Dedicated to innovation in aerospace

NLR 90 years

About NLR and Smart Antennas

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Where is NLR?

The Netherlands

NLR-Amsterdam

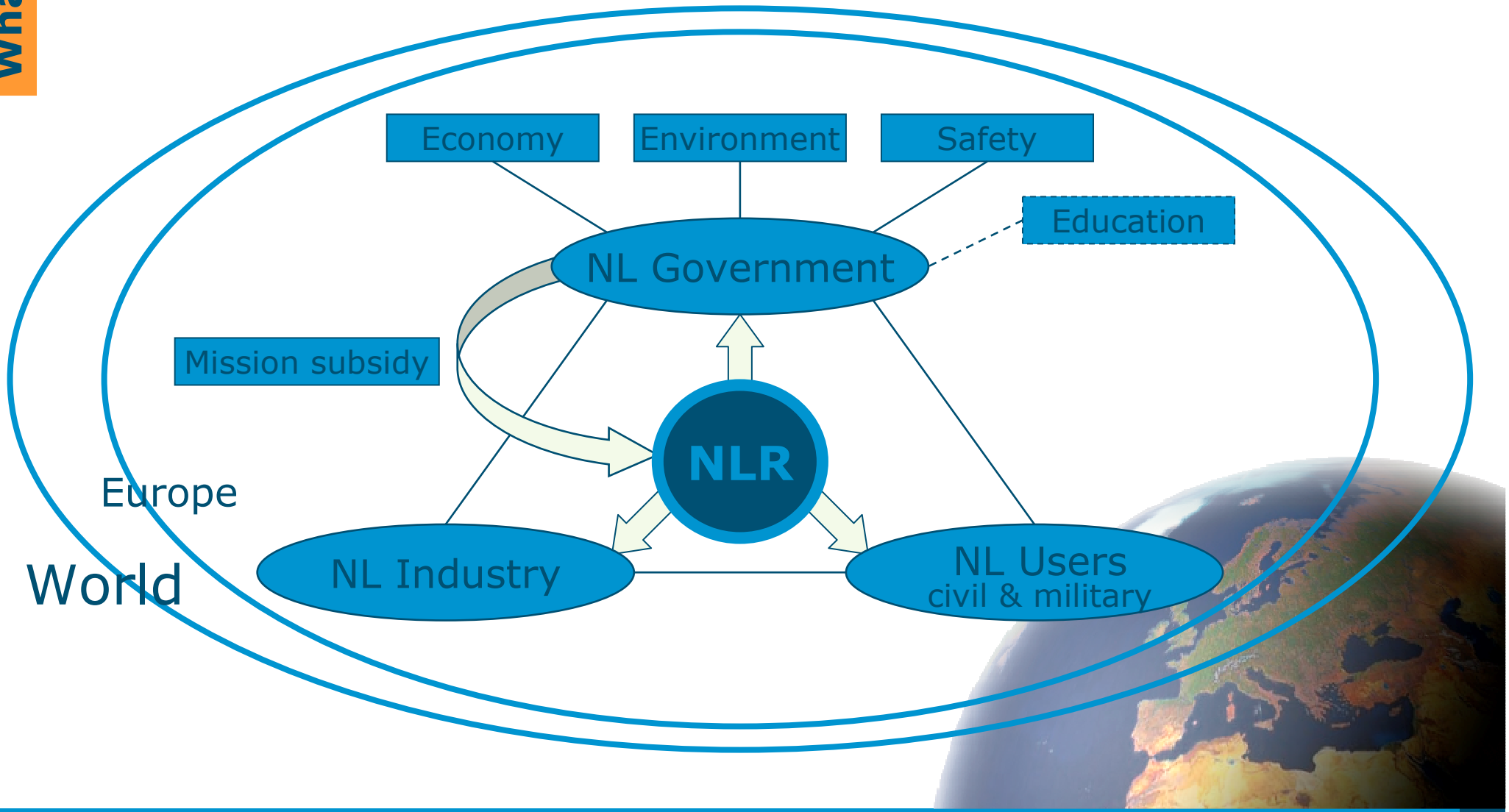
NLR-Flevoland

NLR: *The* Netherlands national knowledge centre for aeronautics and space technology

- **NLR Mission**
  - To develop high-tech aerospace products and processes
  - To provide market-driven, socially relevant products and services on a not-for profit basis
  - To support the Netherlands government and businesses in staying innovative and effective

What & how

NLR's position in the Netherlands and the world



NLR Stakeholders

Civil aviation:

- Airports
- Air Traffic Control Authorities
- Aviation Regulatory Authorities
- Airlines
- Air Transport Industry

Aeronautics industry (civil/defence):

- Lead Aeronautics industries
- Systems & Component providers
- MRO and Logistics companies
- Training and ICT providers

Defence - Government:

- Defence Materiel Command and Operational Commands
- International Armed Forces

Space:

- Space industry
- European Space Agency (ESA)

Government

Work Force and Organisational Structure

Board of Directors

- **Strategy and Policy**
- **Personnel & Organisation**
- **Other Staff & Supporting Services**

Aerospace Systems & Applications

Avionics Development & Qualification
Flight Test Systems & Applications
Avionics Systems
Military Operations Research
Space

Air Transport

NLR Air Transport Safety Institute
Air Traffic Management & Airports
Air Transport Systems Technology
Training, Human Factors & Cockpit Operations
Environment & Policy Support

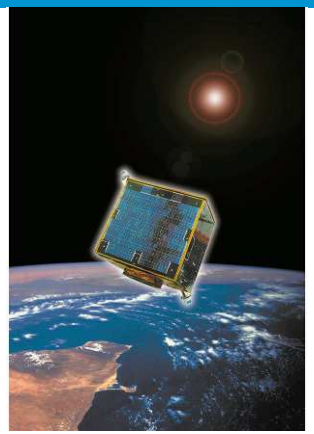
Aerospace Vehicles

Gas Turbines & Structural Integrity
Flight Physics & Loads
Helicopters & Aeroacoustics
Collaborative Engineering Systems
Structures Technology
Engineering & Technical Services
Structures Testing & Evaluation

Work force: about 700 employees,

51% university-trained and 24% with a higher professional qualification

Research facilities



Smart Antennas: Overview

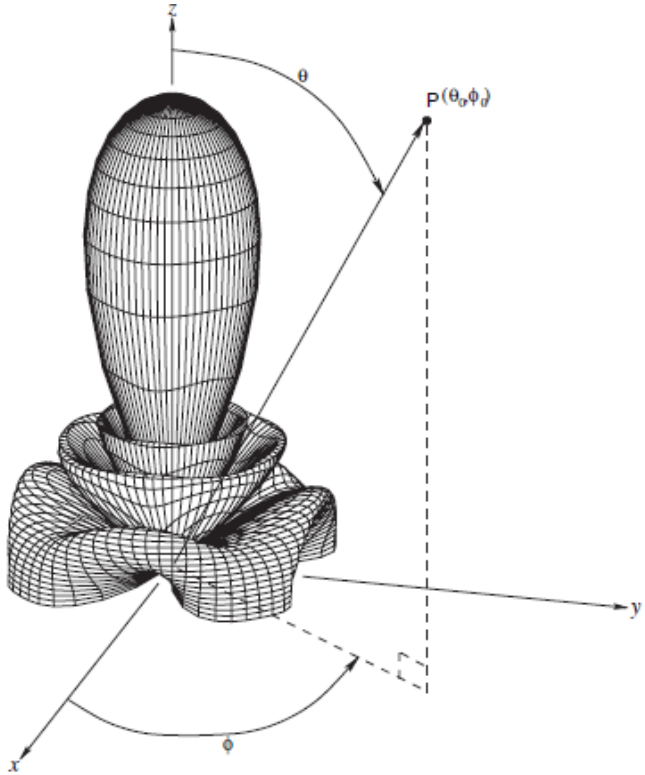
- Introduction
- Some examples
- Antenna arrays
- Signal processing
- Beam forming and beam steering
- Ku-band receive antenna array for SATCOM
- Antenna array on vibrating plate

Introduction

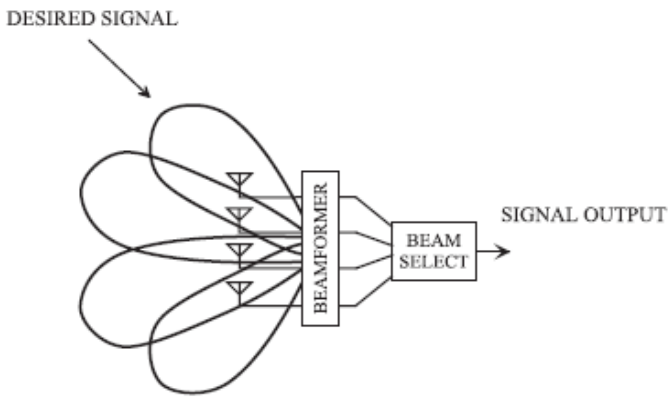
- **Smart antennas** are **antenna arrays** with:
  - **signal processing algorithms** used to identify spatial signal signature such as the direction of arrival (DOA) of the signal,
  - and use it to calculate beam forming vectors, **to track and to steer antenna beams** in a certain direction (on a moving target).

- **Antenna array** consists of a **group** of radiating or receiving **antenna elements**, coupled to common electronic hardware to produce a **directive radiation pattern**.

