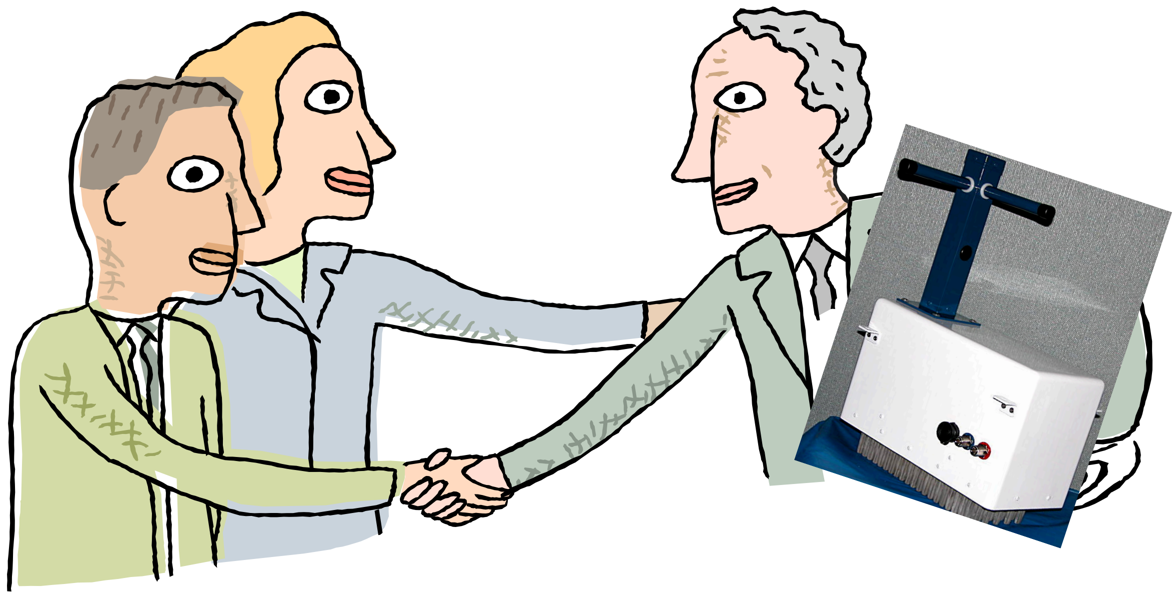
Student Introduction to AMISR and Phased Arrays



How is it different from other ISRs?
What are the measurement improvements?

Early Technology vs. New

Early Technology

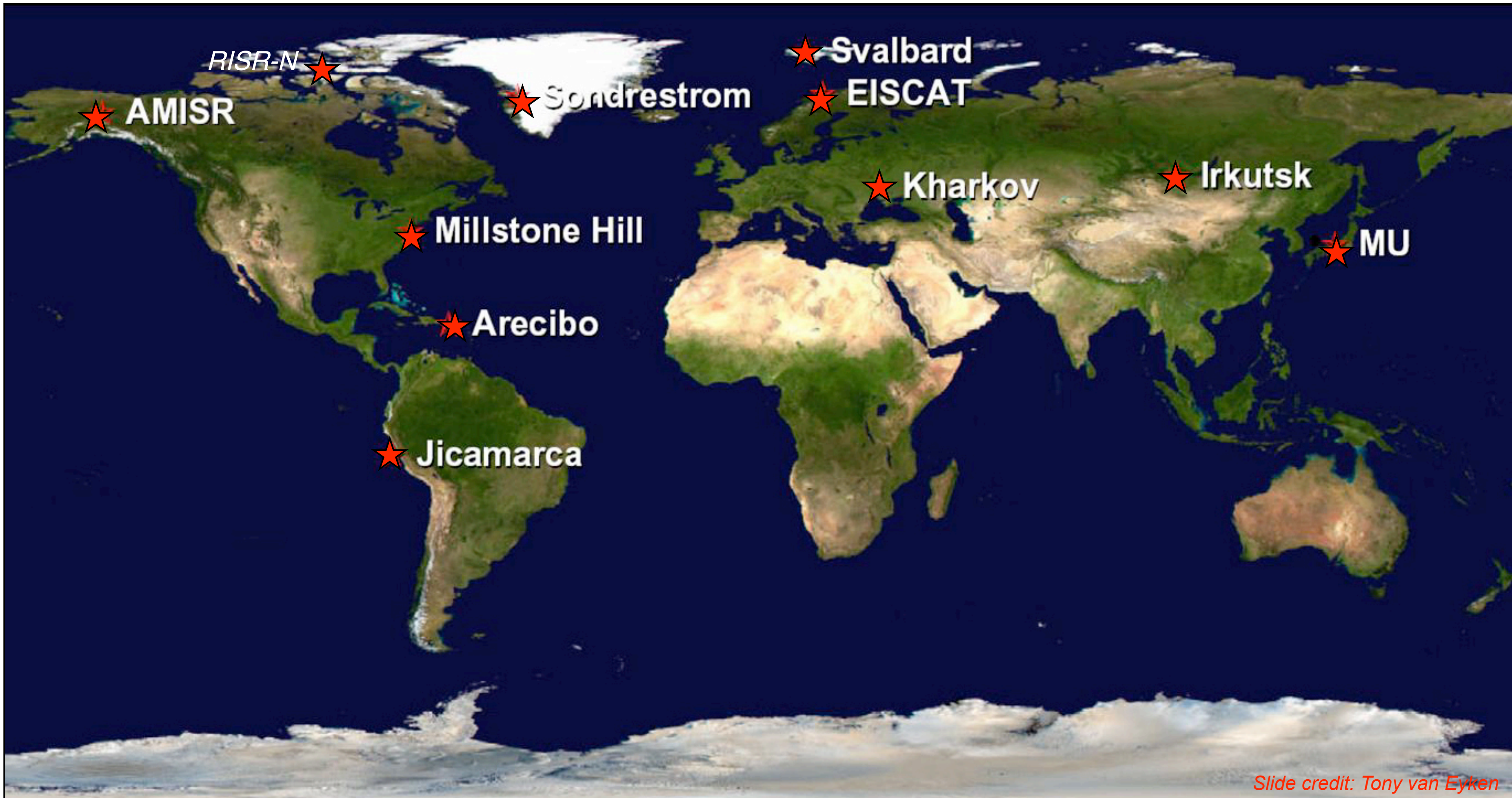
- Fixed location
- Single, large steerable antennas (fixed steering phased array)
- Vacuum tube power amplifiers
- High voltage power supplies
- Liquid cooling heat exchangers

New

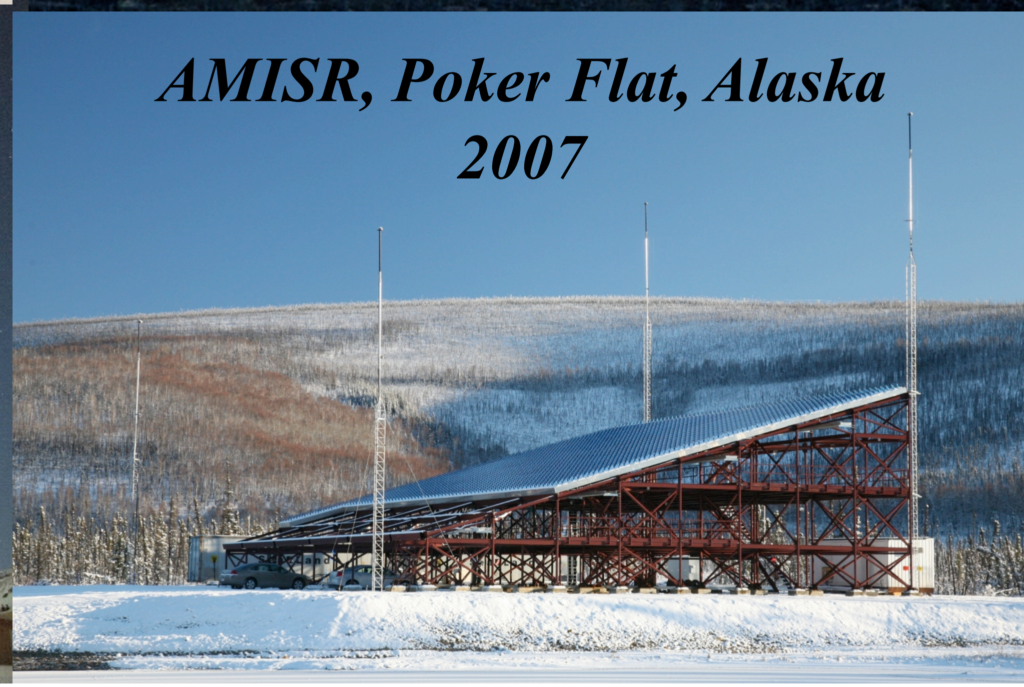
- Distributed solid state amplifiers
- Modular, scalable design
- Heavily networked – lots and lots of inexpensive computing power

Present IS Radars

10 radars operate routinely



High Latitude ISRs

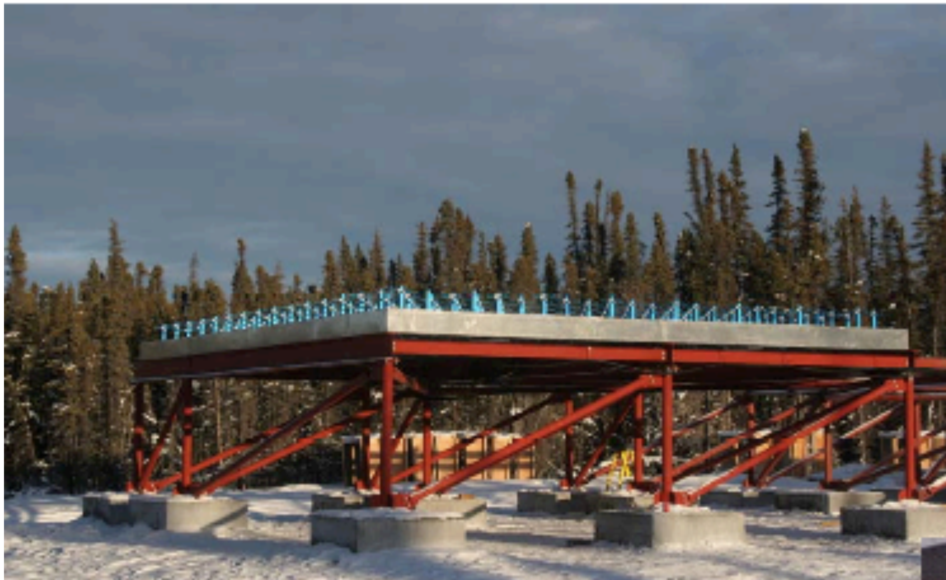


Polar Cap ISR

RISR-N and RISR-C

PFISR

MUIR (HAARP, AK) and AMISR-7 (Jicamarca)



HAARP Site, Alaska
University of Alaska

Jimarca, Peru @ Magnetic Equator
Cornell University

What is a Phased Array?

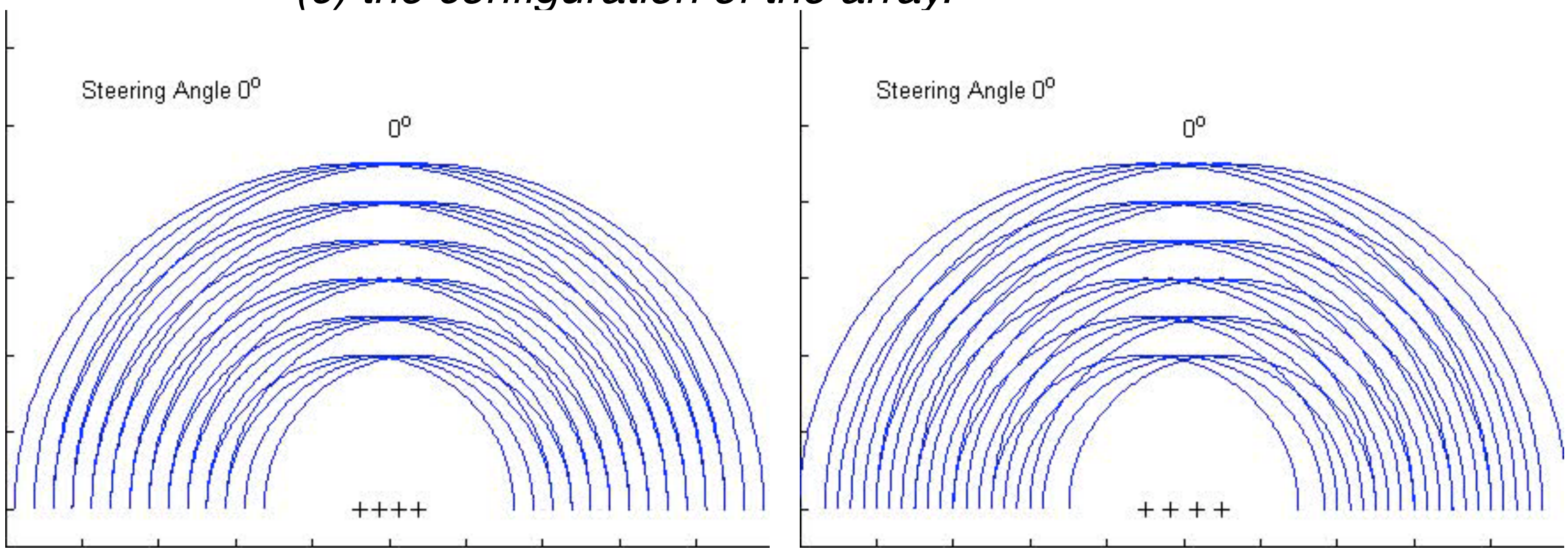
- A phased array is a group of antennas whose effective (summed) radiation pattern can be altered by phasing the signals of the individual elements.

- By varying the phasing of the different elements, the radiation pattern can be modified to be maximized / suppressed in given directions, within limits determined by

(a) the radiation pattern of the elements,

(b) the size of the array, and

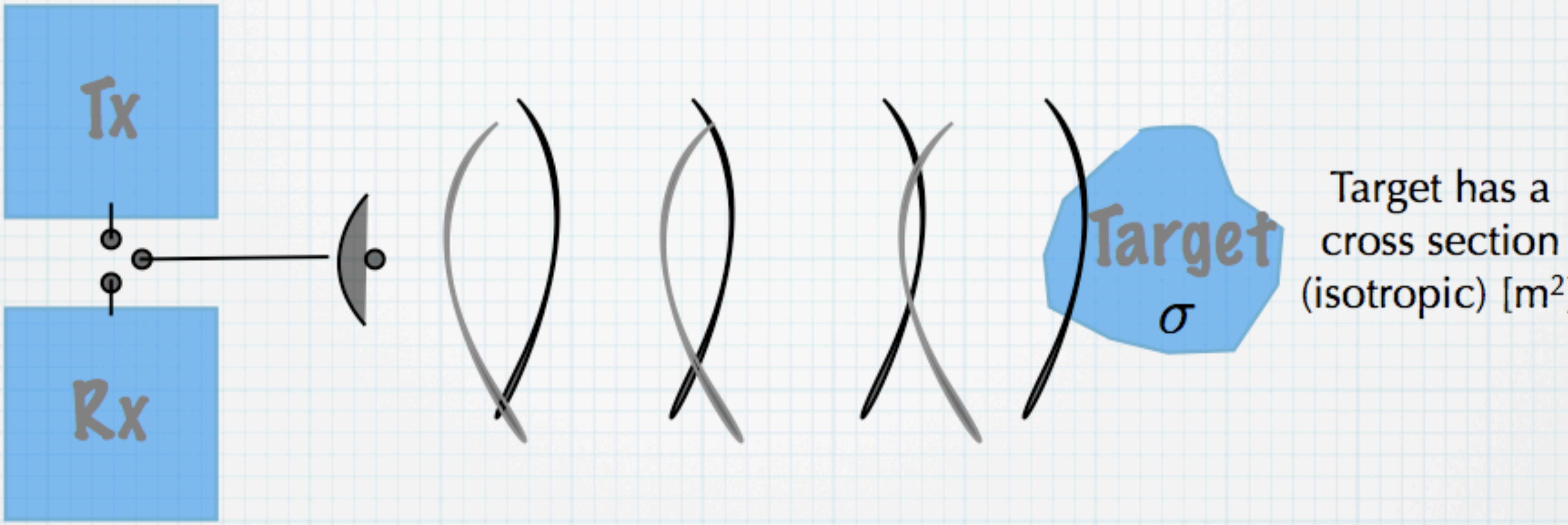
(c) the configuration of the array.



