CW range processing.



DDMA induced Range – Angle ambiguity.

4. Data Fusion

Main principles

Use of a common referential:

- **The Data Fusion requires all data to be expressed in the same referential:**
  - A common **spherical coordinates system is preferable**: Common axis of fusion between Radar and E/O sensors are angles (E/O provides only angles data).

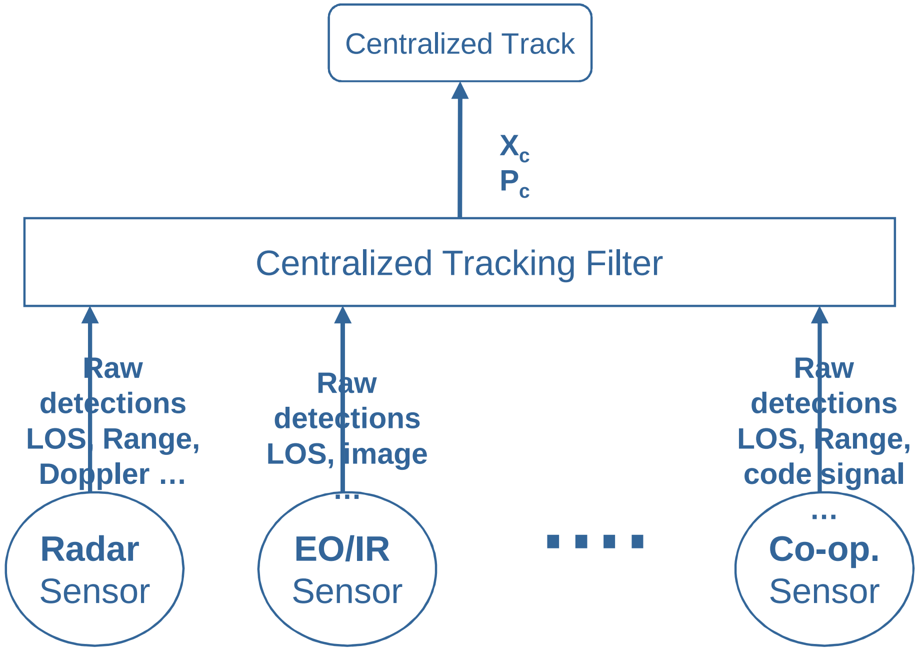
Data association:

- **It aims to determine what data issued from various sensors correspond to the same target.**
  - Data association is based on “statistical distance” between data.
  - Data association performance is limited by the sensor the less accurate.

Data fusion:

- **After data association, the data is fused.**
  - The data fusion performance relies on the most accurate sensor.