Introduction



Directive radiation pattern

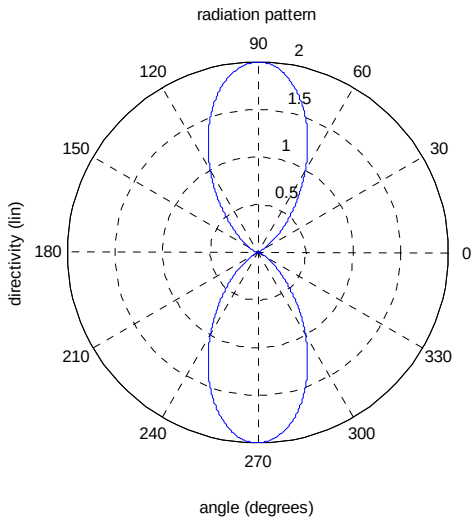


Concept of array antenna:

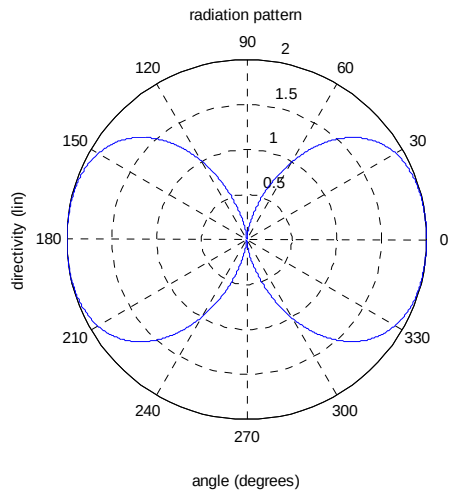
- Multiple antenna elements
- Beam forming hardware

Introduction

- Consider an array antenna consisting of two isotropic radiators at distance $d = \lambda / 2$ along the x-axis
- Then the total radiated field reads $E_T = w_1 E_1 + w_2 E_2$



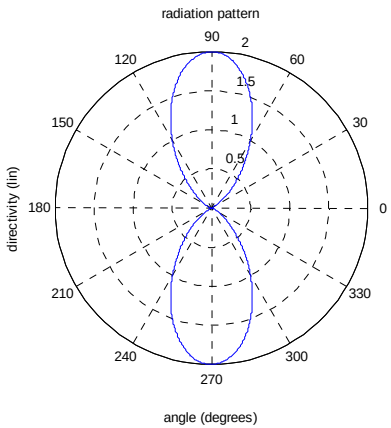
$$w_1 = w_2 = 1$$



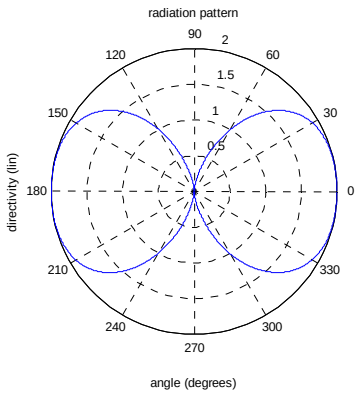
$$w_1 = 1, \quad w_2 = e^{j\pi}$$

Introduction

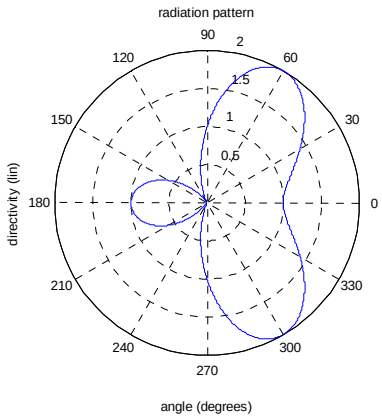
- Same array antenna consisting of two isotropic radiators at distance $d = \lambda / 2$ along the x-axis
- Let $w_1 = 1, \quad w_2 = e^{-j\pi \sin\theta}$



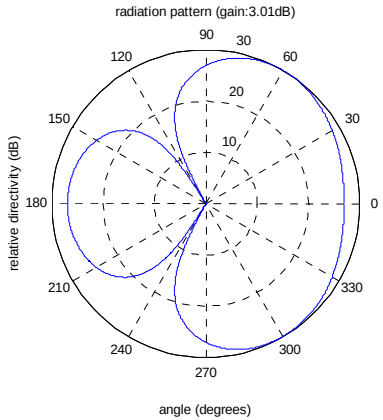
$\theta = 0$



$\theta = -\pi$



$\theta = \pi / 6$



$\theta = -\pi / 6$

Introduction

- By **choosing appropriate weights** for the elements of the antenna array we can **form and steer** the antenna radiation pattern
- **Maximize antenna gain** in a certain direction, for instance to establish links with communication satellites
- **Minimize antenna gain** in a certain direction, for instance to avoid signal from jammers

Some examples

- Very Large Array for astronomical radio observatories.
- Array consists of 27 radio antennas in a Y-shaped configuration.
- Data from the antennas is combined electronically.

Some examples

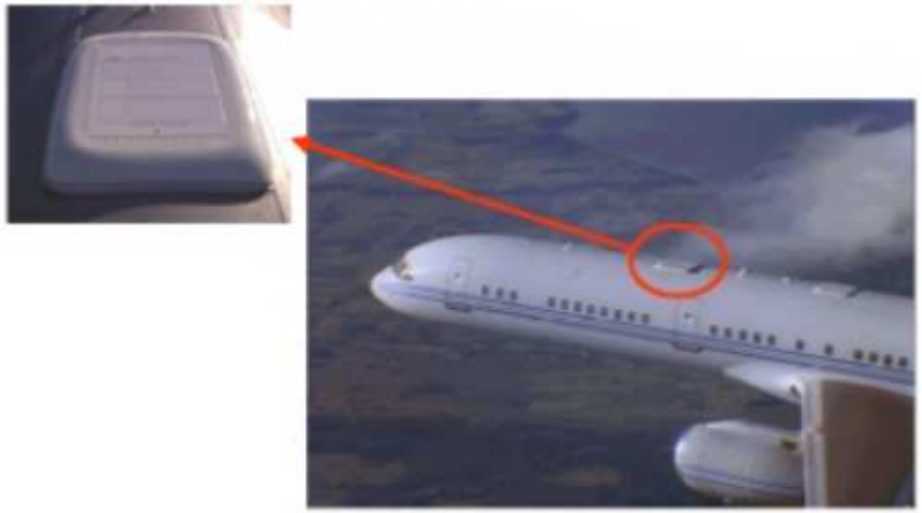
Early warning radar system for detection of ballistic missiles

Active phased array radar onboard of ship for multiple target detection and tracking

Some examples

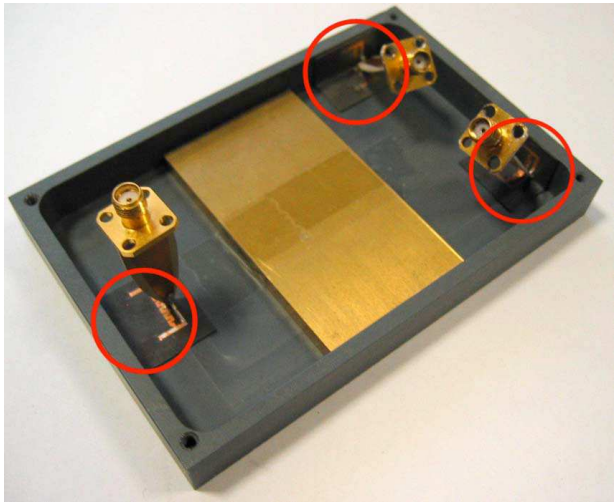
Connexion by Boeing
Advanced Electronically Steerable Antenna array for communication with geostationary satellites

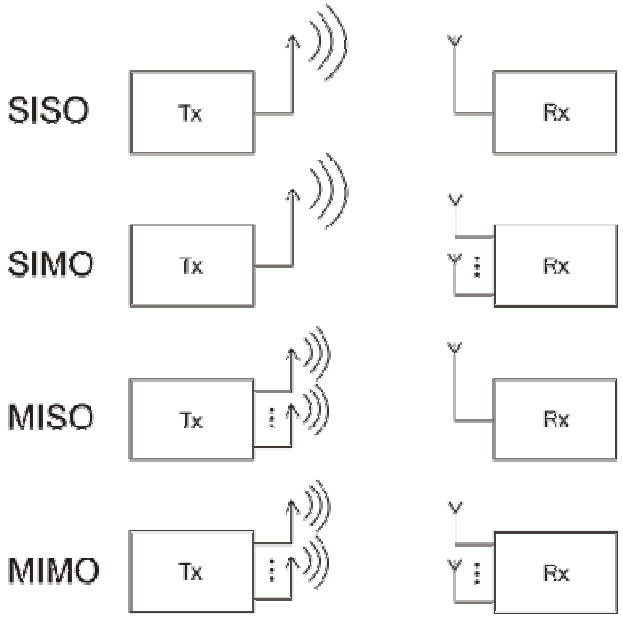
- Overall Bandwidth: 11.45 GHz to 12.75 GHz
- Active Aperture: 43 x 66 cm
- Antenna Thickness: 4.3 cm
- Antenna Beamwidth: 2° x 3°



Some examples

- Three inverted F-antennas in a PDA housing
- Antenna suitable for MIMO and diversity systems at WLAN frequency bands





- MIMO technology increases data throughput and link range without additional bandwidth or transmit power.

Summary of examples

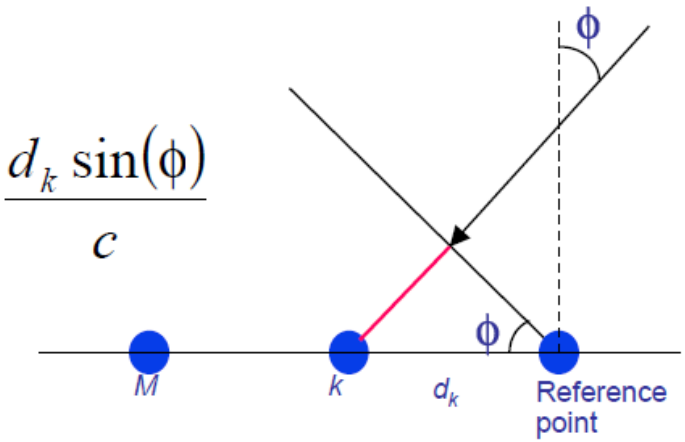
- **A smart antenna array may refer to:**

  - an interferometric array of Radio telescopes used in radio astronomy.
  - an electronically steerable directional phased array antenna typically used in RADAR and
  - phased array antenna for wireless communication systems, in view to achieve beamforming, multiple-input and multiple-output (MIMO) communication

Antenna arrays

- Consider a uniform linear array
- An incoming plane wave has a delay τ_k at element *k*

$$\tau_k = \frac{d_k \sin(\phi)}{c}$$



- A small time delay can be modelled as a phase shift:

$$\psi_k = \omega_k \tau_k = \frac{2\pi c}{\lambda} \frac{d_k \sin\phi}{c} = \frac{2\pi}{\lambda} d_k \sin\phi$$

Antenna arrays

- The received signals at the antenna elements due to D wave fronts F and noise W are

$$\begin{bmatrix} X_1 \\ X_2 \\ \vdots \\ X_M \end{bmatrix} = \begin{bmatrix} a(\phi_1) & a(\phi_2) & \cdots & a(\phi_D) \end{bmatrix} \begin{bmatrix} F_1 \\ F_2 \\ \vdots \\ F_D \end{bmatrix} + \begin{bmatrix} W_1 \\ W_2 \\ \vdots \\ W_M \end{bmatrix}$$