Element Spacing 0.50λ　　*Element Spacing 0.67λ*

"Equations are the devil's sentences"
- **Stephen Colbert**

Basic Radar



$$P_{inc} = P_t \frac{G_{tx}}{4\pi R^2} \quad \mathrm{W/m^2}$$ Power incident on target

$$P_{scat} = P_{inc}\sigma_{radar} \quad \mathrm{W}$$ Scattered power

$$P_{rec} = P_{scat}\frac{A_{eff}}{4\pi R^2} \quad \mathrm{W}$$ Received power

$$= P_t \frac{G_{tx} A_{eff} \sigma_{radar}}{16\pi^2 R^4} \quad \mathrm{W}$$ Radar equation

Hertzian Dipole

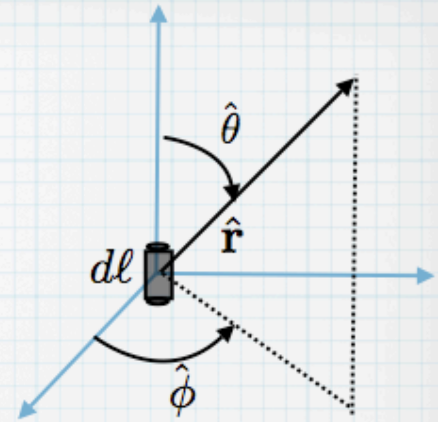
far field near field

$$H_\phi = I d\ell \sin\theta \frac{1}{4\pi}\left[\frac{jk_0}{r} + \frac{1}{r^2} + 0\right] e^{j(\omega t - k_0 r)}$$

$$E_r = I d\ell \cos\theta \frac{j z_0}{2\pi k_0}\left[0 + \frac{jk_0}{r^2} + \frac{1}{r^3}\right] e^{j(\omega t - k_0 r)}$$

$$E_\theta = I d\ell \sin\theta \frac{j z_0}{4\pi k_0}\left[\frac{k_0^2}{r} - \frac{jk_0}{r^2} + \frac{1}{r^3}\right] e^{j(\omega t - k_0 r)}$$

Spherically expanding wavefront



$$z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} = 120\pi\ \Omega$$

$$k_0 = \frac{2\pi}{\lambda} = \frac{\omega}{c} = \omega\sqrt{\mu_0\epsilon_0}$$

For $r \gg \lambda$, keep terms only linear in r - **far field approximation.**

$$E_\theta \perp H_\phi \perp \hat{\mathbf{r}} \qquad \frac{E_\theta}{H_\phi} = z_0$$

Power flow represented by Poynting vector

$$\mathbf{P} = \mathbf{E} \times \mathbf{H} \qquad \langle P_r \rangle = \frac{1}{2}\Re\{P_r\} = \frac{1}{2}\Re\{\mathbf{E} \times \mathbf{H}\} \cdot \hat{\mathbf{r}} \quad \mathrm{W/m^2}$$

Hertzian Dipole (2)

far field near field

$$H_\phi = I d\ell \sin\theta \frac{1}{4\pi}\left[\frac{jk_0}{r} + \frac{1}{r^2} + 0\right] e^{j(\omega t - k_0 r)}$$

$$E_r = I d\ell \cos\theta \frac{j z_0}{2\pi k_0}\left[0 + \frac{jk_0}{r^2} + \frac{1}{r^3}\right] e^{j(\omega t - k_0 r)}$$

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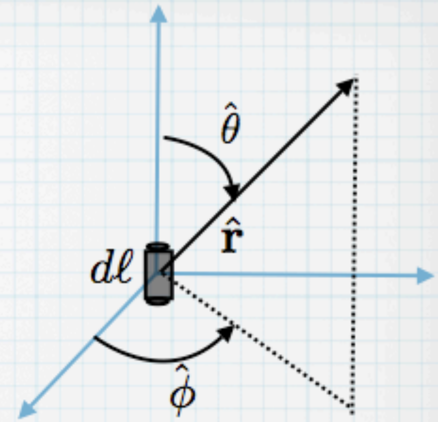
Spherically expanding



Directivity pattern:

$$D(\theta,\phi) = \frac{\text{Power Density Radiated In } (\theta,\phi) \text{ Direction}}{\text{Average Power Density}} = 4\pi R^2 \frac{\text{Power Density In } (\theta,\phi)}{\text{Total Power Radiated}}$$

$$\langle P_r \rangle = \frac{1}{2}\Re\{\mathbf{E}\times\mathbf{H}\}\cdot\hat{\mathbf{r}} = I^2 z_0 (d\ell)^2 k_0^2 \sin^2\theta \frac{1}{32\pi^2 r^2} \ \mathrm{W/m^2}$$

$$P_{total} = \int_0^{2\pi} d\phi \int_0^{\pi} \langle P_r \rangle r^2 \sin\theta d\theta = z_0 \frac{\pi}{3}\left(\frac{I d\ell}{\lambda}\right)^2 \ \mathrm{W}$$

$$P_{total} = \frac{1}{2} I^2 R_{rad}$$

$$D(\theta,\phi) = \frac{3}{2}\sin^2\theta$$

Directivity Patterns for Dipoles

Hertzian Dipole

$$D(\theta, \phi) = \frac{3}{2}\sin^2\theta$$

$$\text{HPBW} = 90^\circ$$

Half-Wave Dipole

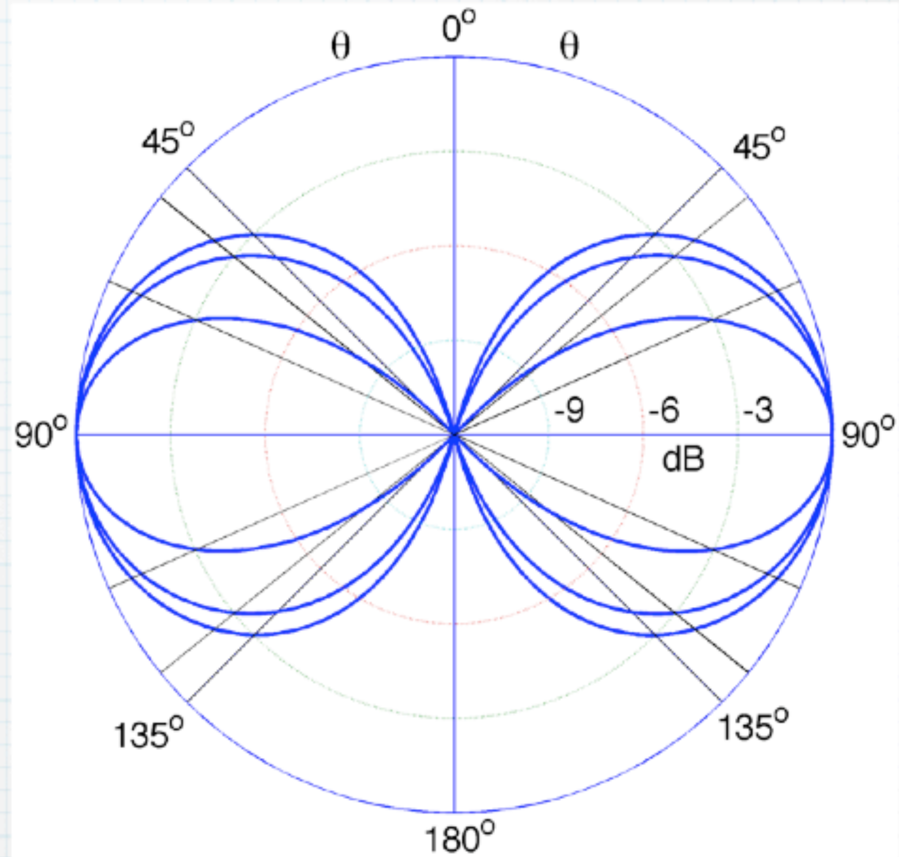
$$D(\theta, \phi) = 1.64\left[\frac{\cos(\frac{\pi}{2}\cos\theta)}{\sin\theta}\right]^2$$

$$\text{HPBW} \approx 78^\circ$$

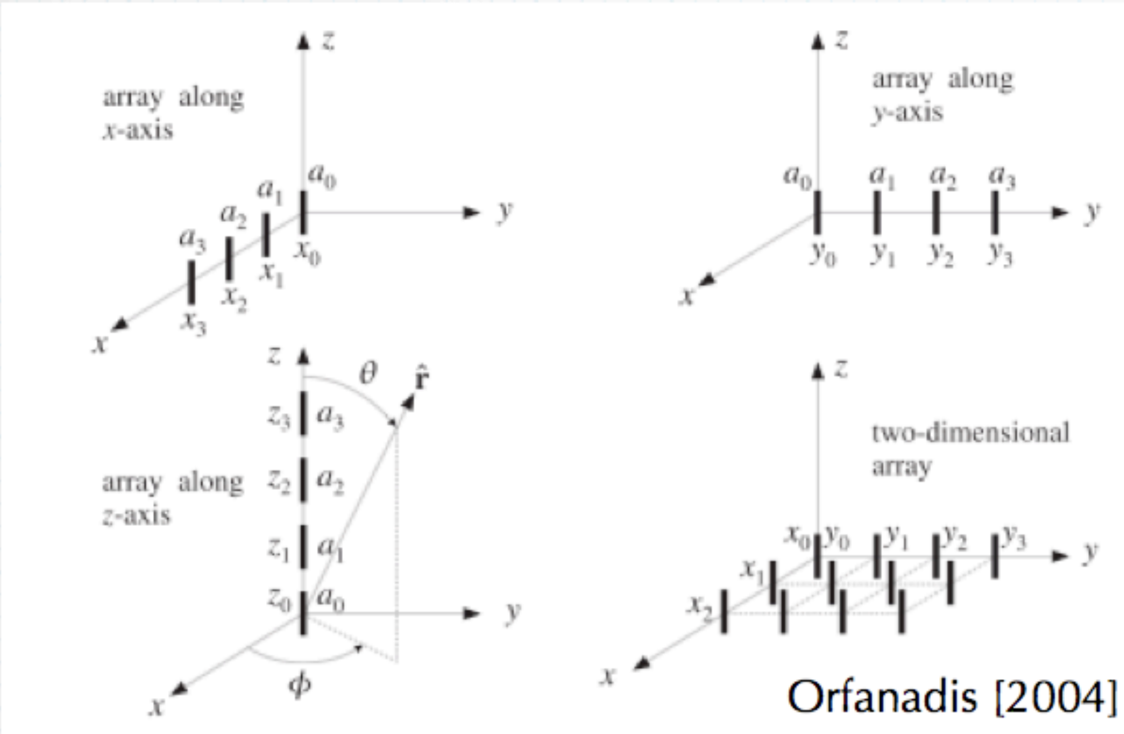
Full-Wave Dipole

$$D(\theta, \phi) = 2.41\left|\frac{\cos(\pi\cos\theta) - 1}{\sin\theta}\right|^2$$

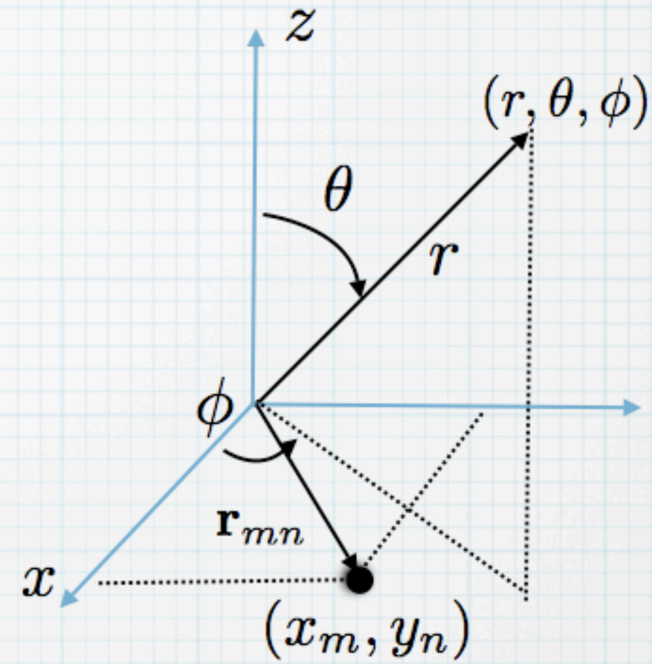
$$\text{HPBW} \approx 48^\circ$$



Antenna Arrays



Orfanadis [2004]

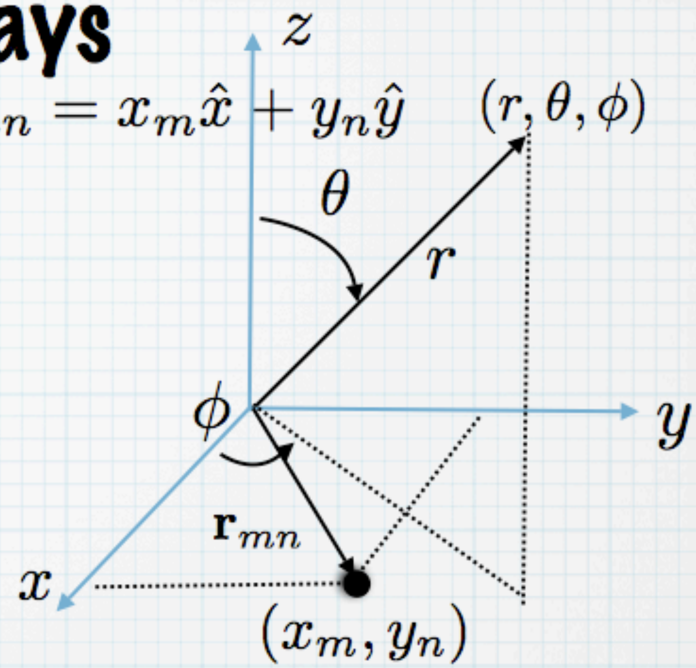


$$\mathbf{r}_{mn} = x_m \hat{x} + y_n \hat{y}$$

Assumptions:

1. Far field
   - parallel rays, 1/r amplitude dependence
2. No mutual coupling between elements (will discuss later)
3. A "reference" element radiates from the origin
4. All elements/radiators are identical, max radiation in z direction (broadside)

Antenna Arrays



Reference element at origin will produce a vector electric field at point (r, θ, ϕ)

$$\mathbf{E}_{00} = I_{00}(E_\theta\hat{\theta} + E_\phi\hat{\phi})$$

Constant

Fields due to *mn*th element is:

$$\mathbf{E}_{mn} = I_{mn}(E_\theta\hat{\theta} + E_\phi\hat{\phi})e^{jk\mathbf{r}_{mn}\cdot\hat{\mathbf{r}}}$$

$$= I_{mn}(E_\theta\hat{\theta} + E_\phi\hat{\phi})e^{jk(x_m \sin\theta\cos\phi + y_n \sin\theta\sin\phi)}$$

Total vector field at (r, θ, ϕ)

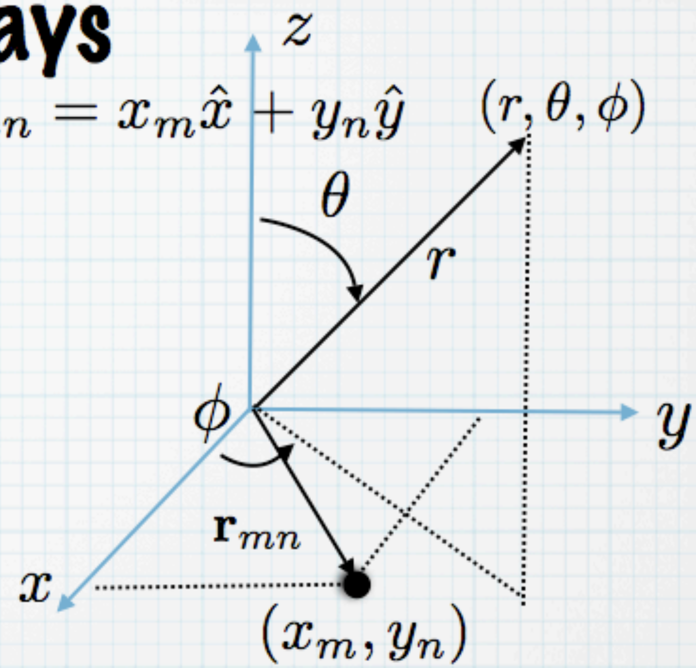
$$\mathbf{E} = (E_\theta\hat{\theta} + E_\phi\hat{\phi}) \sum_m \sum_n I_{mn} e^{jk\mathbf{r}_{mn}\cdot\hat{\mathbf{r}}}$$

