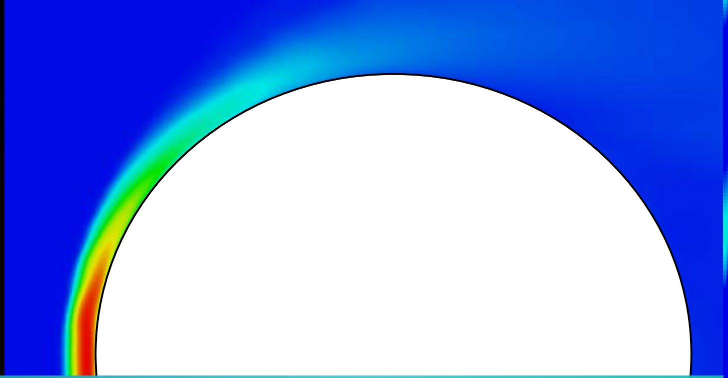
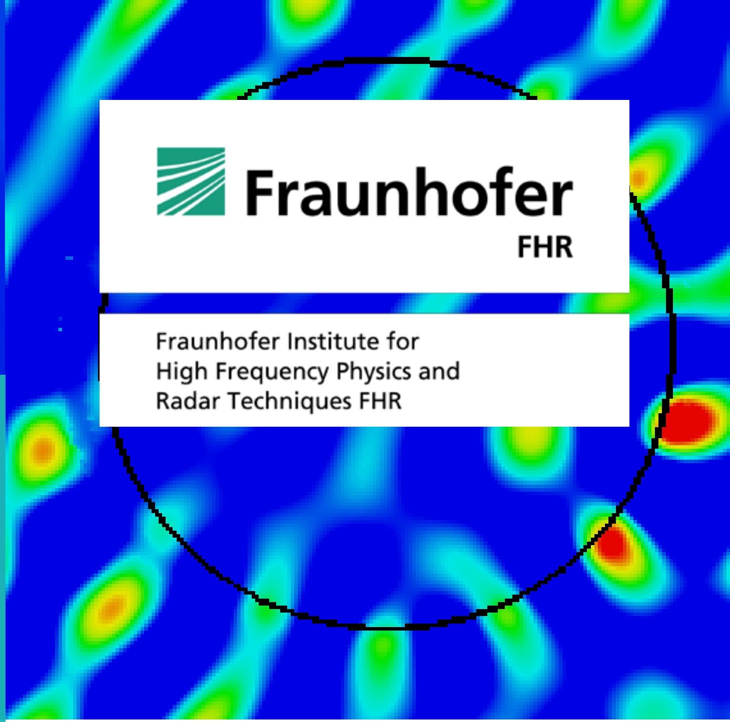




The Impact of Plasma and Hypervelocity on the Detection and Tracking of Hypersonic Radar Targets from a Distributed Perspective

René Petervari Kognitives Radar, Fraunhofer FHR
Tobias Müller
Stefan Brüggenwirth

NATO SET-312 Reasearch Specialists‘ Meeting on Distributed Multi-Spectral/-Statics Sensing,
Bled 23rd-24th May 2022

ISL Fraunhofer FHR

Outline

1. Tracking Hypersonic Targets

- Trajectories
- Motion models of maneuvering high speed targets
- Impact on monostatic and multistatic radar

2. Detecting Hypersonic Targets

- Aerodynamic Plasma and its impact
- Interaction with signature engineering
- Impact on monostatic and multistatic radar

