Wideband Synthetic Aperture Test Bed for Intelligent Reflecting Surfaces

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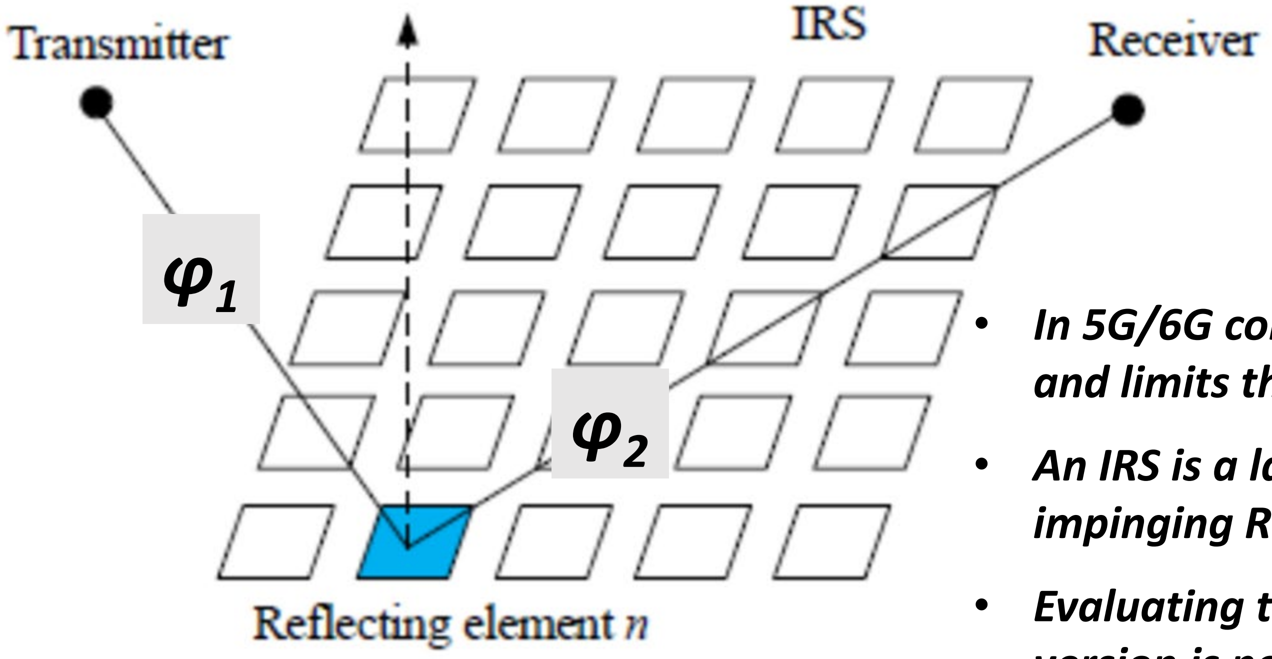
Overview

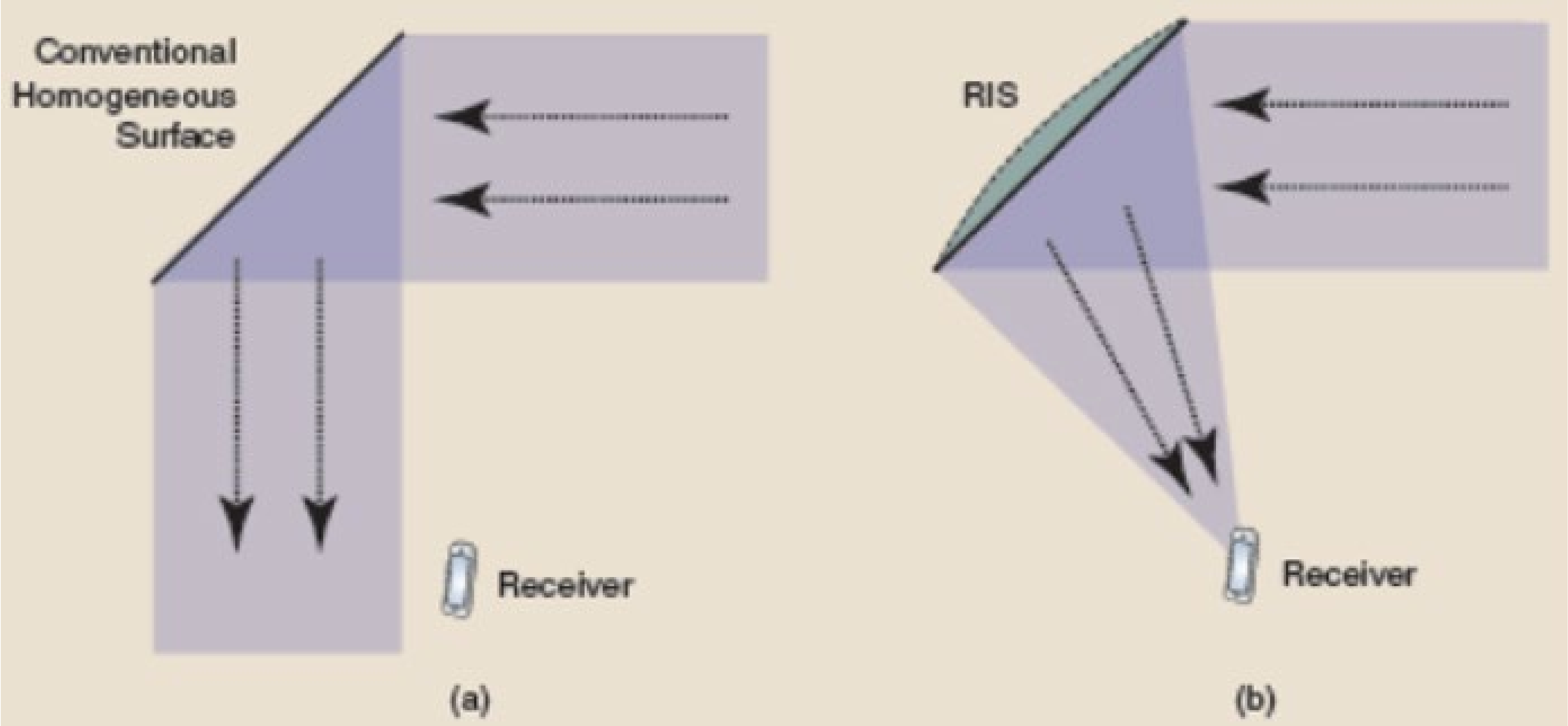
- ***Intelligent Reflecting Surfaces***
- ***Synthetic Apertures***
- ***Planar Wavefronts***
- ***Spherical Wavefronts***
- ***Spherical Beamforming***
- ***Simulation Results***
- ***Measured Results***
- ***Conclusion***