Element Factor

Array Factor

Antenna Arrays

$$\mathbf{r}_{mn} = x_m\hat{x} + y_n\hat{y}$$



$$F_{array}(\theta,\phi) = \sum_m \sum_n I_{mn} e^{jk\mathbf{r}_{mn}\cdot\hat{\mathbf{r}}}$$

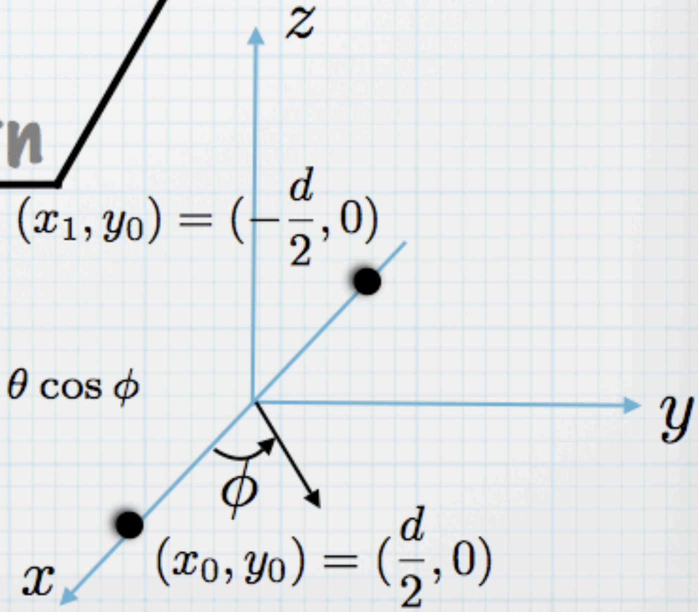
Poynting vector

$$\mathbf{P} = \frac{1}{2}\Re\{\mathbf{E}\times\mathbf{H}\} = \frac{1}{2z_0}|\mathbf{E}|^2\hat{\mathbf{r}}$$

$$= \frac{1}{2z_0}(|E_\theta|^2 + |E_\phi|^2)|F_{array}|^2\hat{\mathbf{r}}$$

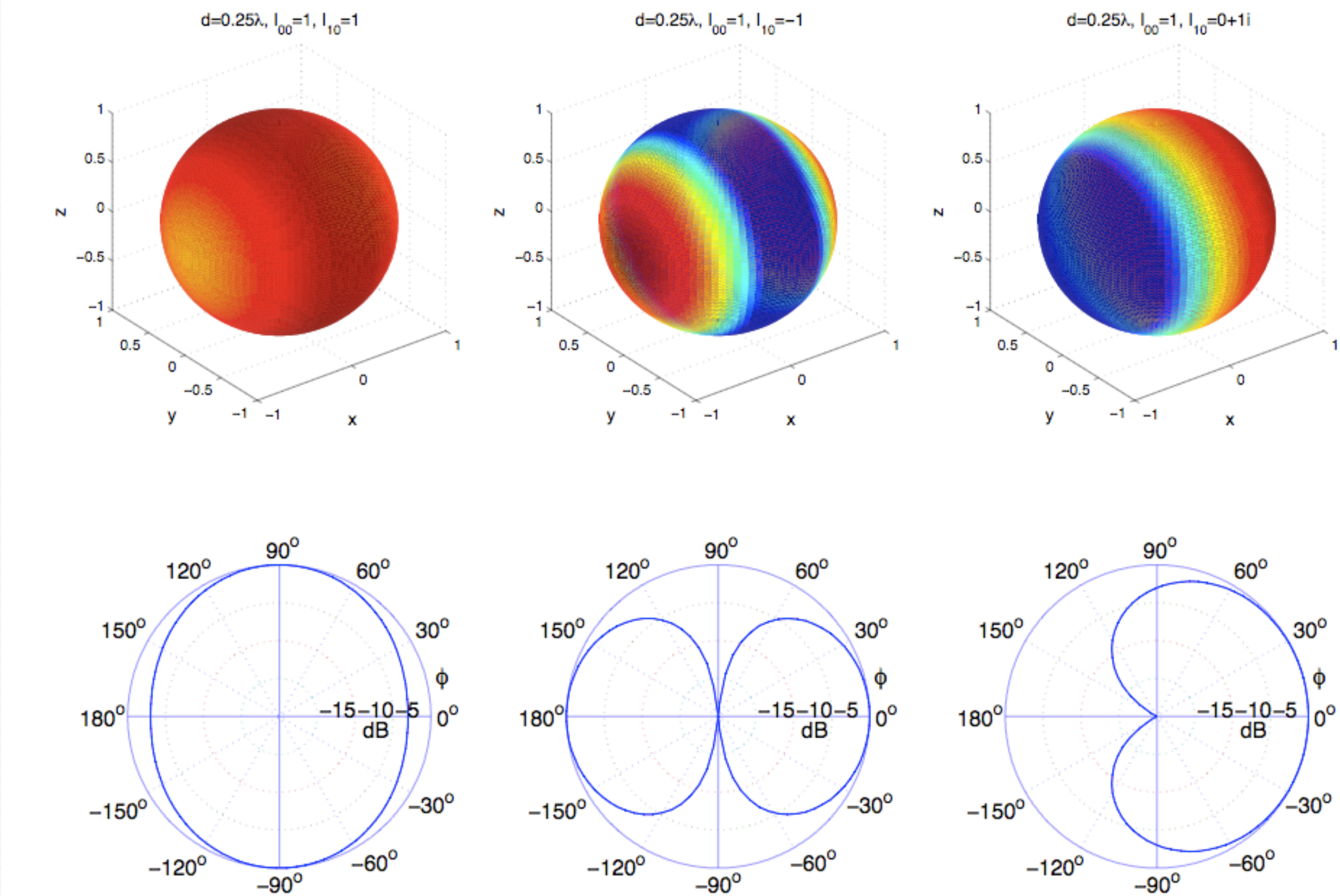
Element Pattern — Array Pattern

Simple Two Element Array

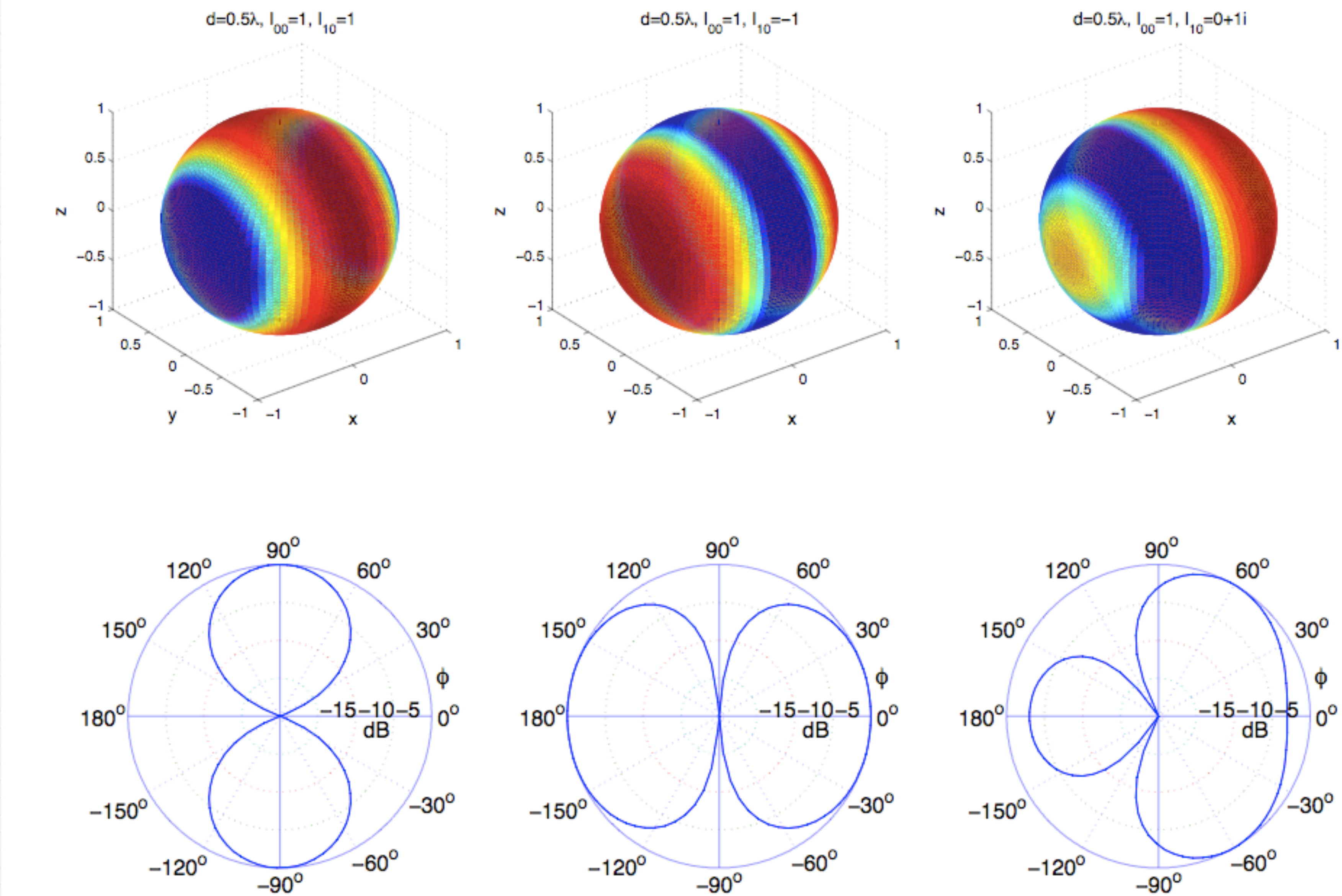


$$F_{array} = I_{00}e^{jk(d/2)\sin\theta\cos\phi} + I_{10}e^{-jk(d/2)\sin\theta\cos\phi}$$

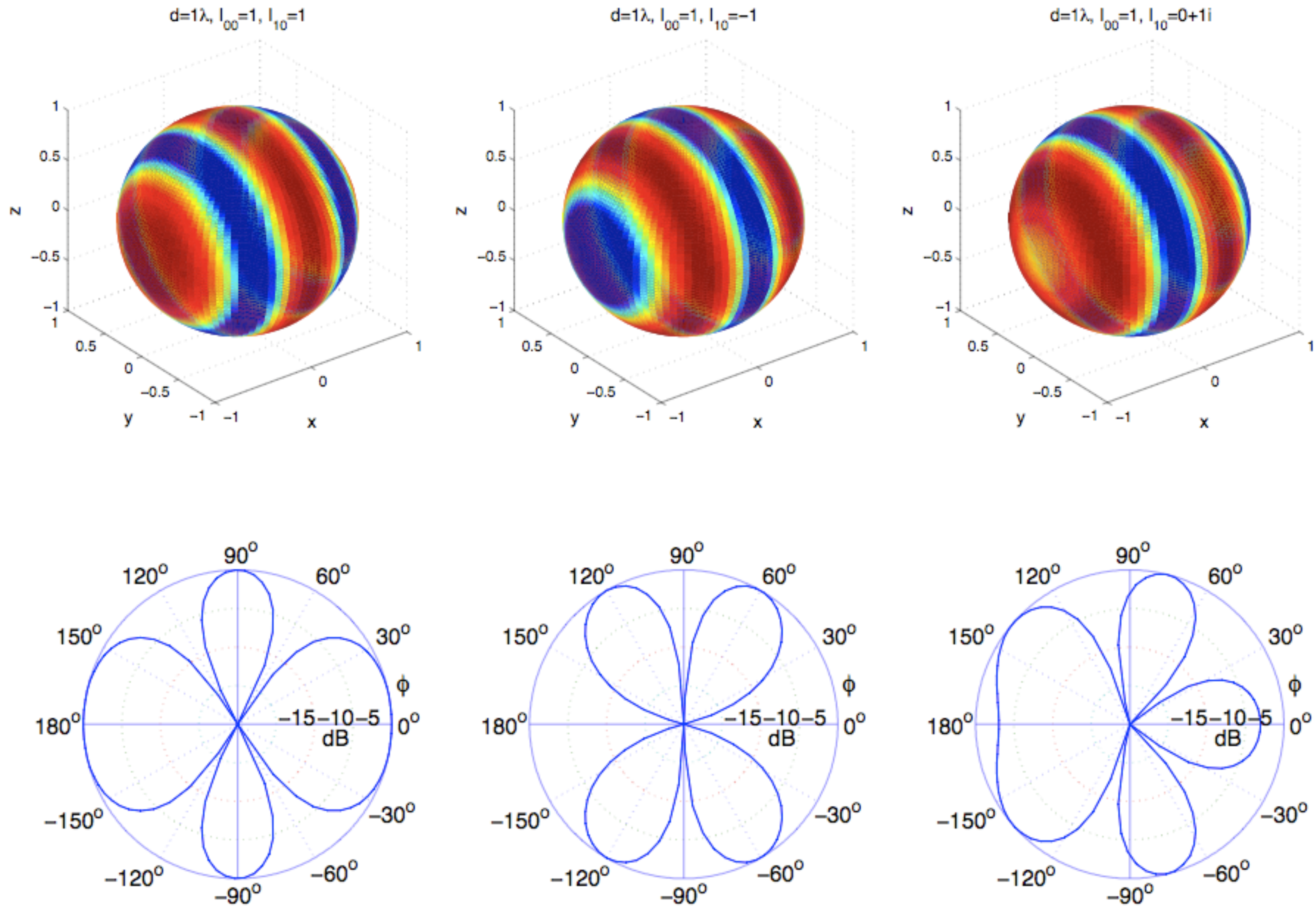
Two-element Array



Two-element Array



Two-element Array



Array Steering

$$F_{array}(\theta,\phi) = \sum_m \sum_n I_{mn} e^{jk(x_m \sin\theta\cos\phi + y_n \sin\theta\sin\phi)}$$

If the element constants have no phase angles, beam maximum will be in direction:

$$x_m \sin\theta\cos\phi + y_n \sin\theta\sin\phi = 0 \longrightarrow \theta = 0$$

Say we want to point in direction (θ_0, ϕ_0)

$$x_m \sin\theta_0\cos\phi_0 + y_n \sin\theta_0\sin\phi_0 + (\psi_m + \psi_n) = 0$$

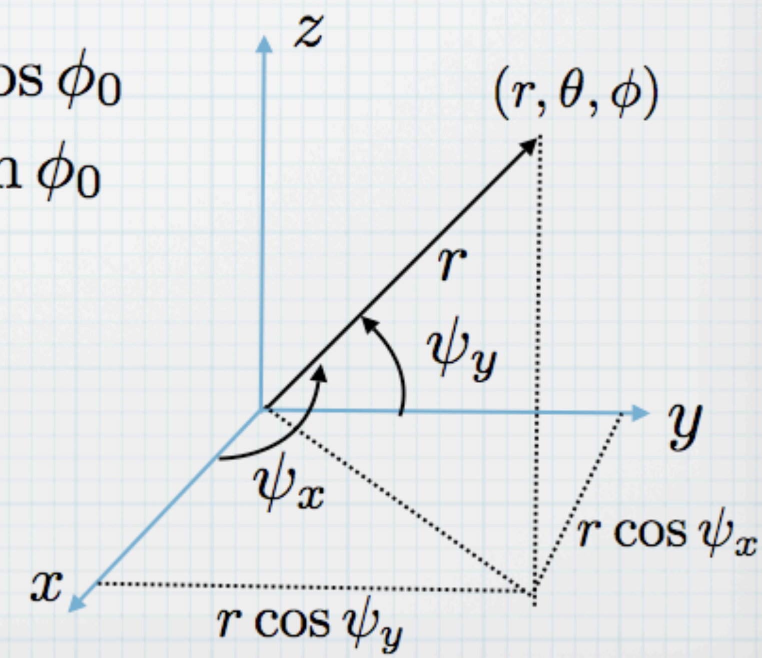
$$\psi_m = -kx_m \sin\theta_0\cos\phi_0$$

$$\psi_n = -ky_n \sin\theta_0\sin\phi_0$$

Direction cosines:

$$\cos\psi_{x0} = \sin\theta_0\cos\phi_0$$

$$\cos\psi_{y0} = \sin\theta_0\sin\phi_0$$



Array Steering

$$F_{array}(\theta,\phi) = \sum_m \sum_n I_{mn} e^{jk(x_m \sin\theta\cos\phi + y_n \sin\theta\sin\phi)}$$

$$F_{array} = \sum_{m,n} I_{mn} e^{jkx_m(\cos\psi_x - \cos\psi_{x0})} e^{jky_n(\cos\psi_y - \cos\psi_{y0})}$$

