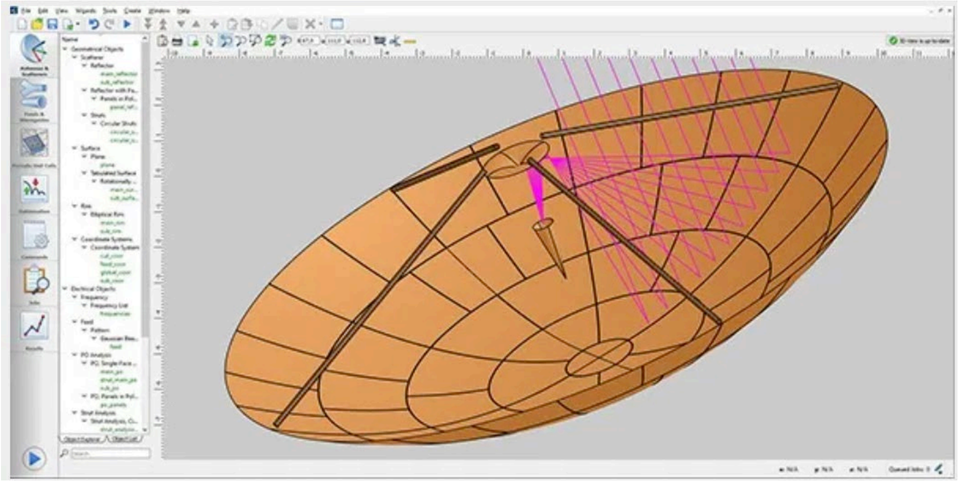
Collaboration between Industry and DTU Compute

Presentation given at Prof. Per Christian Hansens 40th anniversary

Oscar Borries

26. August 2022

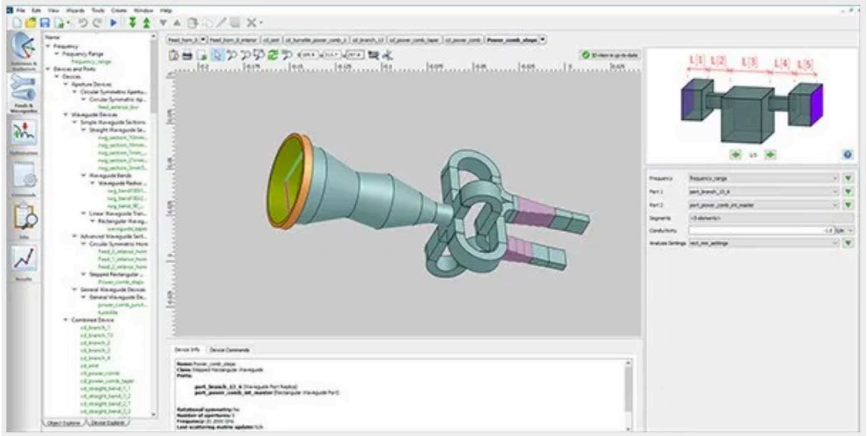
TICRA & me



- TICRA sells simulation software for antenna design. Our primary niche is the space segment.

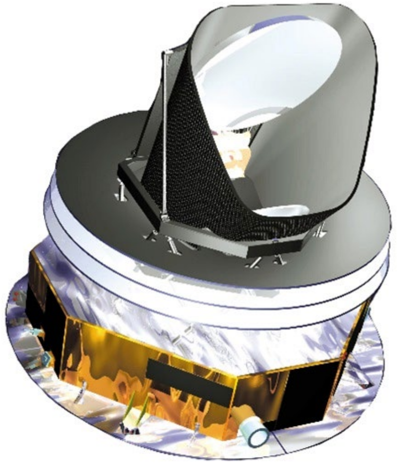
- Industrial foundation. Around 50 mio DKK in revenue. 7 years ago we were ~20 employees, now we are ~40 people with ~25 phd's.

- Oscar: Mathematical engineer from DTU and Industrial Ph.D. with DTU & TICRA
  - (2006): First met Per Christian Hansen (PCH).
  - (2010): Took the CSI course with PCH as teacher.
  - (2011): Master thesis with TICRA and PCH as advisors.
  - (2012-2014): Industrial Ph.D. with TICRA and PCH as advisors.
  - (2014-Now): TICRA: Head of Mathematics & AI Team, Chairman of the Board



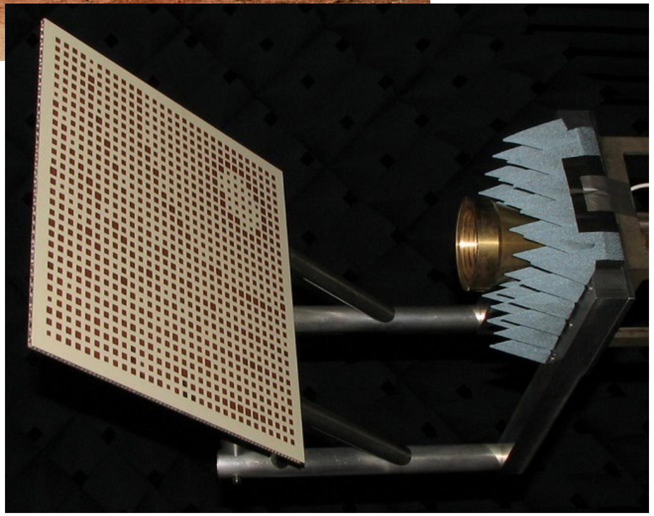
- **Now**: 2 quick slides on TICRA as a company.
- **The rest of the talk**: How colloboration with PCH (and SciComp team!) has helped shape TICRAs products over the last >12 years.

Applications



Planck Space Telescope

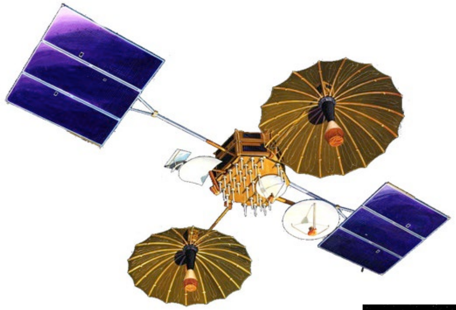
Panel CATR EPG



Reflectarray

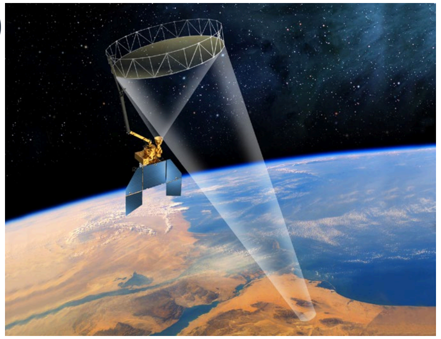
Eutelsat 9B (Ku)

SKA



NASA TDRS (S, Ku, Ka)

Helios Cmd. Station In Weilheim (S, Ka)



NASA SMAP(L)

Key Customers

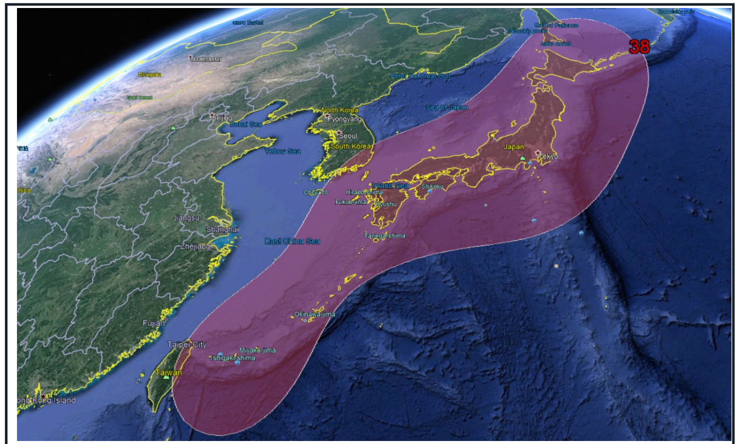
Satellite Manufacturers

BOEING

LOCKHEED MARTIN
We never forget who we're working for™

AIRBUS

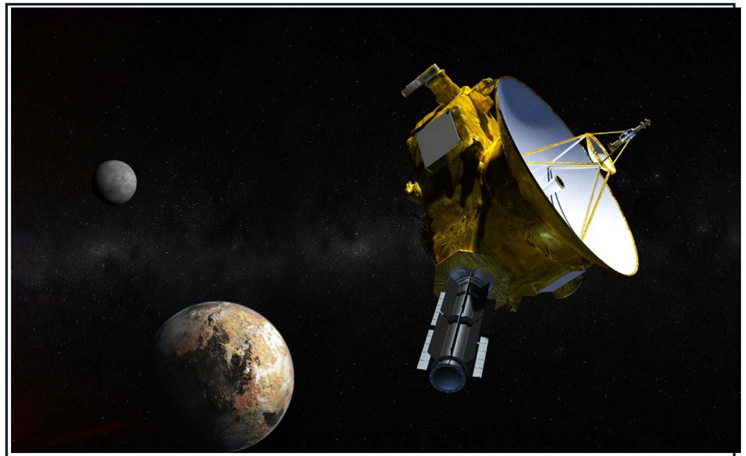
Satellite Operators



ViaSat

eutelsat
COMMUNICATIONS

Space Agencies



esa space for europe

NASA

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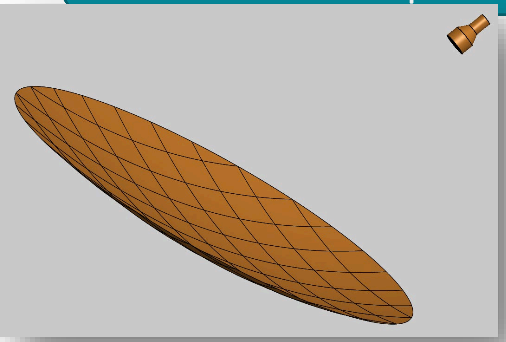
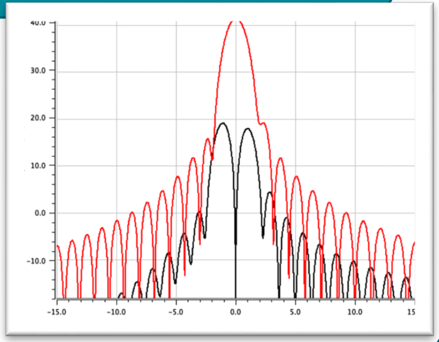
TICRA

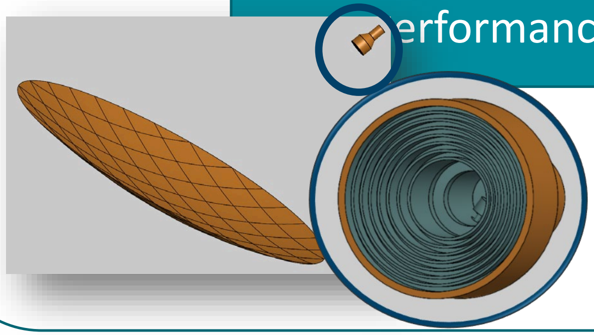
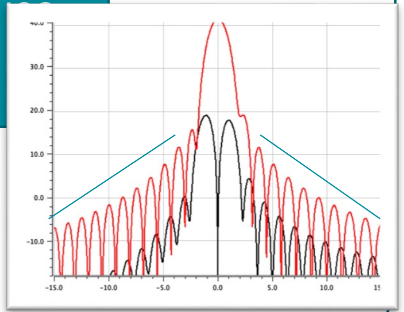
12 years of collaboration in 25 minutes – please excuse the lack of details!

