Reducing the Effects of RF Obstructions with Artificial Impedance Surface (AIS) technology

March 9, 2011

Christopher Magnan

Agenda

- ARA / HRL Collaboration
- AIS Technology
- AIS Fundamental Theory
- AIS Platform Integration and Results
- Current Development
  - Circular Polarization
  - Conformal AIS Appliques
  - Lower Dielectric Material
- Future Development
- Conclusions
- Questions

ARA / HRL AIS Collaboration

- HRL developed the AISA technology to redirect RF radiation around obstructions.
- In 2010, ARA and HRL collaborated to integrated a curved AISA surface onto UAV fuselage.
  - ARA learned theoretical concepts of AISA technology
  - ARA designed and fabricated a test platform to characterize the AIS
  - ARA developed manufacturing plans to fabricate AIS PCBs.
- In 2011, ARA and HRL are collaborating to develop a circularly polarized conformal AIS.
- In 2012, ARA will begin environmentally qualifying the conformal AIS.

AIS Technology

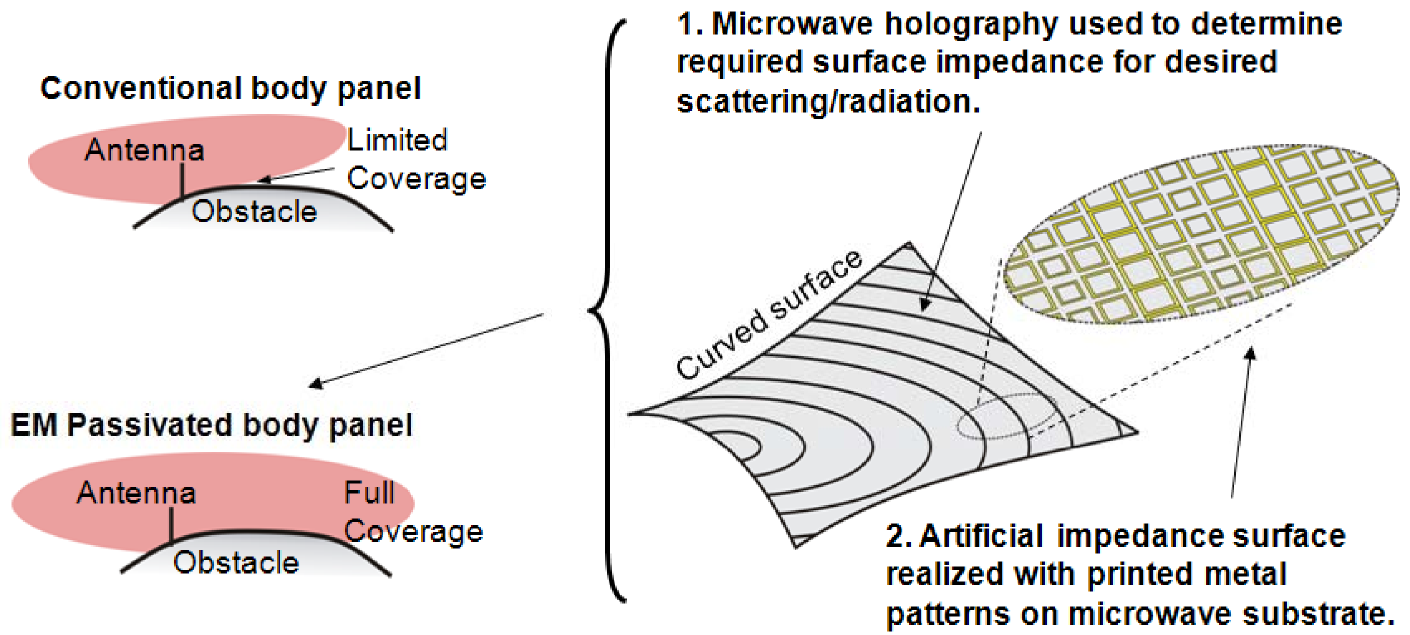
- AIS Technology is a synthesized impedance surface that redirects RF radiation past obstruction
- AIS's optical analog of the diffraction grating
  - Surface waves on AIS produce interference pattern.
  - Primary radiation lobe is developed by interference pattern.
  - Lobe angle is frequency dependent.