Say we want to point in direction (θ_0, ϕ_0)

$$x_m \sin\theta_0 \cos\phi_0 + y_n \sin\theta_0 \sin\phi_0 + (\psi_m + \psi_n) = 0$$

$$\psi_m = -kx_m \sin\theta_0 \cos\phi_0$$
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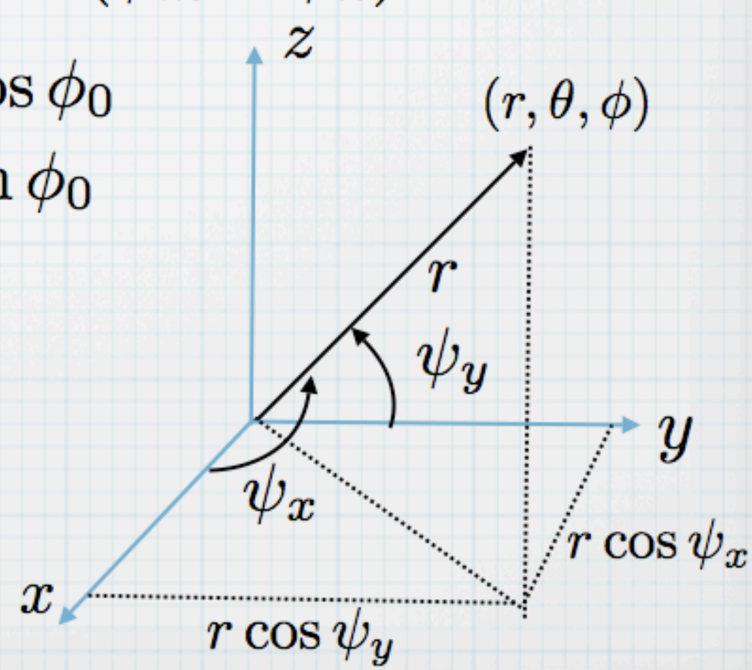


Directive Gain of Antenna Array

Recall:

$$D(\theta,\phi) = \frac{\text{Power Density Radiated In } (\theta,\phi) \text{ Direction}}{\text{Average Power Density}} = 4\pi R^2 \frac{\text{Power Density In } (\theta,\phi)}{\text{Total Power Radiated}}$$

$$\langle P_r \rangle = \frac{1}{2}\Re\{\mathbf{E}\times\mathbf{H}\}\cdot\hat{\mathbf{r}} = \frac{1}{2z_0}|\mathbf{E}|^2|F_{array}|^2 = P_{el}|F_{array}|^2$$

$$P_{total} = \int_0^{2\pi} d\phi \int_0^{\pi} P_{el}|F_{array}|^2 r^2 \sin\theta d\theta$$

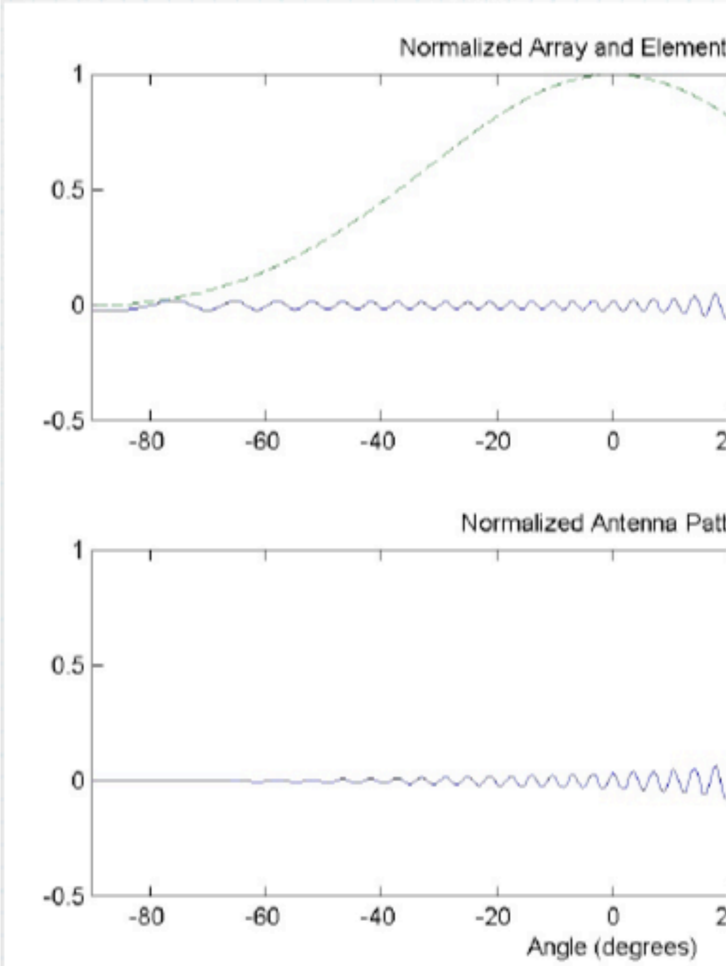
$$D(\theta,\phi) = 4\pi r^2 \frac{P_{el}|F_{array}|^2}{\int_0^{2\pi} d\phi \int_0^{\pi} P_{el}|F_{array}|^2 r^2 \sin\theta d\theta}$$

If element pattern is much broader than array pattern,

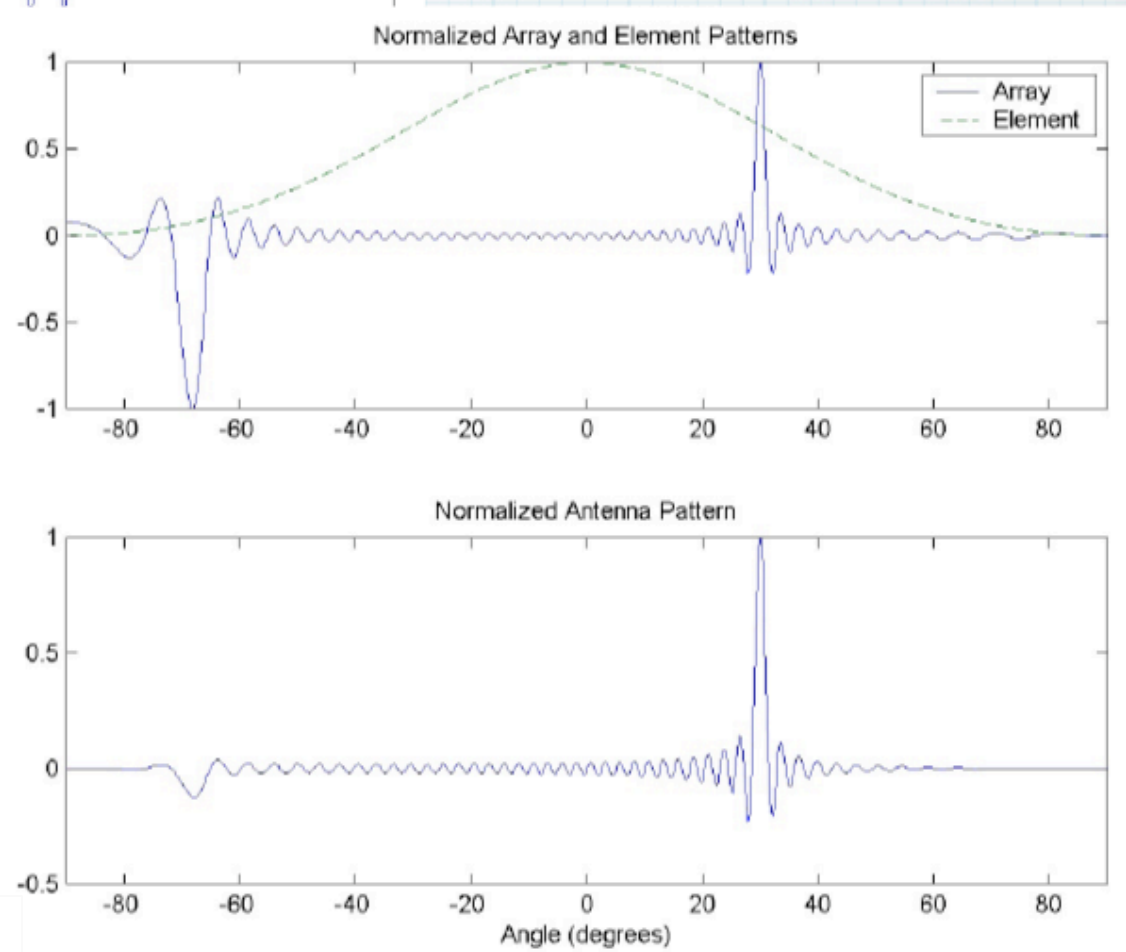
Element pattern doesn't matter.

$$D(\theta,\phi) = 4\pi r^2 \frac{|F_{array}|^2}{\int_0^{2\pi} d\phi \int_0^{\pi} |F_{array}|^2 r^2 \sin\theta d\theta}$$

Directive Gain of Antenna Array



$$\text{n} \quad = 4\pi R^2 \frac{\text{Power Density In } (\theta, \phi)}{\text{Total Power Radiated}}$$



$$D(\theta, \phi) = 4\pi r$$

The Fourier Analogy

$$
\begin{aligned}
F_{array} &= \sum_m I_m e^{jkdm(\cos\psi_x - \cos\psi_{x0})} \\
&= \sum_m I_m e^{jm\gamma} \\
&= \sum_m I_m z^m
\end{aligned}
$$

Array factor can be interpreted as DFT of weighting factors

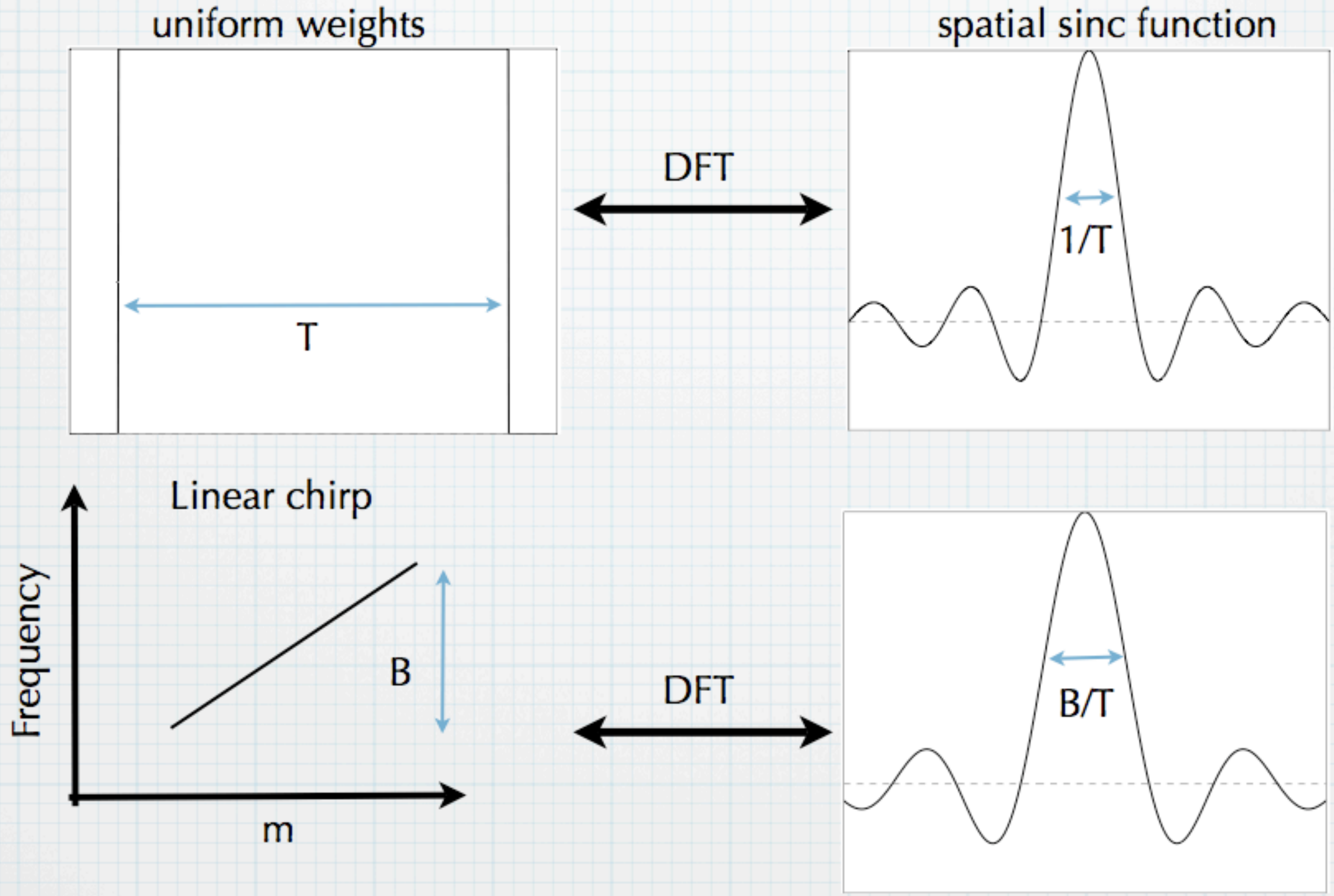
Array factor in spatial z domain

$$I_m = \frac{1}{2\pi}\int_{-\pi}^{\pi} F_{array}(\gamma) e^{-j\gamma m} d\gamma$$

Inverse DFT - principle of many array design methods (analogous to FIR filter design)

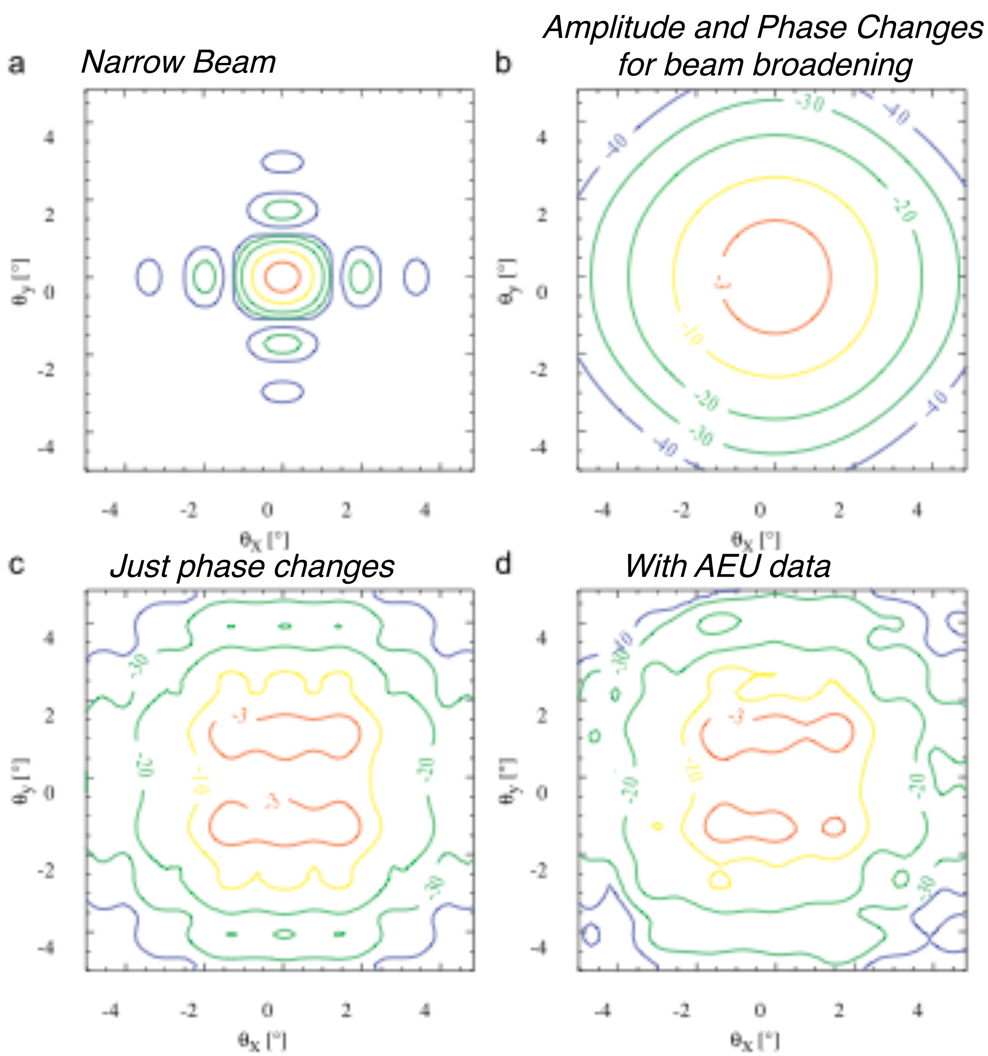
The Fourier Analogy (2)