Design of antennas

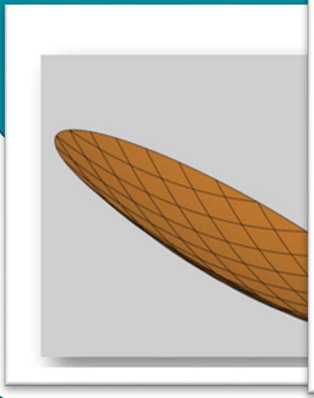
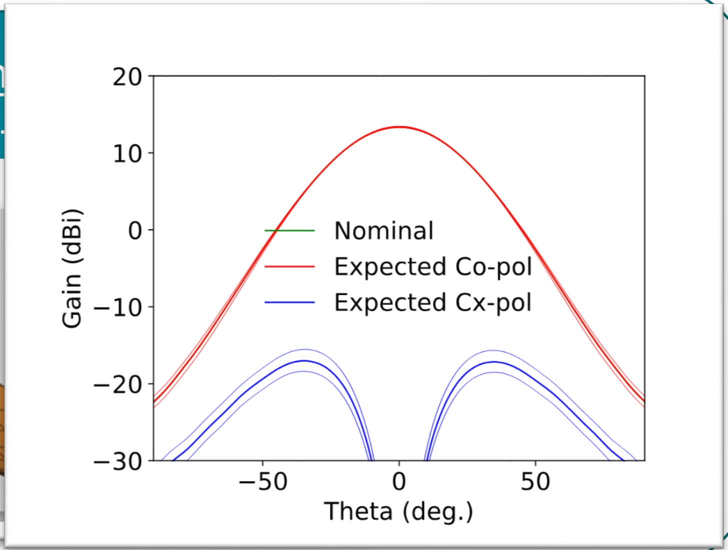
1960s-now
Simulation – use a computer to predict performance

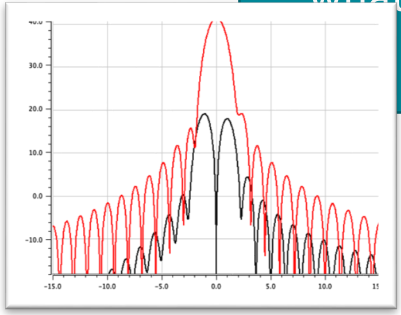
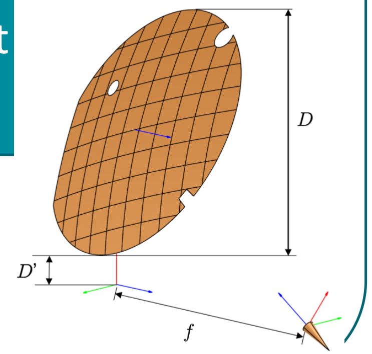
1980s-now
Optimisation – use a computer to optimi
erformance

2010s - n
Uncertainty -

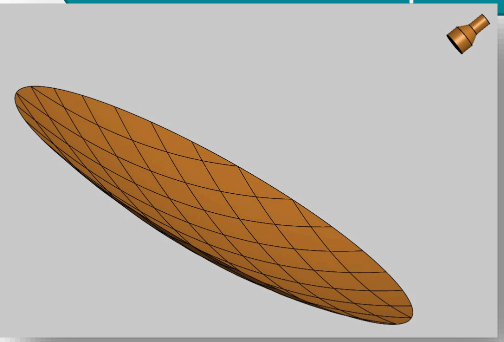
?s-now
Inverse problems – what the heck went wrong?

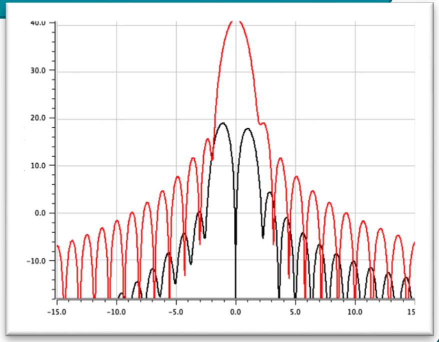



TICRA

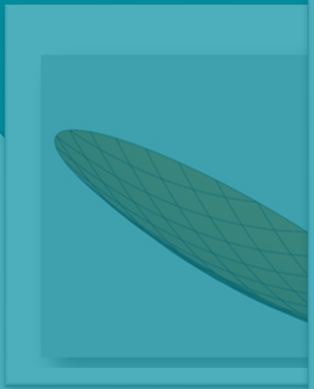
Part 1 – Simulation

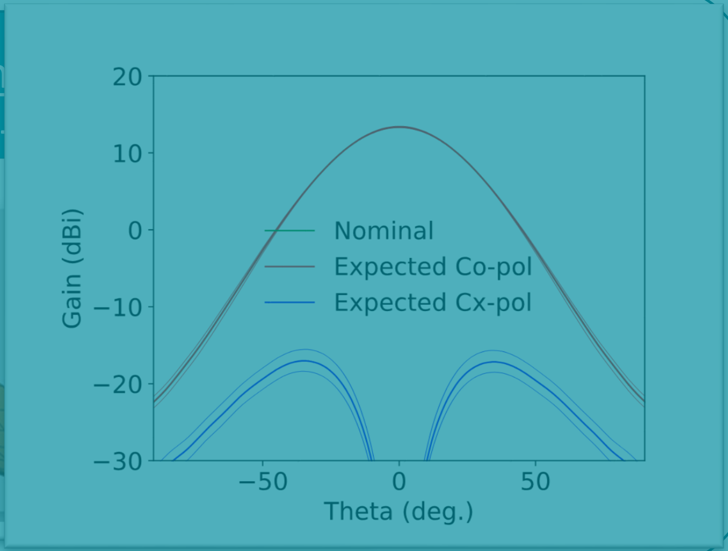
1960s-now
Simulation – use a computer to predict performance





2010s - n
Uncertainty





1980s-now
Optimisation – use a computer to optimi
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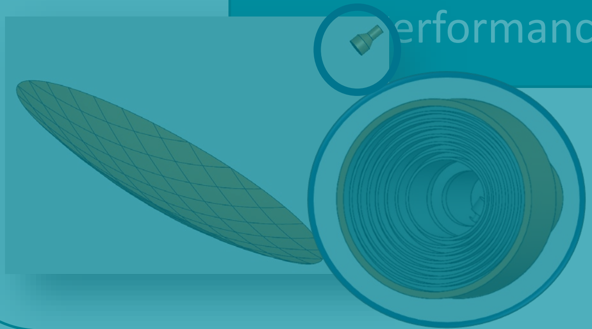

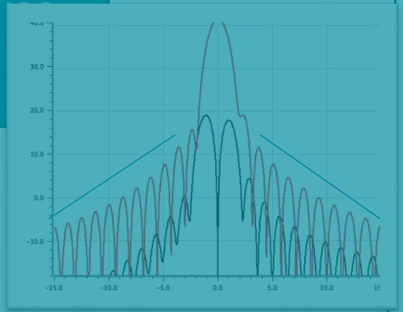

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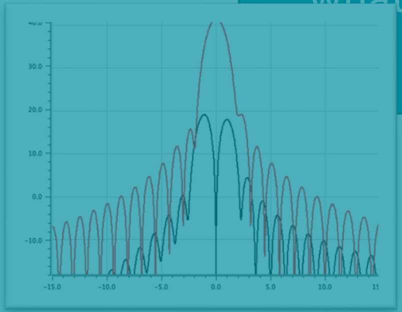
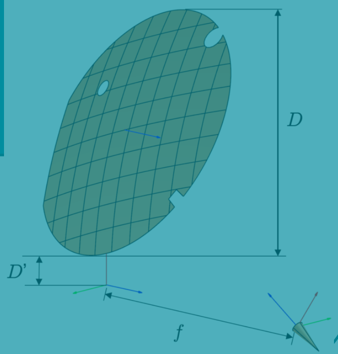
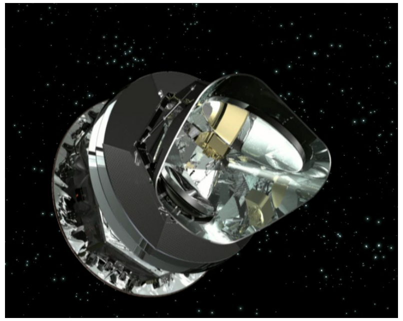




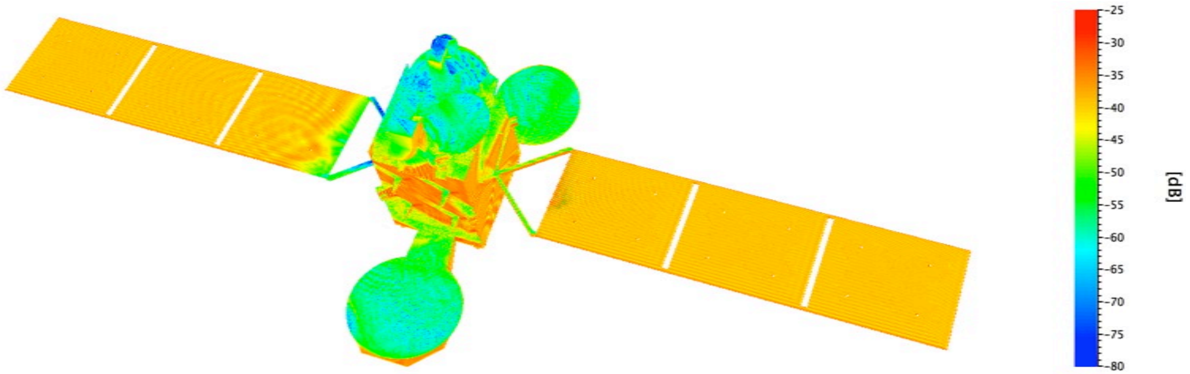
TICRA

EM Simulation of a scattering problem

- Scattering analysis:
- An electromagnetic field is incident on a structure. How does the structure respond?
  - Platform scattering
  - Antenna coupling
  - Antenna interference
- Of main interest are reflector antennas, e.g. mounted on satellite platforms.
- Obtaining the induced current requires the solution of a large linear system of N equations.
- When we double the frequency, we require 16 to 64 times the computer resources: N^2 or N^3
- Worked with PCH to reduce to N log N.