Intelligent Reflecting Surface

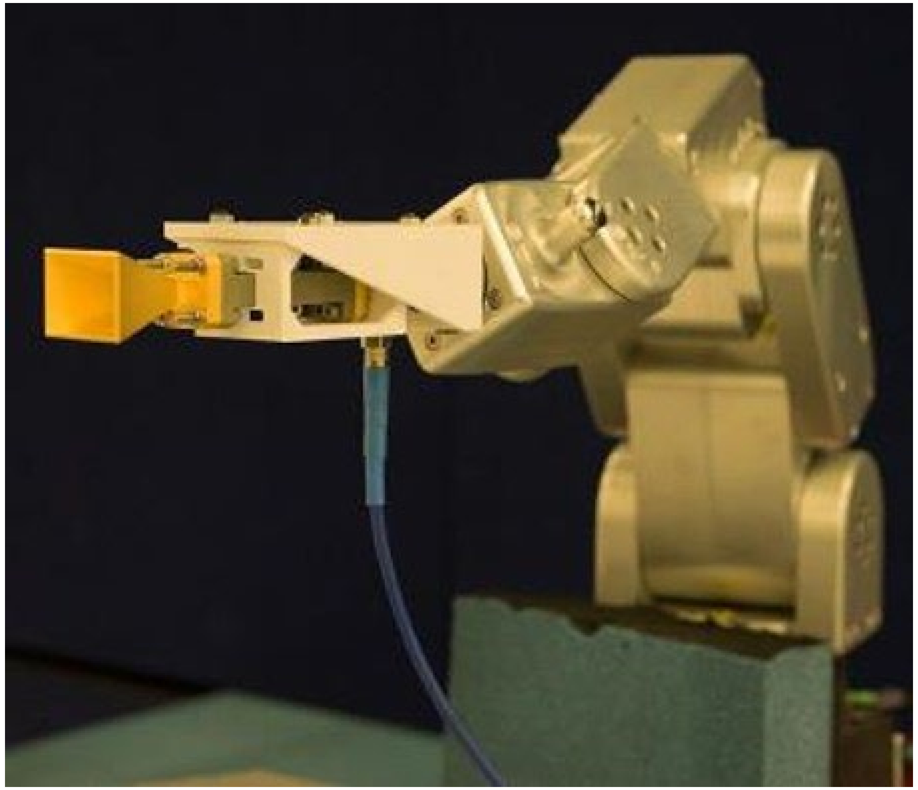


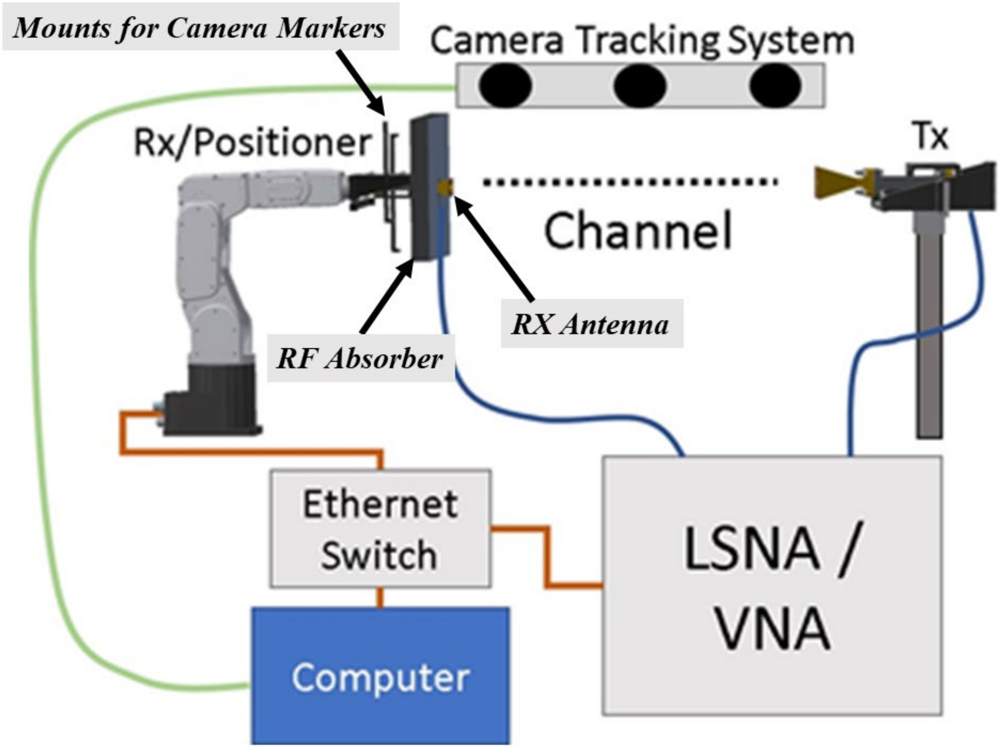
- *In 5G/6G communications above 28 GHz, path loss is a severe challenge and limits the range of wireless links*
- *An IRS is a large passive surface with discrete elements that can reflect impinging RF signals after imparting a phase shift from φ_1 to φ_2*
- *Evaluating the performance of an IRS is difficult since a manufactured version is not always available for testing*
- *A synthetic aperture however can serve as a proxy for the IRS and provide measurements of the phase of impinging signals in realistic multipath environments*