One application - beam broadening



Tx/Rx Beam Pattern Control

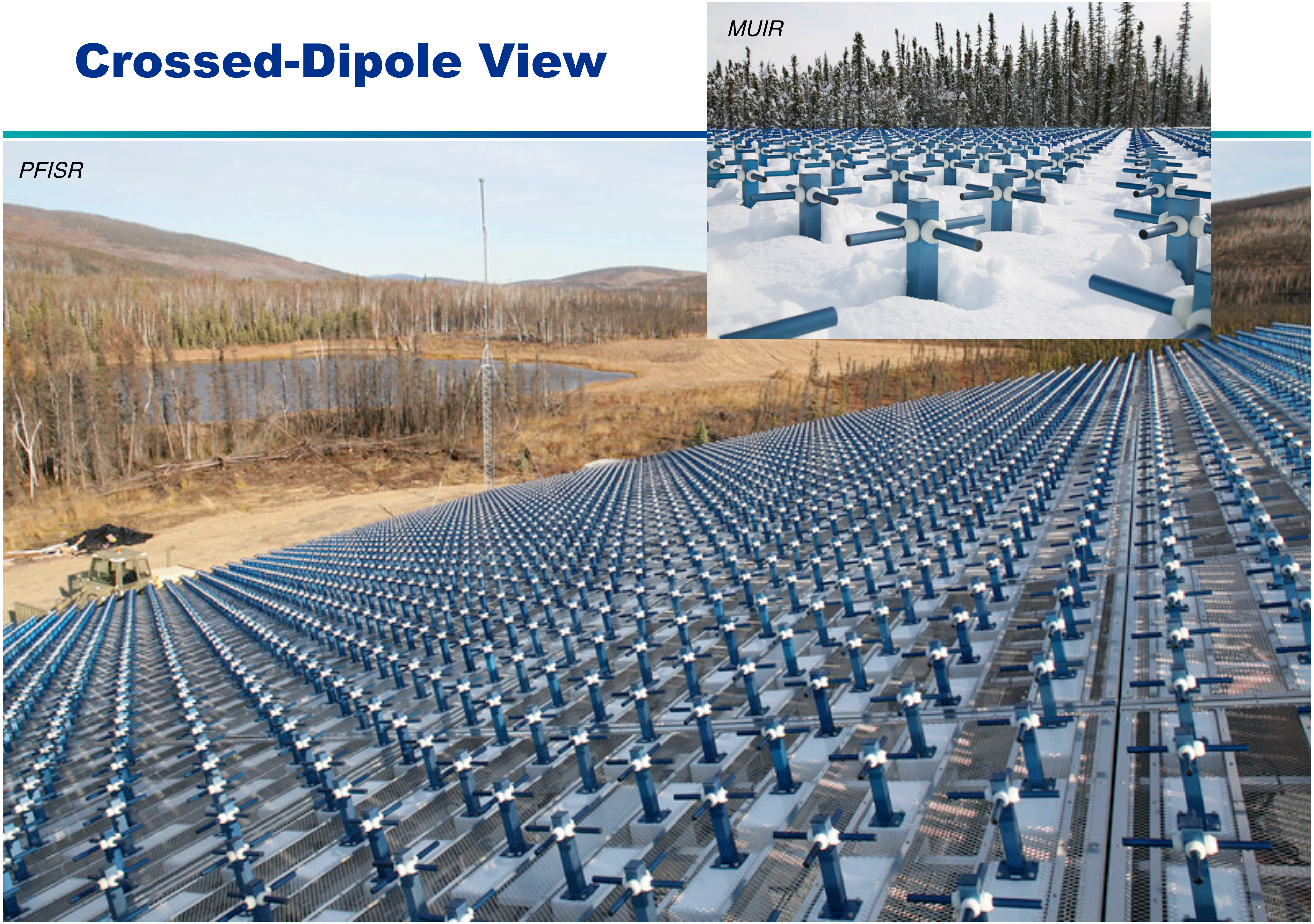
Chau et al., [2009]



- Determine which meteors in the narrow beam are coming from sidelobes (~15 %)

- Increase number of large cross-section meteor detections

Crossed-Dipole View



Photos by Craig Heinselman

AMISR Buildup

AEU

- 500 W solid state transmitter
- Phasing control
- Status monitoring

Panel

PC104
PCU

- 32 Antenna Element Units
- Embedded linux controller
- Basic system building block

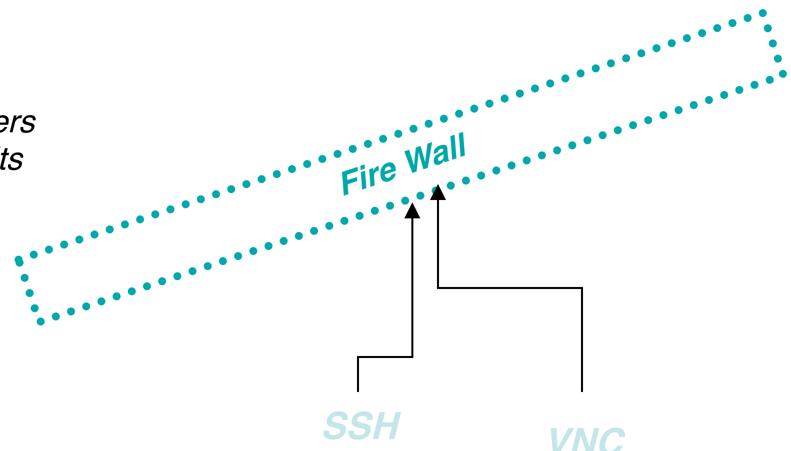
Group

UDU

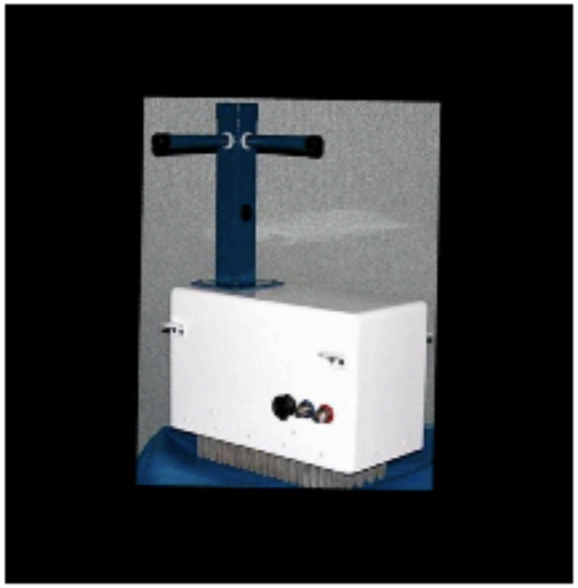
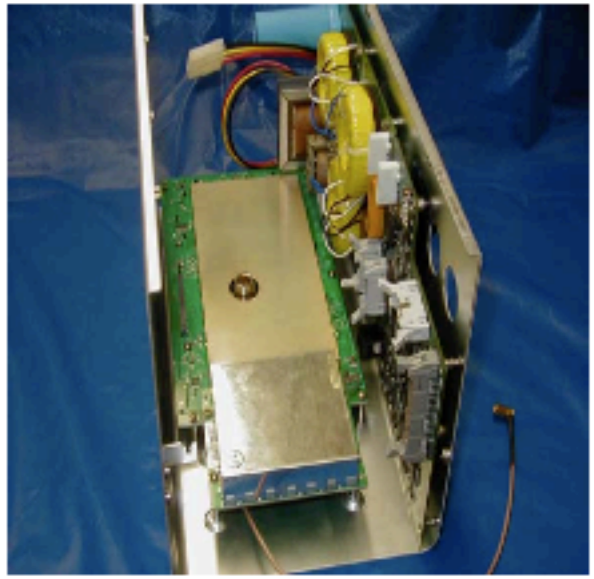
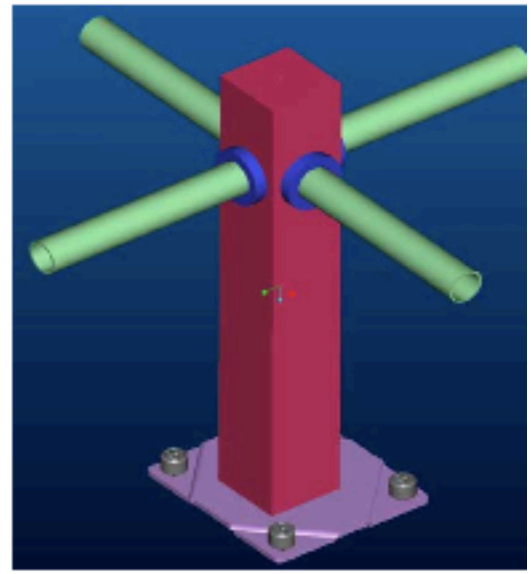
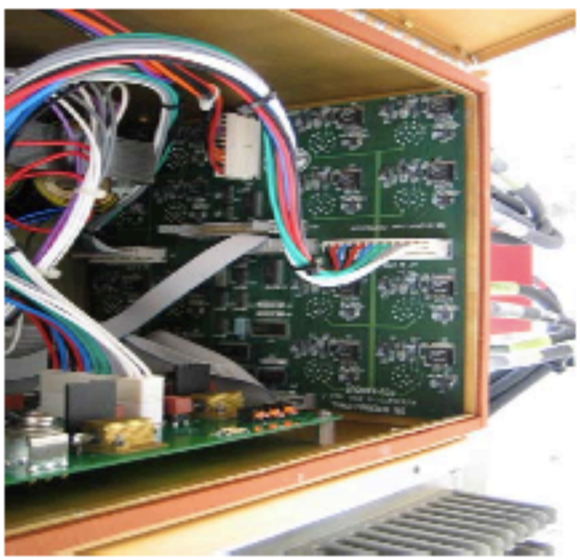
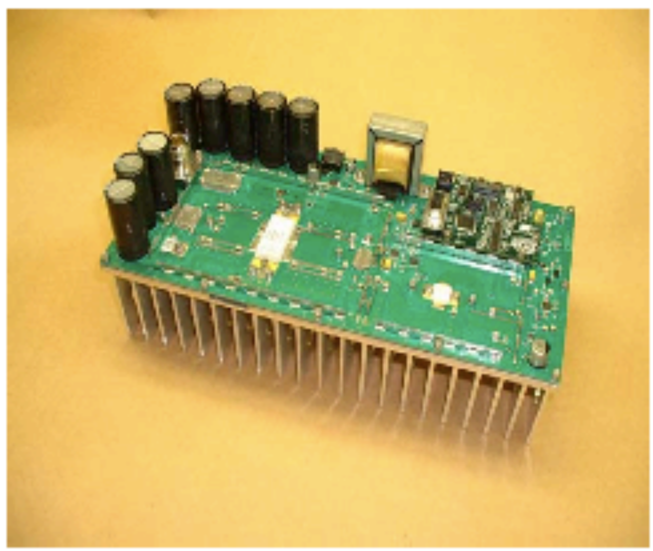
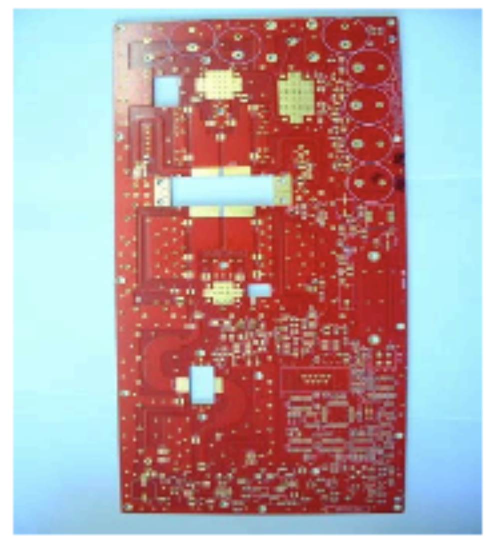
- 400 Hz JetPower converters
- Remote power control units
- Fiber distribution system

Face

DAQ



Sub-components

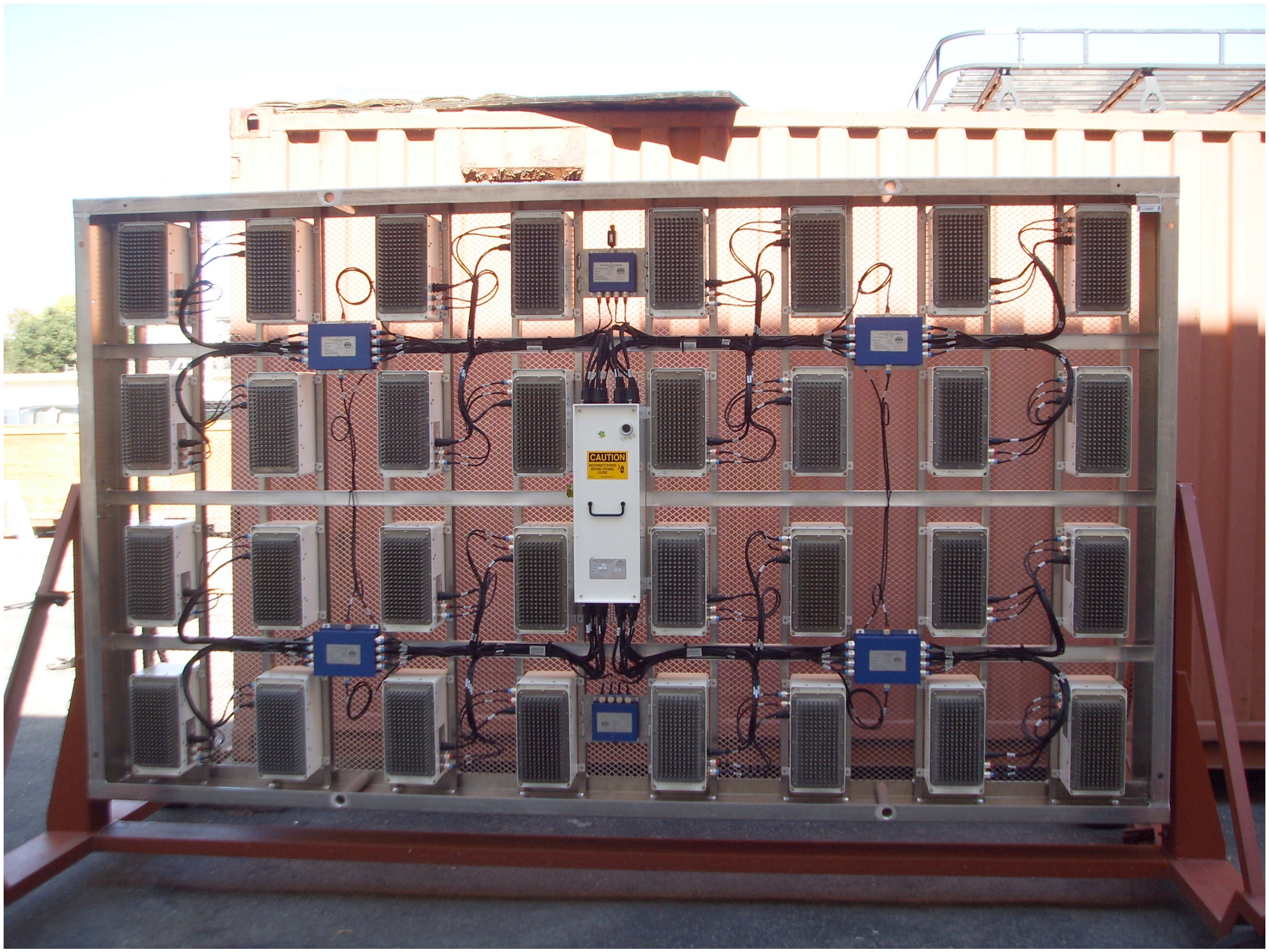







Power Amplifiers and Antennas

- Distributed Solid State Power Amplifiers (SSPAs)
- 430-450 MHz instantaneous bandwidth
- 10% Maximum duty cycle
- Minimum PRF interval 500 usec
- Maximum pulsewidth 2 msec
- Passive cooling (no moving parts
- 400 Hz prime power