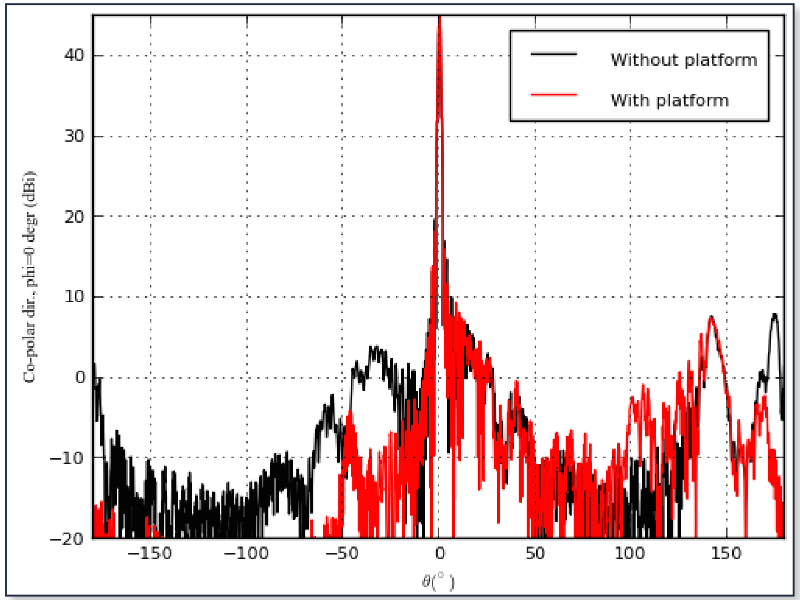
Planck Space Telescope



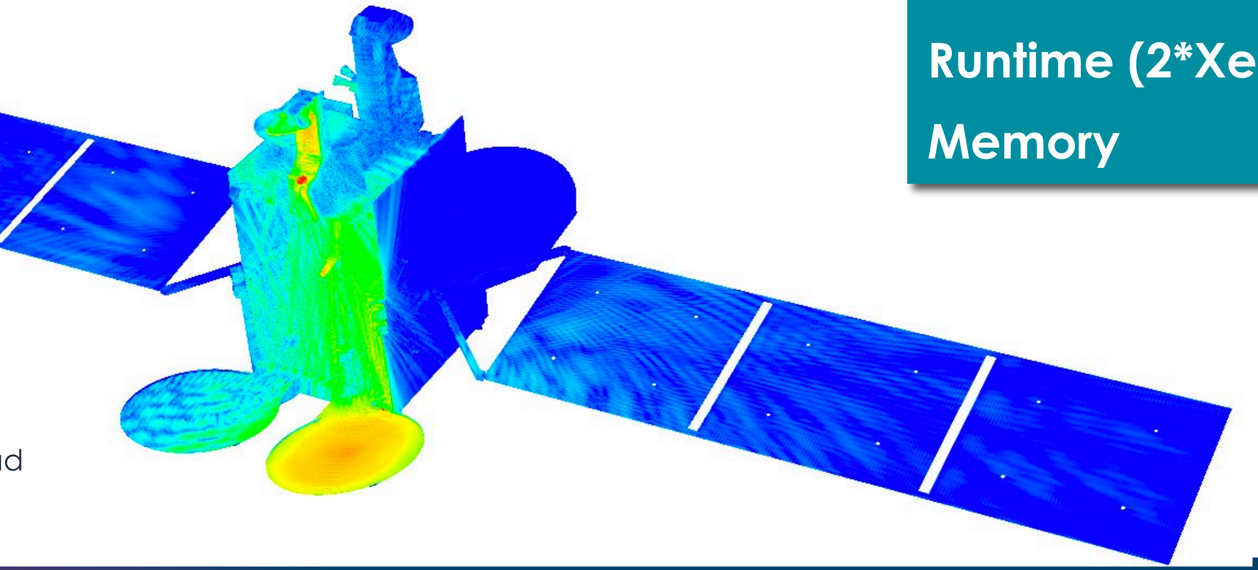
Currents excited on a satellite due to an incident plane wave.

Eutelsat-9B satellite in the Airbus Defense & Space anechoic test chamber.

Full simulation of a Telecom Satellite

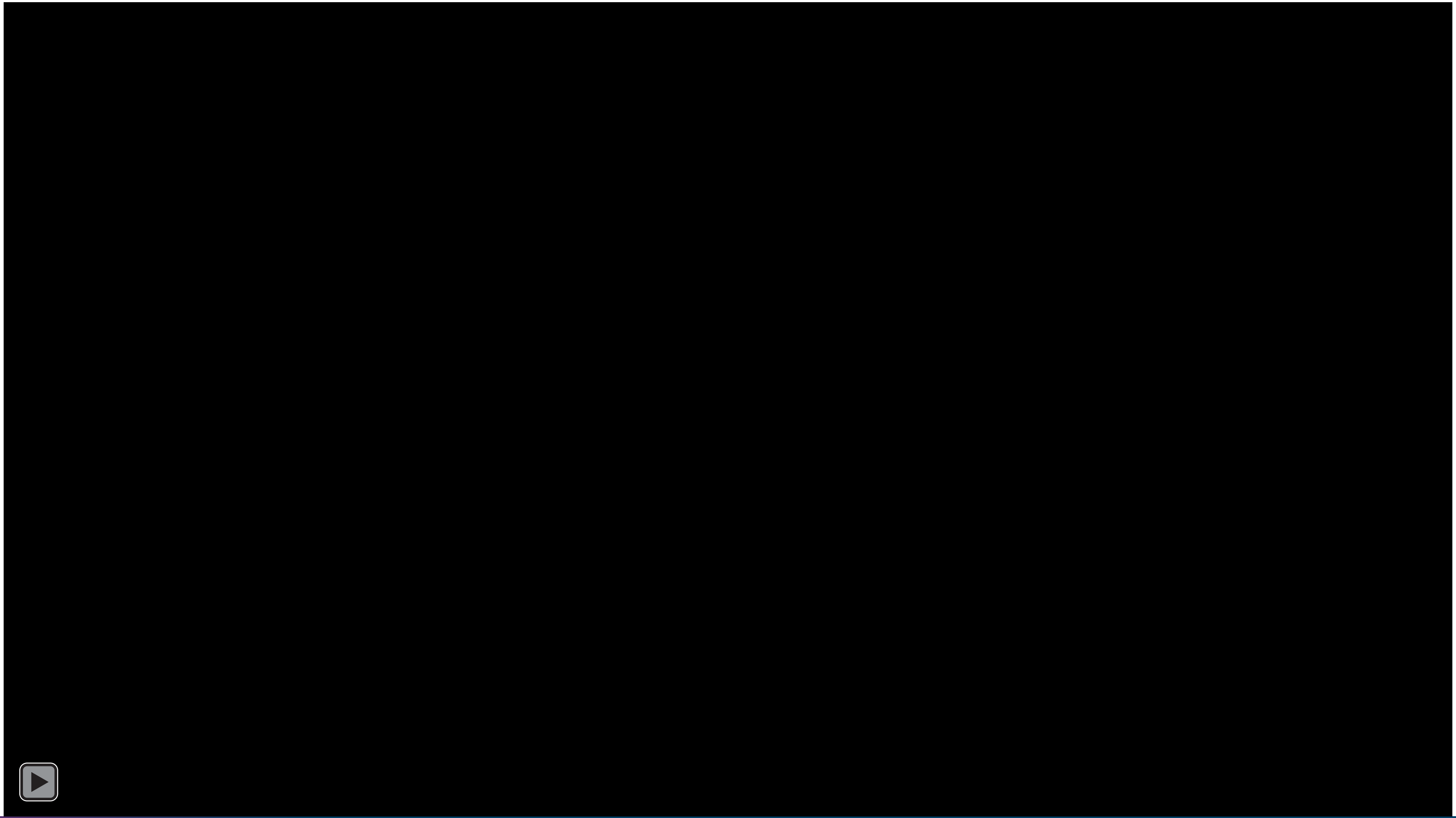


Frequency	12 GHz
Electrical size	167,762 λ^2
Patches	105,436
Smallest patch	λ/200
Largest patch	2.2 λ
HO Unknowns	4,475,955
Equiv. RWG unknowns	22,000,000
Iterations	90
Runtime (2*Xeon @2.9 GHz)	2:50 hours
Memory	122 GB

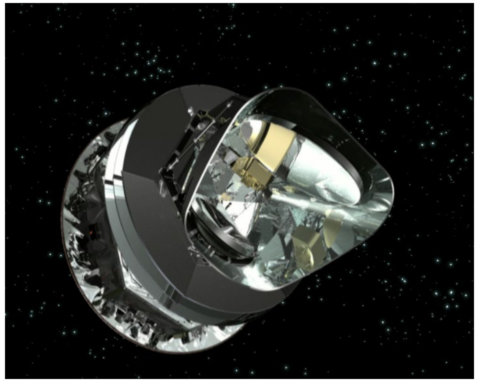


Ku-band payload
antenna

Planck Space Telescope

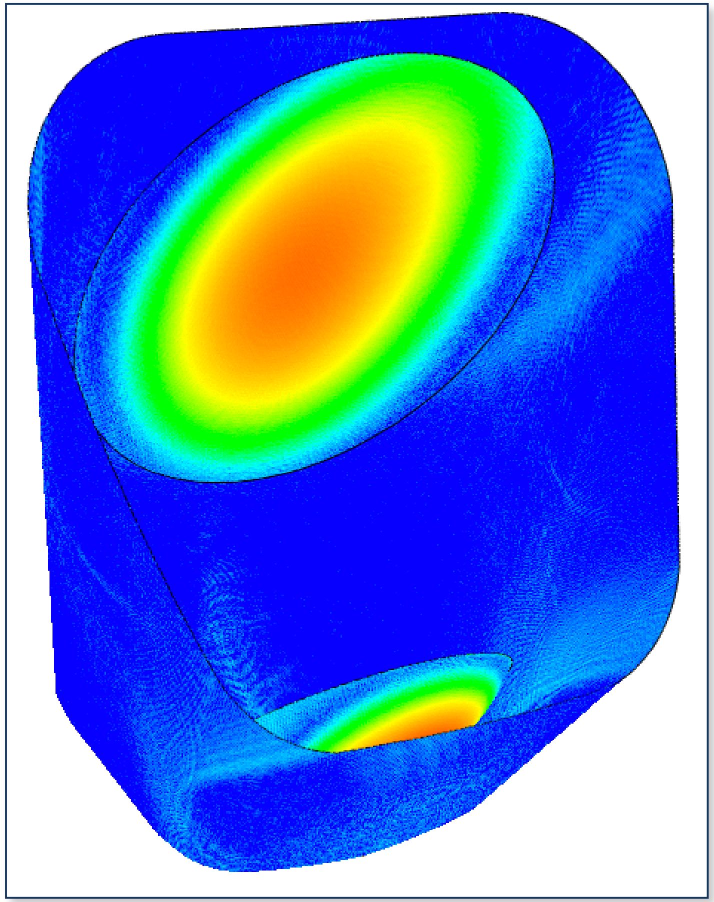


Full-wave simulation of the Planck Space Telescope



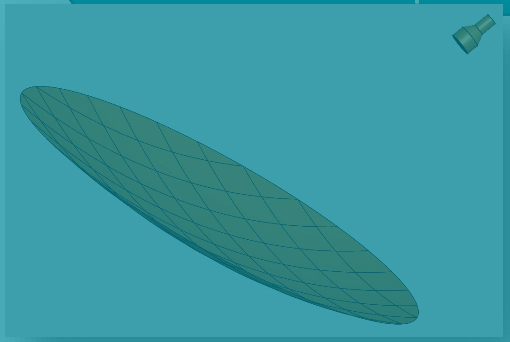
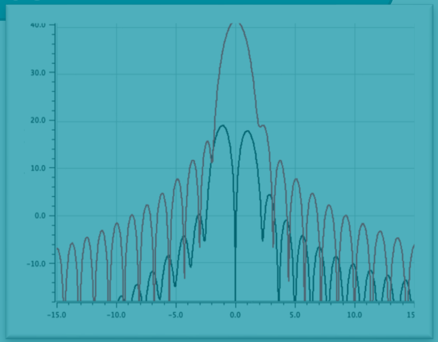
ESA's Planck Space Telescope

Frequency	30 GHz	44 GHz
Electrical size	168,477λ^2	362,413λ^2
HO Unknowns	5,337,075	11,397,375
Equiv. RWG unknowns	25 million	55 million
Iterations	101	139
Runtime (2*Xeon @2.9 GHz)	2:22 hours	7:09 hours
Memory	51 GB	125 GB

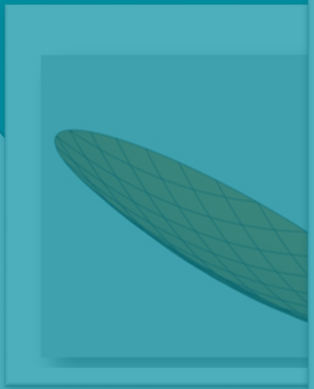
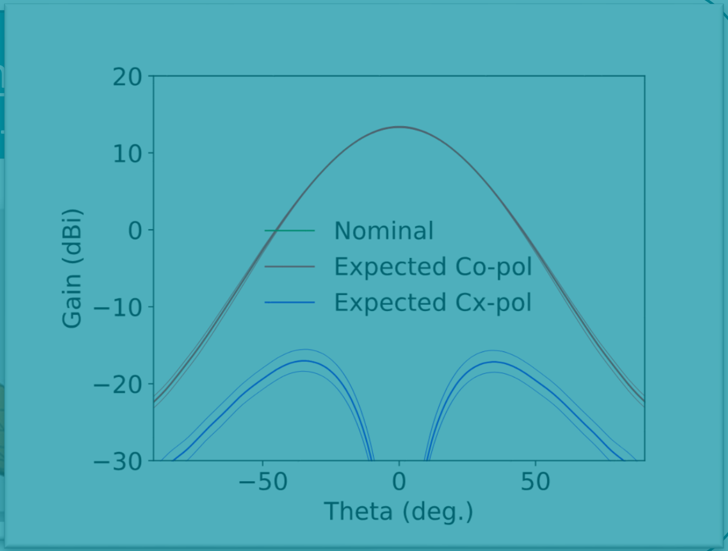