Two Basic Approaches



Centralized Track

X_c
P_c

Centralized Tracking Filter

Raw detections LOS, Range, Doppler …

Raw detections LOS, image …

Raw detections LOS, Range, code signal …

Radar Sensor

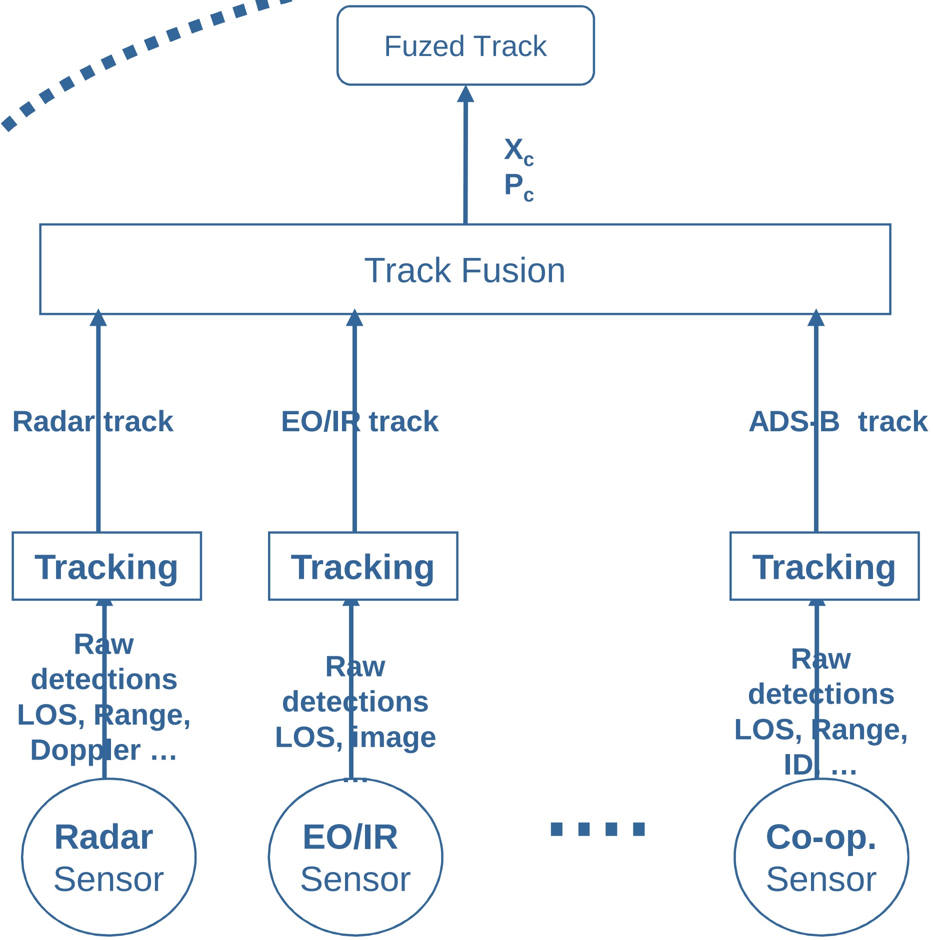
EO/IR Sensor

….

Co-op. Sensor

Centralized fusion

- Sensors provide **raw *detections***
- **Fusion performs *detection* correlation and fusion**



Fuzed Track

X_c
P_c

Track Fusion

Radar track

EO/IR track

ADS-B track

Tracking

Tracking

Tracking

Raw detections LOS, Range, Doppler …

Raw detections LOS, image …

Raw detections LOS, Range, ID …

Radar Sensor

EO/IR Sensor

….

Co-op. Sensor

Distributed fusion

- **Sensors provide *tracks***
- **Fusion performs *tracks* correlation and fusion**

Proposed method

Hybrid hierarchical method:

- **Theoretically, the centralized architecture is optimal, but:**
  - **Sensors usually need internal self tracking for detection (*e.g*. false alarm regulation) and resources management purposes.**
  - A “full” centralized fusion would need a large amount of feedback to sensors:
    - **Large amount of data to transfer, large computational load to associate data;**
    - **Industrial issues with sensors coming from different vendors.**
- **The proposed method is:**
  - **Hybrid:**
    - **Data association is from individual tracks coming from each sensor**;
    - **Data fusion uses the raw data from each sensor after the association step.**
  - **Hierarchical:**
    - **The sensor level provides the fusion with its own tracks and the last data associated with these tracks.**
    - **The fusion level associates tracks corresponding to the same target, then fuses the raw associated data.**

5. Simulations

Simulations cases

Simulation cases:

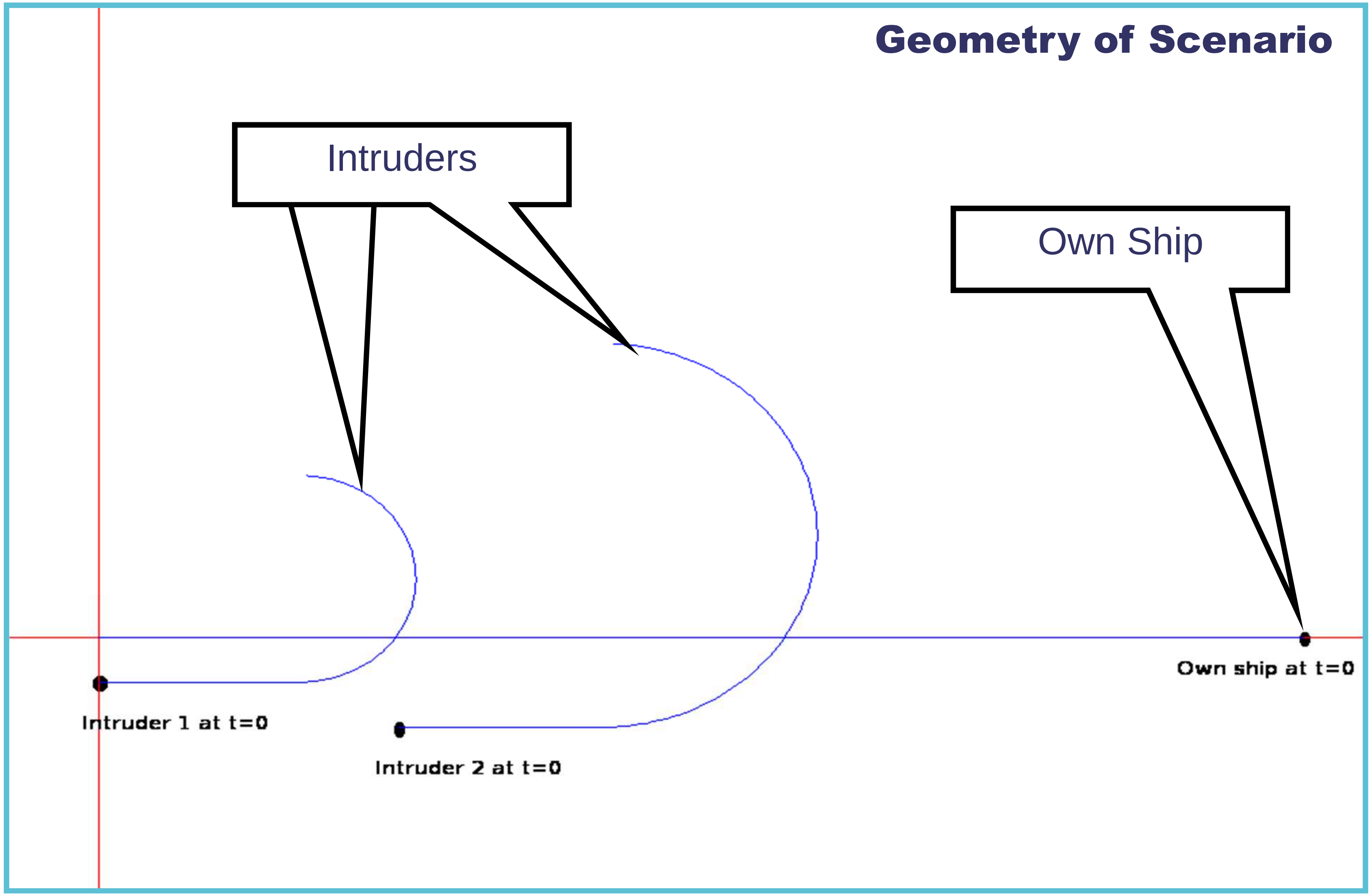
- **ADS-B + Radar, not addressed here:**
  - Trivial results: The data fusion only aims to check the integrity of ADS-B data.
  - If integrity is checked, ADS-B data are used, since they are, by far, much more accurate.
- **Radar only;**
- **Radar + E/O.**

Two intruders:

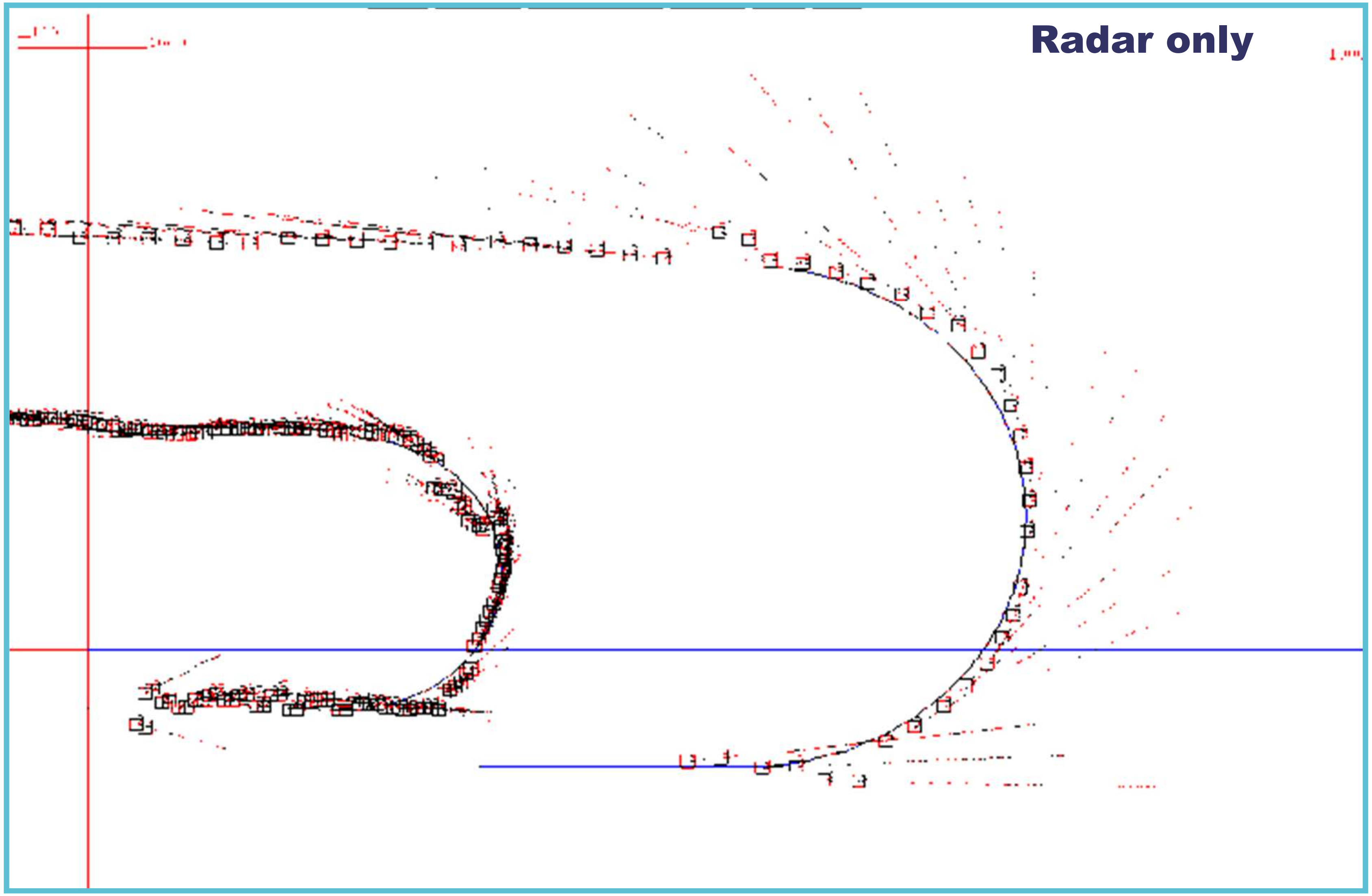
- **A slow one: V = 60 m/s, constant velocity then left turn @ 3°/s.**
- **A fast one: V = 260 m/s, constant velocity then left turn @ 7°/s.**