Sample Use Case



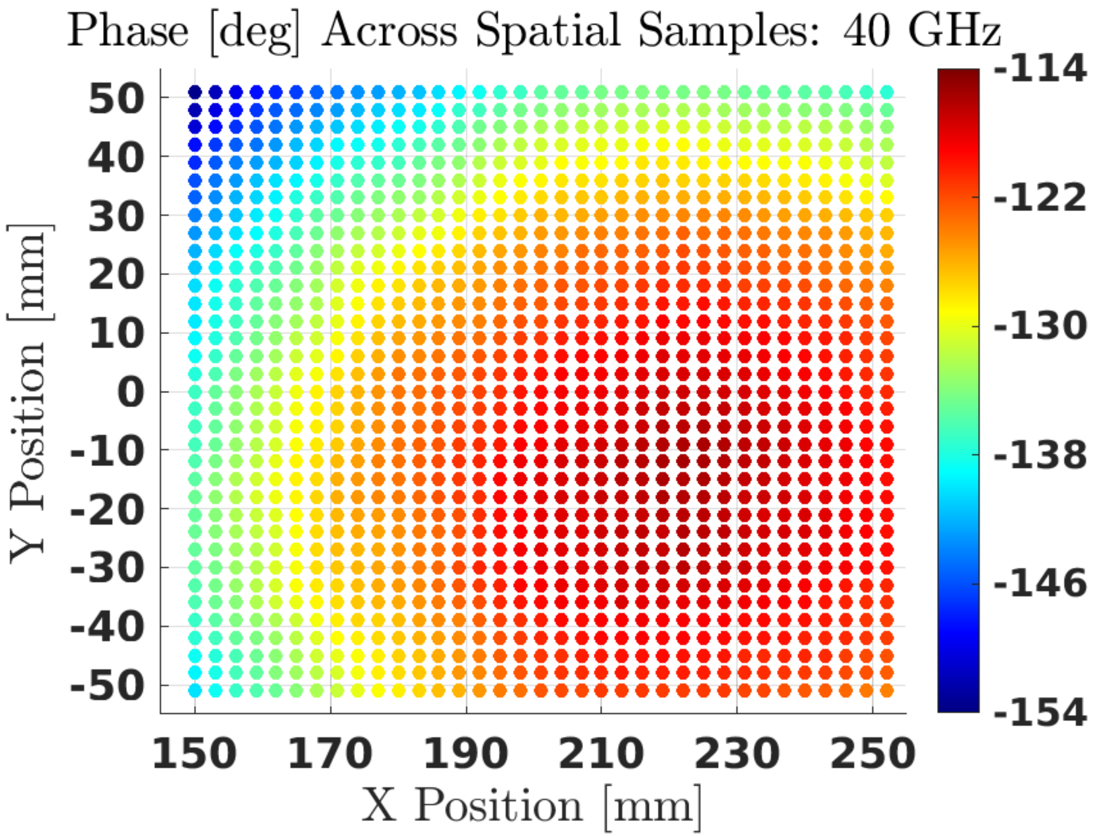
Synthetic Aperture

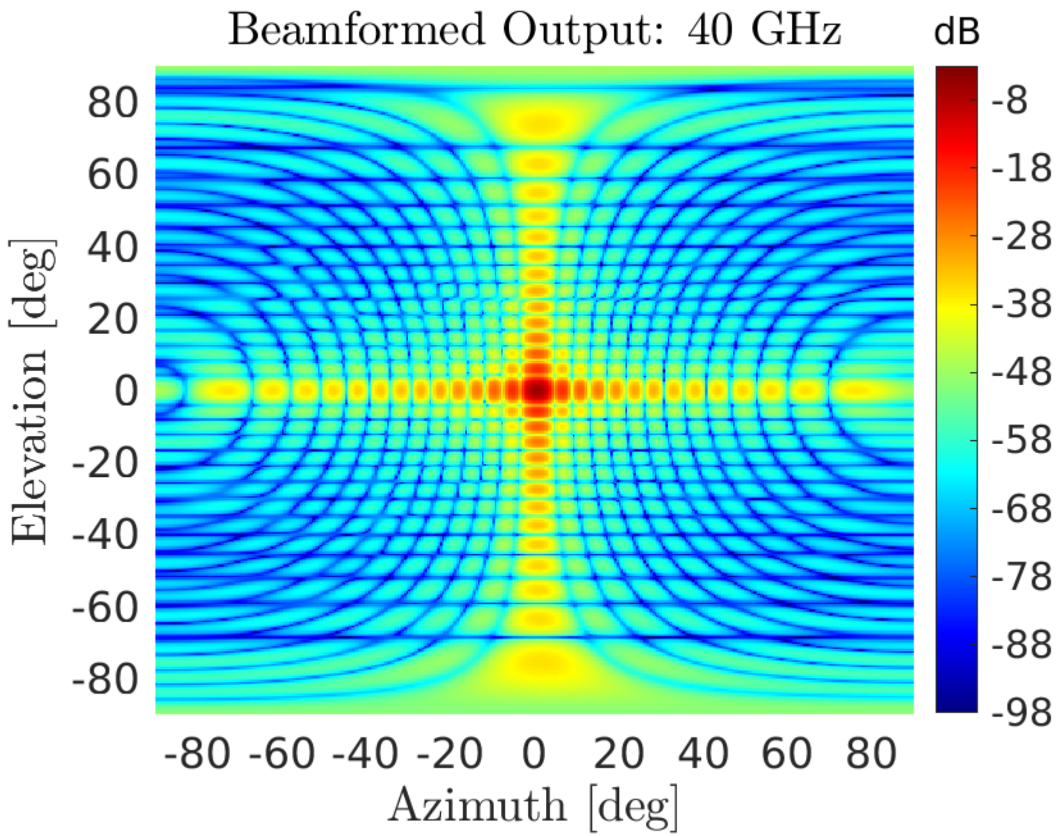




- ***A synthetic aperture is created by using a robot to move an antenna through space***
- ***The antenna samples the propagating electric fields at discrete points along a sampling lattice***
- ***If the measurements are phase coherent, they can be combined in post-processing to create high resolution images of the scattering environment***