Part 2 – Optimisation

1960s-now
Simulation – use a computer to predict performance

2010s - n
Uncertainty

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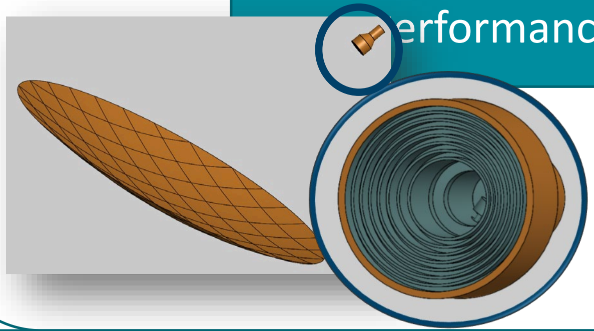
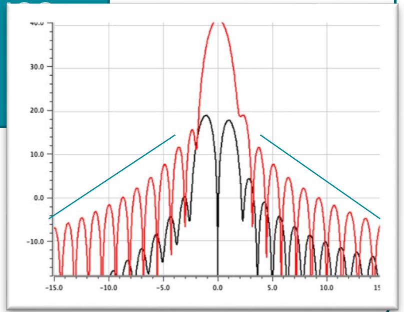
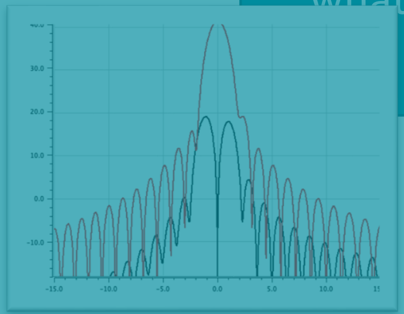
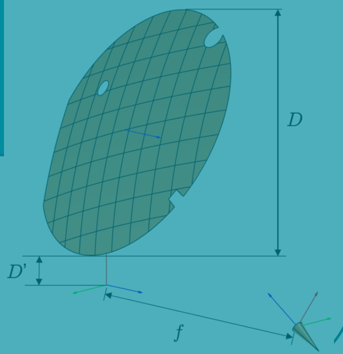



?s-now
Inverse problems – what the heck went wrong?

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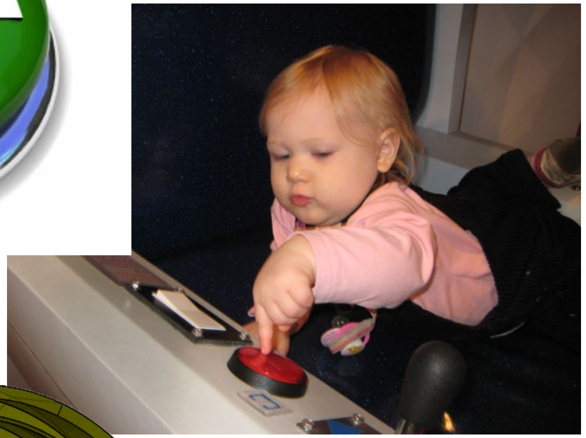
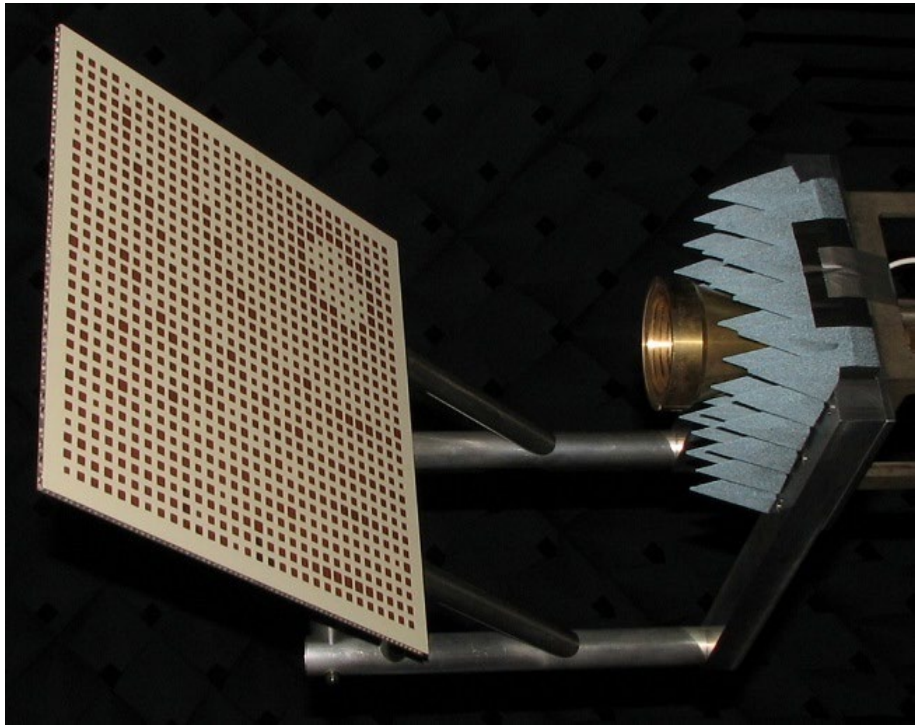
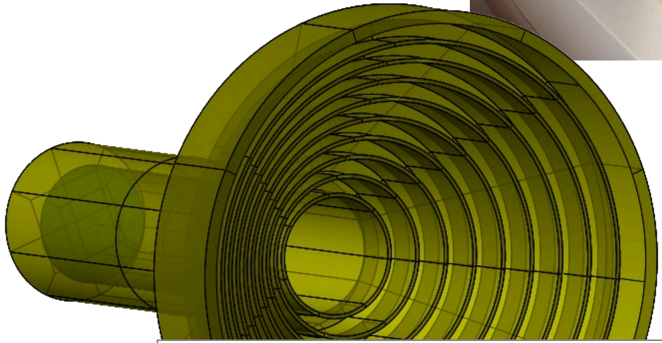
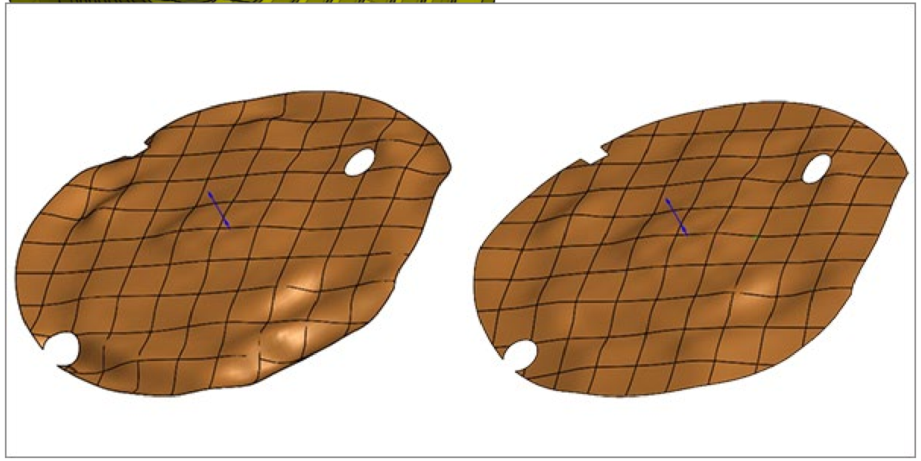
Optimisation

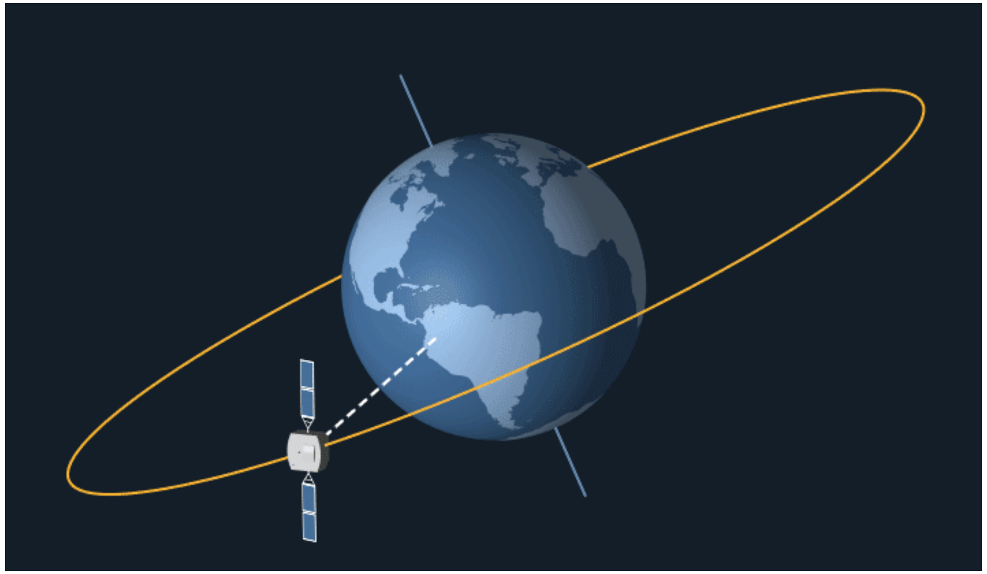
- General implementation ideas:

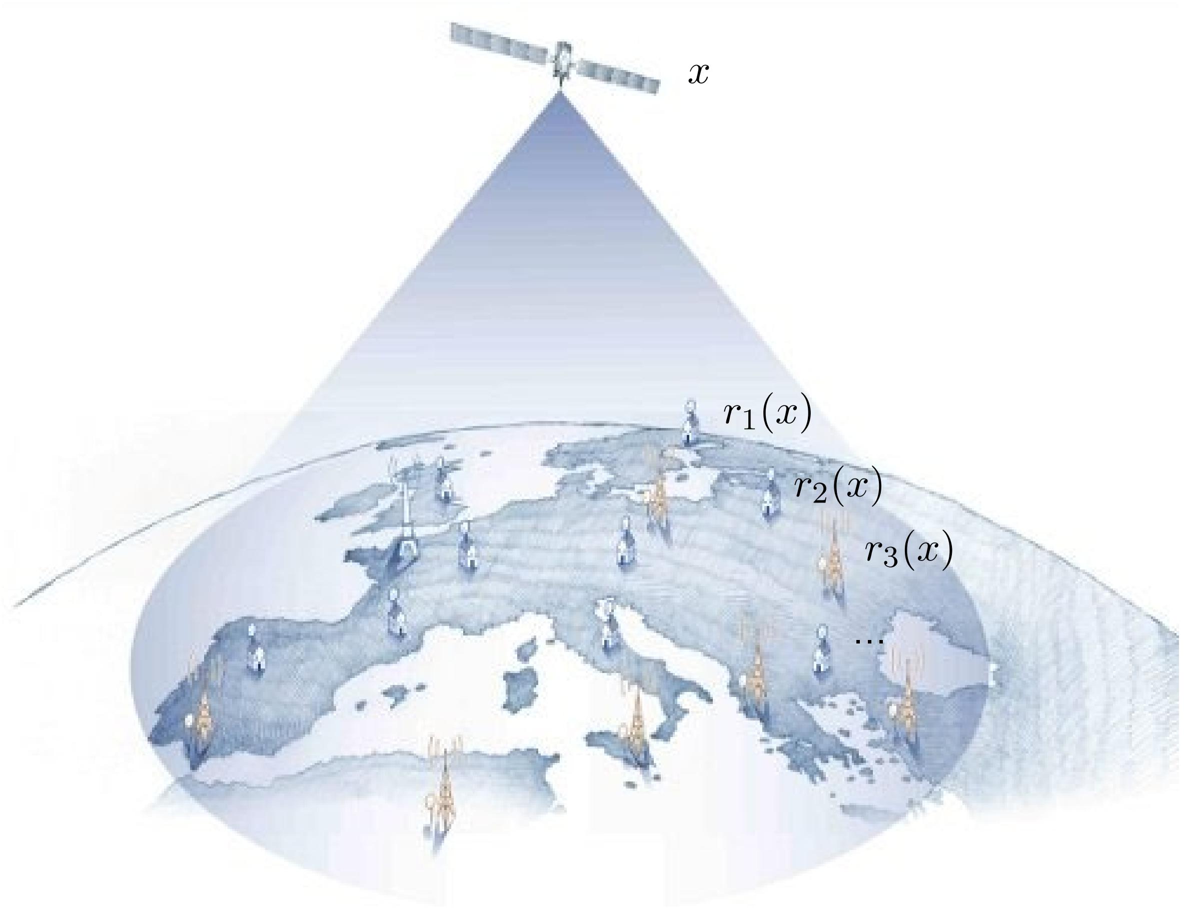



- Applications

Application – Optimisation of antennas for GEO satellites

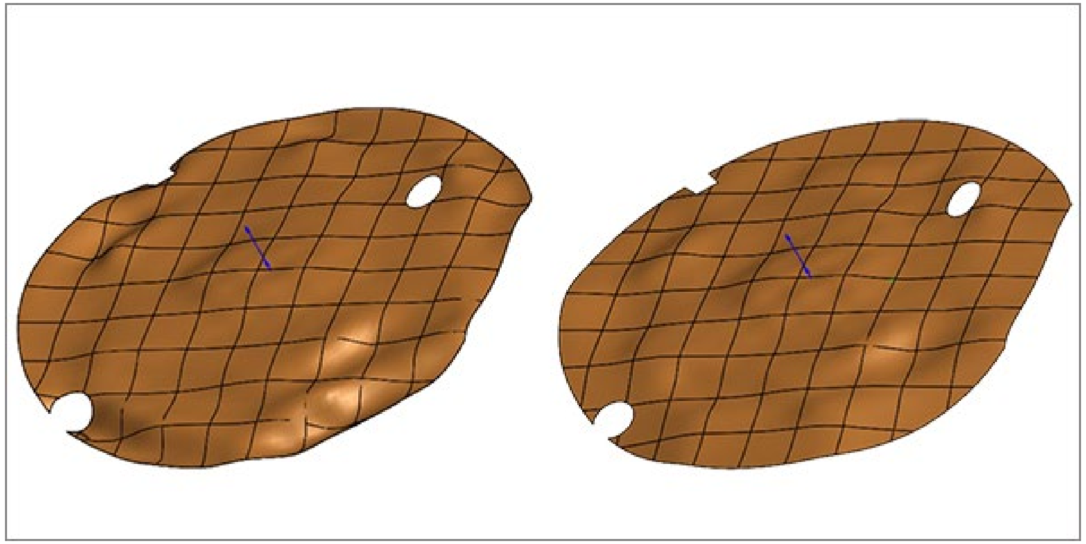


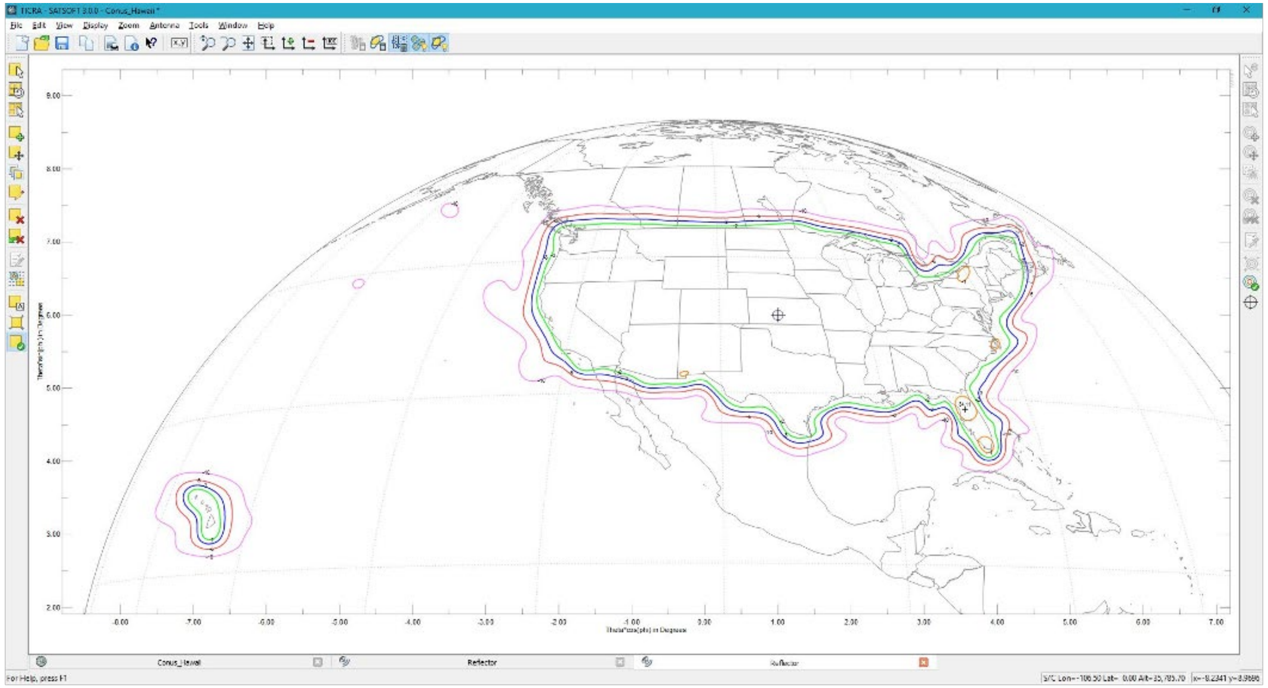


Application – Optimisation of antennas for GEO satellites

- Joint work with Anders Eltved & Martin S. Andersen, DTU Compute

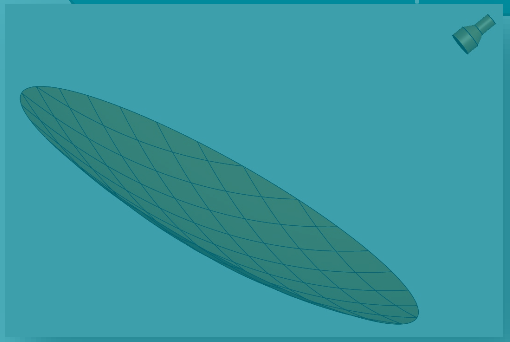
$$
\begin{aligned}
\min_{\overline{X}} . \quad & F(\overline{X}) = \max\left(\gamma_1 - F_1(\overline{X}), \gamma_2 - F_2(\overline{X}), \ldots, \gamma_m - F_m(\overline{X})\right), \\
\text{s.t.} \quad & \overline{\overline{A}}\,\overline{X} \leq \overline{B}
\end{aligned}
$$

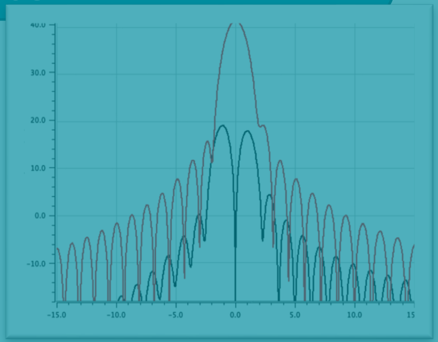




Part 3 – Uncertainty quantification

1960s-now
Simulation – use a computer to predict performance





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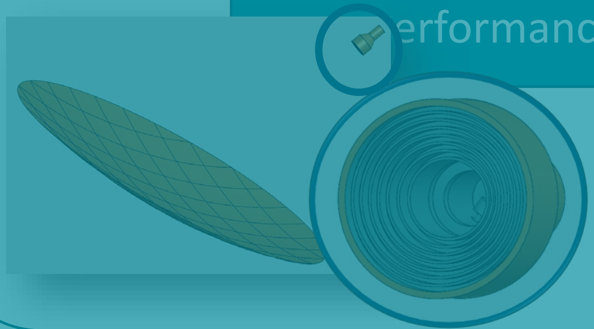
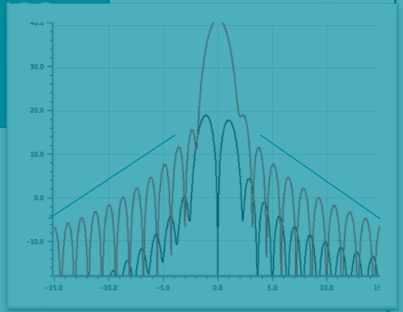
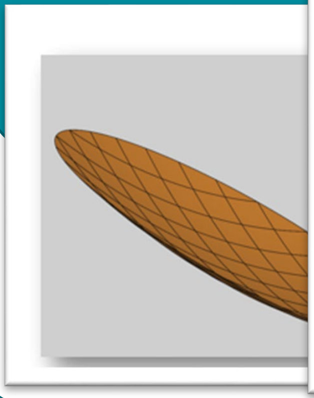
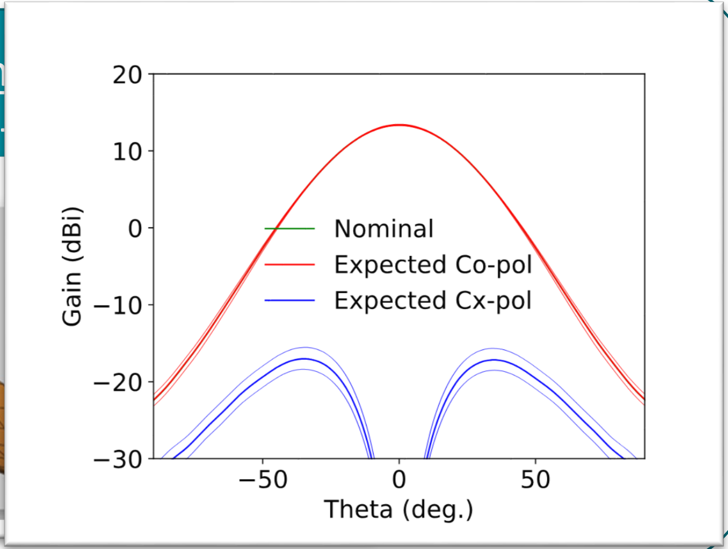


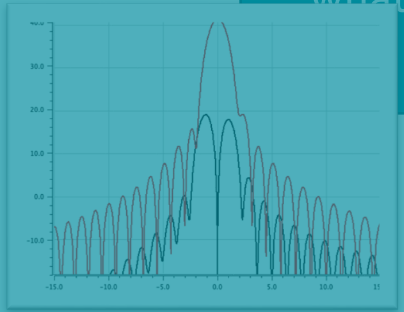


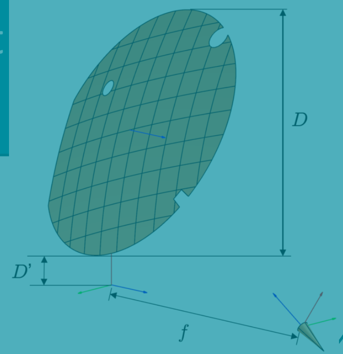
2010s - n
Uncertainty -





?s-now
Inverse problems – what the heck went wrong?