- The steering vector has the form

$$a(\phi) = \begin{bmatrix} 1 & e^{-i\psi_1} & e^{-i\psi_2} & \ldots & e^{-i\psi_{M-1}} \end{bmatrix}^T$$

- The angle ϕ can be estimated; note that $\psi_k = \frac{2\pi}{\lambda} d_k \sin\phi$

Signal processing

- Let $\vec{X}_n$ be the measured set of signals at time step t_n .
- Hence, $\vec{X}_n = \left[X_1(t_n), \quad X_2(t_n), \quad \cdots, \quad X_M(t_n) \right]^T$
- A matrix of snapshots can be defined by a set of subsequent measurements in time. Let this matrix of *T* snapshots be given by $X = \left[\vec{X}_n \quad \vec{X}_{n+1} \quad \ldots \quad \vec{X}_{n+T-1} \right]$
- The covariance matrix *R* of *X* is computed as $R = \mathrm{E}(XX^*)$

Signal processing

- The eigen decomposition of covariance matrix *R* reads

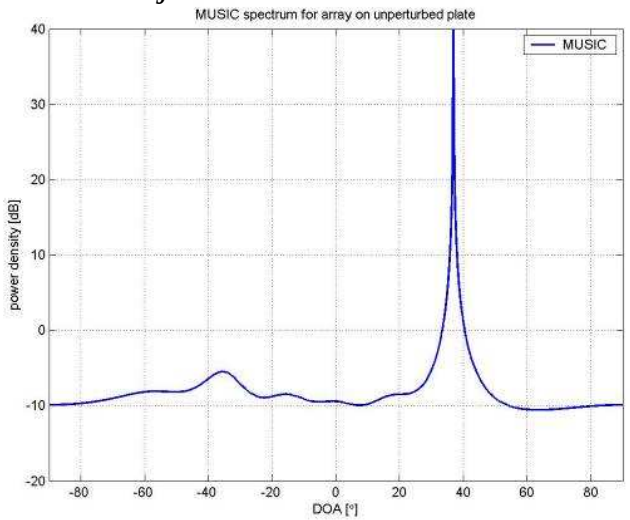
$$R = V_s \Lambda_s V_s^* + \sigma^2 V_n V_n^*$$

- where V_s the *d*-dimensional subspace of signal eigenvectors with eigenvalues larger than σ^2 and V_n the *(M-d)*-dimensional subspace of noise eigenvectors

- MUSIC algorithm computes spectrum as $P_{MU}(\phi) = \dfrac{1}{a^*(\phi) V_n V_n^* a(\phi)}$

Signal processing

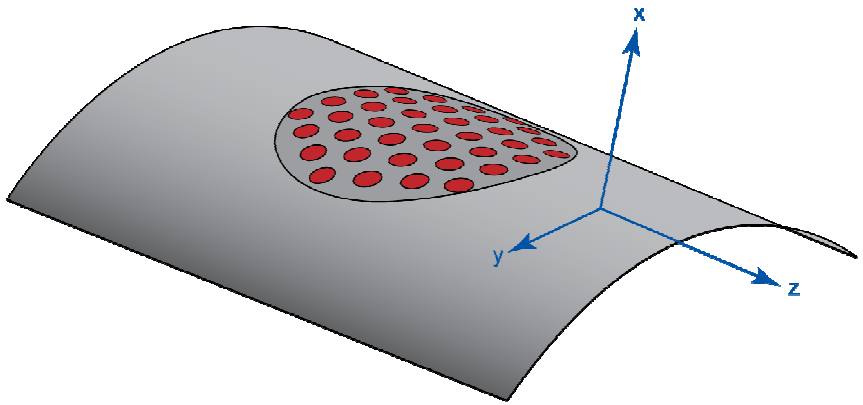
- Consider a linear array of 8 equally distributed patch antennas on a steady horizontal plate
- The centers of the patch antenna are at $x_j = (j-1)\,0.6\lambda$



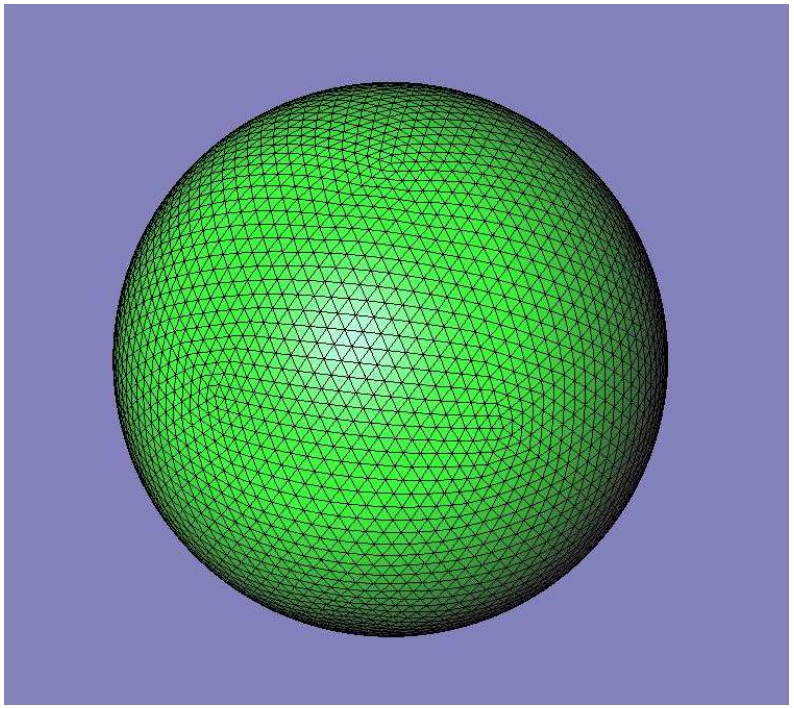
- The direction of arrival is estimated to be $\phi = 38$
- This information can be used to steer and to form the beam

Beam forming and beam steering

Conformal Phased Array



Pattern Samples on Far Field Sphere



Beam forming and beam steering

Desired pattern

$$D(\vec{u}) = D(\theta, \varphi)$$

Phased array pattern

$$E(\vec{u}) = \sum_{n=1}^{N} a_n e^{jk_0 \vec{r}_n \cdot \vec{u}} g_n(\vec{u})$$

Least squares minimization

$$\left\| D(\vec{u}_k) - E(\vec{u}_k) \right\|$$

To be determined:

$$A = [a_1, \cdots, a_N]^T$$

Beam forming and beam steering

- **Least Squares Method**

Minimize: $\left\| D - XA \right\|$

$$A_{LS} = X^{+} D \qquad \text{with} \qquad X^{+} = V \Sigma^{+} U^{H}$$

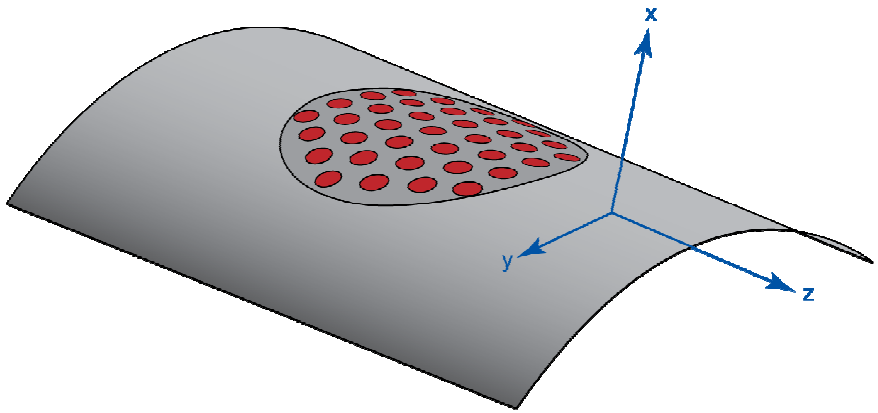
$$\Sigma^{+} = \begin{bmatrix} \frac{1}{\sigma_1} & 0 & 0 & 0 & 0 & 0 & . & 0 \\ 0 & . & 0 & 0 & 0 & 0 & . & 0 \\ 0 & 0 & \frac{1}{\sigma_i} & 0 & 0 & 0 & . & 0 \\ 0 & 0 & 0 & . & 0 & 0 & . & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{\sigma_N} & 0 & . & 0 \end{bmatrix}$$