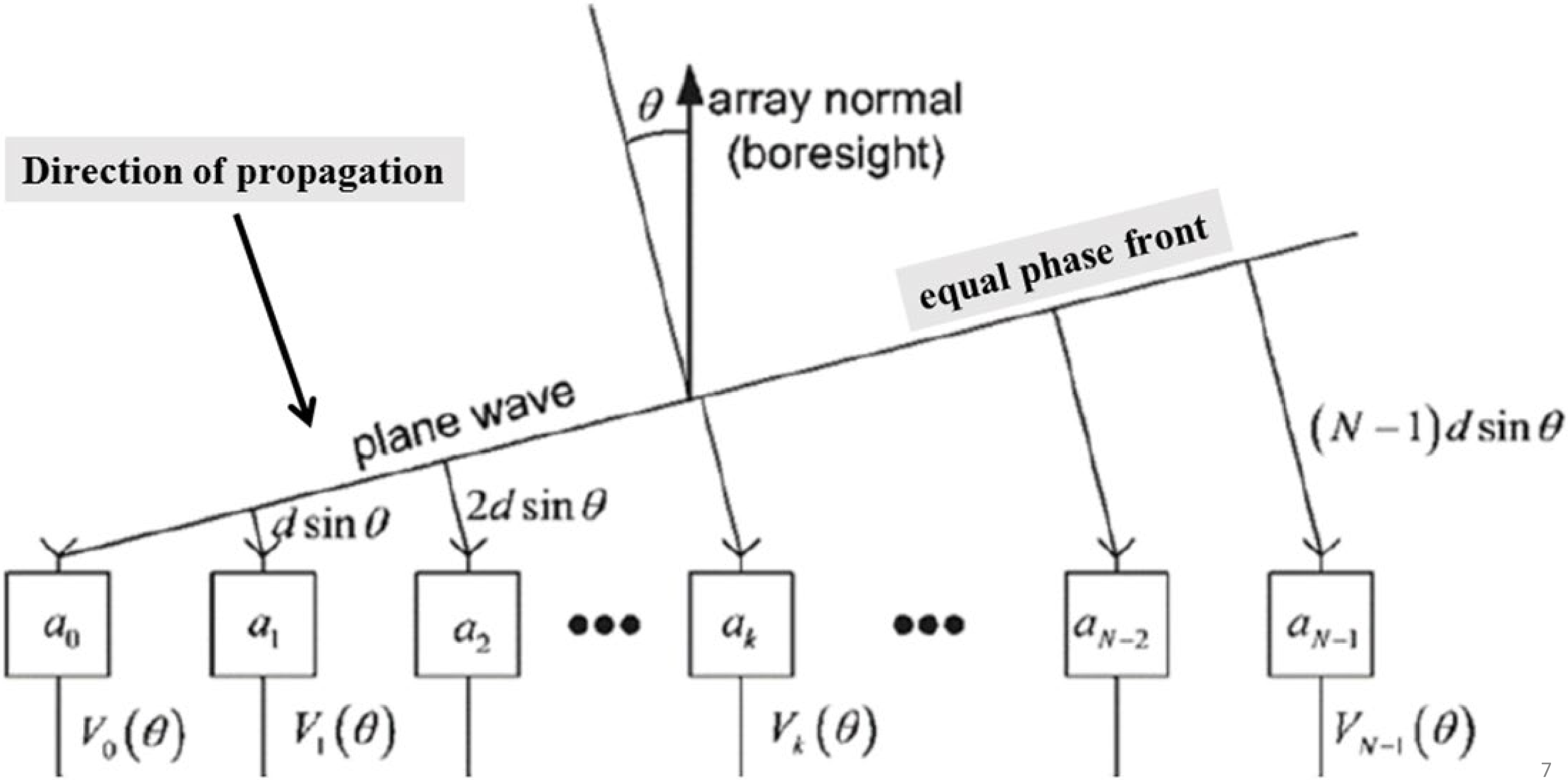
Point Spread Function



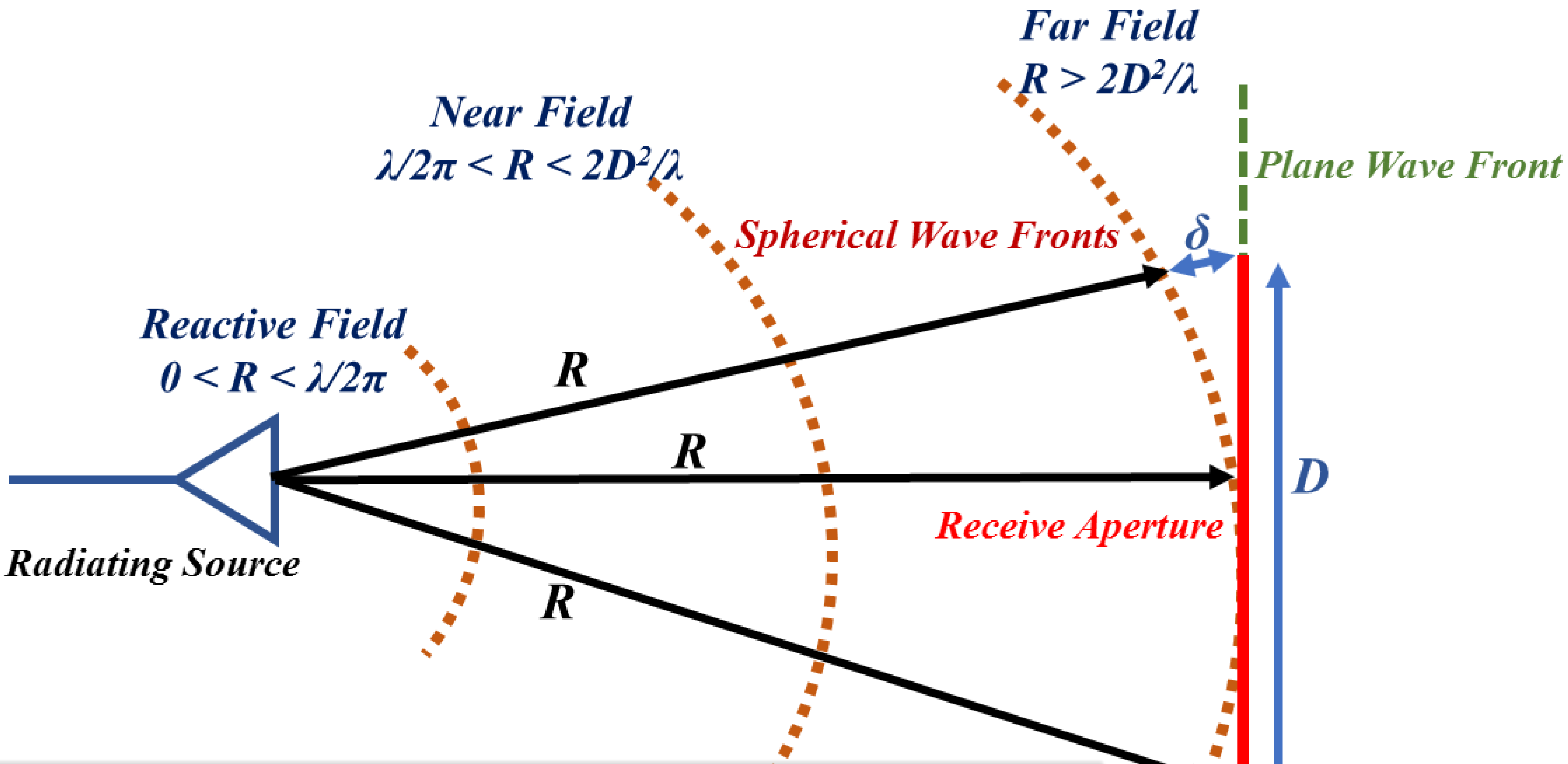


- ***Plot on left depicts phase of a sinusoidal signal at 40 GHz measured along a 35-by-35 planar grid***
- ***Plot on right illustrates the point spread function of a 35-by-35 synthetic aperture measured using a point scatterer (aluminum cylinder) at boresight***

Planar Wavefront



Spherical Wavefront



In the far field, the largest phase difference between the spherical wave and the plane wave corresponding to the path length difference δ satisfies

$$\Phi_{error} = (2\pi/\lambda)\delta \leq \pi/8 = 22.5°$$

Spherical Beamforming

- The field of a propagating monochromatic plane wave as a function of space ***x*** and time *t* is given by

$$U(\mathbf{x}, t) = e^{j2\pi(-\mathbf{v}^T\mathbf{x} + ft)}$$

- Here, **v** is spatial frequency along the propagation direction and *f* is temporal frequency
- Spherical beamforming accounts for the curvature of the phase front by computing steering vectors with distance-dependent phase according to

$$V(\mathbf{x}, t) = e^{-j\frac{2\pi}{\lambda}d(\mathbf{x})}e^{j2\pi ft}$$

- Here, *d*(**x**) is the distance between the signal source and the receive location **x**
- Each steering vector can be interpreted as a matched filter that maximizes the signal power received from a given angle of arrival and delay

3D Imaging

Algorithm 2 Spherical Phasefront PADP and Delay Slice Creation

Input: Array output vector $\mathbf{y}(\omega_k)$ at each frequency ω_k for $k = 0, \ldots, S-1$ and desired beam pointing direction (Az_0, El_0) corresponding to (u_0, v_0).