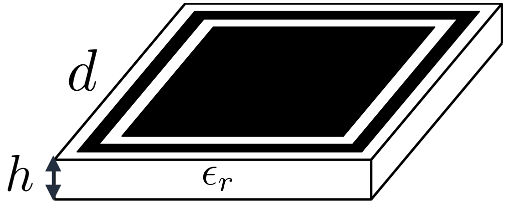




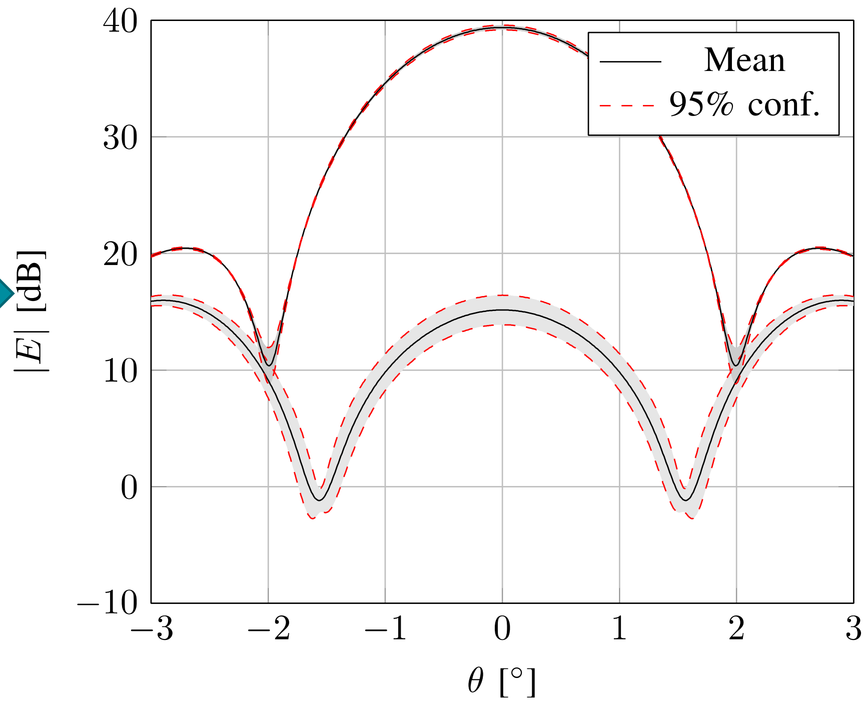
TICRA

What is Uncertainty Quantification?

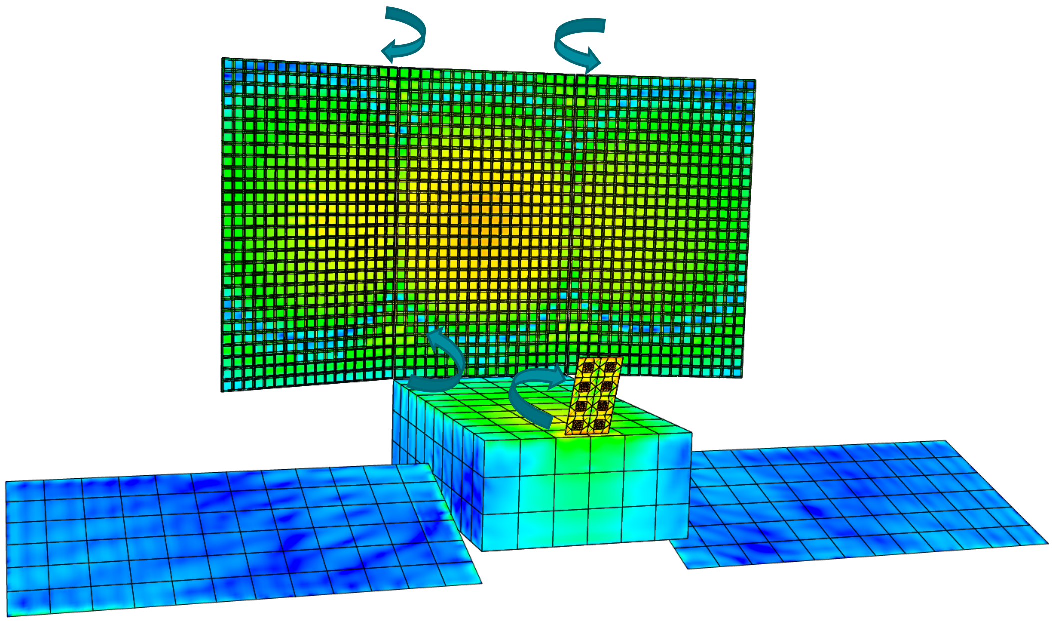
h = 4 mm +/- 0.01 mm
d = 13.33 mm +/- 0.02 mm
ϵ_r = 1.05 +/- 0.01



Uncertainty Quantification



Result 1: Reflectarray for Cubesat

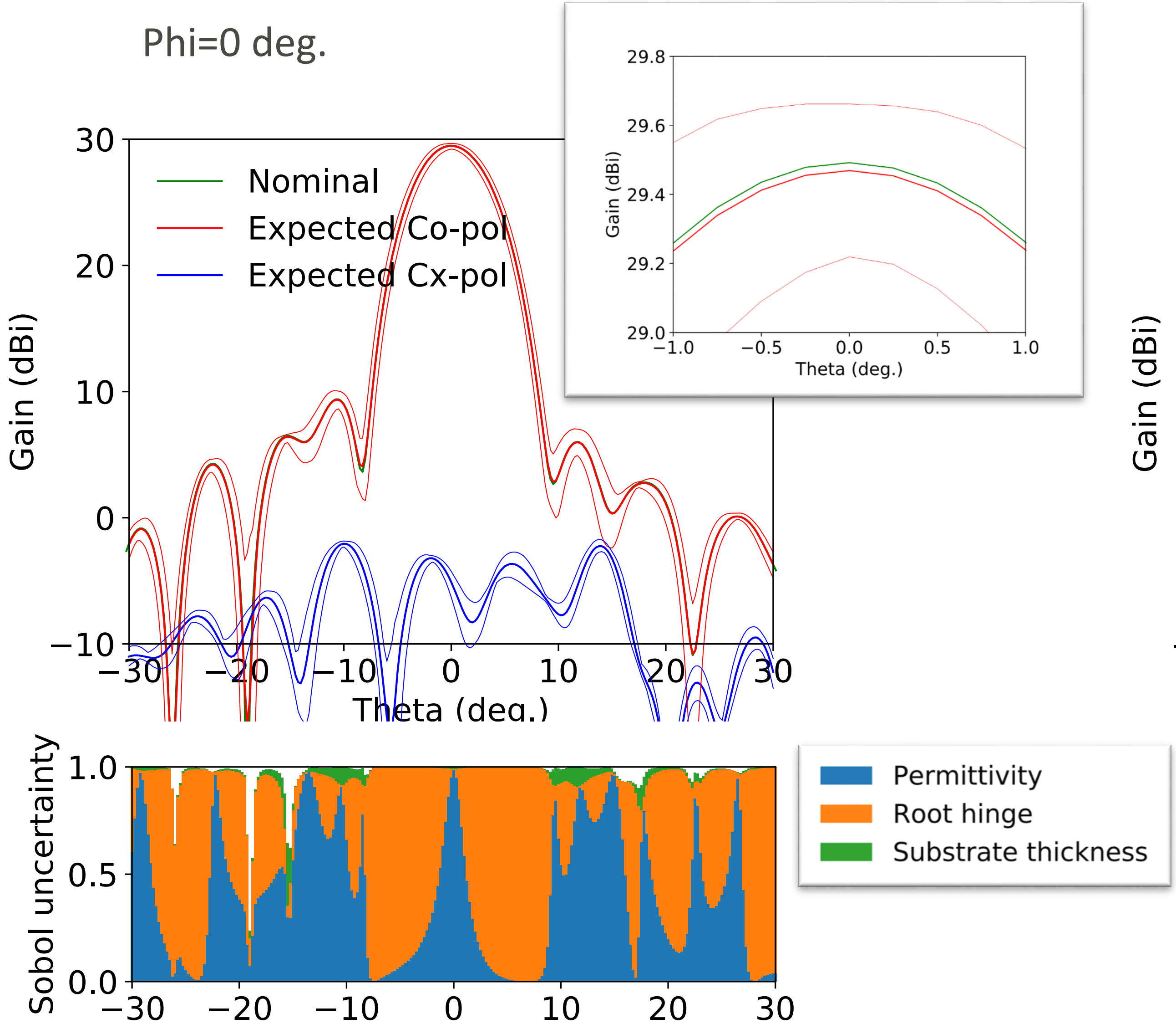


- Feed angle changes => full wave solution of platform scattering obtained in each UQ iteration

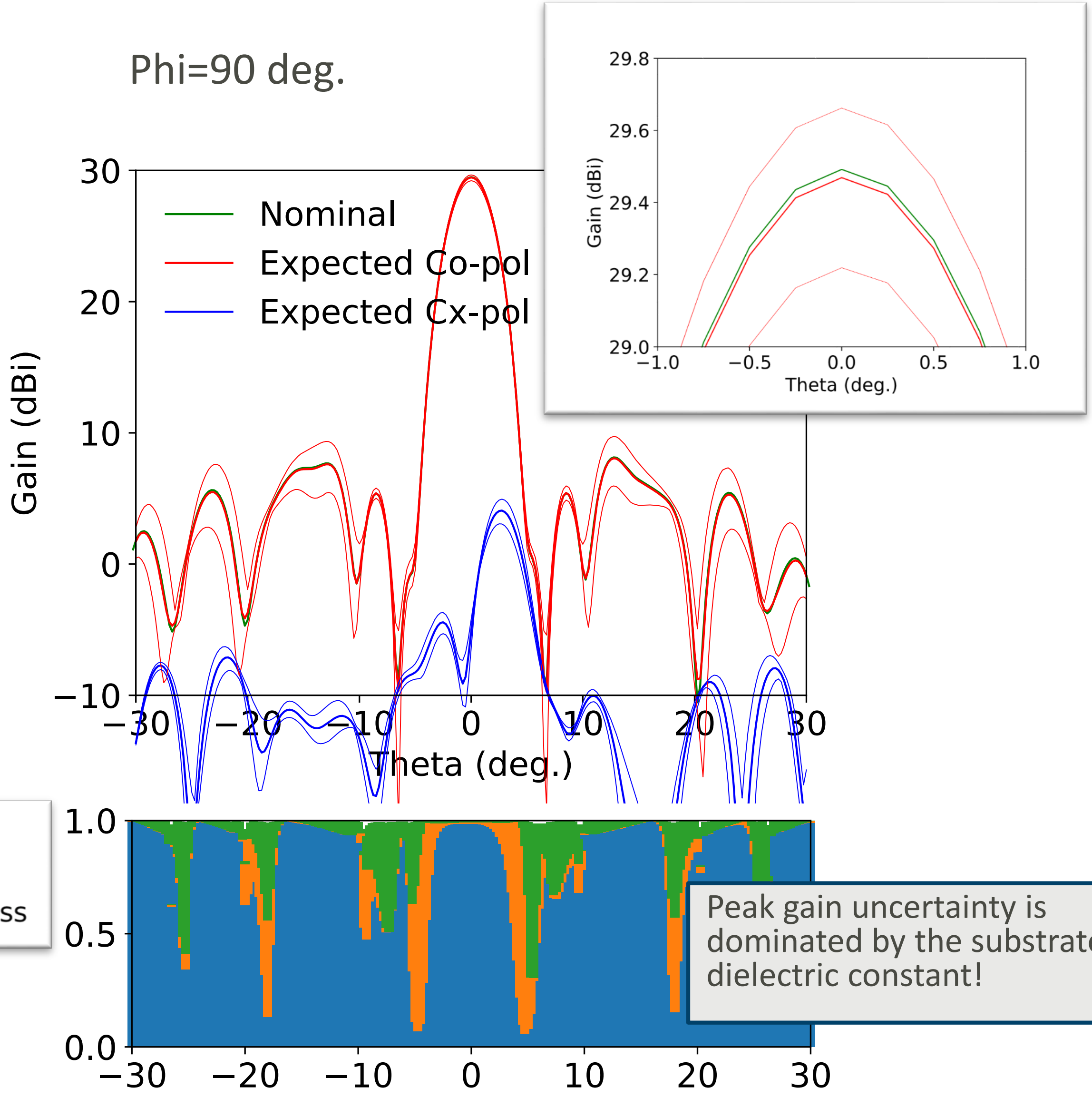
- Uncertainty on angles of deployed panels (± 0.2 deg.)
  - Root hinge
- Uncertainty on substrate permittivity and thickness
- Polynomial chaos expansion is used
  - 3 variables
  - 99% Confidence interval reported

Result 1: Reflectarray for Cubesat - Substrate Tolerance

Phi=0 deg.