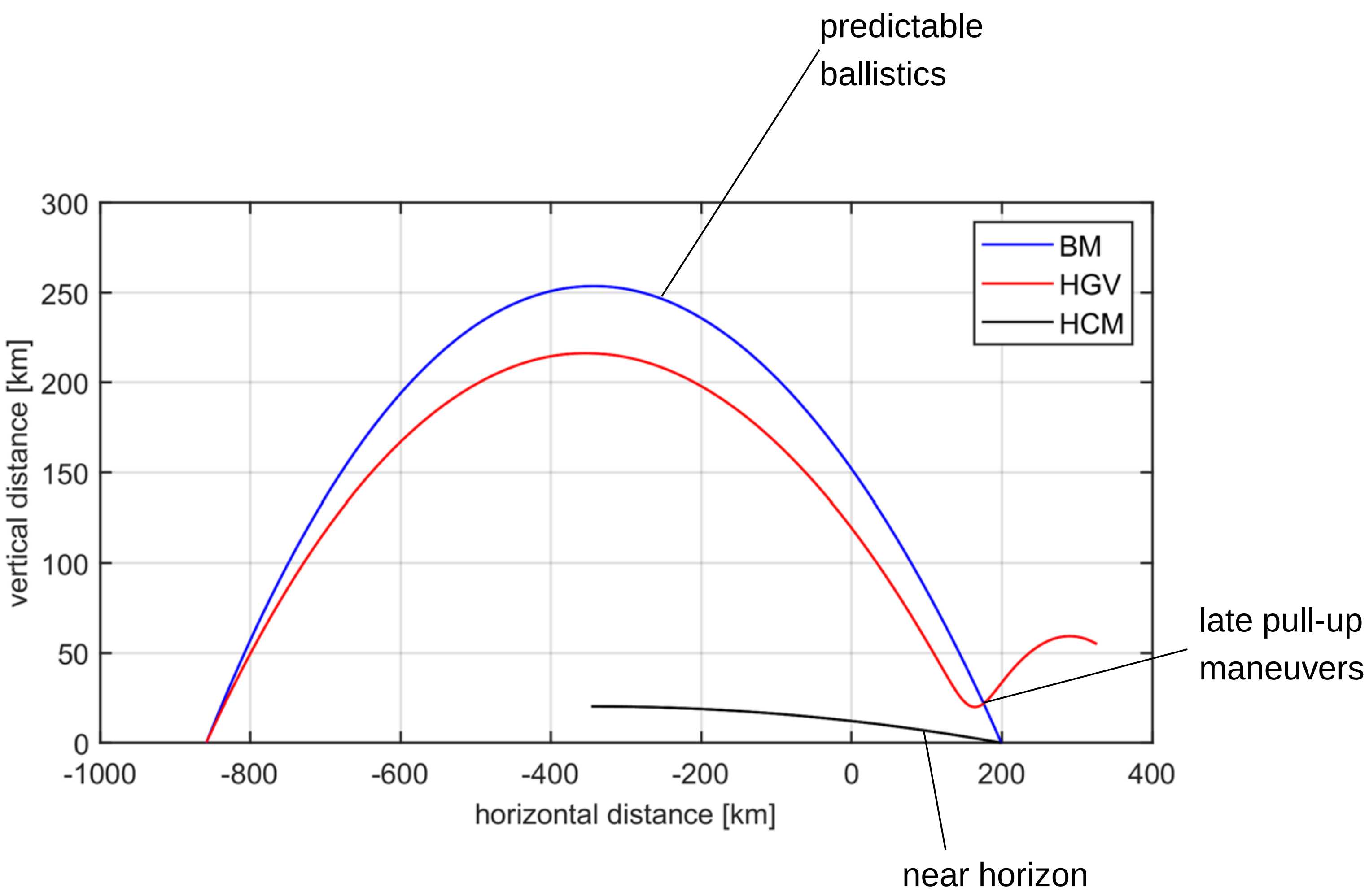
3. Conclusion

Tracking Hypersonic Targets - Overview

Trajectories

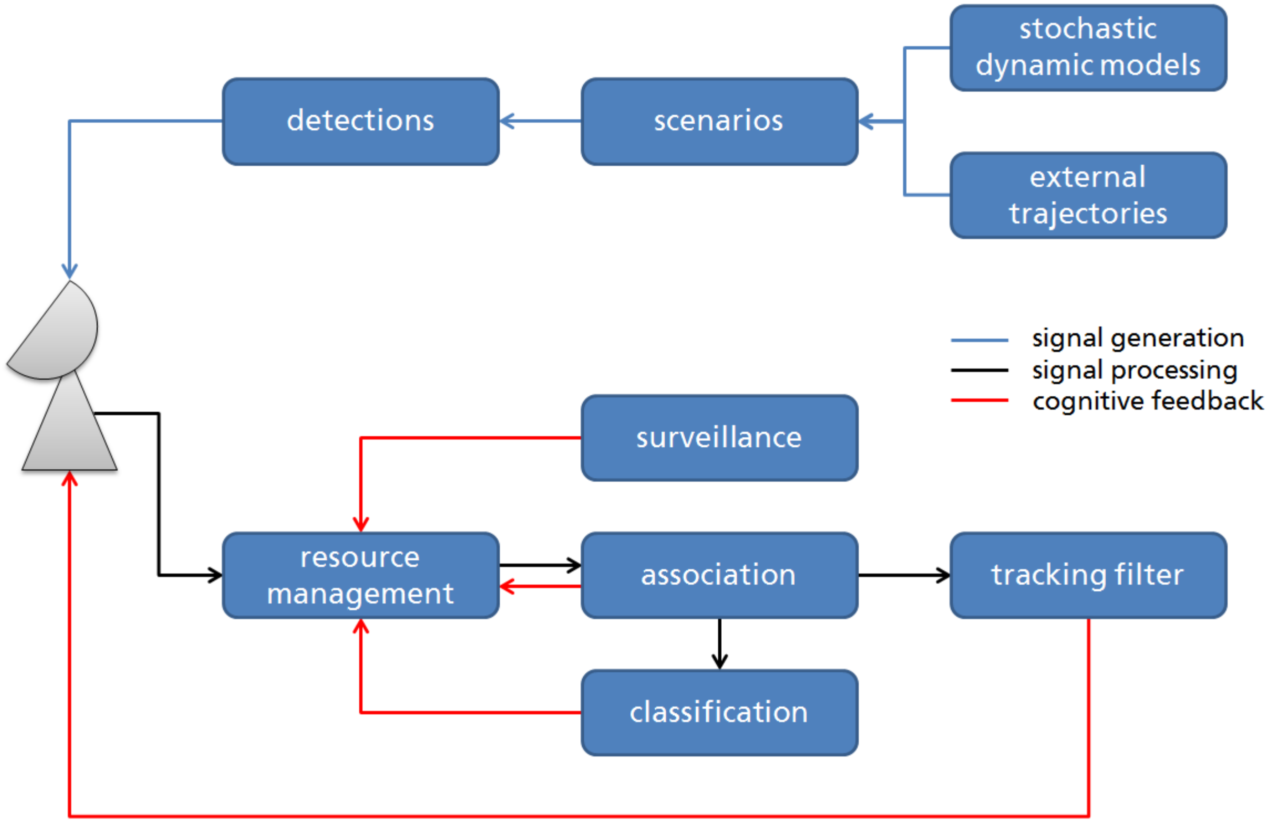
Types:

- Ballistic Missiles (BM)
- Hypersonic Glide Vehicles (HGV)
- Hypersonic Cruise Missiles (HCM)



Tracking Hypersonic Targets - Simulation

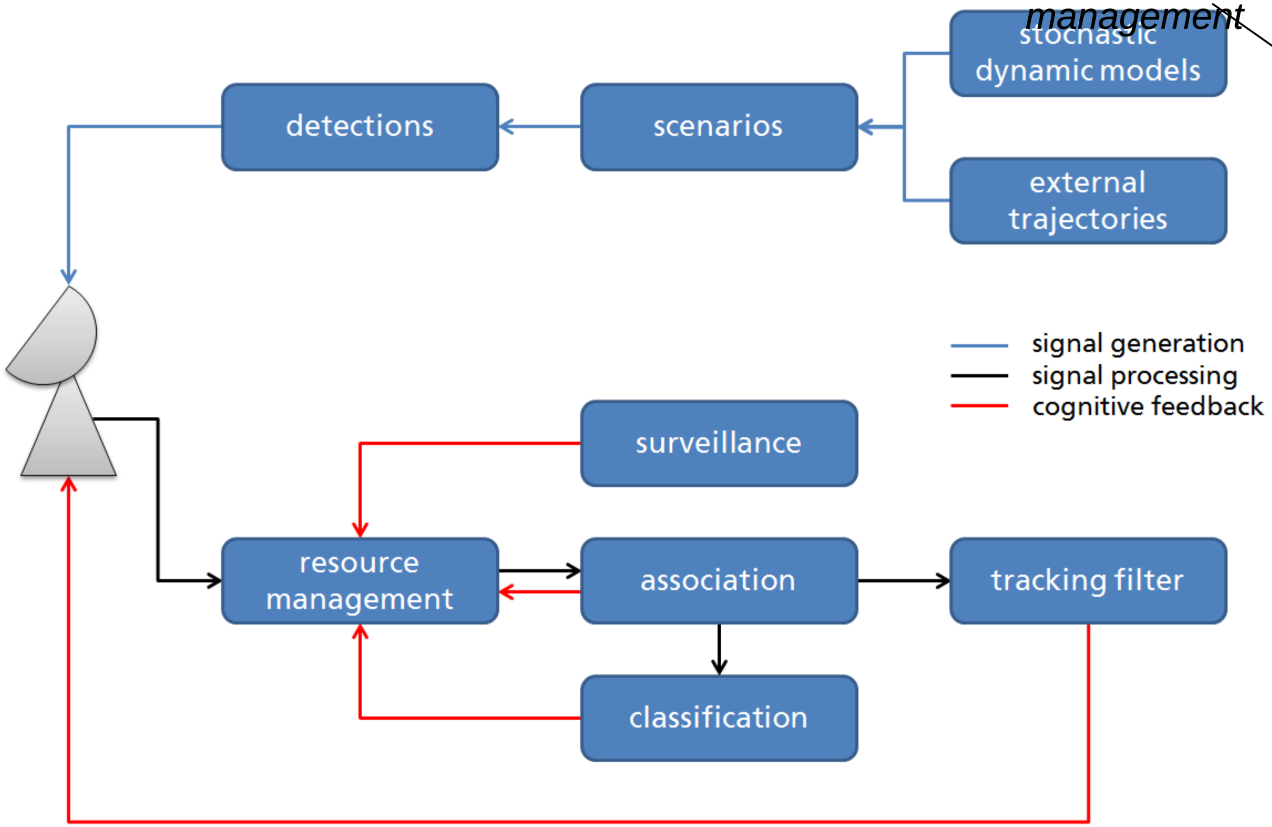
Cognitive Radar Simulation (CoRaSi)



 24.05.2022 **Open**

Tracking Hypersonic Targets -Simulation

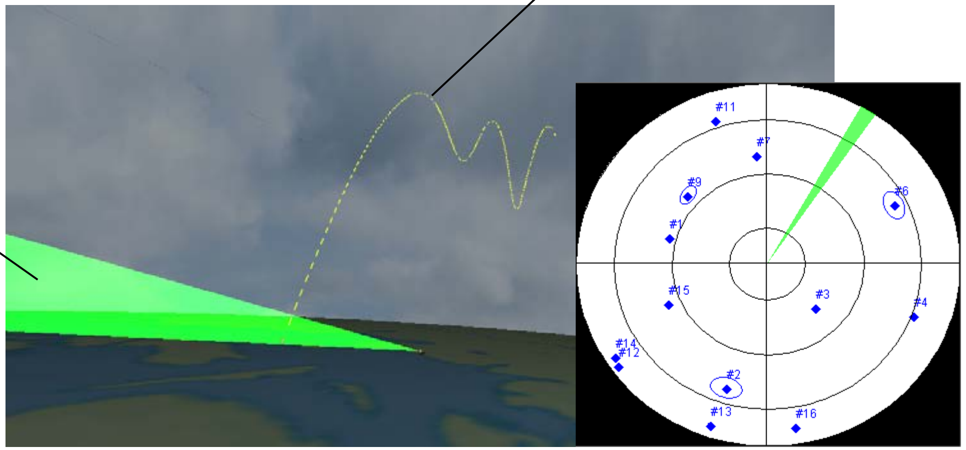
Cognitive Radar Simulation (CoRaSi)