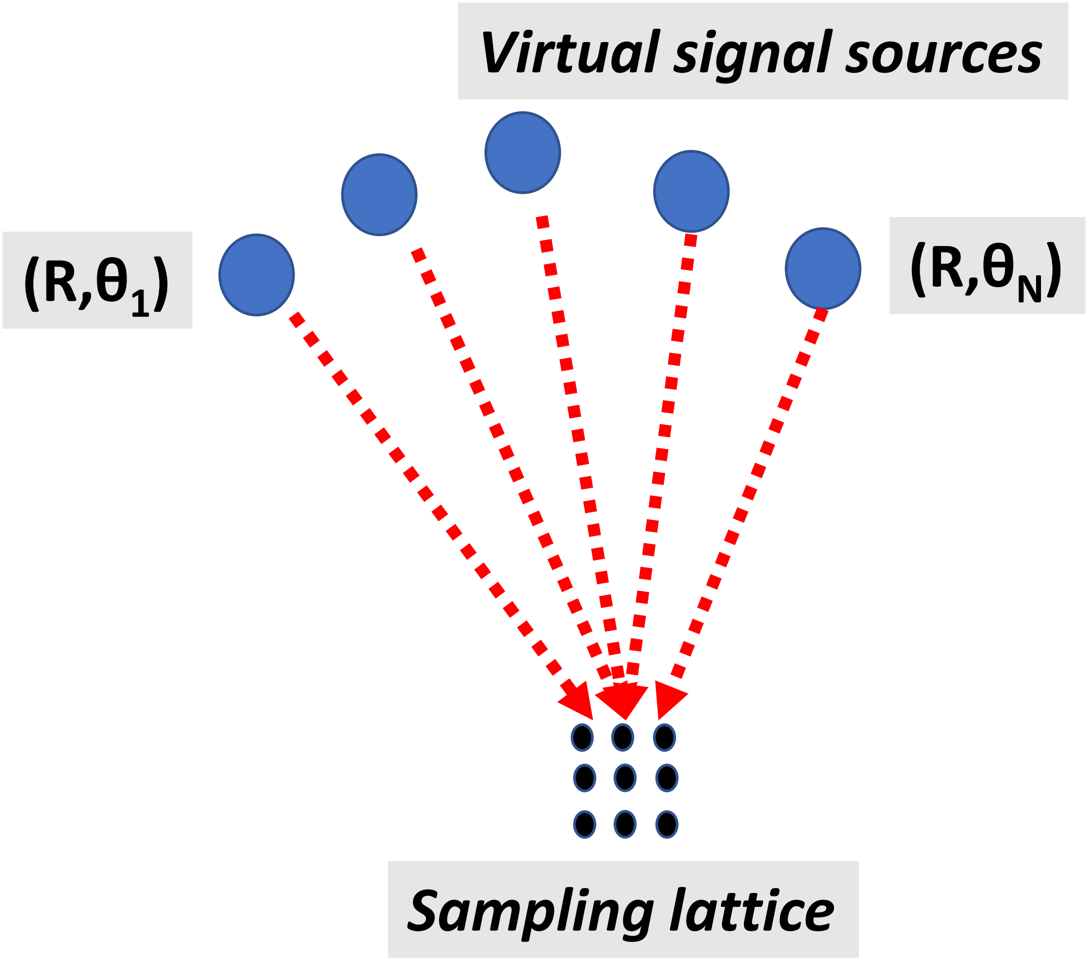
1: Starting from an initial range R_0 and proceeding to a final range R_1 in increments of ΔR, compute the Cartesian coordinates (x_k, y_k, z_k) corresponding to the spherical coordinates (R_k, u_0, v_0).

2: Compute the distance from (x_k, y_k, z_k) to each spatial sample in the synthetic aperture.

3: Compute the spherical steering vector, $\mathbf{w}(\omega_k; u_0, v_0, R_k)$, for each frequency. Each component of the spherical steering vector corresponds to the propagation phase $e^{jkD_{mn}}$ where $k = 2\pi/\lambda$. Here (m, n) denotes the indices of each spatial sample in the synthetic aperture and $D_{mn} = \sqrt{(x_k - x_m)^2 + (y_k - y_n)^2 + (z_k - z)^2}$.

4: Stack all the frequency-dependent steering vectors into $\hat{\mathbf{w}}(\omega; u_0, v_0, R_k)^H$ and all the array output vectors into $\hat{\mathbf{y}}(\omega)$. Then beamform the wideband array output by forming the dot product $b(u_0, v_0, R_k) = \hat{\mathbf{w}}(\omega; u_0, v_0, R_k)^H \hat{\mathbf{y}}(\omega)$

5: Repeat steps 1 through 4 for all angles on a discrete grid at a fixed range R_k to create a delay slice $x(u, v; R_k)$.



For each frequency, components of steering vector are range and angle dependent

Conventional Wideband Beamforming

Algorithm 1 PADP and Delay Slice Creation

Input: Array output vector $\mathbf{y}(\omega_k)$ at each frequency ω_k for $k = 0, \ldots, S-1$ and desired beam pointing direction (u_0, v_0)

1: Compute the phase steering vector for each frequency, $\mathbf{w}(\omega_k; u_0, v_0)$.

2: Beamform the array output vector $\mathbf{y}(\omega_k)$ at each frequency by forming the dot product $b(\omega_k; u_0, v_0) = \mathbf{w}(\omega_k; u_0, v_0)^H \mathbf{y}(\omega_k)$

3: Compute the Inverse Fourier Transform (temporal) to obtain the beam output (directional PDP), $x(\tau_k; u_0, v_0) = IFT[b(\omega_k; u_0, v_0)]$

4: To reduce high-frequency, time-domain ripple in wide bandwidth measurements and to increase sampling resolution, compute a window function c_k of length S with low sidelobes, e.g. Hamming window. Then zero-pad the sequence $c_k b(\omega_k; u_0, v_0)$ to L times its original length before computing the IDFT