Beam forming and beam steering

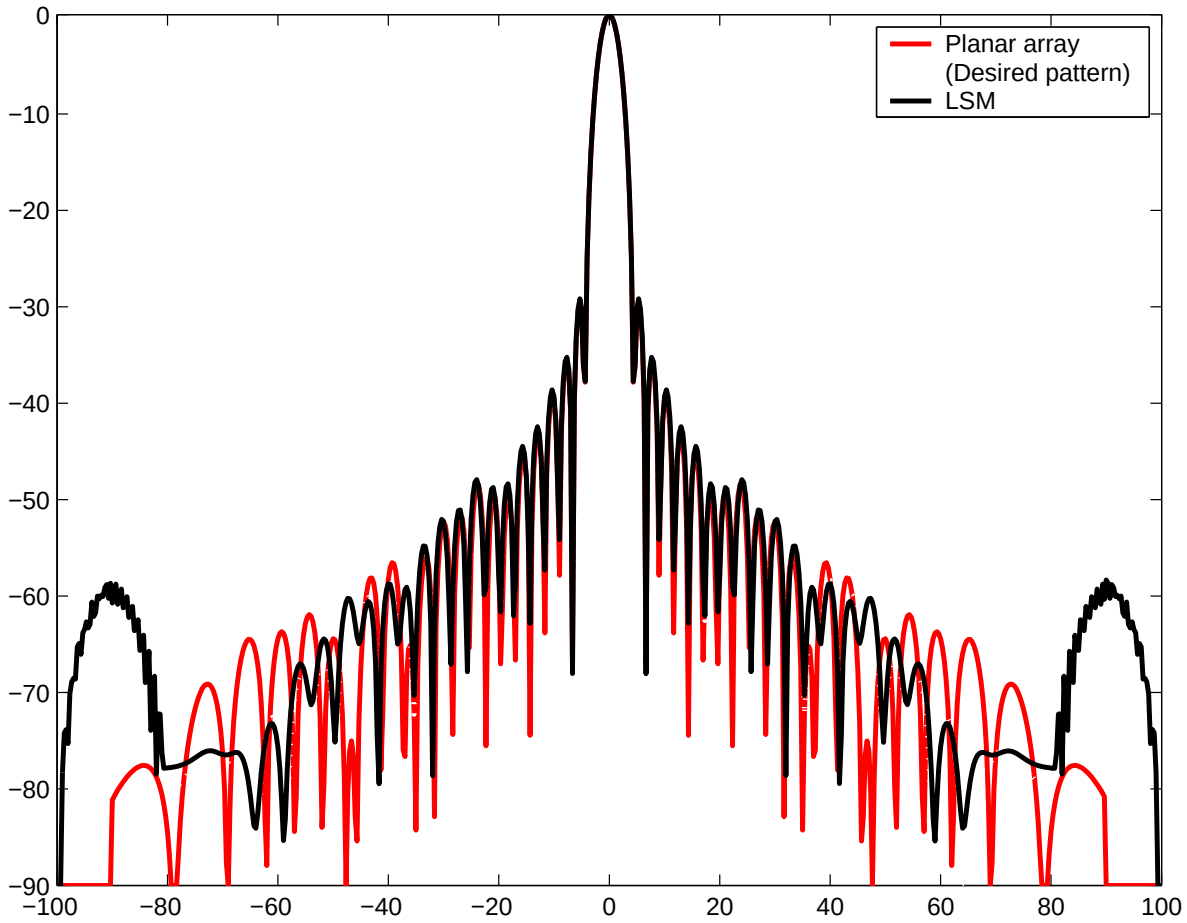
- **Planar array (=> Desired Pattern, f=11.7GHz):**
- **Ku-band phased array (10.7-12.75 GHz)**
- **Circularly shaped boundary (radius $10\lambda_{max}$)**
- **Square lattice (d=0.55 λ_{mid})**
- **1237 elements**
- **One-parameter circular aperture distribution (SLL=30dB)**
- **Circularly polarized patch antennas**

Beam forming and beam steering

- **Conformal array:**
- **Planar array curved around a cylinder of radius 1.65m (≈ radius fuselage Fokker 100)**



Beam forming and beam steering



Desired pattern and synthesis by LSM

Beam forming and beam steering

Taper efficiency:

$$\varepsilon_T = \frac{1}{N} \frac{\left| \sum_{n=1}^{N} a_n g_{\mathrm{co},n}\left(\hat{u}_{\mathrm{scan}}\right) e^{jk_0 \vec{r}_n \cdot \hat{u}_{\mathrm{scan}}} \right|^2}{\left(g_{\max}\right)^2 \sum_{n=1}^{N} \left|a_n\right|^2}$$

- **Taper efficiency of initial (planar) array:**
- ε_T=0.76 (-1.19 dB)

- **Taper efficiency of curved array via LSM:**

ε_T=0.027 (-15.7 dB)

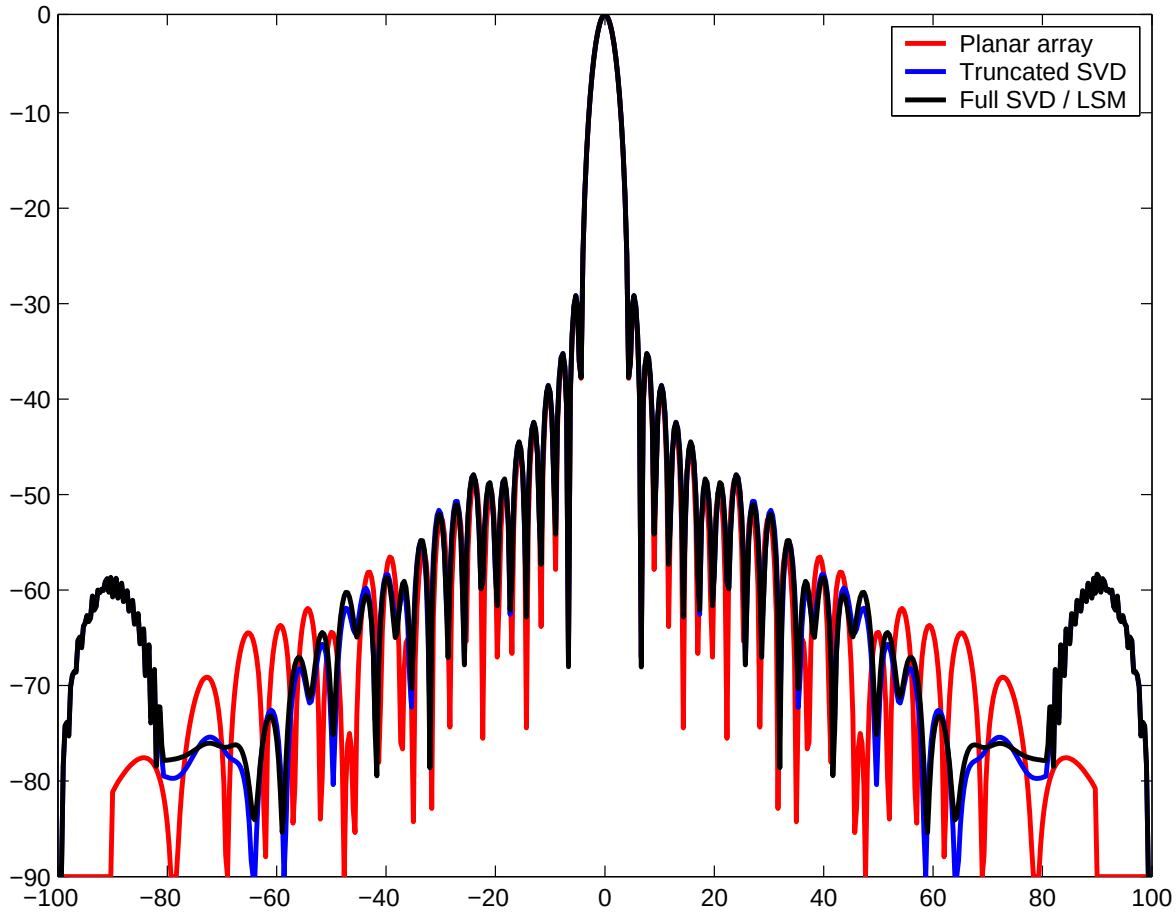
Beam forming and beam steering

Approximate Least Squares Solution via truncated singular value decomposition of X

$$\left\| D - E \right\| = \left\| D - X A \right\| \approx \left\| D - \tilde{X} A \right\| \Rightarrow \tilde{A}_{\mathrm{LS}} = \tilde{X}^{+} D$$

$$\tilde{X}^{+} = V \tilde{\Sigma}^{+} U^{H} \qquad \tilde{\Sigma}^{+} = \begin{bmatrix} \frac{1}{\sigma_1} & 0 & 0 & 0 & 0 & 0 & . & 0 \\ 0 & . & 0 & 0 & 0 & 0 & . & 0 \\ 0 & 0 & \frac{1}{\sigma_{\min}} & 0 & 0 & 0 & . & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & . & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & . & 0 \end{bmatrix}$$

Beam forming and beam steering



Desired pattern, and synthesis by LSM and truncated SVD

Beam forming and beam steering

- **Taper efficiency of initial (planar) array:**

  ε_T=0.76 (-1.19 dB)

- **Taper efficiency of curved array via LSM:**

  ε_T=0.027 (-15.7 dB)

- **Taper efficiency of curved array via TSVD depends on smallest singular value:**

  $\sigma_{min}=0.01\sigma_{max}$: ε_T=0.74 (-1.31 dB)

  $\sigma_{min}=0.1\sigma_{max}$: ε_T=0.75 (-1.22 dB)

Beam forming and beam steering

- **Least-Squares Synthesis Method may yield:**
  - unrealistic amplitude distributions
  - amplitude distributions with unnecessary low taper efficiency

- **Approximate least-squares solution obtained with pseudo-inverse based on truncated SVD is a simple adjustment**

- **Approximate least-squares solution yields efficient weights a_n for the beam forming of conformal phased arrays.**

Design of Ku-band receive antenna array for SATCOM

SATCOM onboard aircraft

Cockpit requires voice services and data link Services (AFIS, AoC, CNS/ATM), can be provided by Inmarsat L-band systems