Realistic beam steering & ressource management

Import / generate realistic trajectories

3D-Visualization



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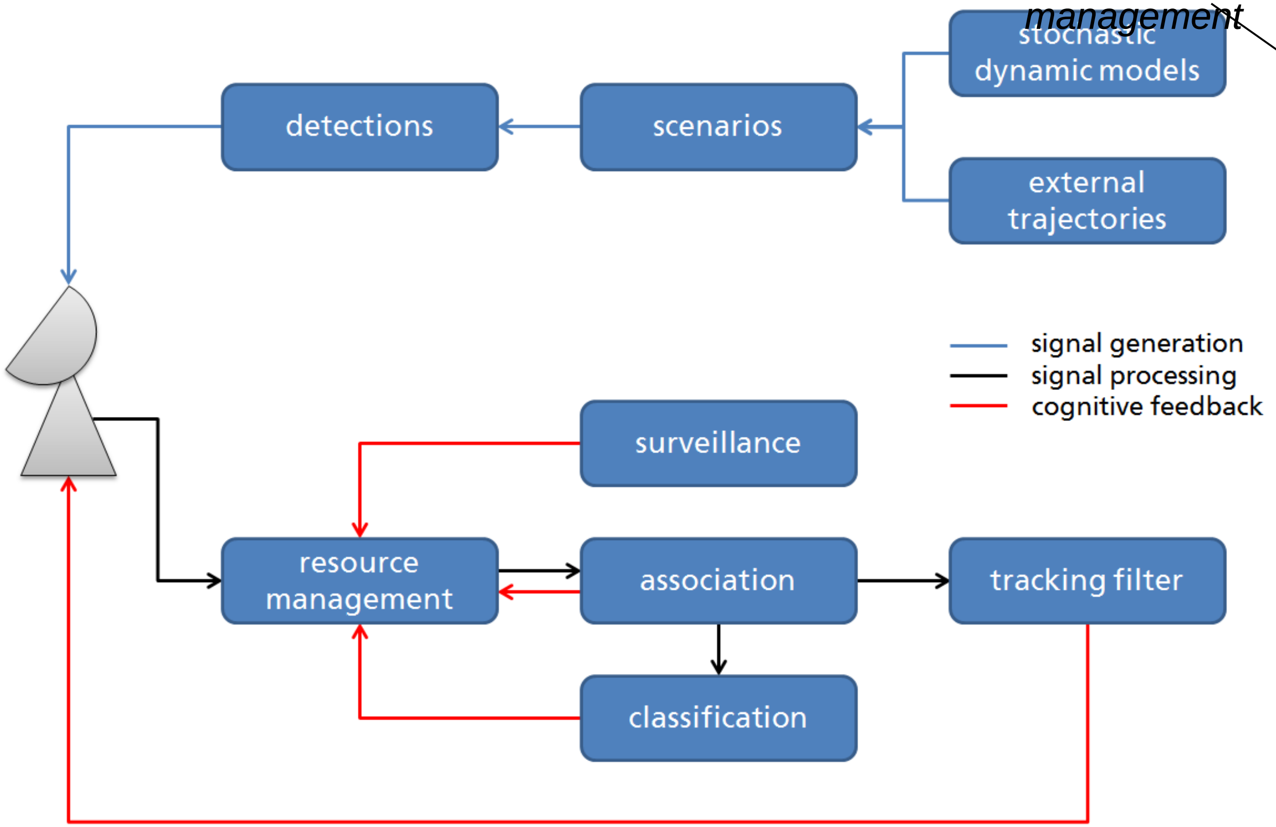
Tracking Hypersonic Targets - Simulation

Cognitive Radar Simulation (CoRaSi)

Realistic beam steering & ressource management



Import / generate realistic trajectories

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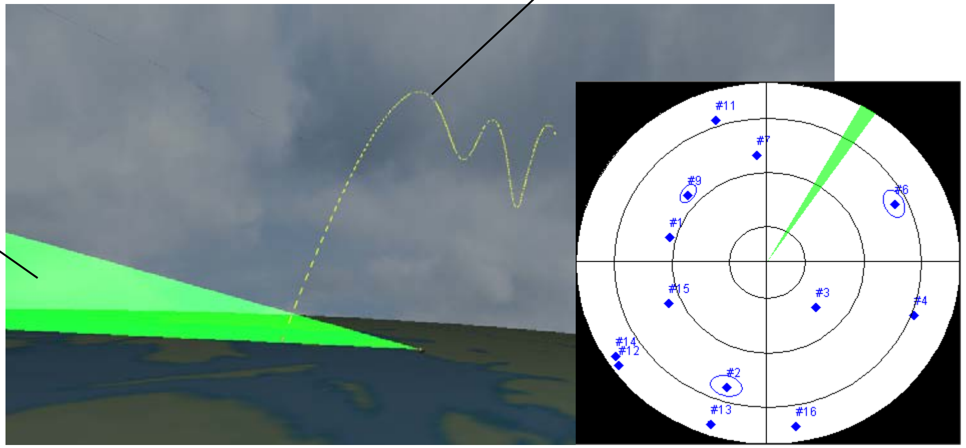
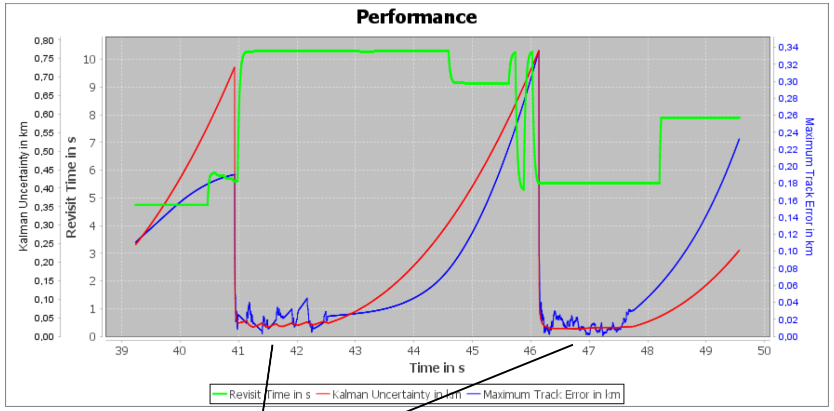


Track-Performance



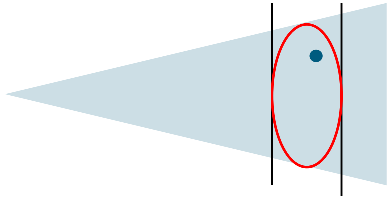
target in the beam → low error

Tracking Hypersonic Targets - Analysis
Monostatic Radar

Standard for Air & Missile Defence Radar

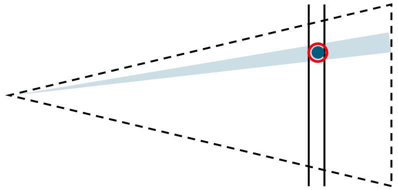
- **Detection & Surveillance Radar**
  frequency: low
  bandwidth: low
  beamwidth: wide

  - anti-stealth
  - coarse localization
  - Track-While-Scan (TWS)

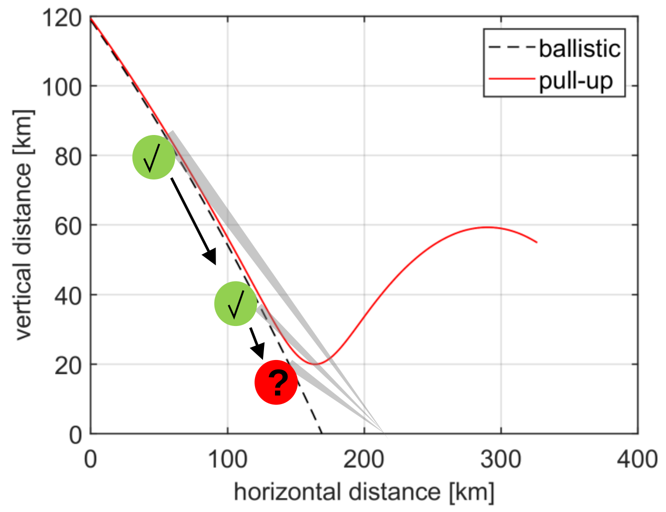


- **Fire-Control Radar**
  frequency: high
  bandwidth: high
  beamwidth: pencilbeam

  - precise localization
  - requires cueing and accurate motion models to keep track

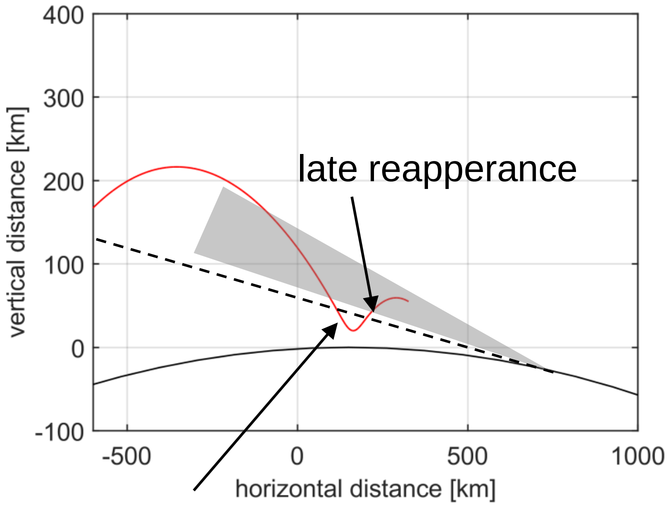


Tracking Hypersonic Targets - Analysis
Monostatic Radar



Possibly challenging cases:

- **Maneuver in the final phase of intercept**
  – short time to reacquire the lost target
  – target maybe soon out of interceptor range



- **Near horizon approach with late target acquisition**
  – Target invisible below horizon
  – short time to reaquire and identify target

Possible solution:

- **motion models for maneuvering highspeed targets**

Tracking Hypersonic Targets - Analysis

Maneuvering Highspeed Target Model

Including maneuverability

- maneuvers can occur at (nearly) any time
- respect multiple hypotheses simultaneuously
  → multi-modal prediction distribution