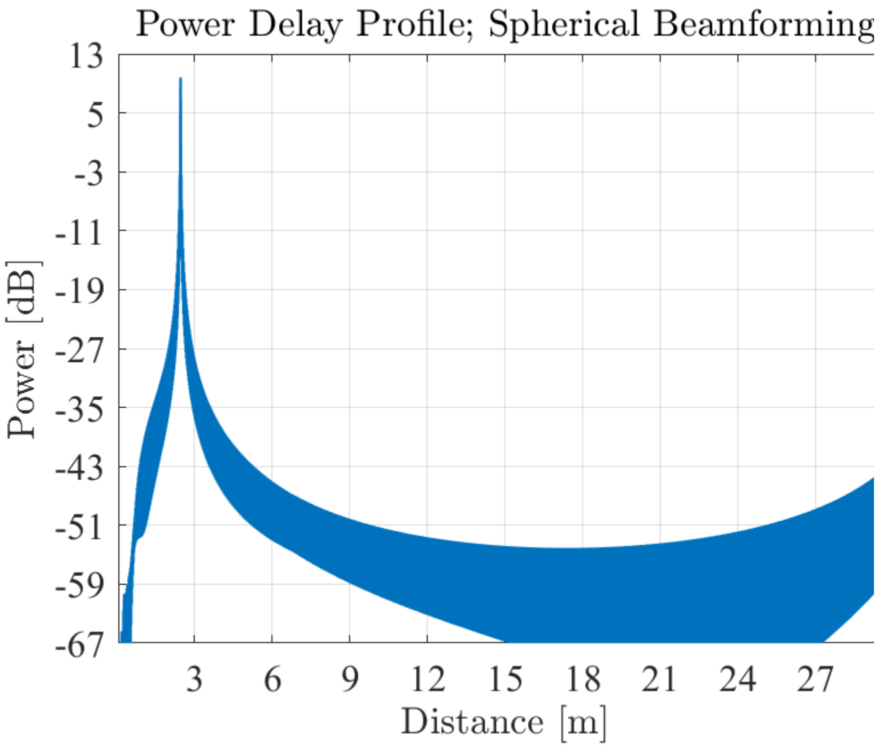
5: For a fixed delay, $\tau = \tau_0$, $x(\tau_0; u, v)$ is the spatial frequency spectrum of all signal sources impinging on the array (also called a delay slice) and can be used to estimate angles of arrival

Outputs: PDP $x(\tau; u_0, v_0)$ in the fixed direction (u_0, v_0). Delay slice $x(\tau_0; u, v)$ at the fixed delay τ_0.

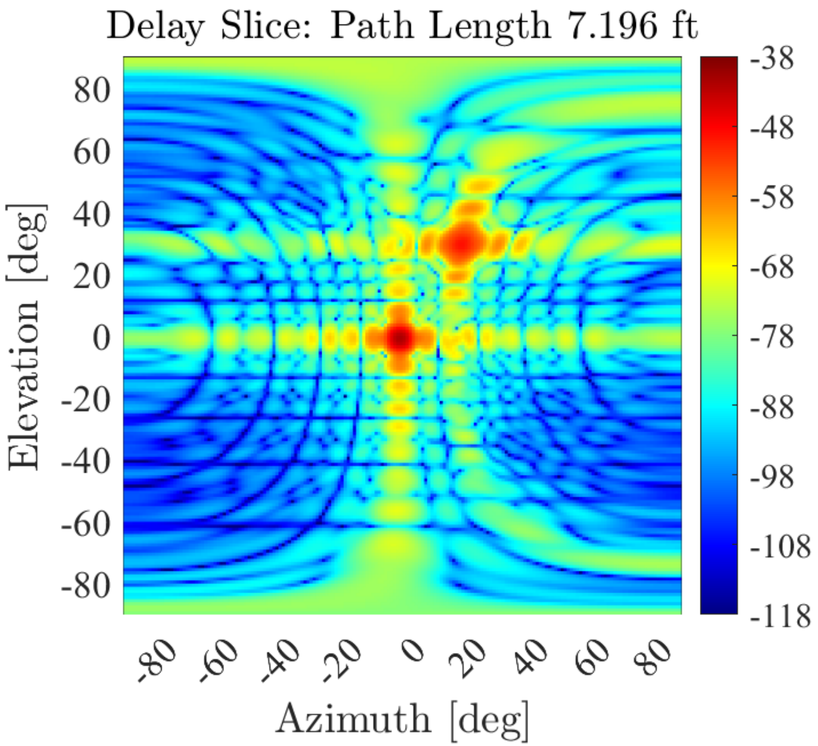
In conventional wideband beamforming, the steering vectors are angle and frequency dependent but range and delay invariant