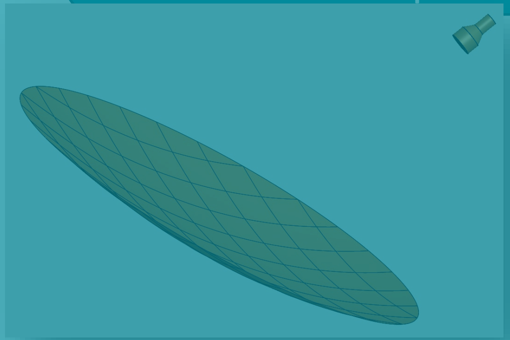
Phi=90 deg.

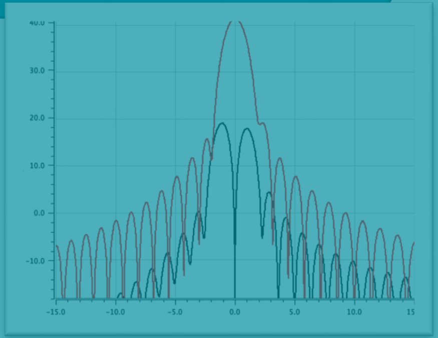


Peak gain uncertainty is dominated by the substrate dielectric constant!

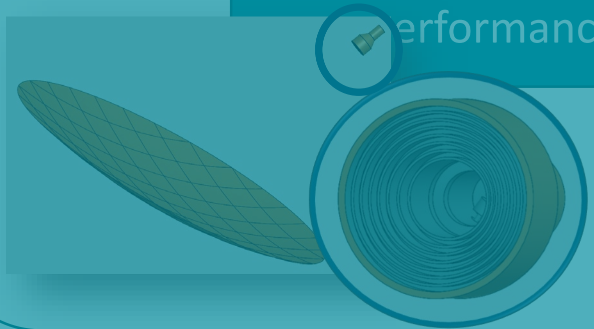
Part 4 – Diagnosis + Inverse problems

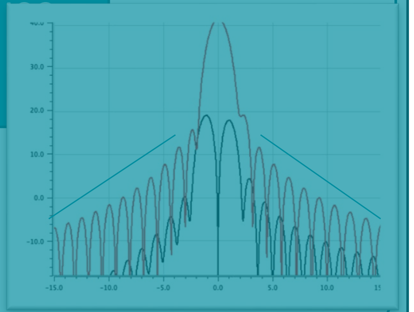
1960s-now
Simulation – use a computer to predict performance



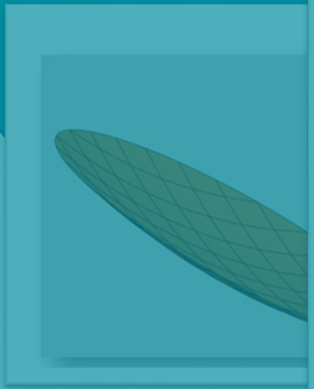


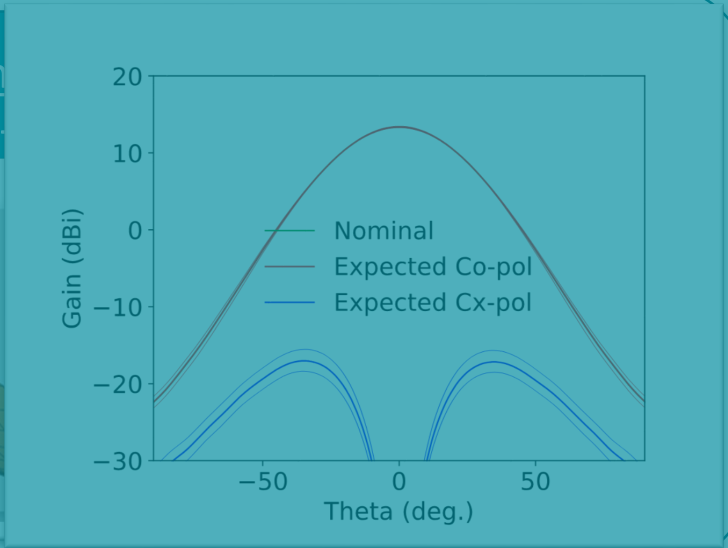
1980s-now
Optimisation – use a computer to optimi... erformance



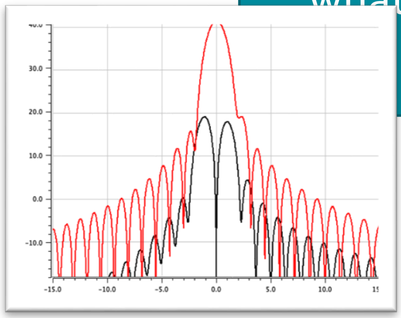


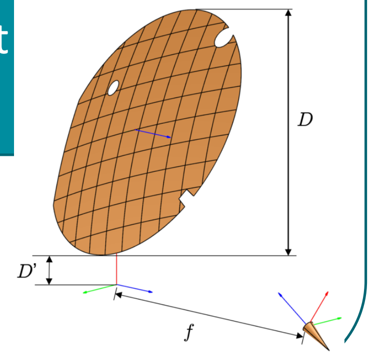
2010s - n
Uncertainty





?s-now
Inverse problems – what the heck went wrong?



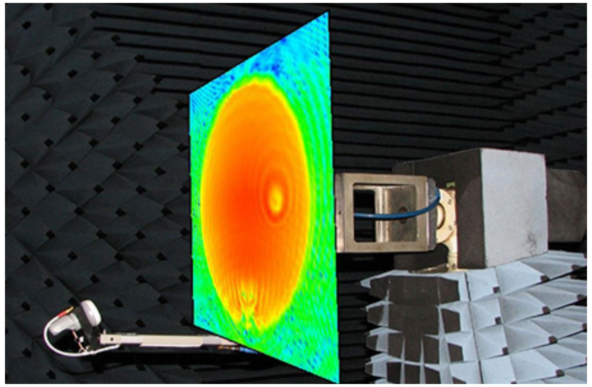


TICRA

Background and motivation

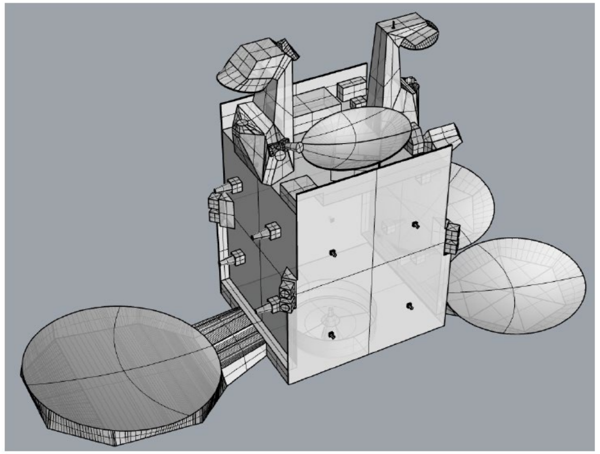
Background

- Source reconstruction = *Find the currents that radiate a given electromagnetic field*
- Source reconstruction is of high relevance in a number of application areas:
  - antenna diagnostics
  - near-field to far-field transformations and filtering
  - antenna placement investigations
  - radiation analyses of 5G devices



Motivation

- TICRA has, for the last decade, worked on expanding software to handle:
  - electrically large antennas
  - antennas on large scattering platforms
  - antenna arrays with hundreds or thousands of elements
  - high frequency antennas
- Still a challenging task



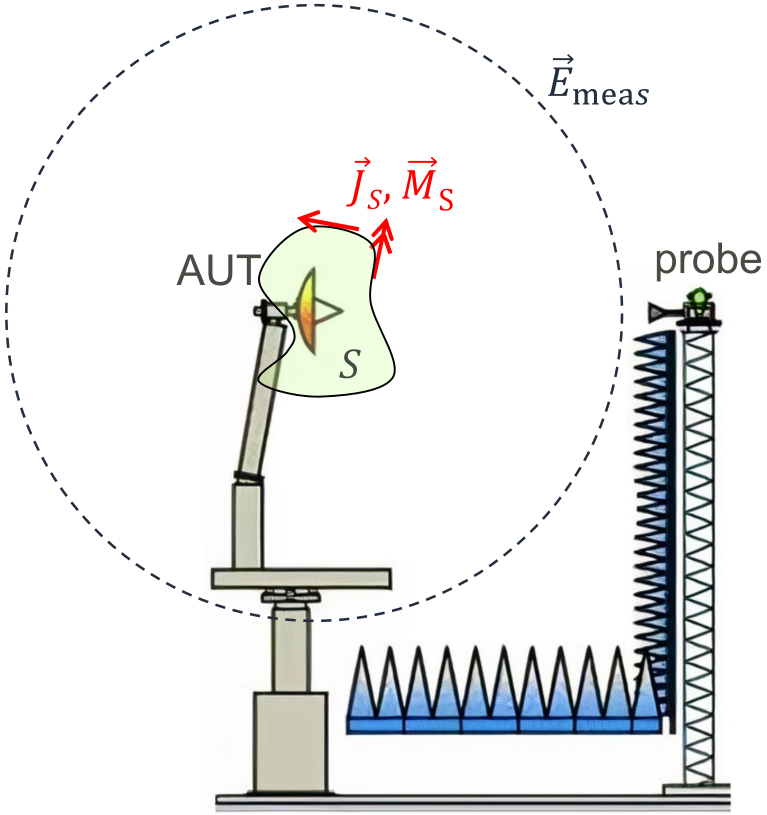
Software development projects (with PCH as advisor during projects)

- *Development of Diagnostics tool*
- *Fast Diagnostic Methods for Large-Scale Full-Satellite Antenna Measurement*

Commercially available source reconstruction software

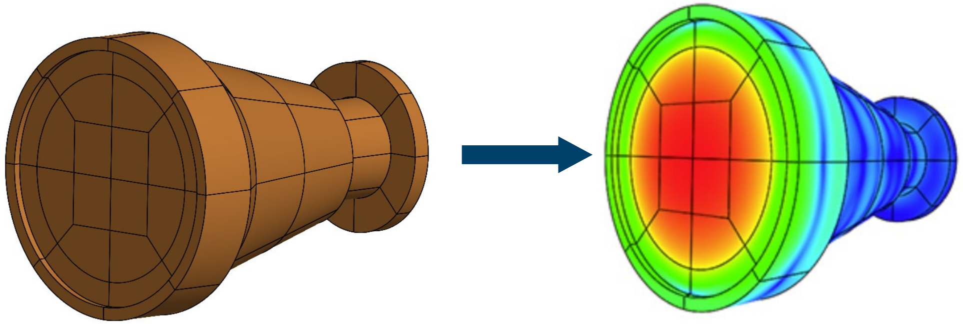
DIATOOL

- Source reconstruction antenna diagnostics software by TICRA
- First version released in 2011, after PCH collaboration.
- Used CGLS applied to standard—form transformed problem.