Simulations scenarios

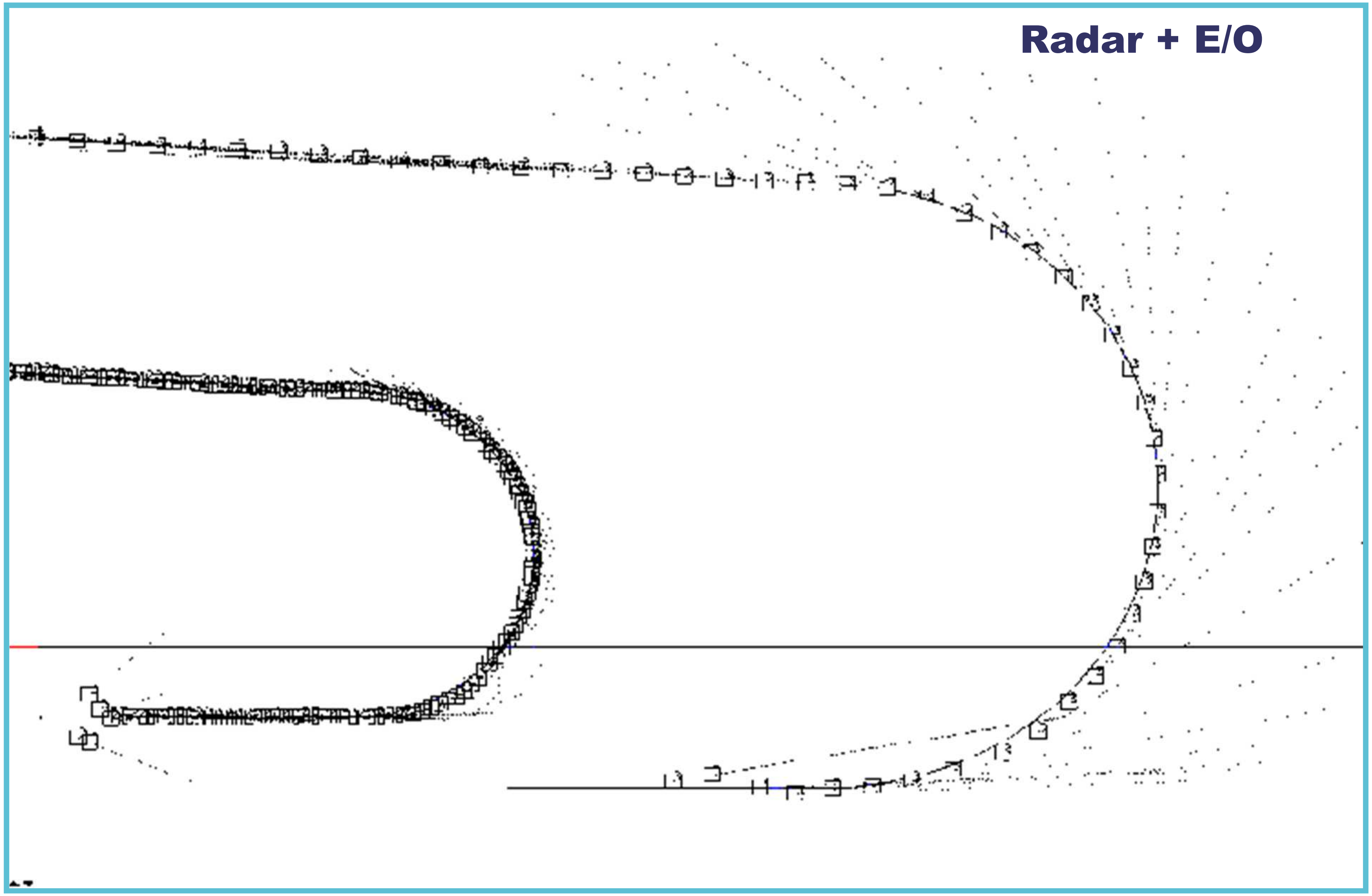
Scenario:



Simulation case: Radar only



Simulation case: Radar + E/O



6. Conclusions and perspectives

The safe insertion of UAV in the Air Traffic requires “Sense and Avoid” systems.

- And not only avoidance systems.

The “Sense” task is the system performance driver.

- High accuracy at long range.

Radar is mandatory for safety and “all weather Sense” operation.

- **All aircraft are not equipped with co-operative means** such as TCAS or ADS-B and the co-operative data must be checked for integrity.
- **However, E/O devices and co-operative sensors can greatly enhance the situation awareness accuracy through data fusion.**

A static Radar solution in X-band has been described.

- **It provides a wide Field Of View thanks to a facetted array.**
- **It is based on Digital Beam Forming and coherent MIMO principles.**

The future: In-flight trials of the proposed system:

- **A Radar mock-up was tested on ground with one flat array on receive but with MIMO localization in elevation.**

THALES

Thank you for your attention

Special acknowledgements to my colleagues : P. Cornic, P. Garrec, L. Ratton

Radar design patented by THALES

THALES