- avoids track loss
- targets will not appear unexpected after diving

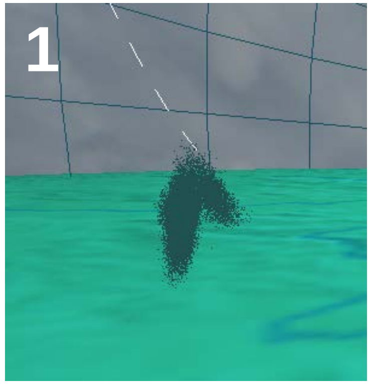
Pull-up maneuver model

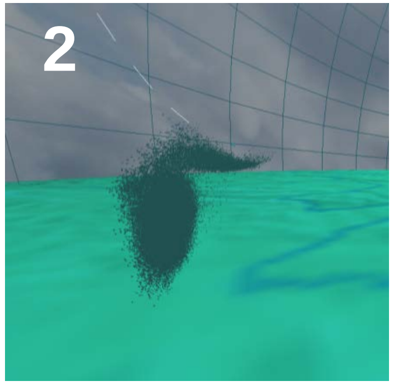
$$a = \frac{1}{2}\rho v^2(\beta^{-1}(1+\lambda^2)u_d + \lambda\delta_c u_c) - \frac{gp}{|p|^2} - 2\omega_E \times v \text{ with}$$

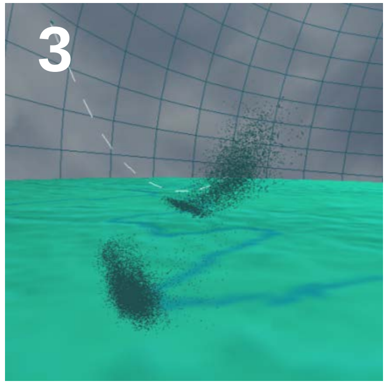
$$\beta = \frac{m}{C_w A};\ \lambda \in [0,1];\ \delta_C = \frac{C_a A}{m}$$

C. B. Chang, R. H. Whiting and M. Athans, Application of Adaptive Filtering Methods to Maneuvering Trajectory Estimation, Lincoln Laboratory, 1975.

Evolution of states without detection







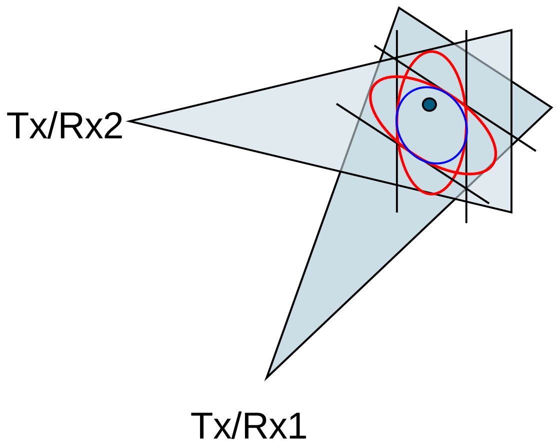
Tracking Hypersonic Targets - Analysis

Multistatic Radar

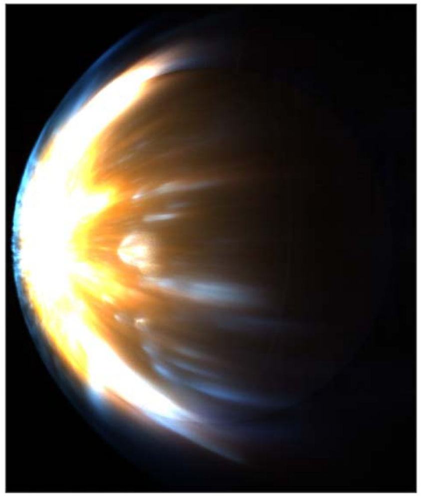
Additional Features of Multistatic Radar

- **Exploit resolution in different directions**
  → increase accuracy
  → earlier detection of maneuvers
  → higher confidence in kinetic classification

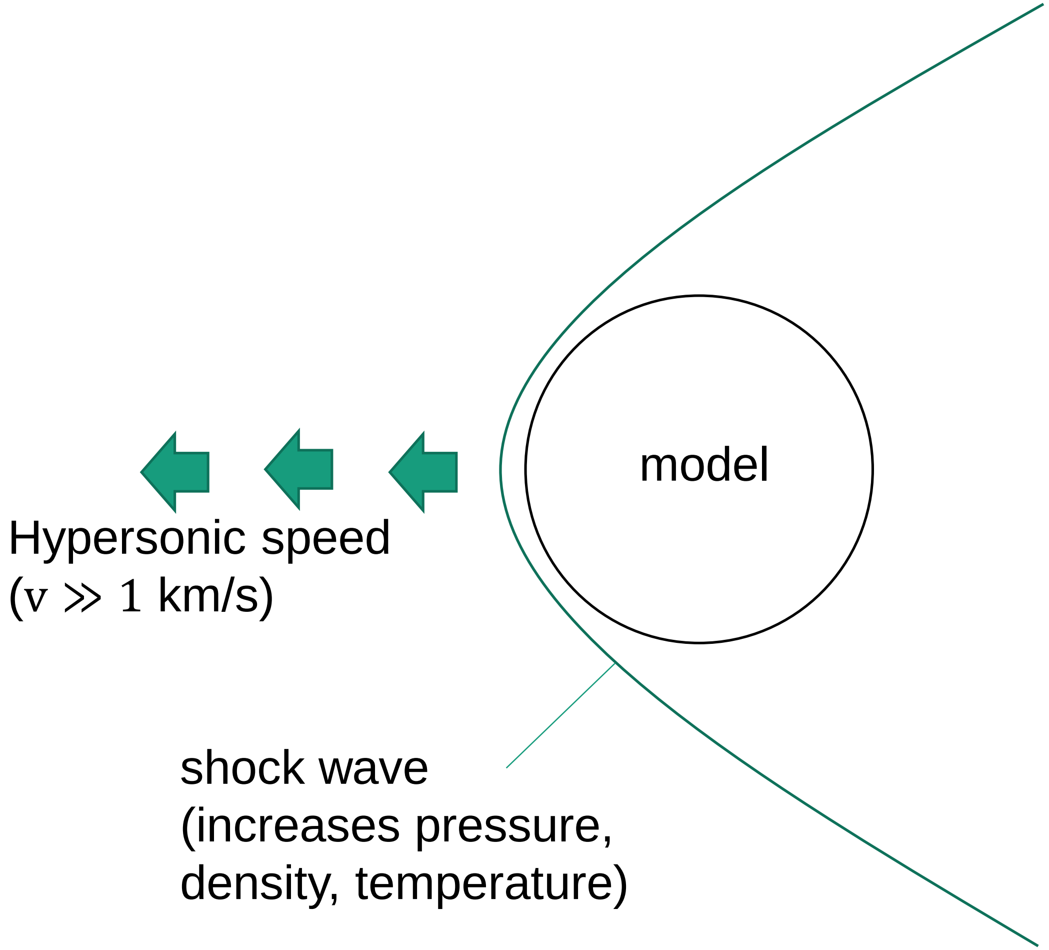
- **also profits from motion models for high speed maneuverable targets**



Detecting Hypersonic Targets – Plasma Reflection Theory
Plasma Generation



photograph of a 15 cm sphere in a Mach 8 hypersonic flow (ISL's shock tube STB)



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Detecting Hypersonic Targets – Plasma Reflection Theory
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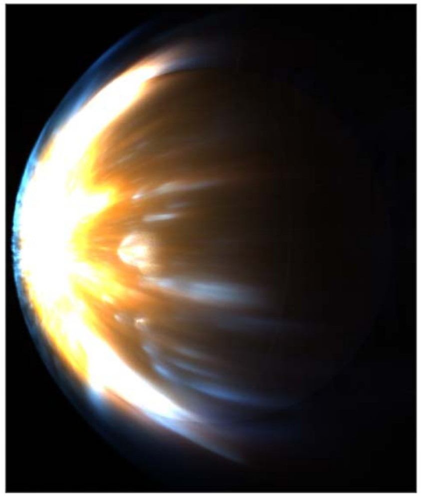