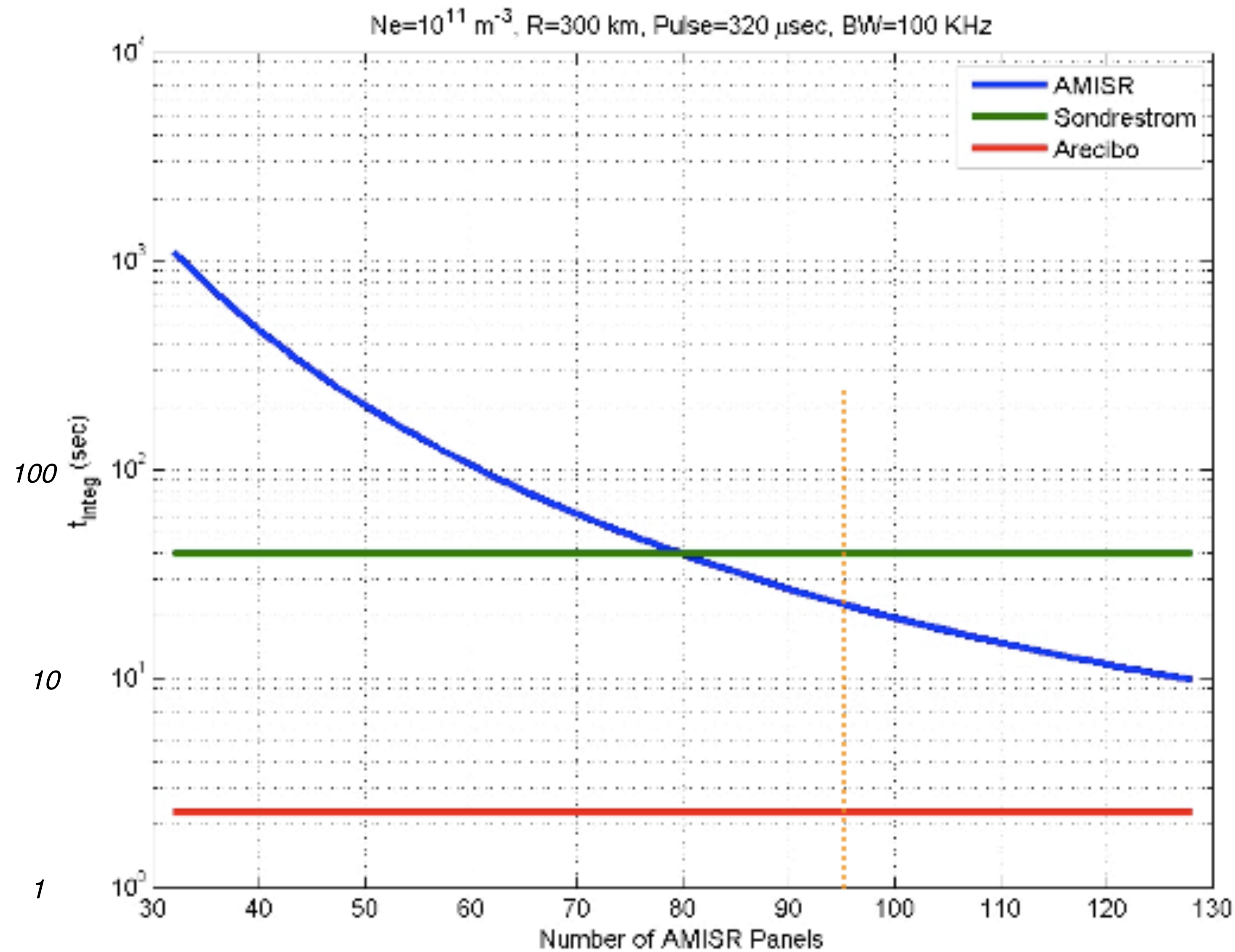
- Crossed dipoles, circular polarization on axis
- Balun built into the antenna support shaft
- Constant impendence over bandwidth and scan angle
- Spacing is hexagonal for efficiency
- Tx/Rx polarizations are opposite and fixed (not measureable)

Panel

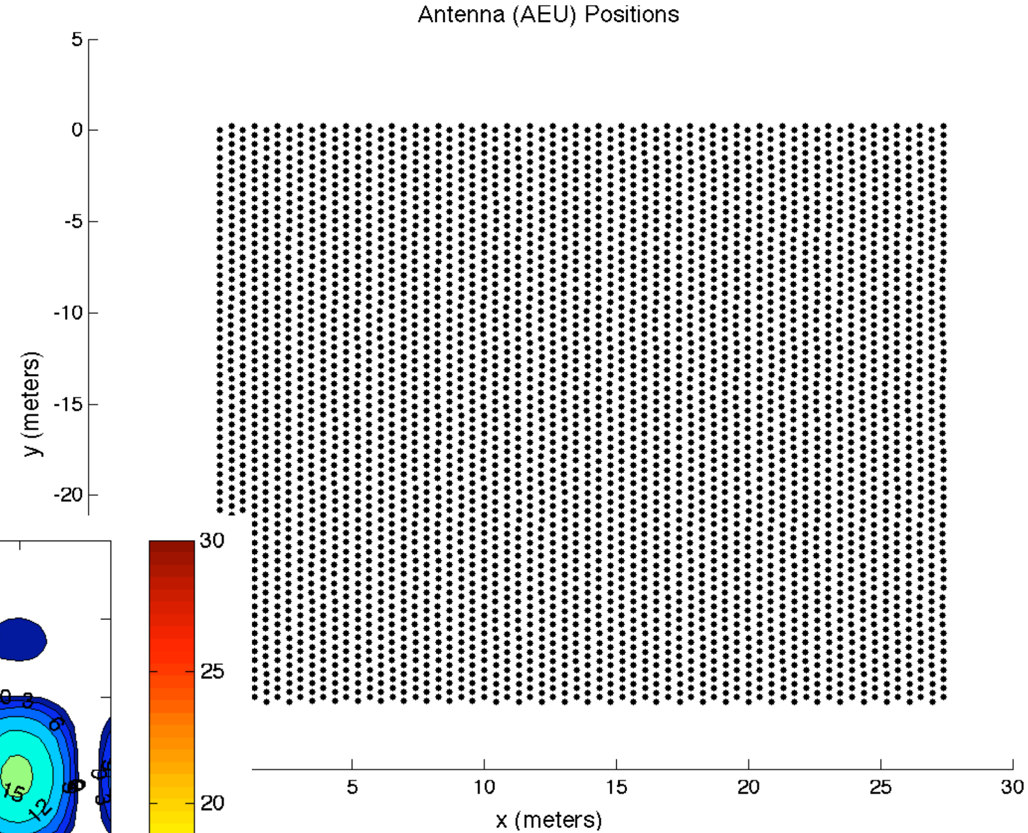


Adding a panel to the group

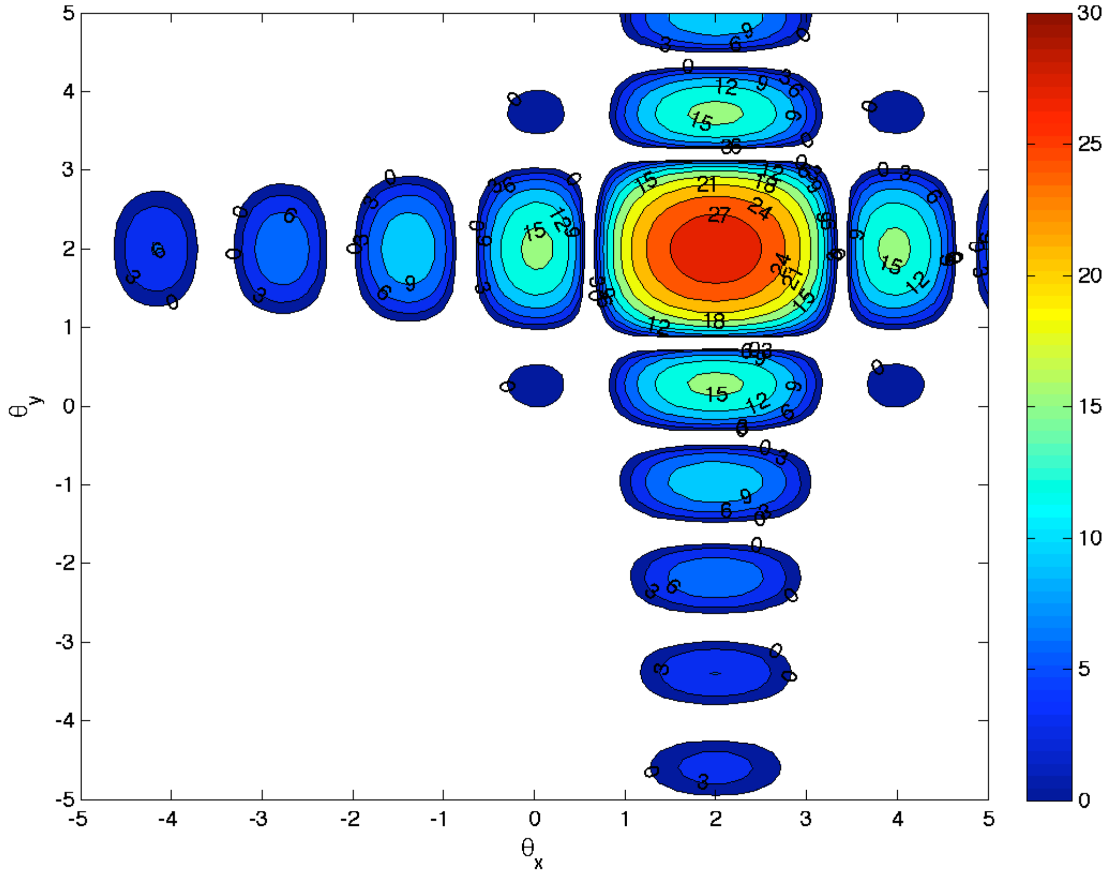
AMISR Sensitivity vs. Size

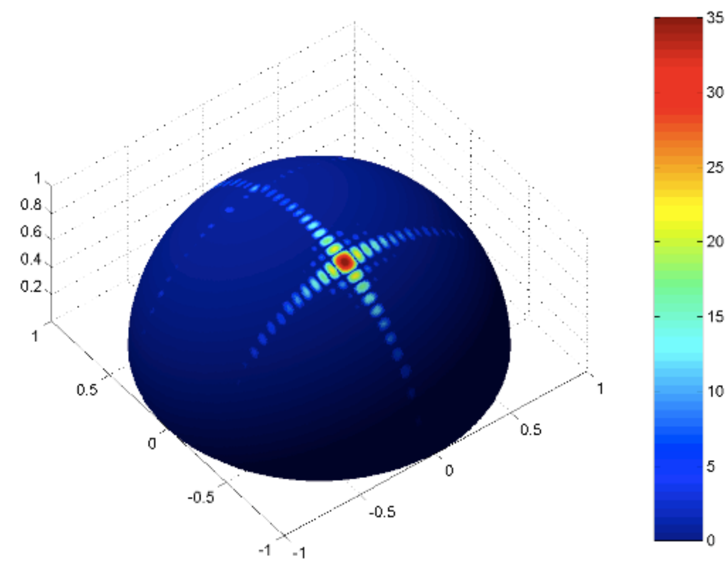


Beam Pattern



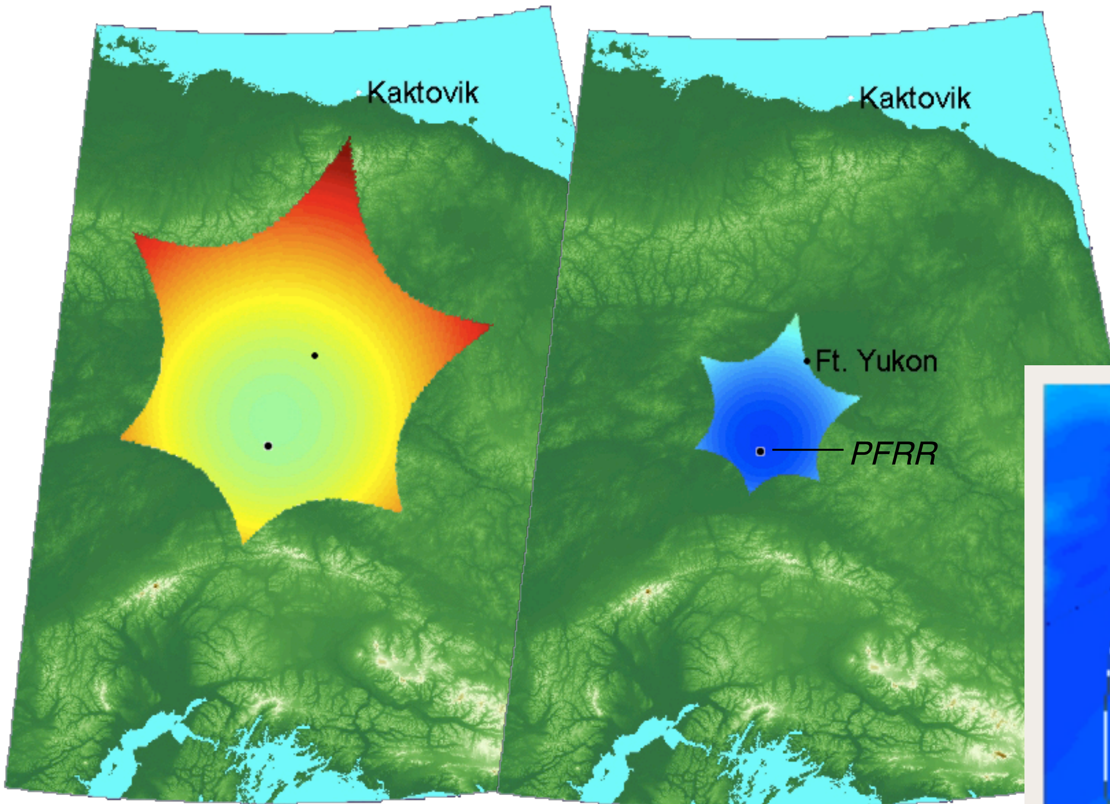
The axes correspond to the angles off boresight