Simulation Results

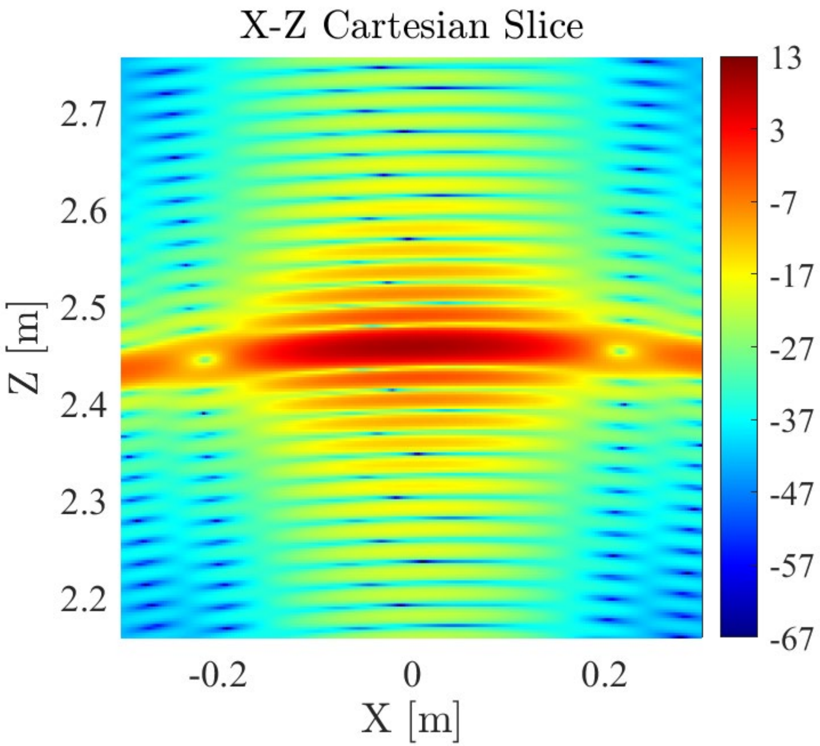
Power Delay Profile



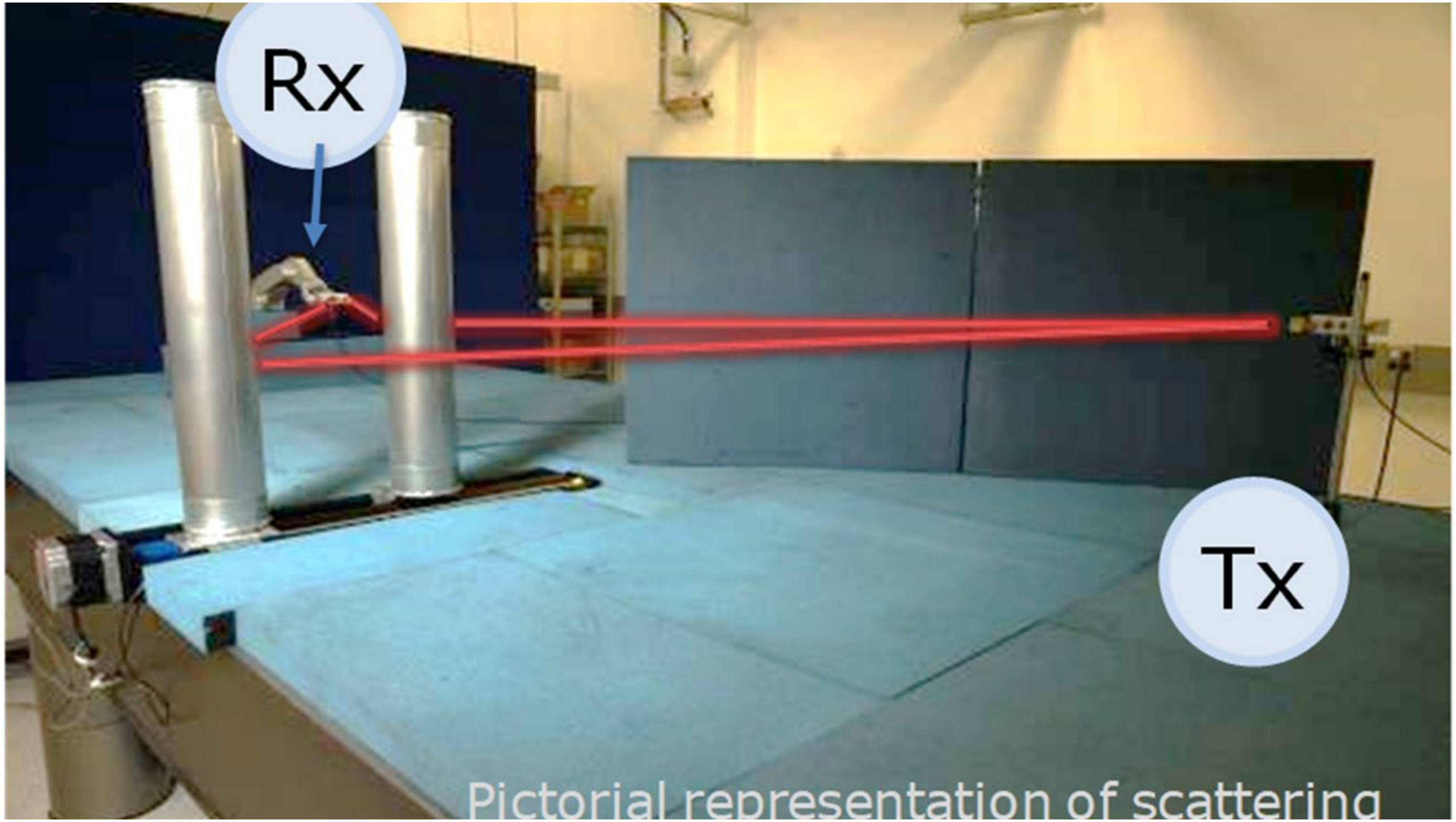
Delay Slice



Cartesian X-Z Slice



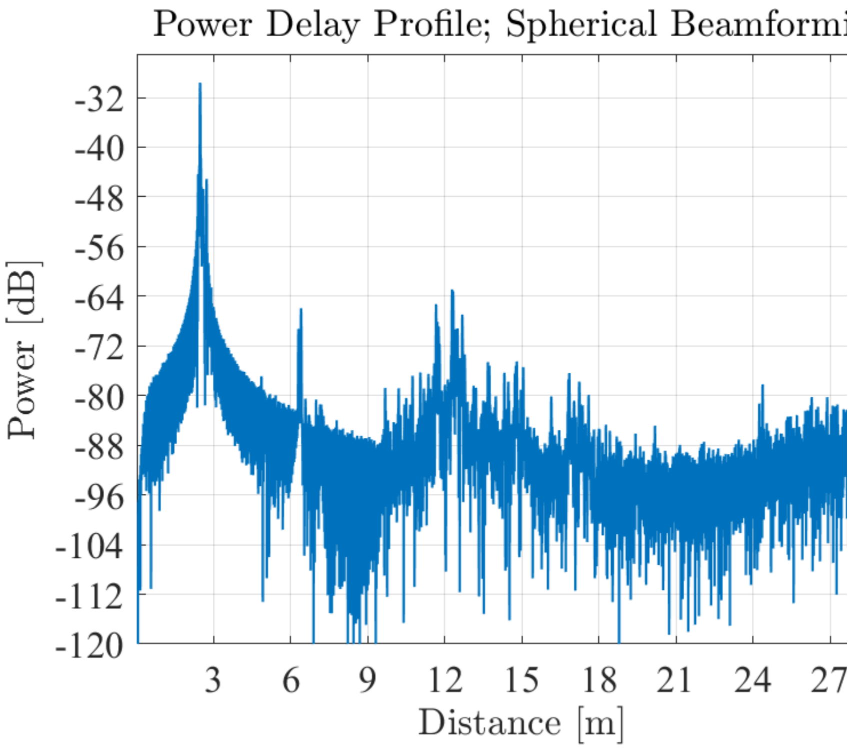
Measurement Scenario



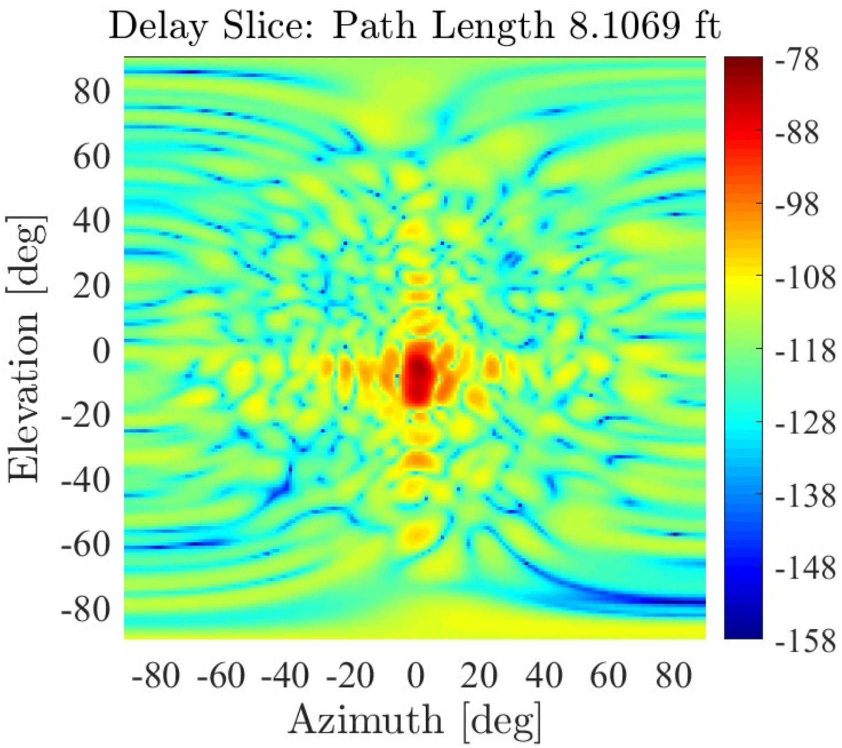
Two aluminum cylinders were measured on an optical table using a 35-by-35 synthetic aperture