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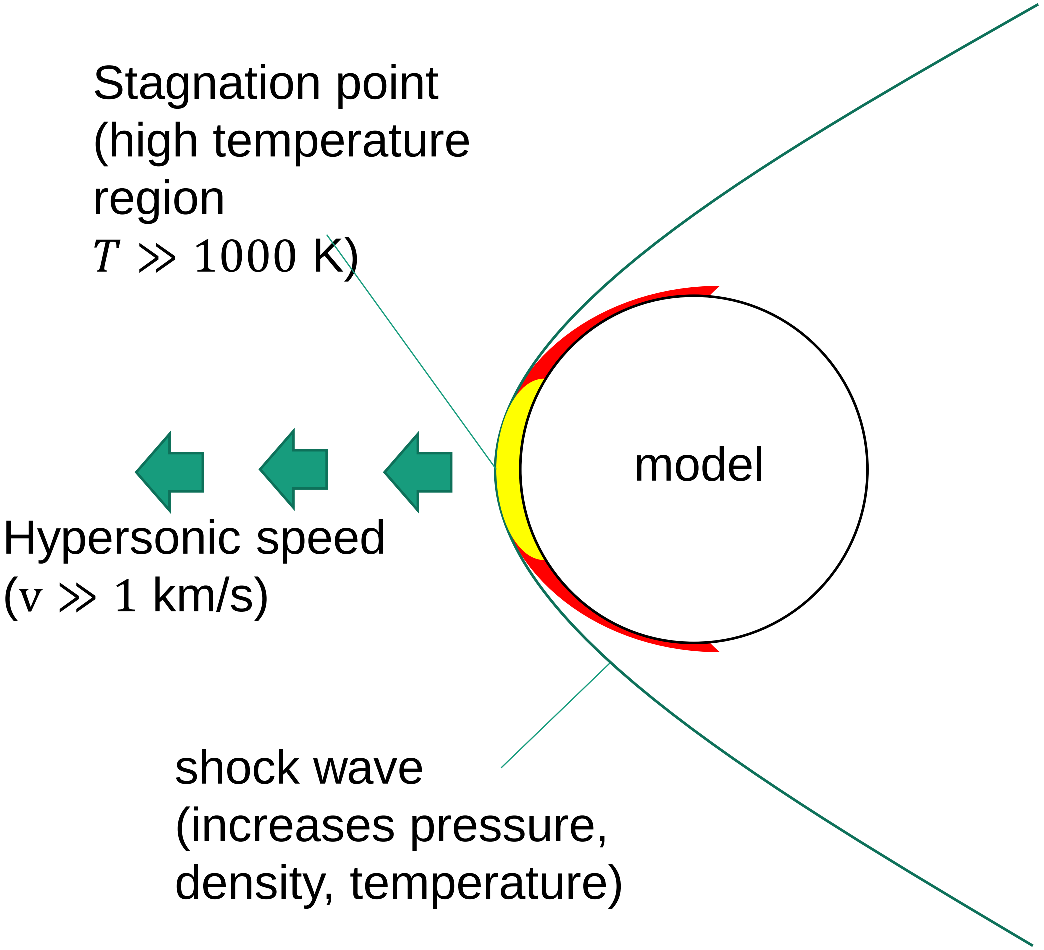

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Detecting Hypersonic Targets – Plasma Reflection Theory

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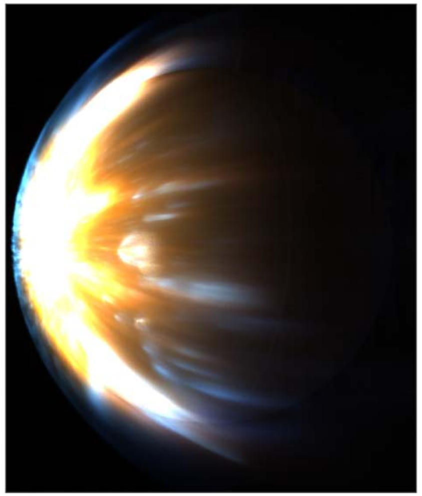

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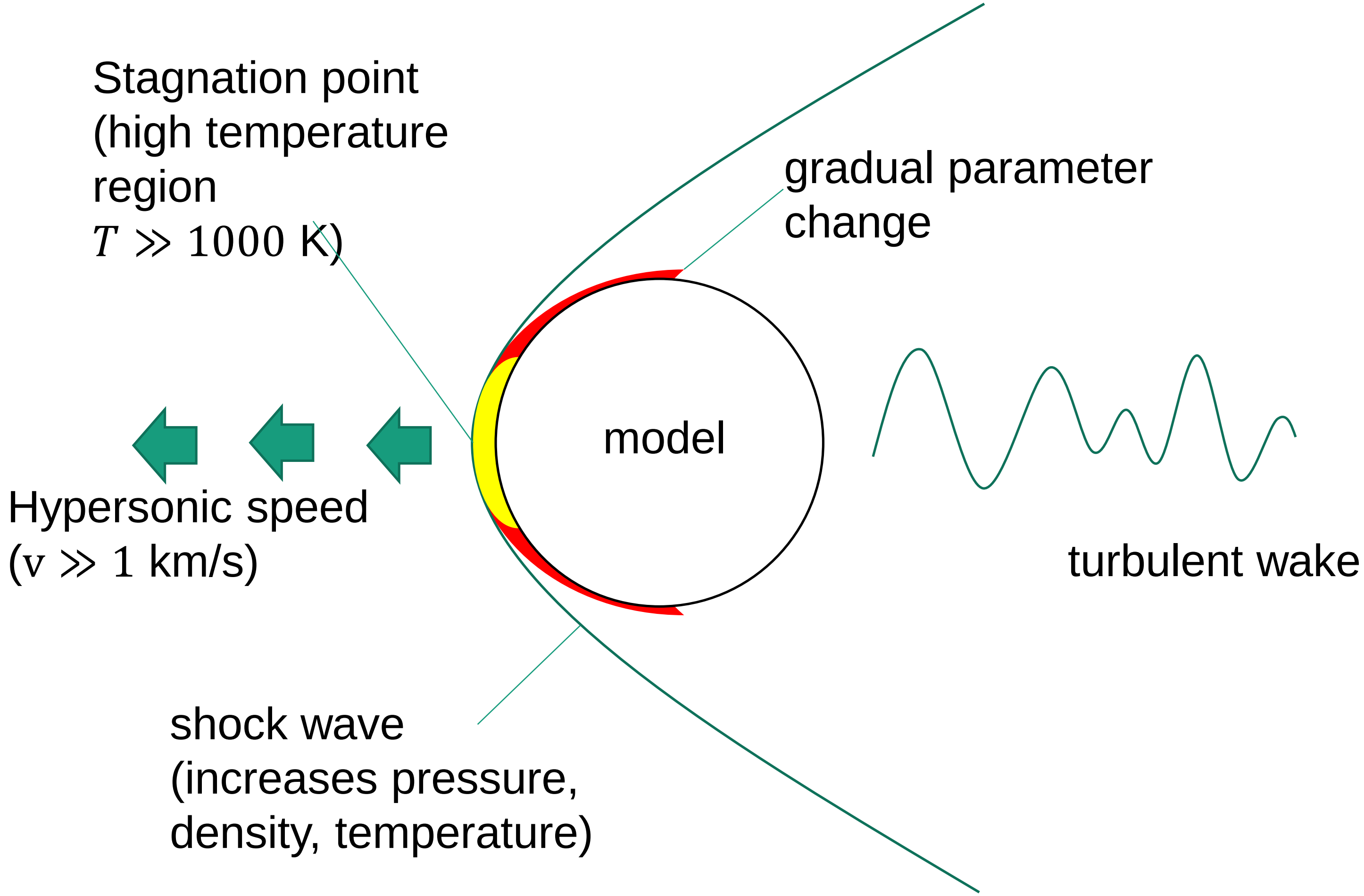

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Detecting Hypersonic Targets – Plasma Reflection Theory
Electromagnetic Plasma Model

Plasma is a lossy, dispersive dielectric medium.
Its electromagnetic properties are given by the
refractive index: $n = \sqrt{\epsilon_r}$

[Standard Textbook]

plasma permittivity

$$\epsilon_r = \epsilon_\infty - \frac{f_P^2}{f_{Radar}^2\left(1 - \frac{j f_c}{2\pi f_{Radar}}\right)}$$

ambient permitivity ϵ_∞
(no plasma contribution)

radar frequency
f_{Radar} [Hz]

  Open

Detecting Hypersonic Targets – Plasma Reflection Theory

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plasma frequency f_P [Hz]
($\propto$ **electron density n_e**)

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  Open

Detecting Hypersonic Targets – Plasma Reflection Theory

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plasma frequency f_P [Hz]
($\propto$ electron density n_e)

[Standard Textbook]

plasma permittivity

$$\epsilon_r = \epsilon_\infty - \frac{f_P^2}{f_{Radar}^2\left(1 - \frac{jf_c}{2\pi f_{Radar}}\right)}$$

collision frequency f_c [Hz]
($\propto$ species particle density n_s,
$\propto$ temperature T)

ambient permitivity ϵ_∞
(no plasma contribution)

radar frequency
f_{Radar} [Hz]

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Detecting Hypersonic Targets – Plasma Reflection Theory

Main Cases

Case 1: „totally reflective plasma (metallic)“

- $\boldsymbol{f_P} > \boldsymbol{f_{Radar}}$ (high electron density)
- $\boldsymbol{f_c} \rightarrow \mathbf{0}$ (low density)

Case 2: „transparent plasma“

- $\boldsymbol{f_c} \gg \boldsymbol{f_{Radar}}$ (high density)

Case 3: „reflection, transmission and absorption (intermediate)“

- all parameters of the same order: $\boldsymbol{f_P} \approx \boldsymbol{f_{Radar}} \approx \boldsymbol{f_c}$