Software features

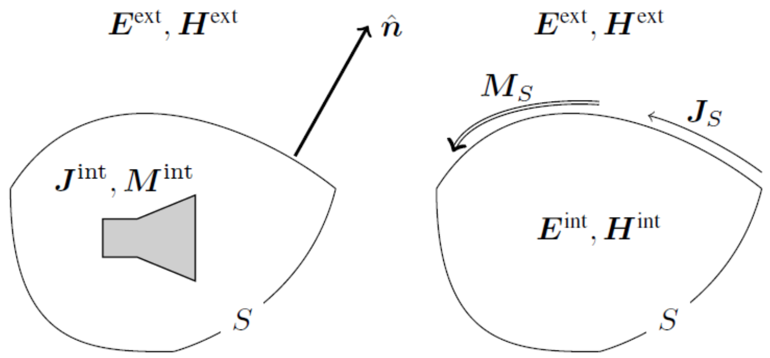
- Uses measured antenna radiation field data as input, amplitude and phase information required
- Reconstructs near-fields and surface currents of an antenna under test → Antenna diagnostics through visual inspection
- Field transformation engine → Compute the radiation from an antenna under test at different locations in space
- Filter undesired radiation from measured radiated fields



Implementation of new source reconstruction solver

- The basis for source reconstruction is the equivalence principle:

  Sources and scatterers enclosed inside a reconstruction surface (S), can be replaced by an equivalent set of surface current densities M_S, J_S *on* S, *such that these currents radiate the same fields* E^{ext}, H^{ext} *outside the surface*



(a) (b)

Based on these surface current densities, a data equation can be set up, linking measurements and the equivalent currents:

$$\boldsymbol{E}^{\mathrm{meas}}(\boldsymbol{R}) = -j\omega\mu_o\mathcal{L}\boldsymbol{J}_S + \mathcal{K}\boldsymbol{M}_S \qquad (1)$$

Measured field Observation point Integral operators Unknown currents

- The solution to (1) is non-unique, which implies that a second condition is needed to find the unique currents:

  Love's condition: $E^{int} = H^{int} = 0$ inside S, expressed as a boundary condition to (1)

$$\left.\begin{aligned} -\left(\hat{\boldsymbol{n}} \times \mathcal{K} + \tfrac{1}{2}\right)\boldsymbol{J}_S - j\omega\epsilon_o\hat{\boldsymbol{n}} \times \mathcal{L}\boldsymbol{M}_S &= 0 \\ -j\omega\mu_o\hat{\boldsymbol{n}} \times \mathcal{L}\boldsymbol{J}_S + \left(\hat{\boldsymbol{n}} \times \mathcal{K} + \tfrac{1}{2}\right)\boldsymbol{M}_S &= 0 \end{aligned}\right\} \ \textbf{for} \ \boldsymbol{R} \to S^- \qquad (2)$$

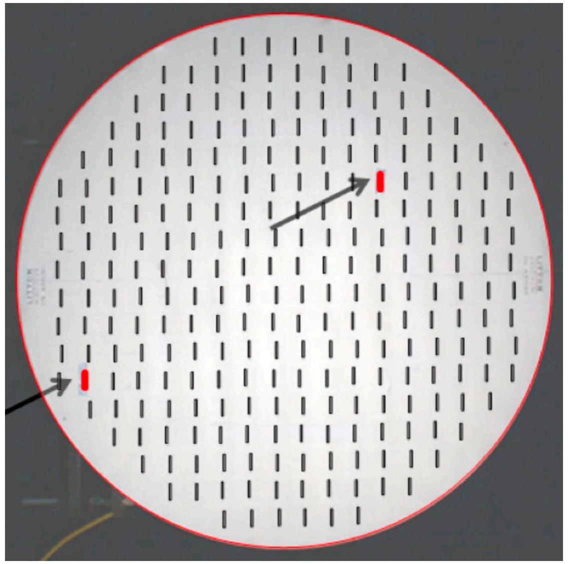
- The solution to (1) and (2) are the sought after unique currents
- Most previous works are based on solving the coupled system of equations in (1) and (2). This approach is computationally expensive, and regularization is needed to balance the two conditions

$$\min_{\bar{x}} \|\bar{\bar{A}}\bar{x} - \bar{b}\|_2, \quad \text{s.t. } \bar{\bar{L}}\bar{x} = 0$$

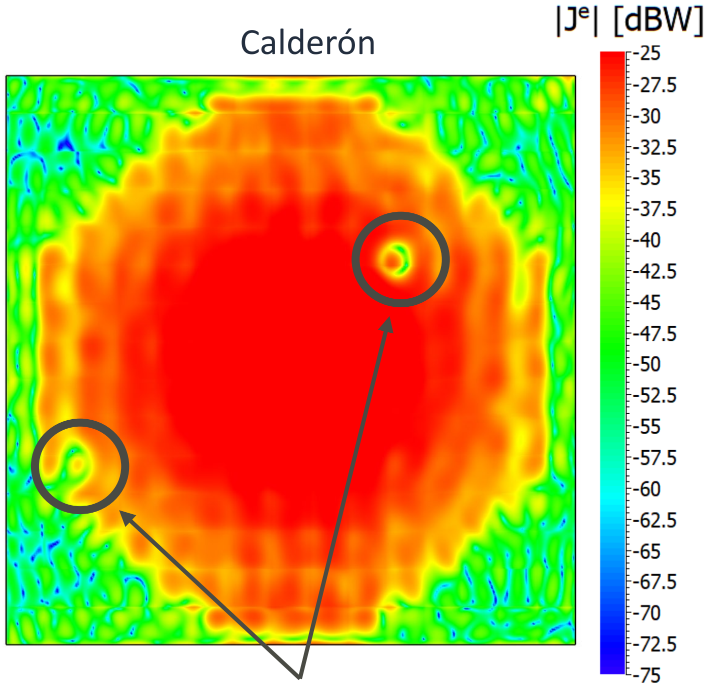
Integral operators Love's condition Unknown currents Measured field

Application case: defect slotted array antenna

- Antenna near-field measured by MI-Technologies in spherical range
- Operating at 9.4 GHz, antenna side length 0.5 m
- Faulty elements introduced by adding conductive tape to two of the radiating slots
- Same project analysed using both the SCGLS and Calderón reconstruction method



Calderón



Faulty elements

Solver	Number of unknowns	Comp. time [hh:mm]	Required memory [GB]
Pre-PCH	31 680	?	?
SCGLS	31 680	01:22	50.60
Calderón	31 680	00:05	0.87

- Good agreement in reconstructed currents achieved by the two methods
- Calderón method offers significant reduction in allocated memory and computation time

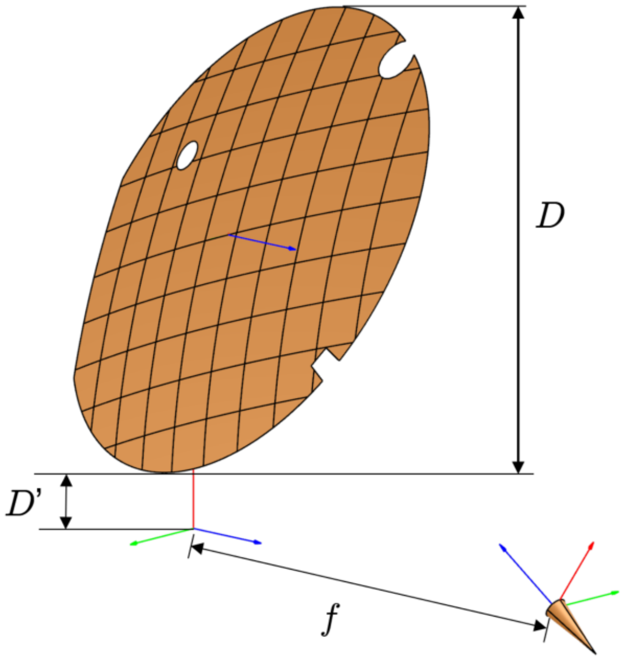
Application case: electrically large reflector antenna

- Operating at 12 GHz, reflector diameter (D) 1.6 m = 64λ, focal length (f) 1.6 m, clearance (D') 0.2 m
- Cut-outs of reflector rim for attachment points
- Circular hole in reflector with diameter of 0.1 m representing a surface defect
- Simulated in TICRA Tools framework, using the MoM/MLFMM solver in ESTEAM
- Antenna far-field computed over full sphere
- Random noise manually added to data corresponding to a signal-to-noise ratio of 60 dB

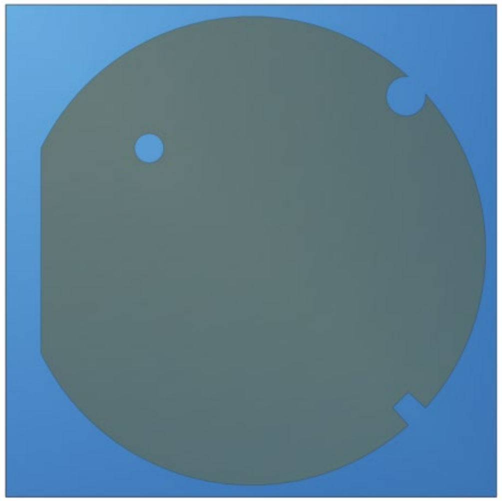
Source reconstruction problem

- Antenna far-field in amplitude and phase as input
- Rectangular box reconstruction surface enclosing the reflector
- Isolate the reflector surface defect and the impact of the reflector rim cut-outs

Reflector antenna in TICRA Tools



Reconstruction surface in DIATOOL



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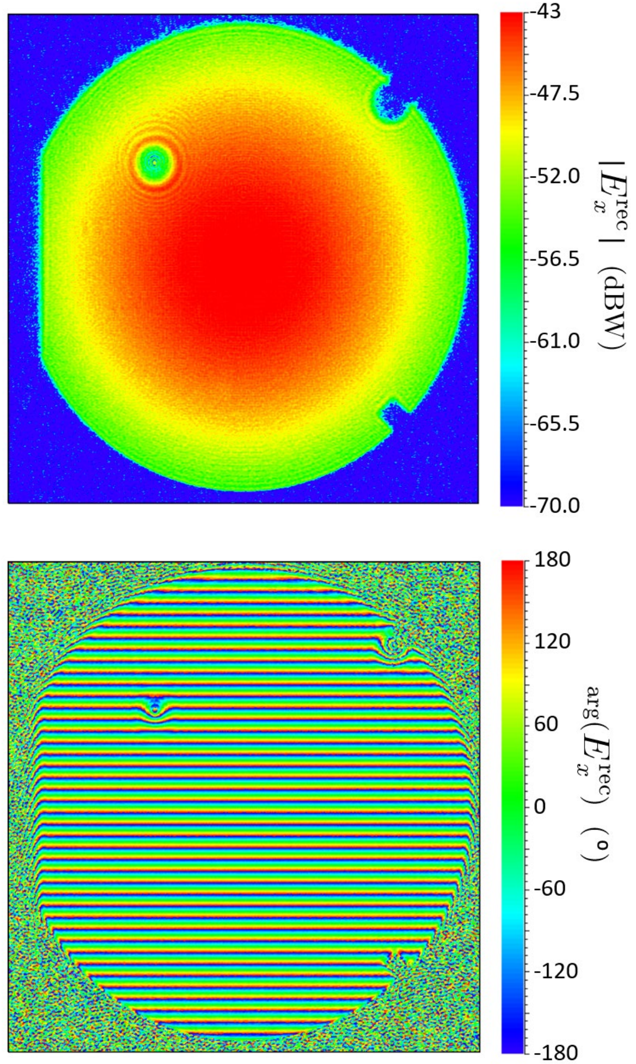
Application case: electrically very large reflector antenna

Solver	Number of unknowns	Comp. time [hh:mm]	Required memory [GB]
SCGLS	2 070 200	--:--	175 921
Calderón	2 070 200	02:14	27

- Reconstruction problem scaled up in electrical size: D = 3.3 m = 128λ, f = 3.3 m, D’ = 0.2 m, frequency = 12 GHz
- Inverse MoM solver in DIATOOL 1.1 would require over 170 TB of RAM!
- Calderón method only requires 27 GB RAM
- Defects clearly visible in reconstructed currents



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Thank you

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