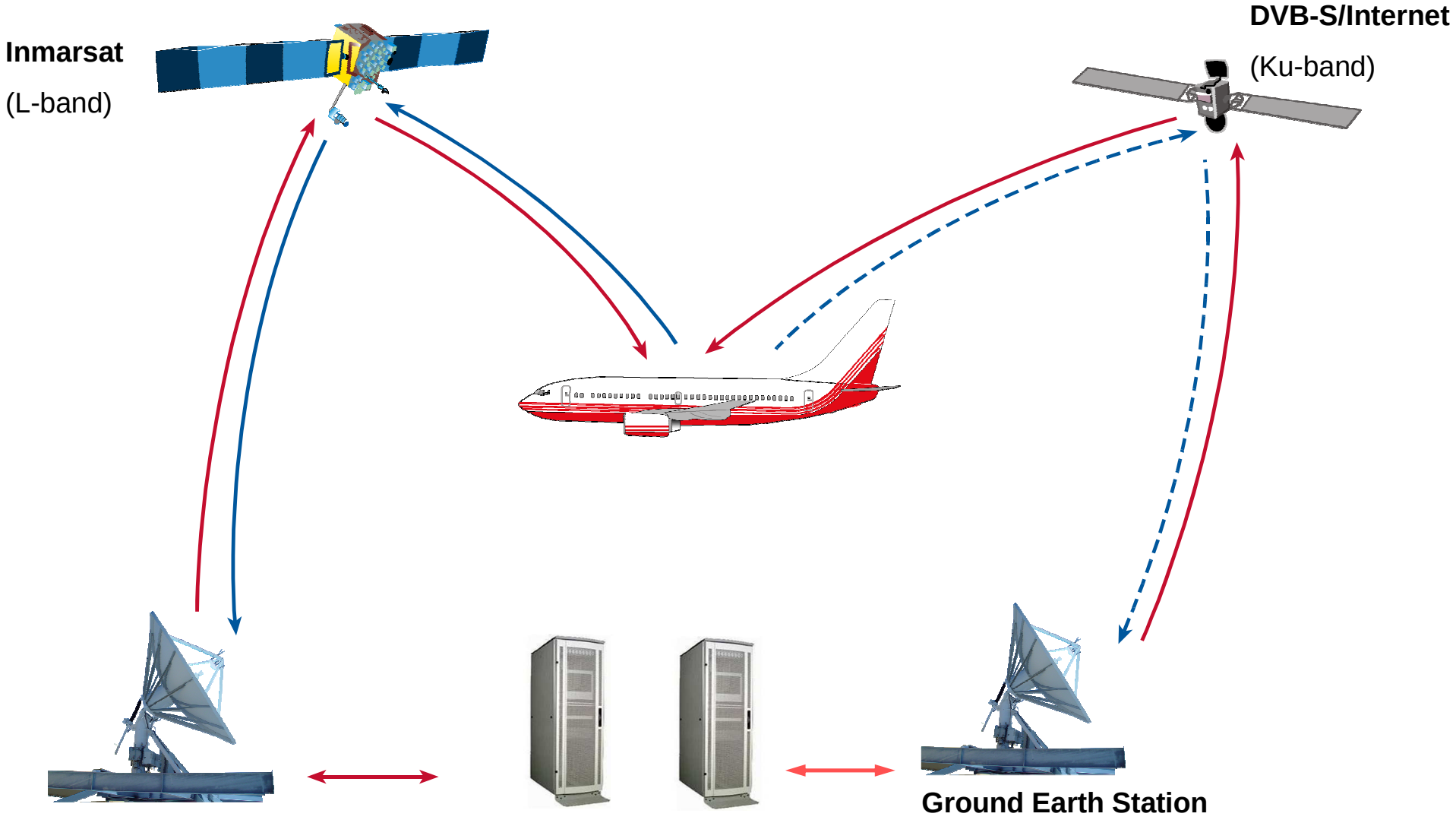
Passengers want

- Voice services (e.g. VoIP)
- High-speed internet (web, multi-media)
- Television (Digital Video Broadcast via Satellite)

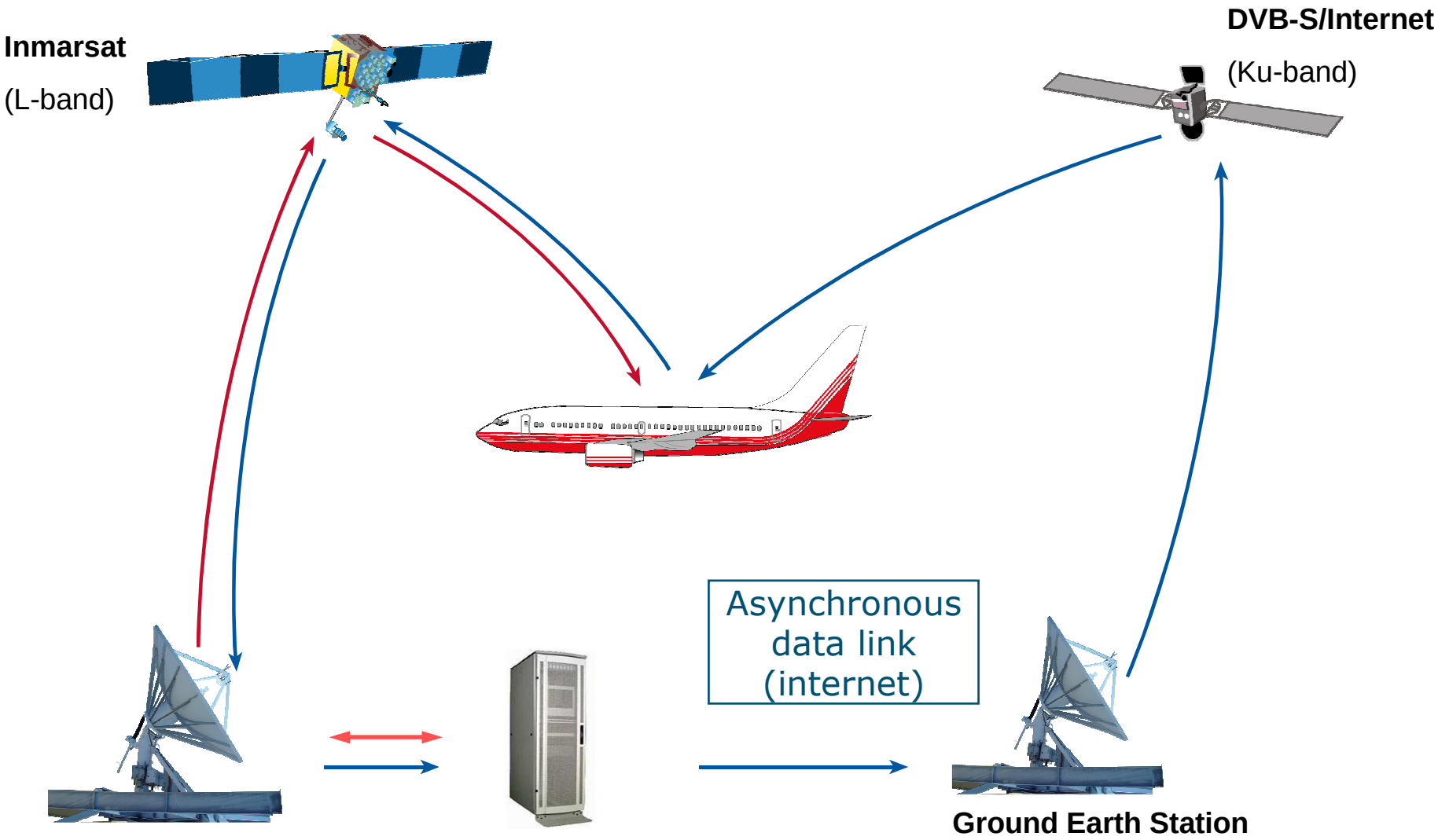
This requires additional Ku-band network services to be provided by GEO Ku-band satellites (Astra, Connexion by Boeing, ARINC Skylink), based on DVB-S2, DVB-RCS

- **Some services operate in L-band, others are in Ku-band**

Design of Ku-band receive antenna array for SATCOM

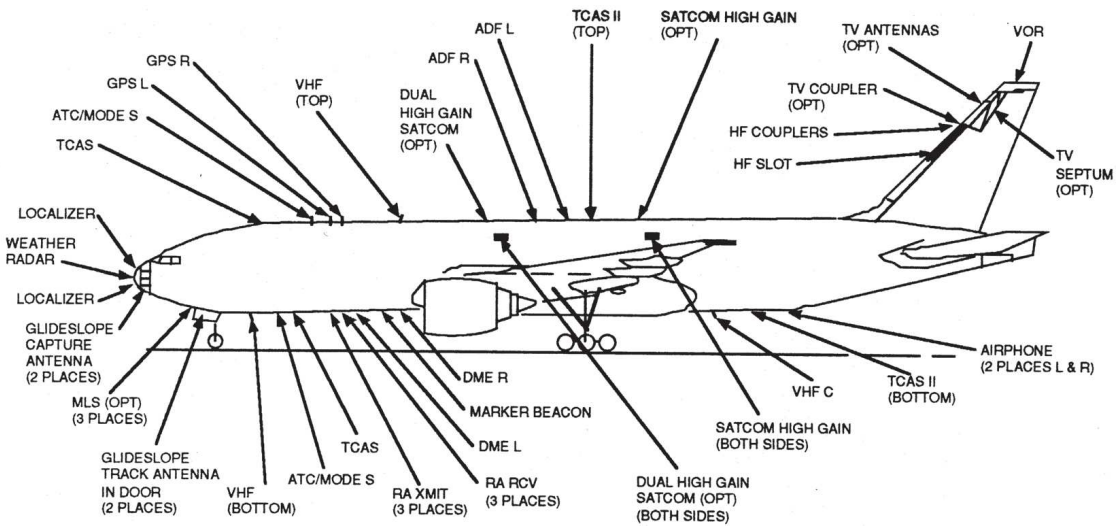


Design of Ku-band receive antenna array for SATCOM



Design of Ku-band receive antenna array for SATCOM

- Lack of surface area for installation of antennas



- **EU project ANASTASIA**: L-band and Ku-satcom in ONE antenna

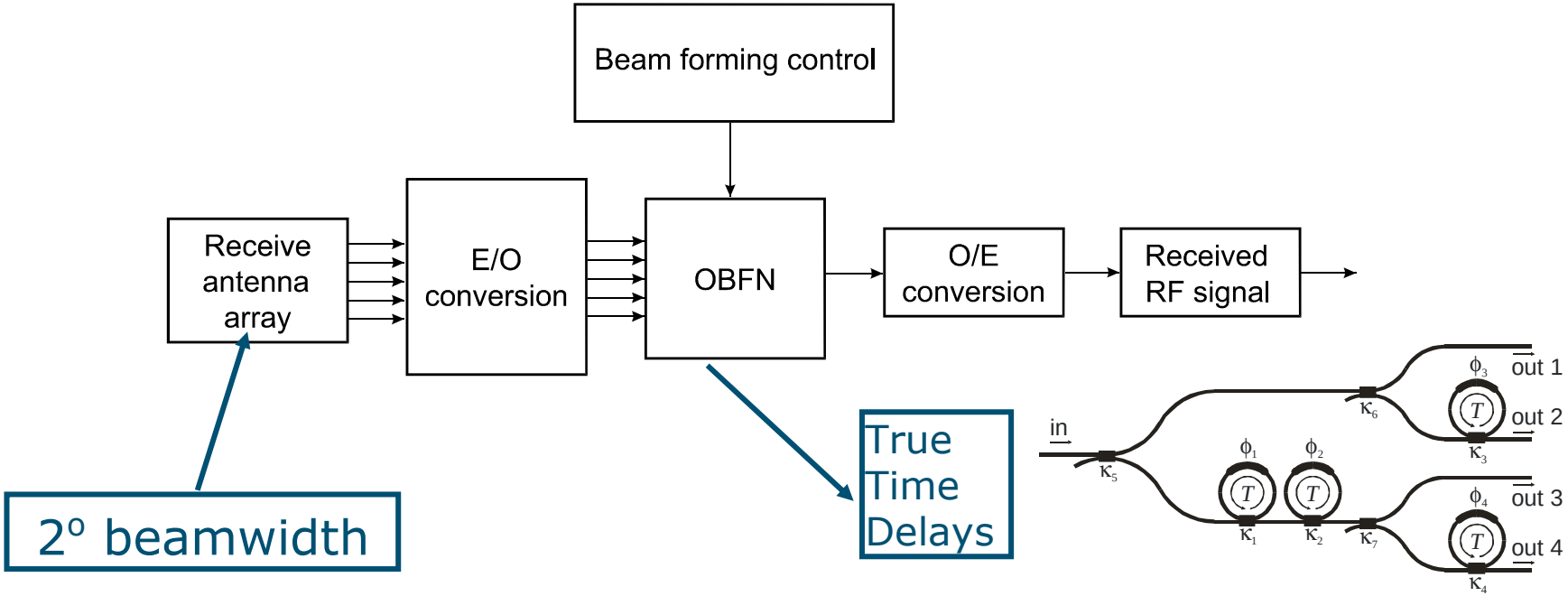
- Novel concept for satcom based ATM and Internet:
  - **Ku-band antenna for receive only**
  - L-band antenna for Tx and Rx