Detecting Hypersonic Targets – Plasma Reflection Theory

Main Cases

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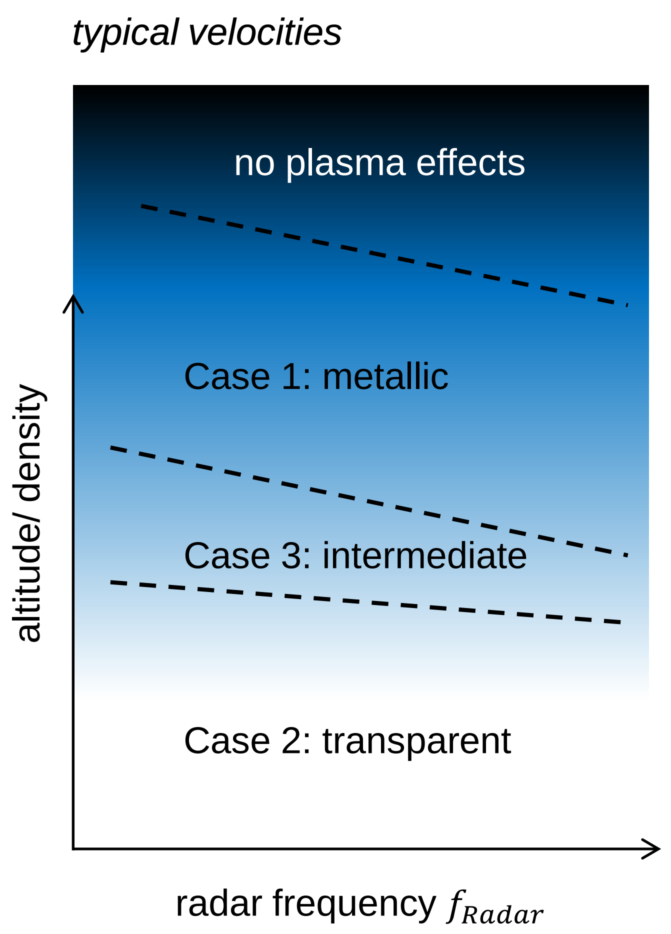

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Detecting Hypersonic Targets – Analysis Test Model

NASA RAM-C Flight Experiments (late 1960s)

- Re-entry radio communication blackout
- Reference Data for radio-plasma-interaction

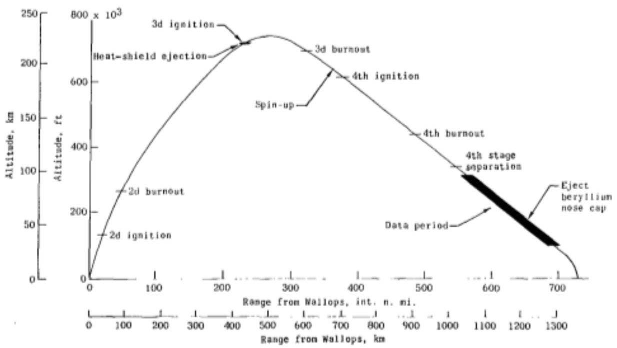


Figure 2.- Trajectory plan view and reentry events.

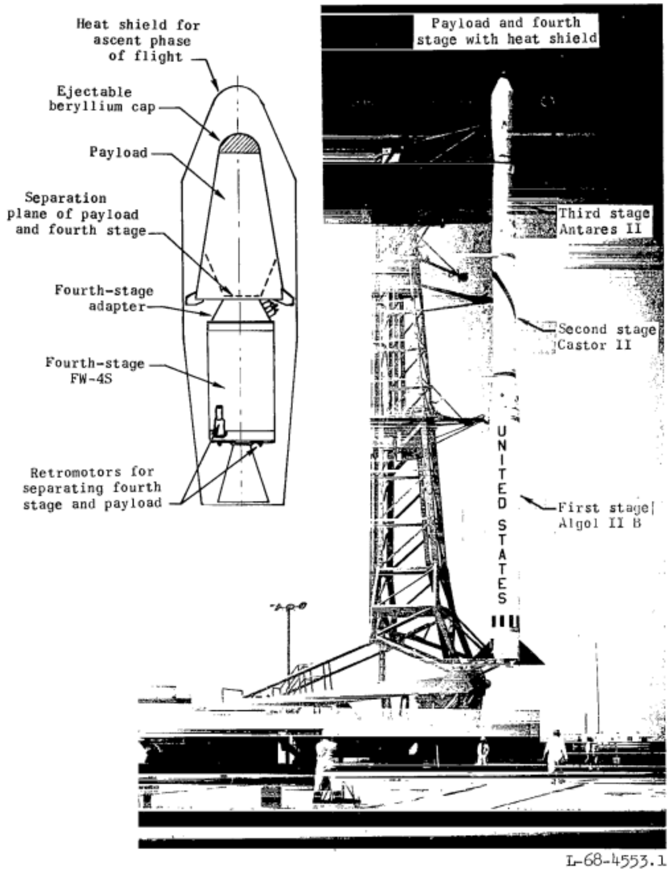
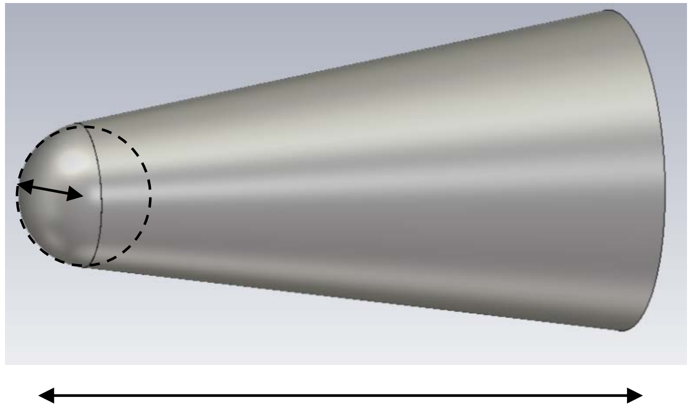


Figure 1.- Scout vehicle and payload.

RAM-CII

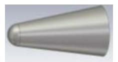
152,4 mm



1295,4 mm

1:8 scaled RAM-CII

(test object for this paper)



Grantham, W. L. (1970). *Flight results of a 25000-foot-per-second reentry experiment using microwave reflectometers to measure plasma electron density and standoff distance* (Vol. 6062). National Aeronautics and Space Administration (NASA).

Detecting Hypersonic Targets – Plasma RCS Simulation

Simulating Radar-Plasma-Interaction

Step 1: Create model without plasma

- geometry
- material

Step 2: Simulate aerodynamic flow field

- plasma frequency f_P
- collision frequency f_c
- ambient permittivity ϵ_∞

Step 3: Solve Interaction with microwaves (FDTD)

- Radiation pattern

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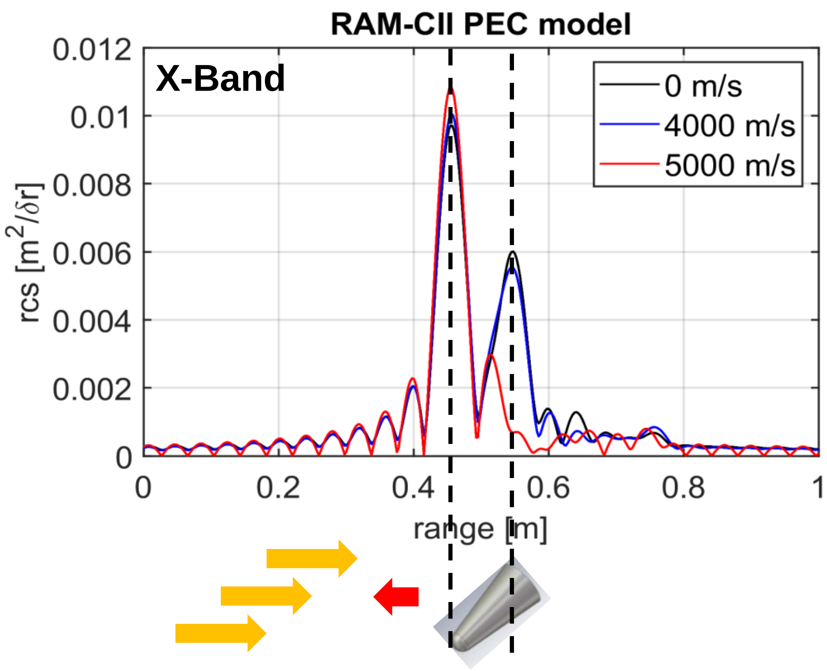
Detecting Hypersonic Targets – Analysis
Monostatic Radar