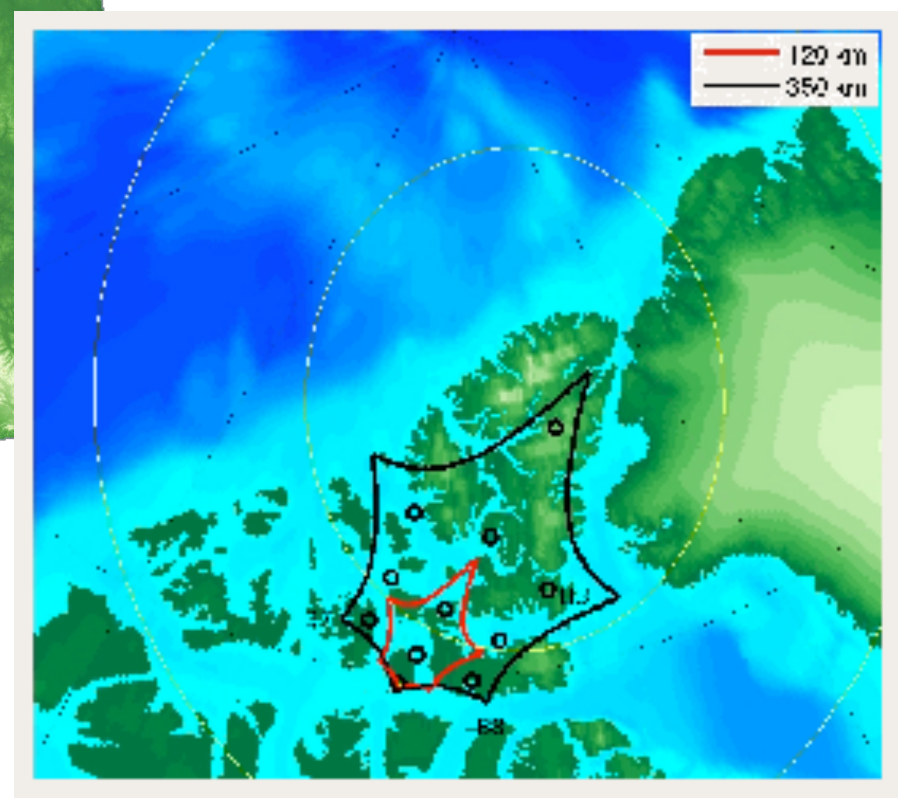
AMISR Coverage – Poker Flat

350 km, 1 x 10^{11}, 10% *150 km, 1 x 10^{11}, 10%*

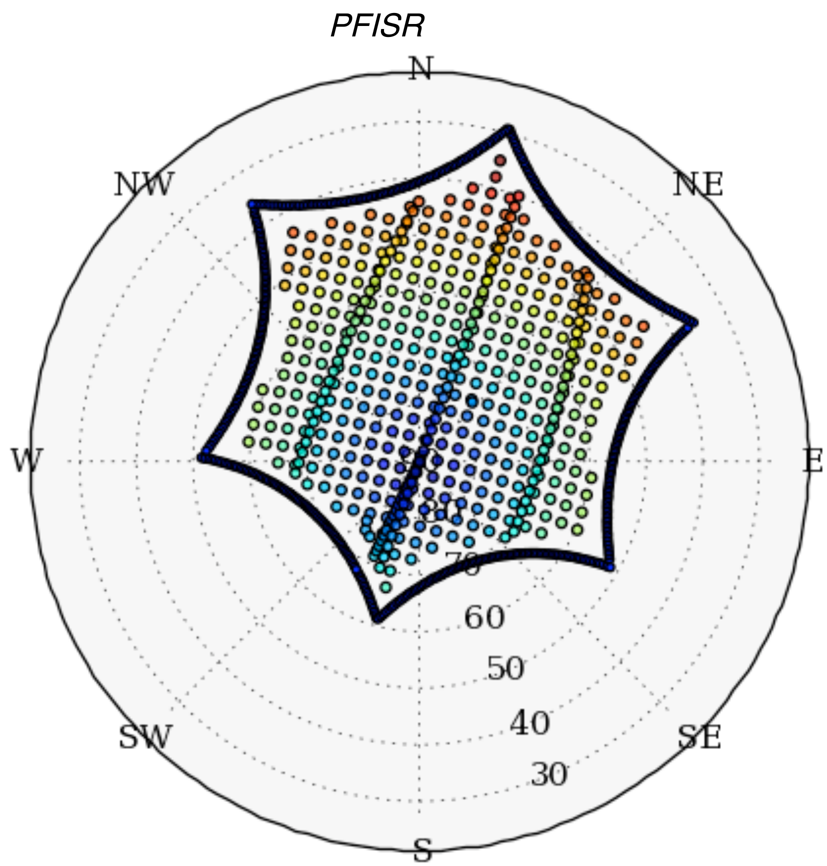


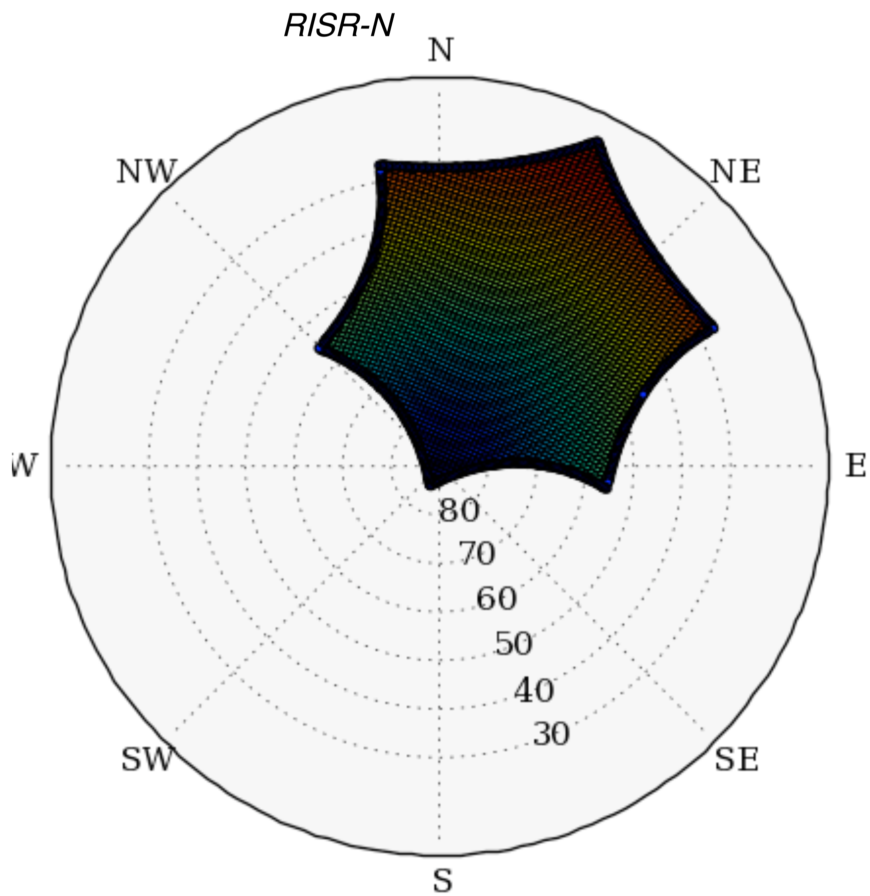
PFISR Coverage

RISR Coverage

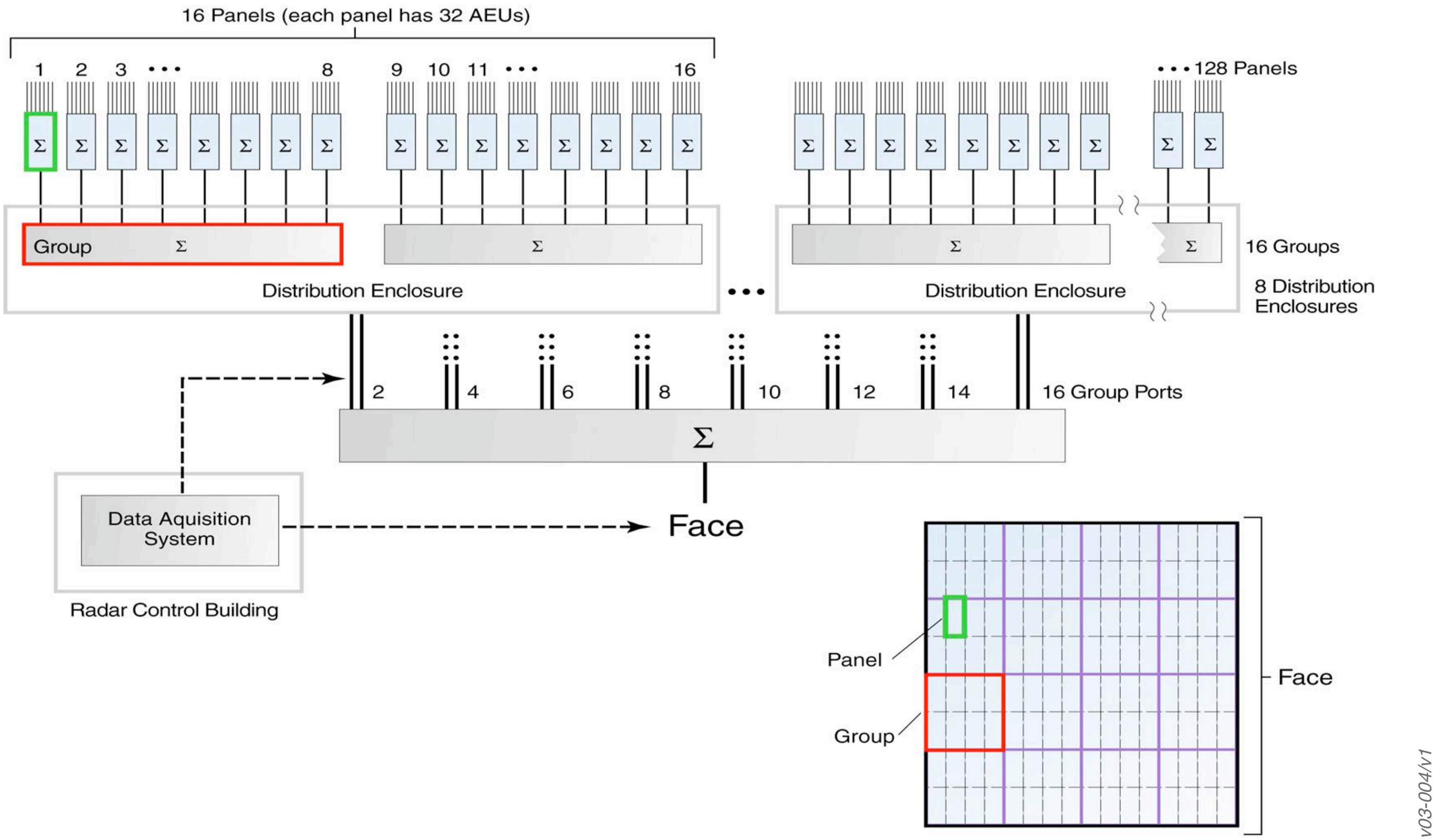


Discrete look directions



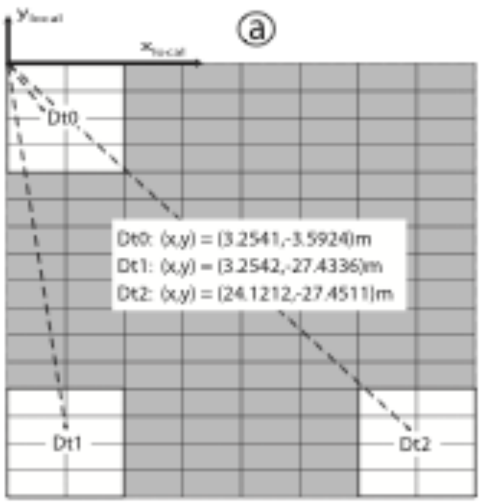


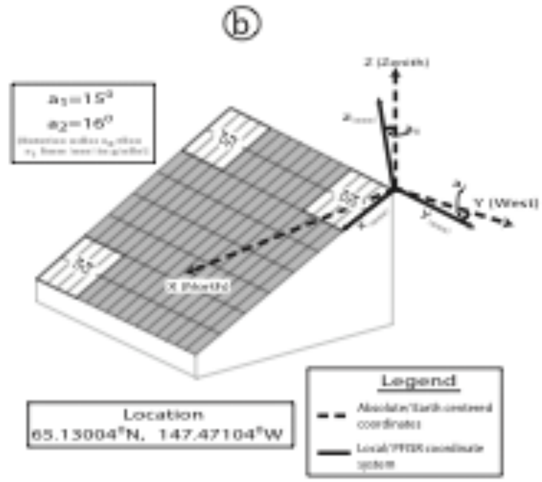
Groups (E.g., interferometry)