Design of Ku-band receive antenna array for SATCOM

- Ku-band receive-only antenna system with broadband optical beam-forming network and broadband phased array antenna

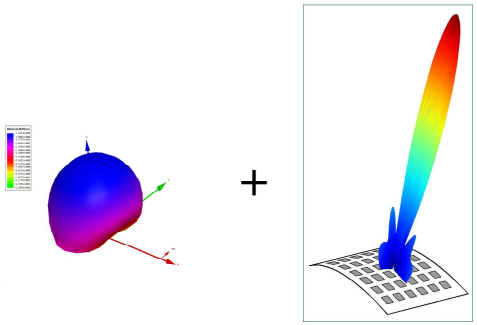
AES receive band 1:	10.70 – 11.70 GHz
Satellite TV:	11.70 – 12.50 GHz
AES receive band 2:	12.50 – 12.75 GHz

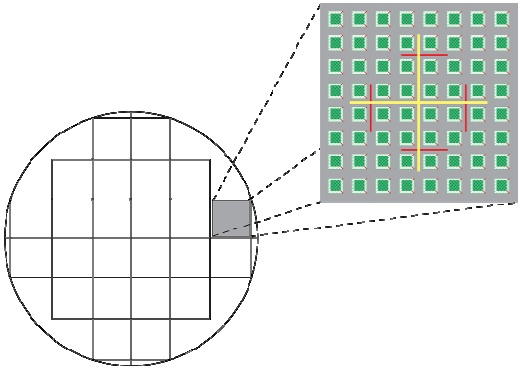
} 2 GHz bandwidth



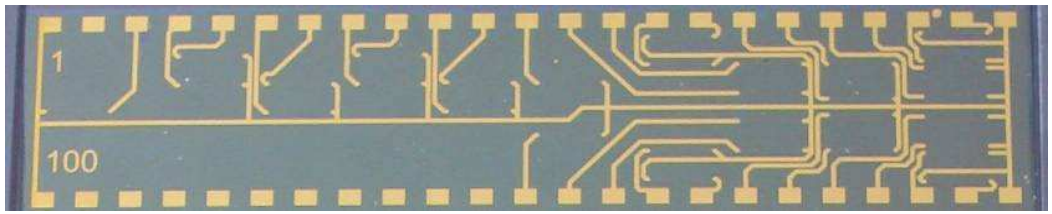
Key technologies

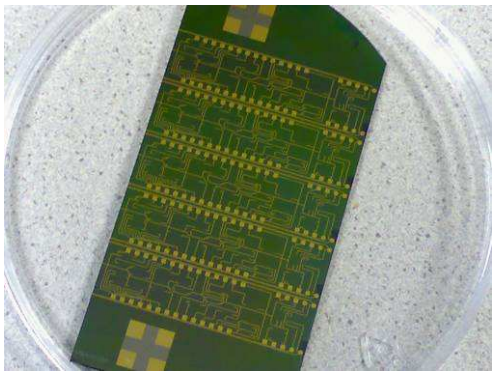
- **Development of broadband L/Ku-band antenna element**





- **Development of broadband optical beam forming network on CMOS chip**





Design of Ku-band receive antenna array for SATCOM

- **Gain decreases:**

$$\approx \cos(\theta_0)$$

- **Beamwidth increases:**

$$\approx \frac{1}{\cos(\theta_0)}$$

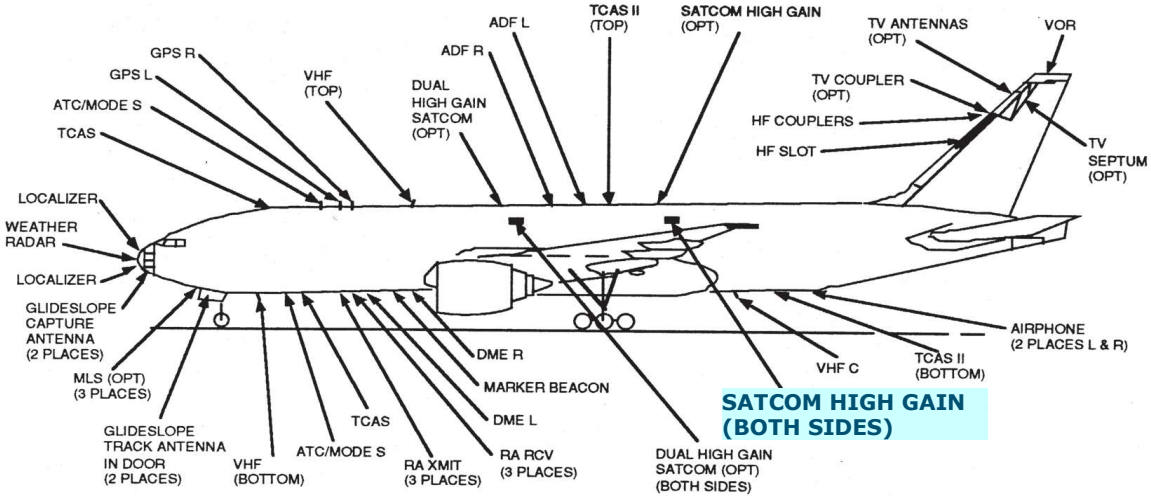
- **Polarization loss and errors increase:**
  - Cross Polarization increases
  - Polarization Mismatch increases

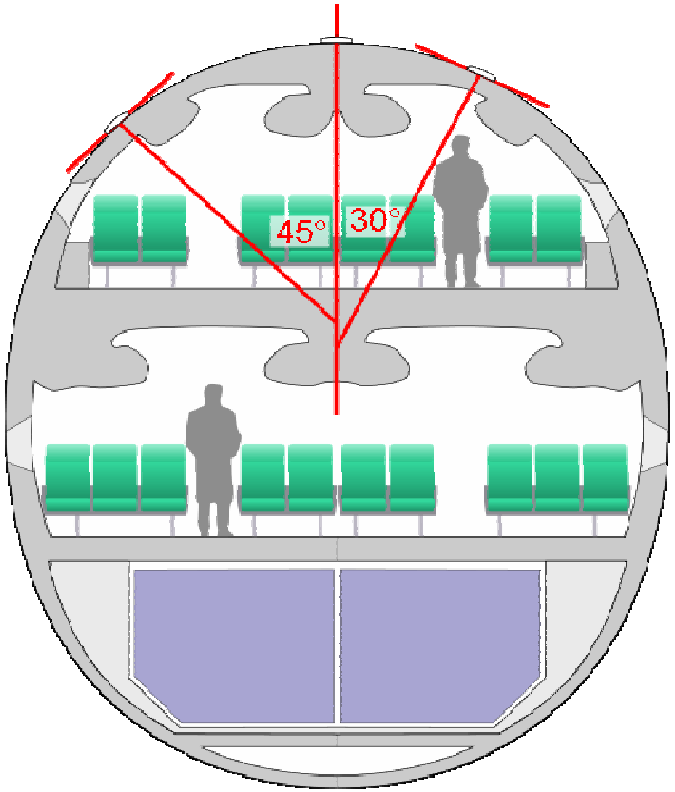
Grating lobes / Side lobes:

$$d < \frac{\lambda}{1+\sin\left|\theta_{0,\max}\right|}$$

Routes covered by CBB

Phased Array Antenna Position(s) on the aircraft





Antenna array on vibrating plate

- Vibration of surveillance array antenna on wings
- Compensation of vibrations via adaptive correction of phases of antenna signals

Demonstrator:

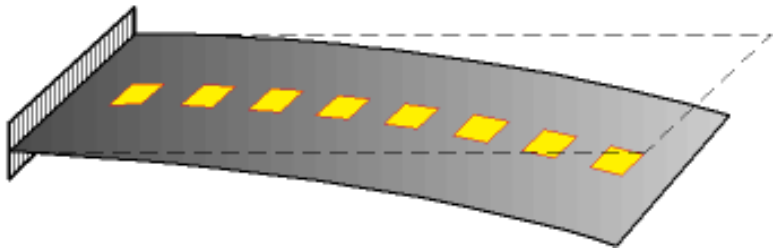
- Antenna array on vibrating plate
- Electronics for mutual tuning of antenna elements
- DSP based real-time control system

Antenna array on vibrating plate

- Vibrating plate with:

$$z(x,t) = Z_0(x) + \alpha(t) + q_1(t) Z_1(x)$$

- $Z_0(x)$ stationary position.
- $\alpha(t)$ position caused by shaker vibration.



- $q_1(t) Z_1(x)$ position due to 1st vibration mode.