The impact of plasma on signature engineering

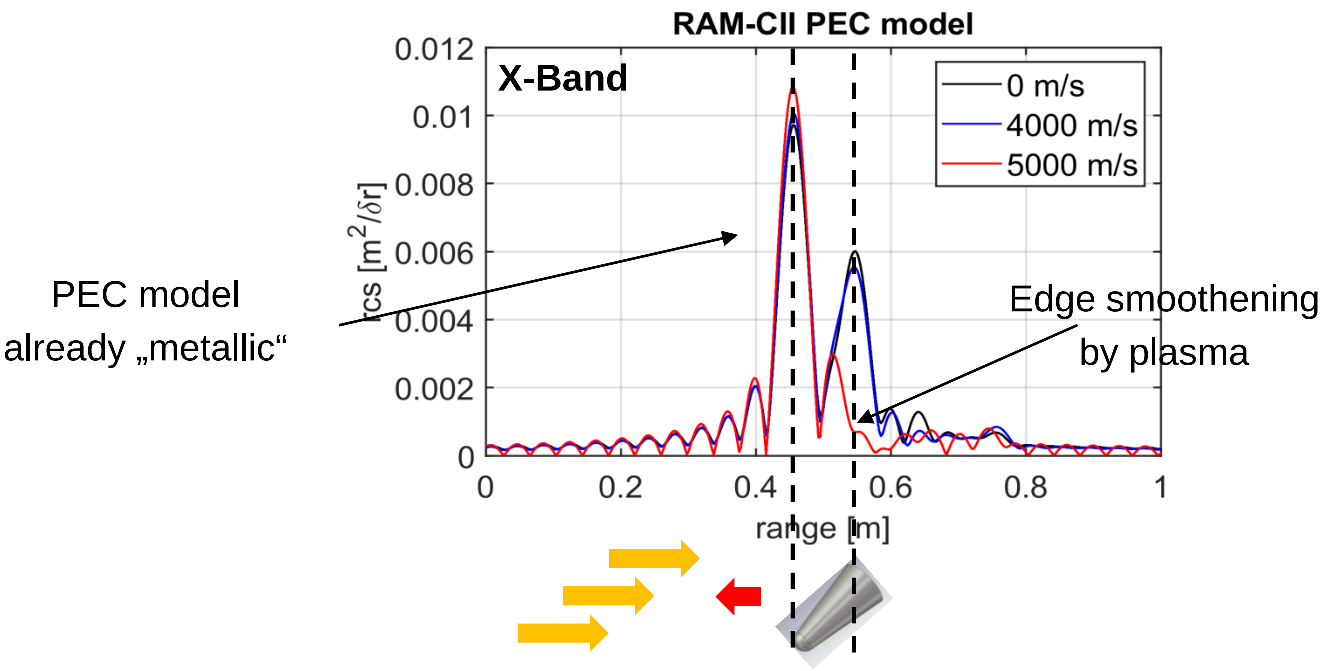


Detecting Hypersonic Targets – Analysis

Monostatic Radar

The impact of plasma on signature engineering

- **Low impact on metallic models**



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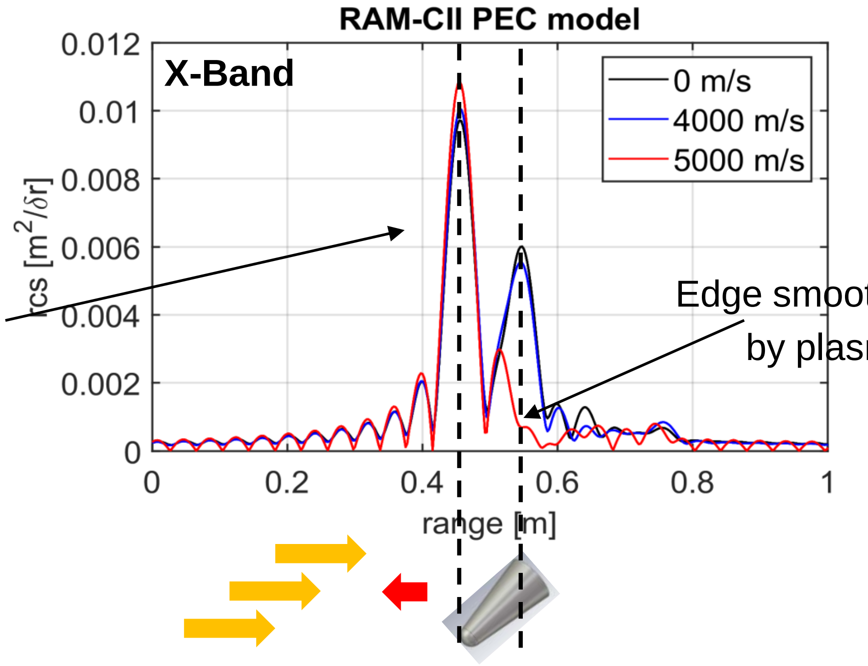
Detecting Hypersonic Targets – Analysis

Monostatic Radar

The impact of plasma on signature engineering

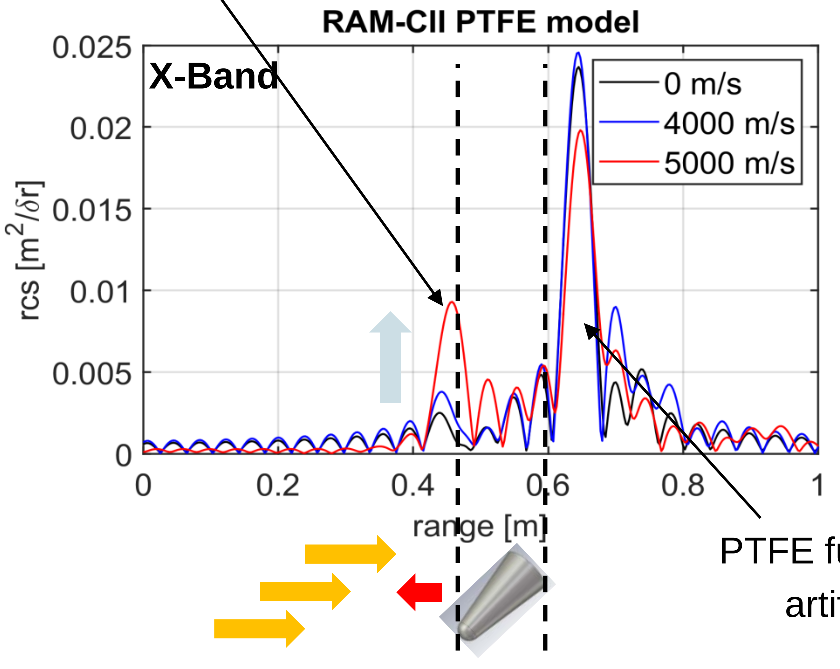
- **Low impact on metallic models**
- **Large impact on low-reflective objects**

PEC model already „metallic“



Edge smoothening by plasma

Plasma makes nose „metallic“



PTFE full body artifact

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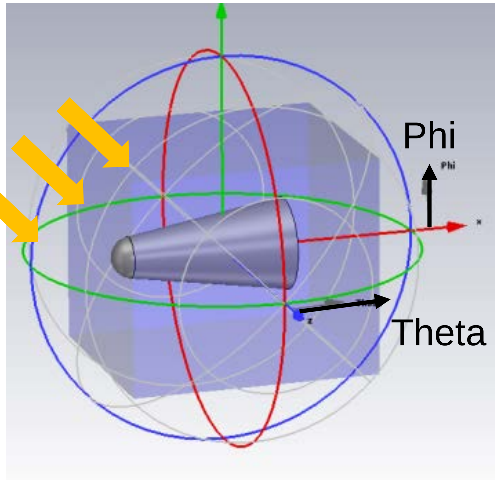
Detecting Hypersonic Targets - Analysis