Measurement Results

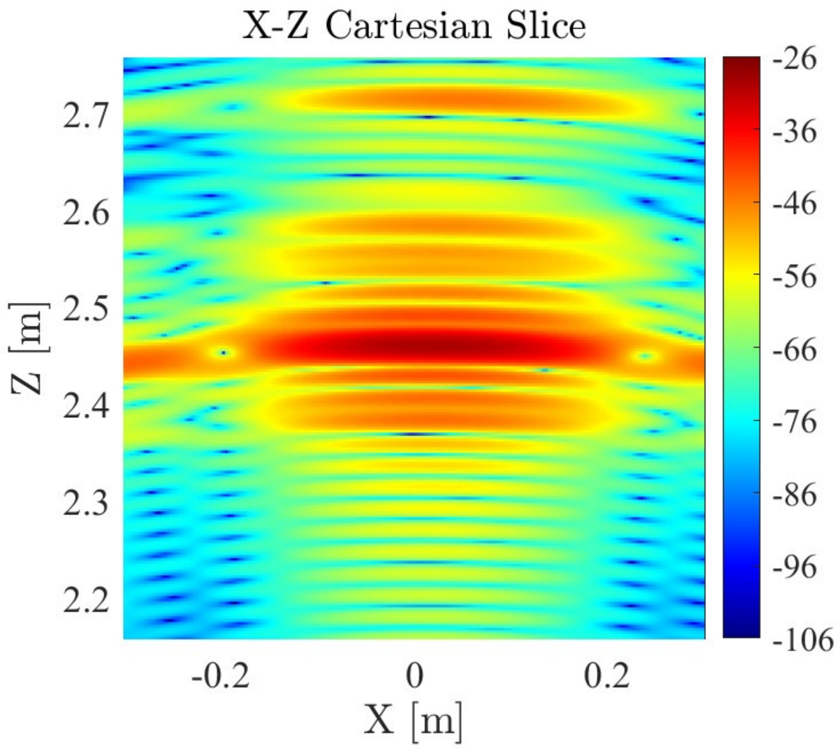
Power Delay Profile



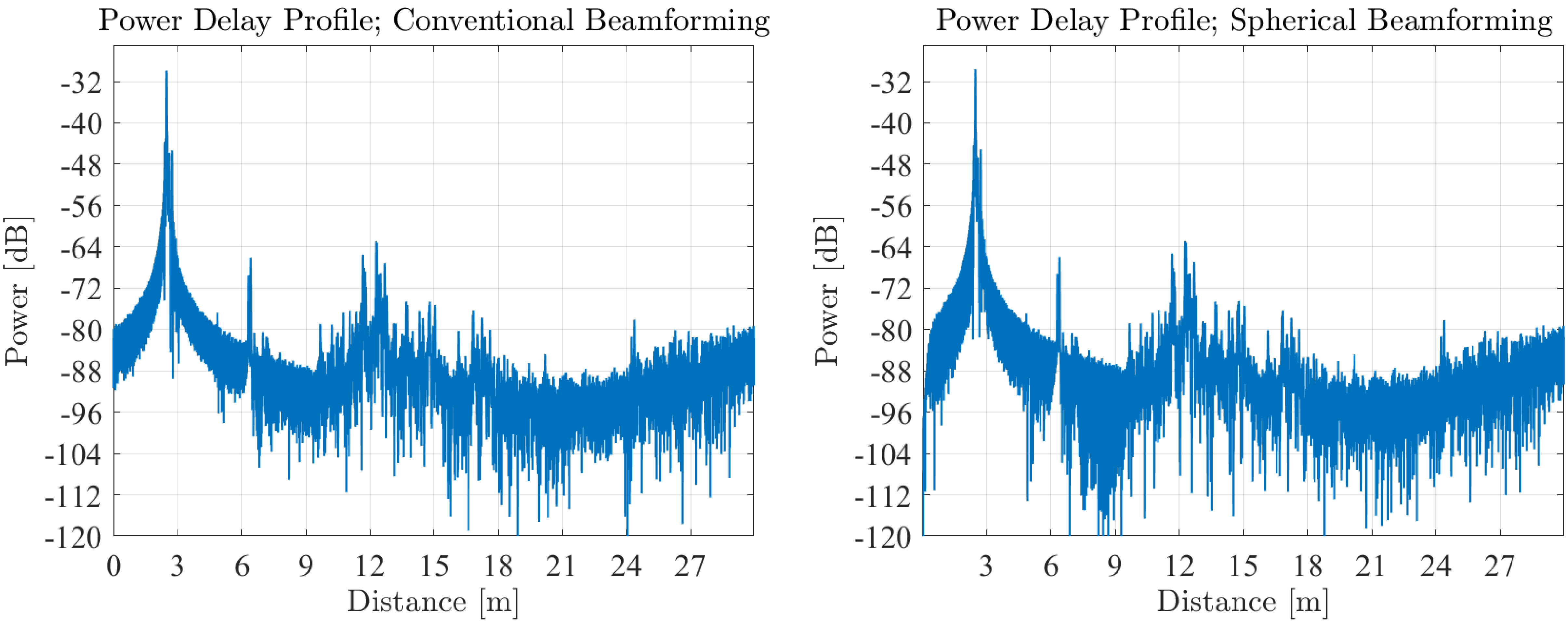
Delay Slice



Cartesian X-Z Slice



Conventional vs Spherical PDPs



Notional far field at 2.7 m

Conclusions

- In hardware implementations of beamforming, the phase front of impinging waves is assumed planar, consistent with far-field propagation
- In many metrology applications however, the spherical curvature of the phase front should be accounted for to provide most accurate results
- Spherical steering vectors account for the distance-dependent phase of incoming radiation
- Spherical beamforming is especially useful for evaluating the performance of Intelligent Reflecting Surfaces that operate in a mix of far-field and near-field conditions
- A synthetic aperture can measure the phase of an arriving signal as each element of an IRS sees it, and in realistic wireless channels with multipath