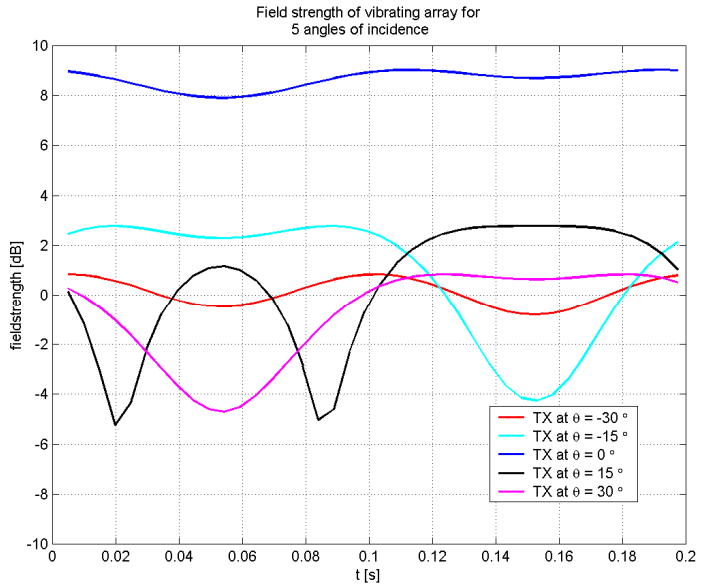
Antenna array on vibrating plate

- Electric field received at antenna *j :* $\vec{E}_j(t) = E_o \hat{e}^i e^{-ik(x_j \sin\theta\cos\varphi + + z(x_j,t)\cos\theta)}$

- with: $z(x,t) = Z_0(x) + \alpha(t) + q_1(t) Z_1(x)$

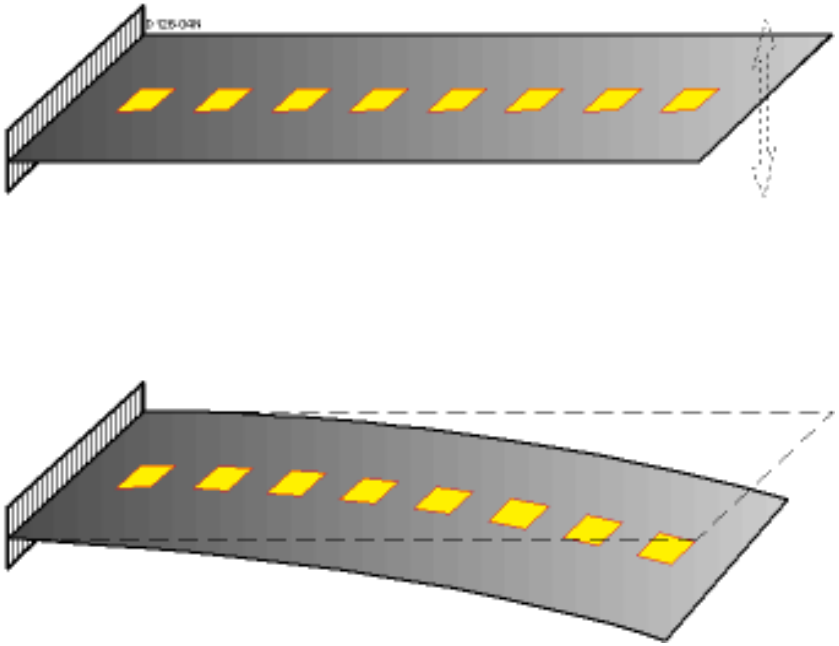
- Total electric field: $\vec{E}_{tot} = \sum_j A_j \vec{E}_j$

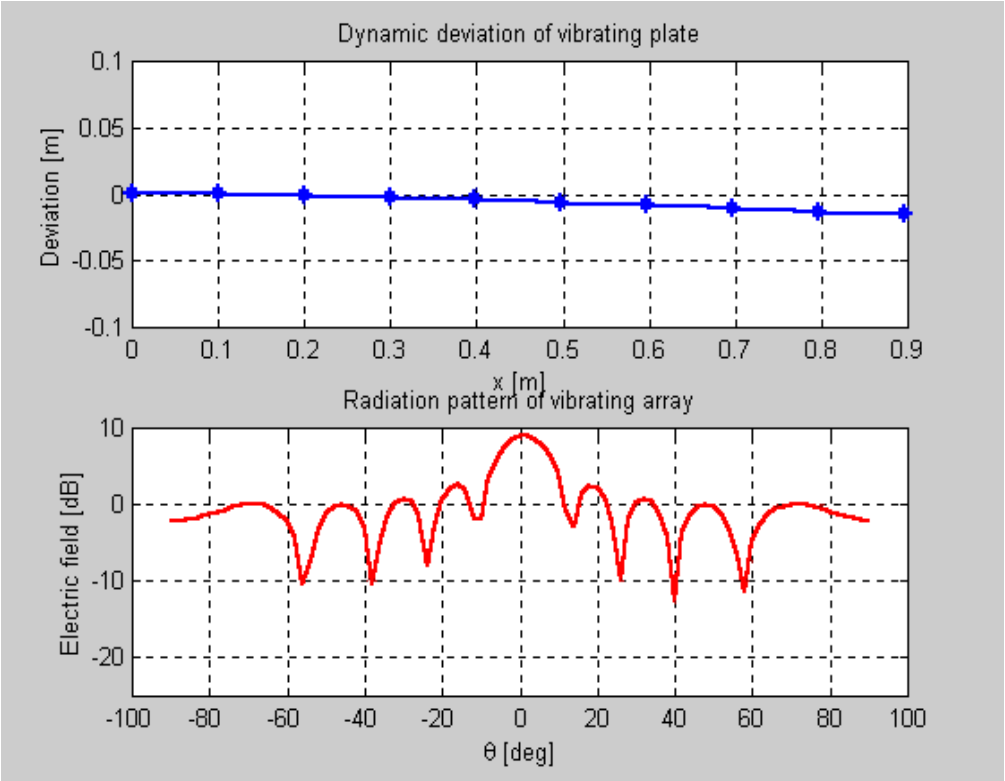
-



Antenna array on vibrating plate

- **Vibrating plate without compensation**





Antenna array on vibrating plate

- Phase difference between antenna patch *j* and reference antenna patch *0* :

$$\Delta\vartheta_j = -k\{\vec{r}_j - \vec{r}_0\} \bullet \hat{k}^i$$

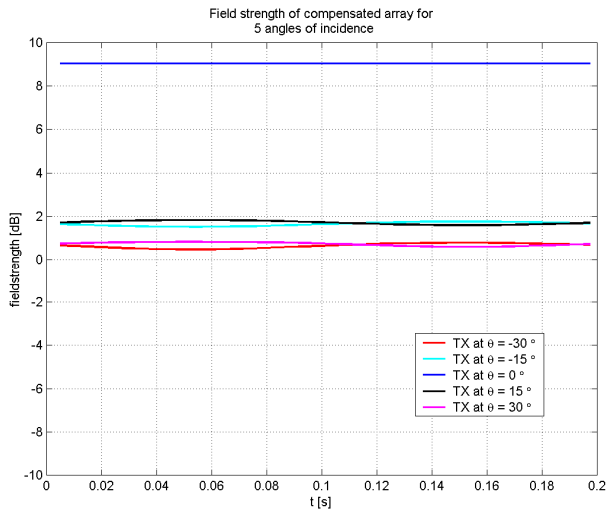
- Phase difference is approximated by: $\Delta\vartheta_j = -k\{(z(x_j,t) - z(x_0,t))\cos\theta\}$

- Adaptive phase compensation:

$$A_j := A_j e^{-i\Delta\vartheta_j}$$

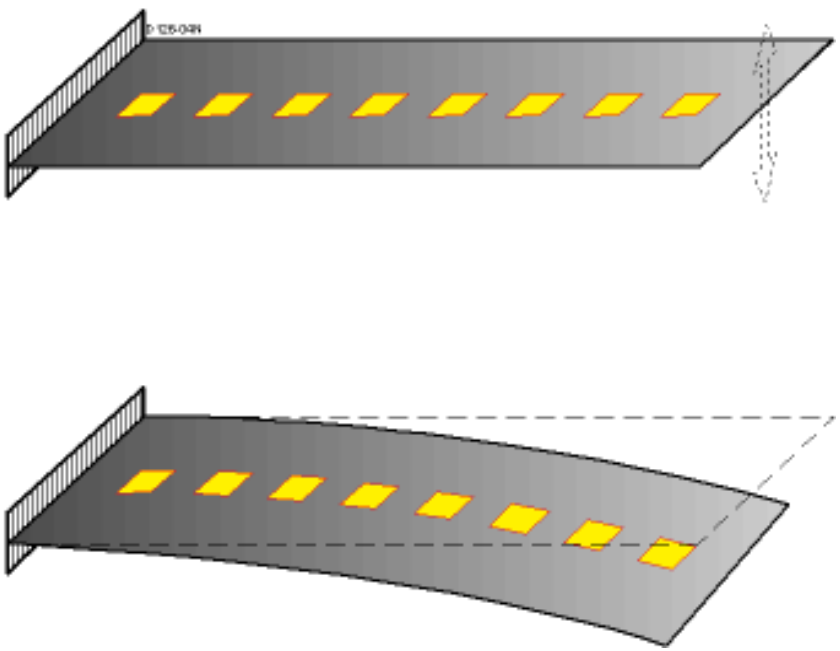
- Total electric field: $\vec{E}_{tot} = \sum_j A_j \vec{E}_j$

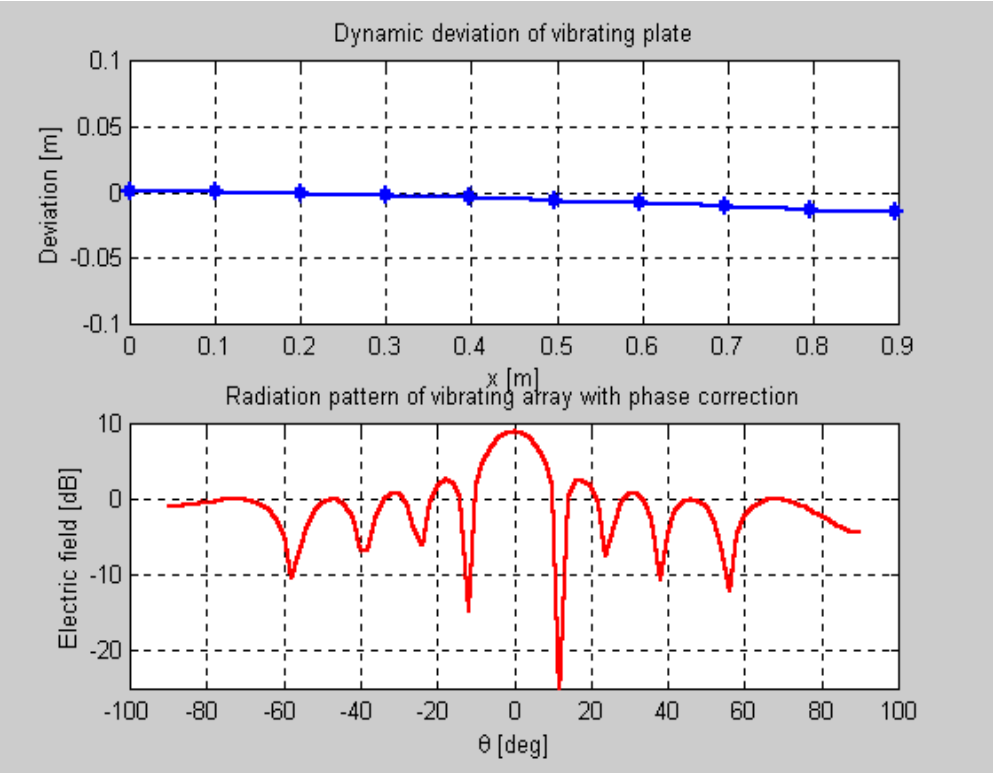
-



Antenna array on vibrating plate

- **Compensation of vibrations by synthetic beam steering (Computer simulations)**