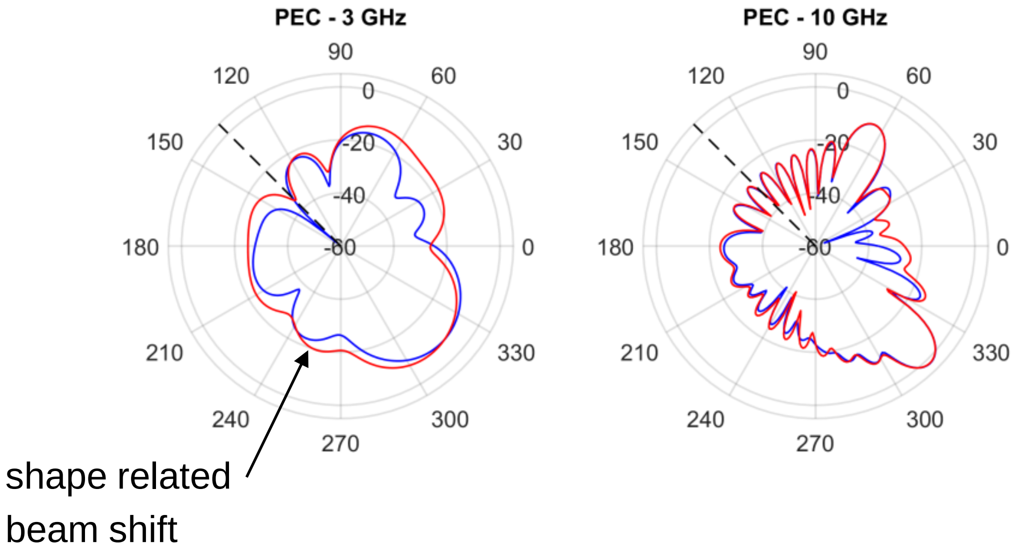
Multistatic Radar



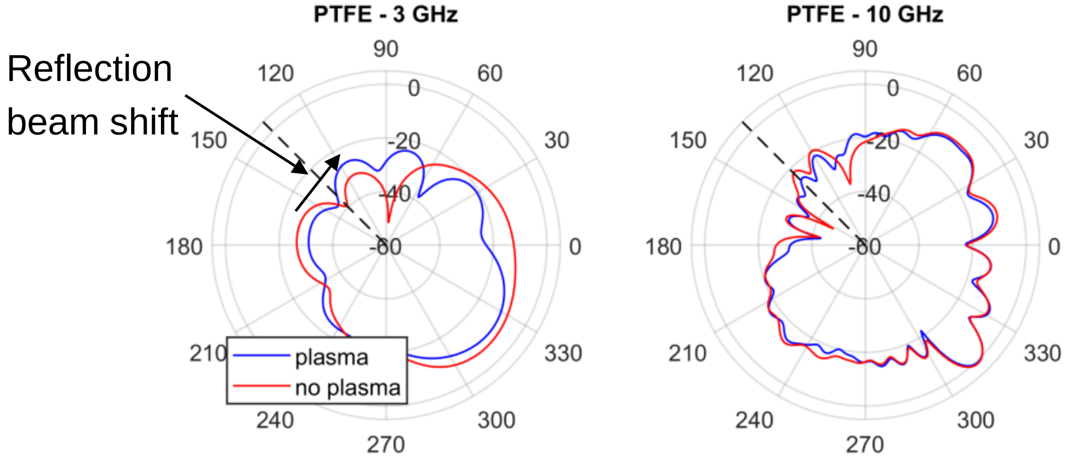
The impact of plasma on bistatic RCS

- **higher impact on low frequencies**
- **Reflection beam shift**
- **no simple solution, complex patterns**

Metallic model



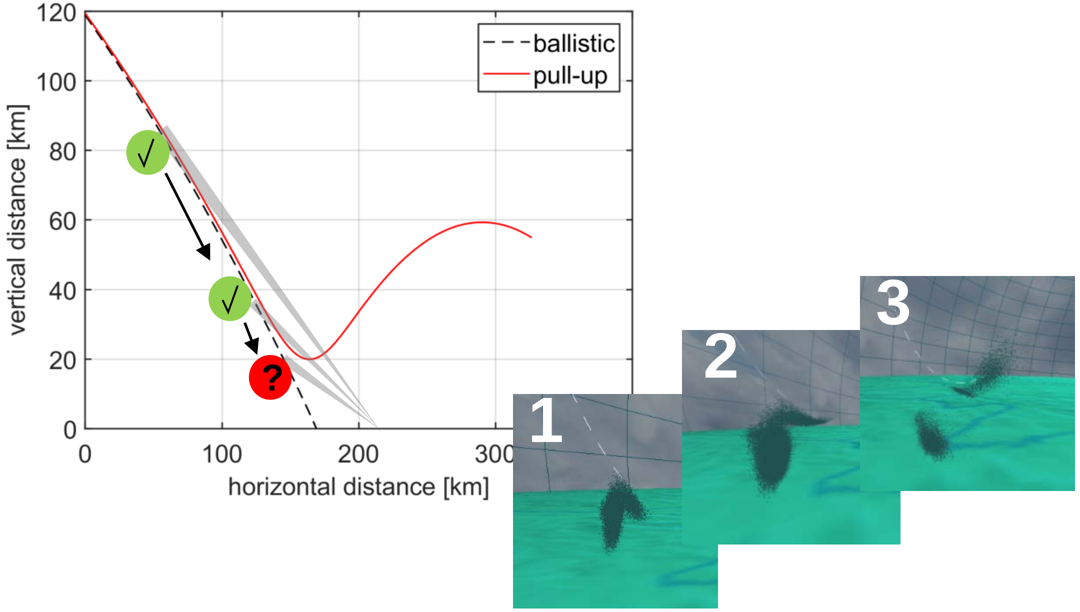
signature engineering



Conclusion

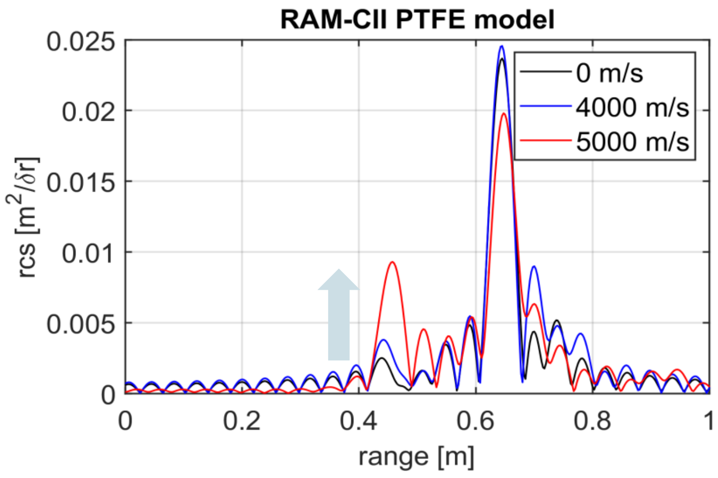
The impact of hypervelocity on tracking

- short reaction times, any error is critical
- maneuvers can cause track loss and mitigate the intercept
- possible solution: respective motion models and multi-mode trackers



The impact of plasma on detection

- Plasma originates from chemical reactions in high speed flows
- Plasma can be transparent, reflective and absorptive
- The impact of plasma depends on object shape and flight conditions
- Plasma can counter act signature engineering
- Less impact at higher frequencies and metallic objects
- In multistatics plasma can lead to shifts in deflection angles



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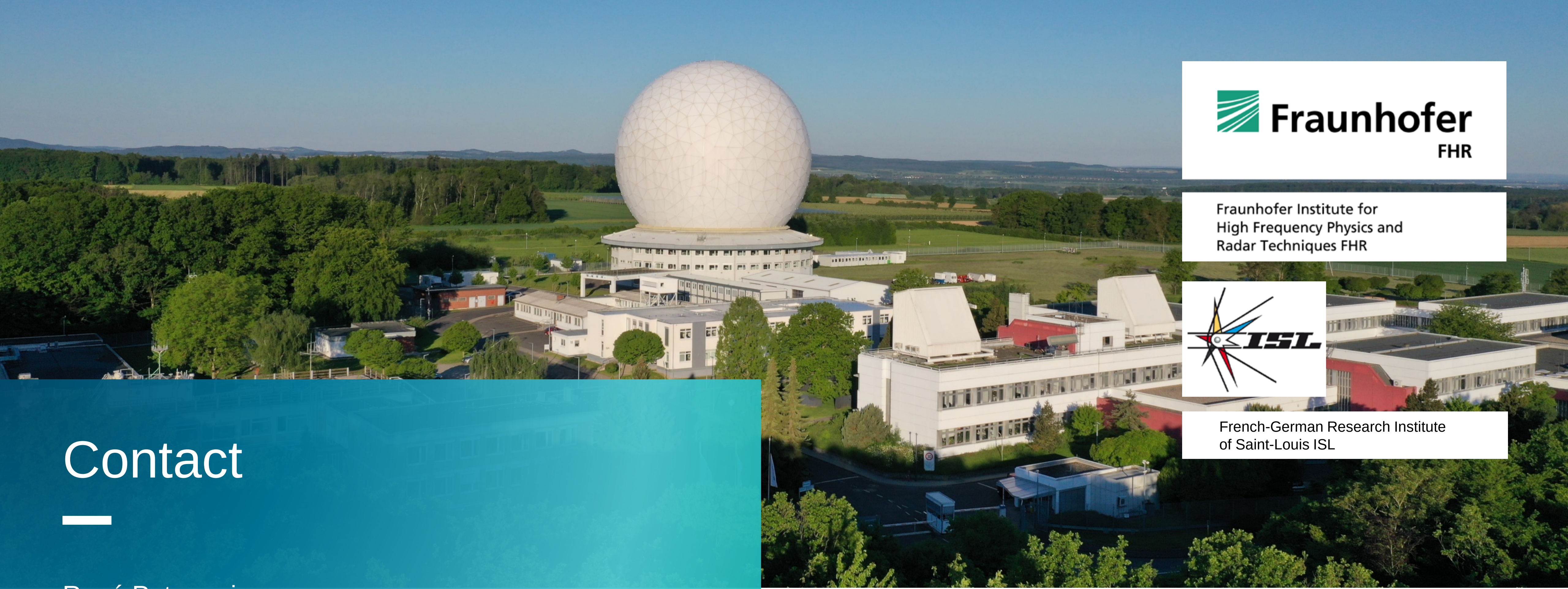

Fraunhofer Institute for
High Frequency Physics and
Radar Techniques FHR

French-German Research Institute
of Saint-Louis ISL

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August 2021 – Experiments at ISL (France)