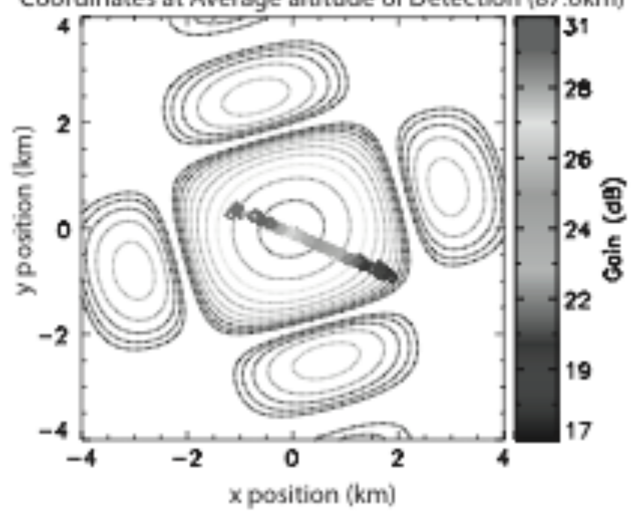
Rx Control - Interferometry

Sparks et al., 2010

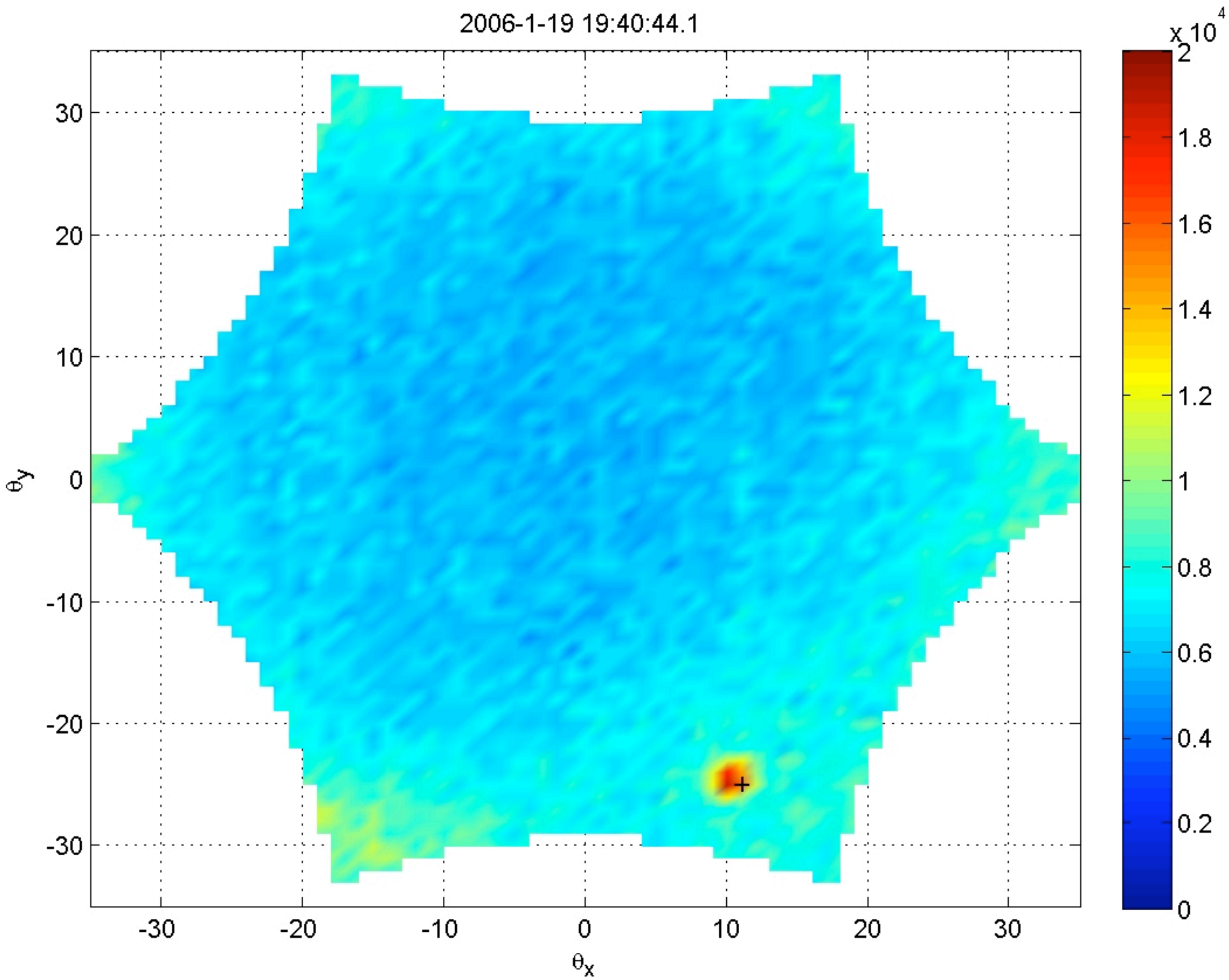




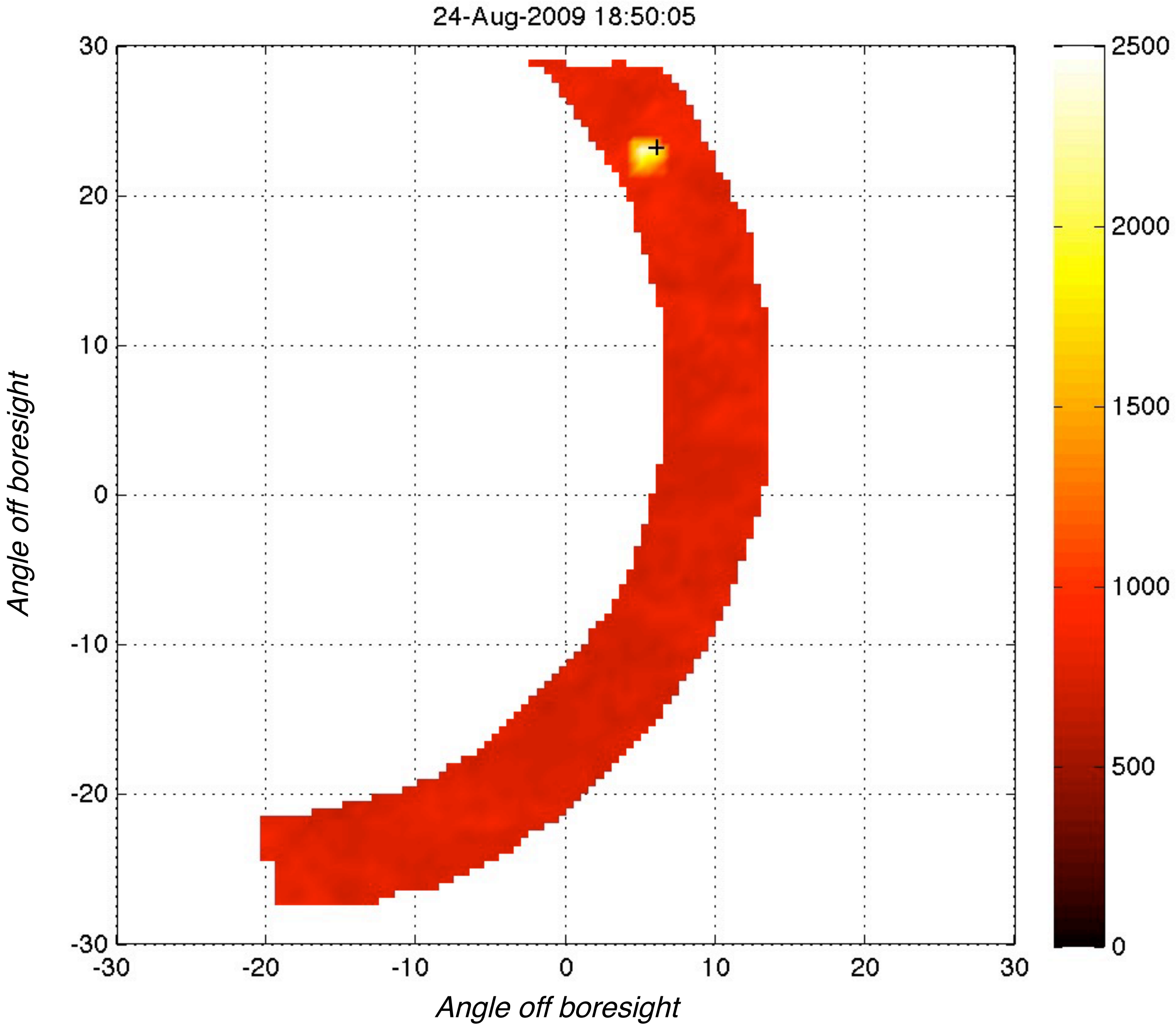
- Determine location of meteor within beam
- Determine trajectory of meteor
- Study source populations



Receive-only Imaging – Beam-Forming Test



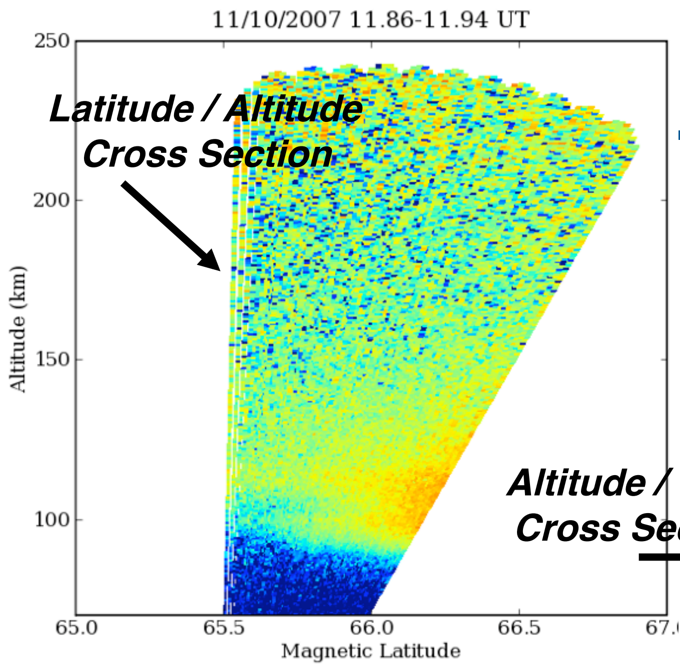
Receive-only Imaging – Beam-Forming Test



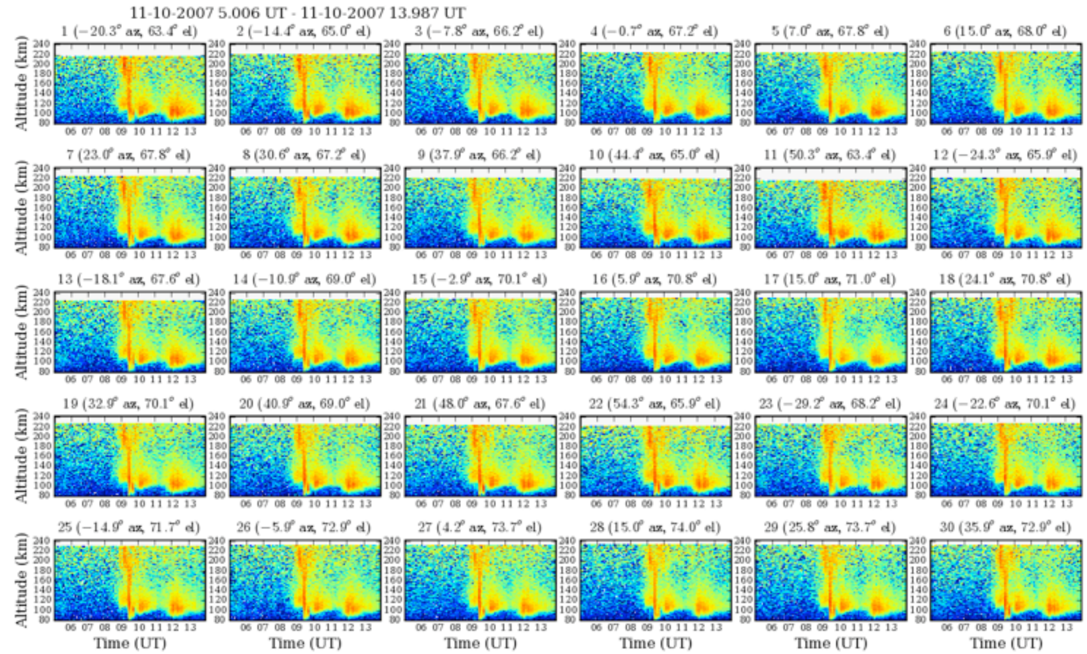
What are the Measurement Improvements

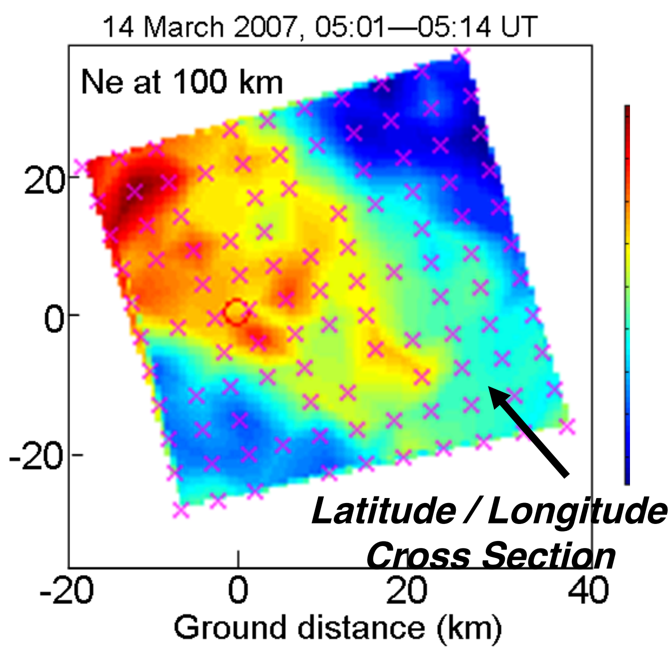
- **Inertia-less antenna pointing**
  - Pulse-to-pulse beam positioning
  - Supports great flexibility in spatial sampling
  - Helps remove spatial/temporal ambiguities
  - Eliminates need for predetermined integration

PFISR: Images of the Aurora in 4-Dimensions (3-D images v. time)

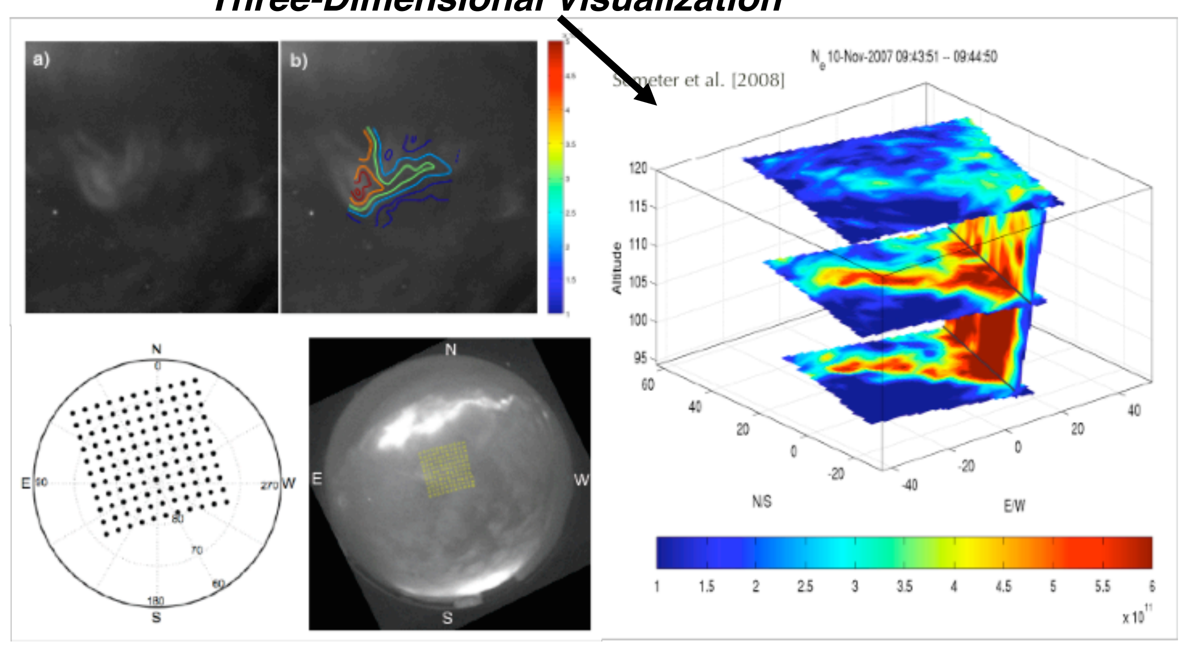


Altitude / Time Cross Section



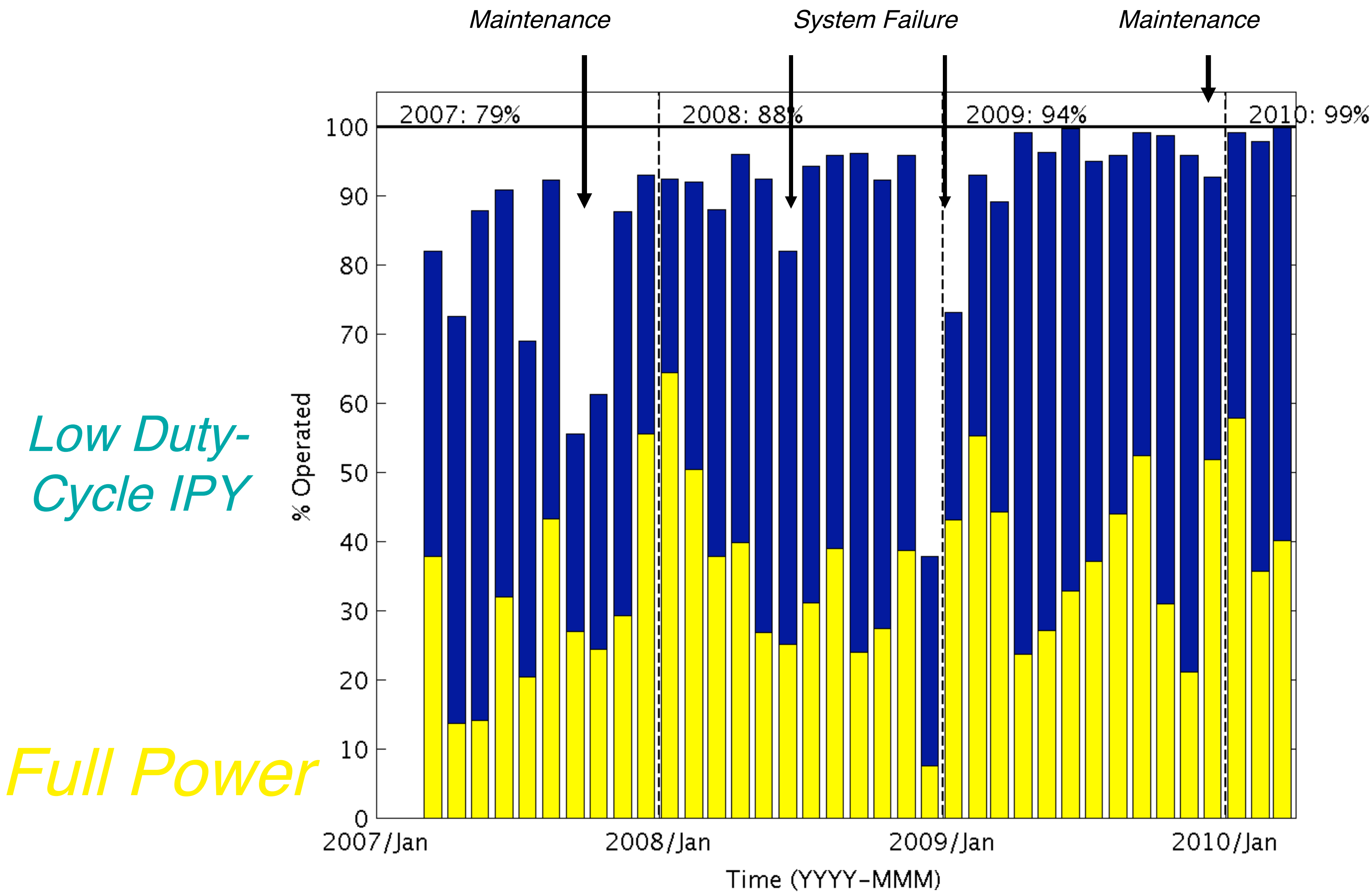


Three-Dimensional Visualization



PFISR Operations

	2007	2008	2009	2010
% full power	30	34	39	45
% low cycle	49	54	55	54
% on	79	88	94	99



AMISR Technical Specifications

- Peak Power: 2 MW
- Max RF Duty: 10%
- Pulse Length: 1 μsec - 2 msec
- TX Frequency: 430-450 MHz
- Antenna Gain: ~43 dBi
- Antenna Aperture: ~715 m^2
- Beam Width: ~1.1^o
- System temperature: ~120 K
- Steering: Pulse to pulse over ~ +/- 25^o
- Max system power consumption: ~700 KW
- Max operations: continuous, depending on power availability
- Unattended operations
- Data volume ~6 TB/year at Poker Flat
- No moving parts on the antenna
- Environment: -40^o C to +35^o C

- Altitude coverage: ~60 km to ?? km (depending on Ne)
- Minimum measurable electron densities: ~1e9 m^{-3}
- Typical time resolution:
- E region <~3 min,
- F region <~1 min,
- ~10 look directions and typical ionospheric conditions - many caveats apply!
- Typical range resolution: 600 meters to 72 km (mode dependent, can be extended)
- Plasma parameters: Ne, Te, Ti, Vi, ν_{in}, composition
- Derived parameters: E, J, J·E, J·E', Un, σ_P, σ_H

Peak Power 1778 KW (3557/476/31)

2010-07-23 21:57 UTC