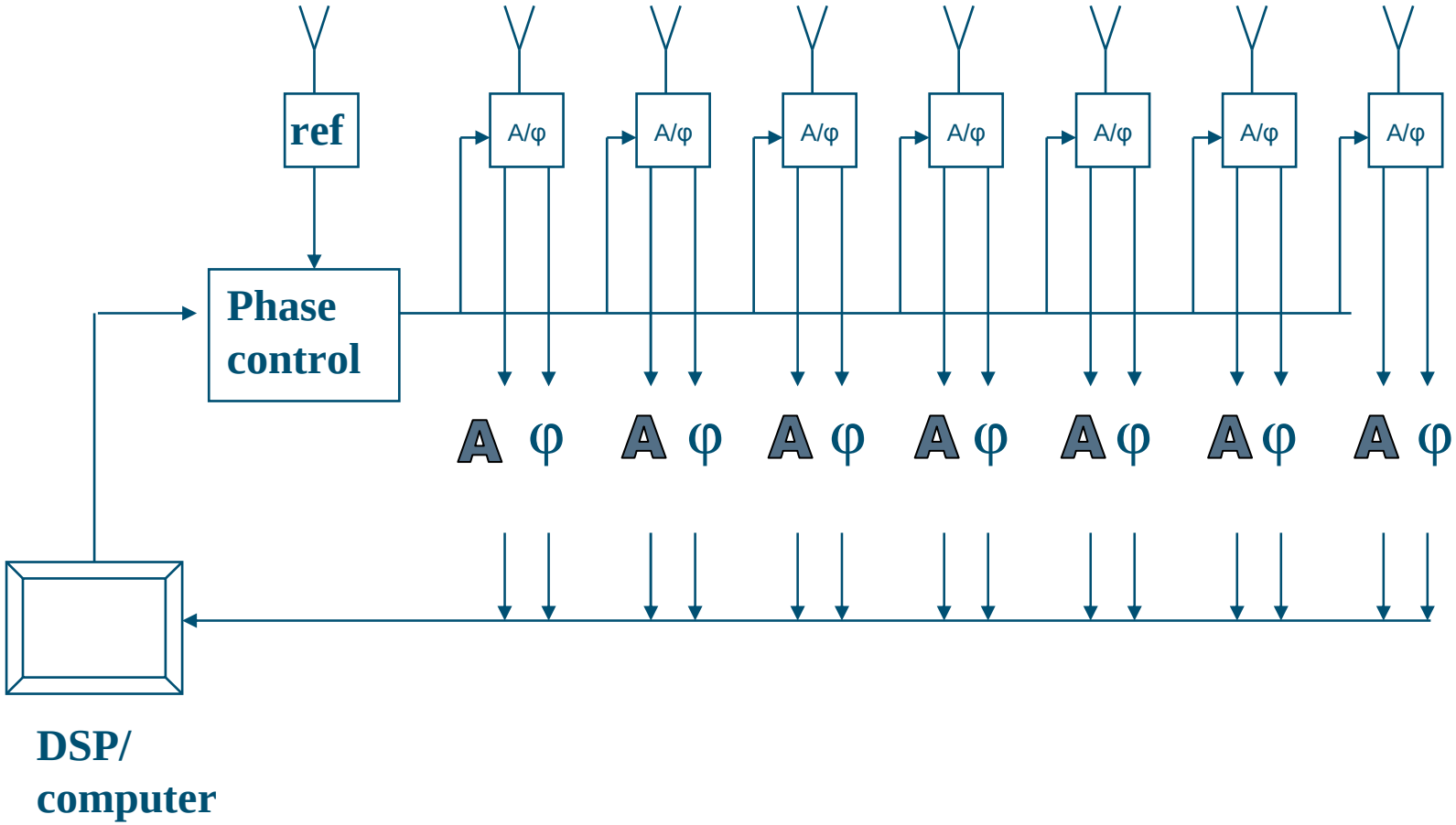


Antenna array on vibrating plate

Compensation techniques for vibrating arrays

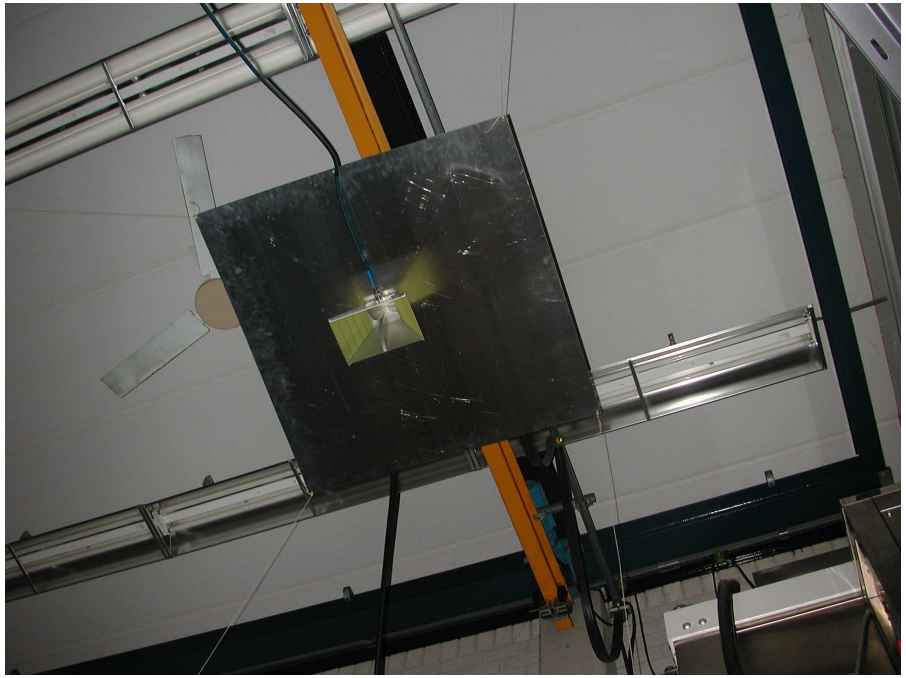
- **Real-time amplitude & phase measurement of array elements**
  - Phase Detector AD8302
- **Radiation pattern computation (distorted)**
- **Real-time computation of counter phase.**
  - DSPACE digital control system (with A/D and D/A converters)
  - PC Interface: instantaneous adaptation of weights
- **Radiation pattern computation (compensated).**

Antenna array on vibrating plate



Antenna array on vibrating plate

- vibrating array



Transmit antenna at ceiling

Antenna array on vibrating plate

- **Adaptive Digital Beam-forming aspects**

- **The measurement system yields time-varying amplitudes and phases:** $A_k \quad \text{and} \quad \phi_k, \quad \text{for } k = 1, \cdots, 7.$

- **The summed result without compensation becomes:**

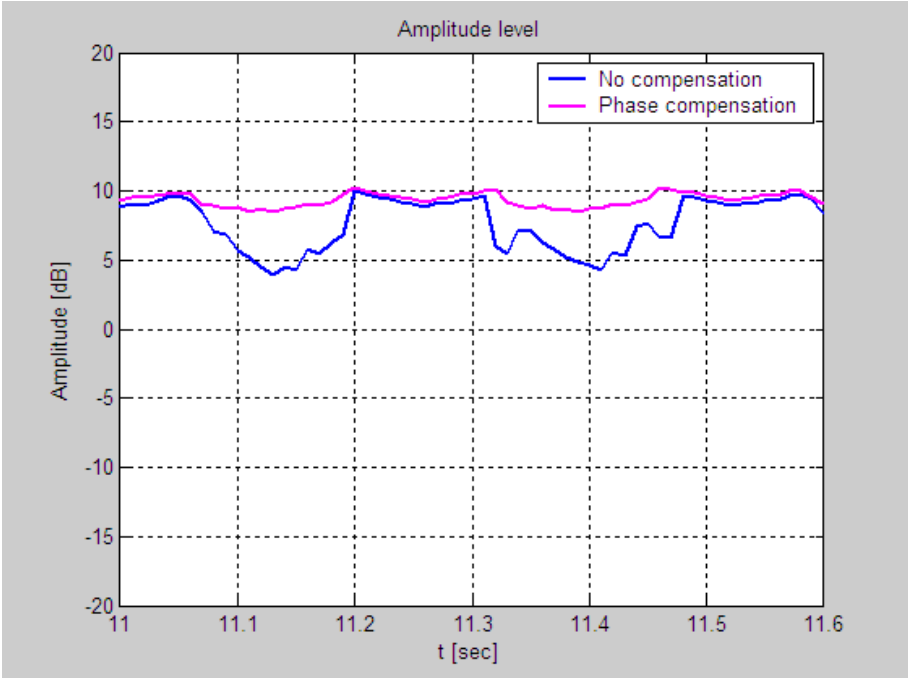
$$S = \sum_k A_k e^{i\phi_k}$$

- **Adaptive digital compensation**

- **Instantaneous calibration**
  - Determine in the computer the weight $w_k = e^{-i(\phi_k - \varepsilon_k)}$
  - Multiply each antenna signal with w_k
  - Then the compensated summed signal becomes $S = \sum_k A_k e^{i\varepsilon_k}$

Antenna array on vibrating plate

- **Received Signal Computation**
- **Vibrating antenna**
- **(Distorted + compensated)**



Antenna array on vibrating plate

- **Effects of vibrations and deformations on performance of large array antennas might be significant**
  - Vibrating radiation pattern – direction of main beam changes
  - Increase of Side Lobe Levels

- **Compensation concept investigated:**
  - Digital adaptive (real time) correction of phase deviations
  - Measuring phase differences

- **Demonstrator appears to be efficient**

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