AIS Competing Technologies

- Electromagnetic Bandgap (EBG)
  - Manufacturing very complex
  - Band-limited
- Dielectric Coatings
  - Not applicable for complex systems
  - Scattering occurs between non-homogenous layers

AIS IS MORE COST-EFFECTIVE AND VERSATILE

AIS Technology: Use the surface of the platform as the aperture



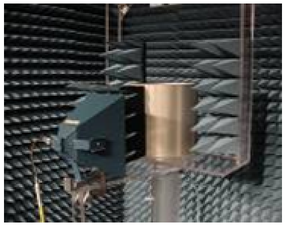
Approach:

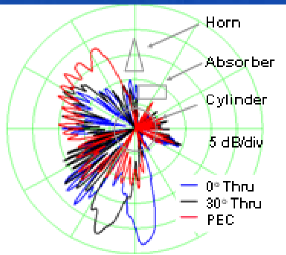
- Use fine (<<λ) metal patterns to create large scale (~λ) index variations – Artificial Impedance Surface
- Large scale (~λ) index variations can produce controlled radiation – Microwave holograph

AIS Approaches to Reduce Structural Effects

Apply AIS on an obstruction to capture free space wave and wrap energy around

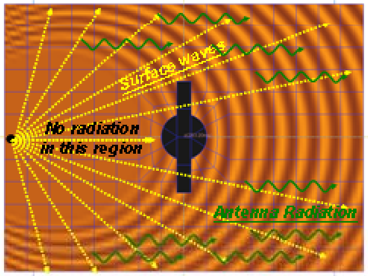
- Previously demonstrated
- Less dependent on the excitation source
- Applicable to larger, fixed obstructions





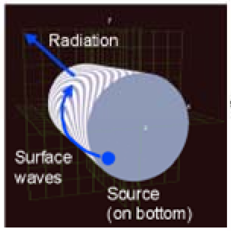
Use AIS to route excitation surface wave energy around obstruction and then radiate it

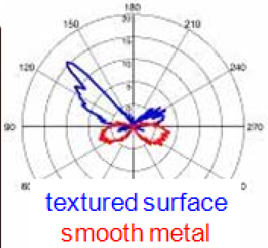
- Dependent on the source excitation
- Nothing to attach to the obstruction

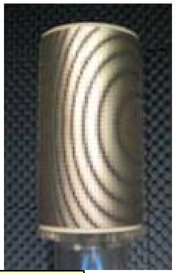


Use AIS to route surface wave energy around surface curvature

- Previously demonstrated
- Dependent on the source excitation
- Can be used to reduce finite ground plane size affects



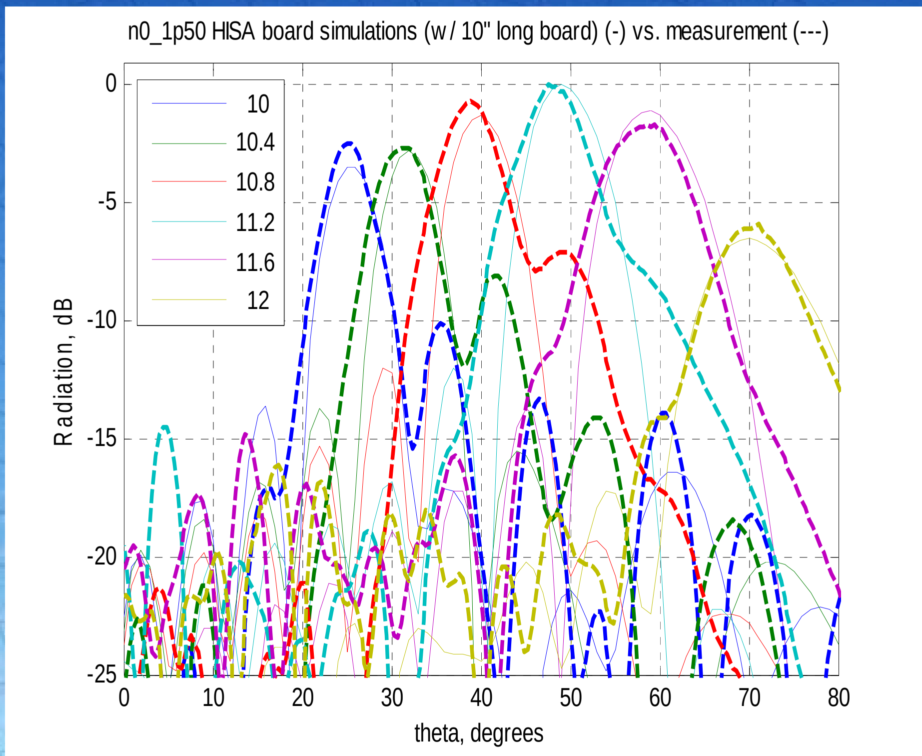


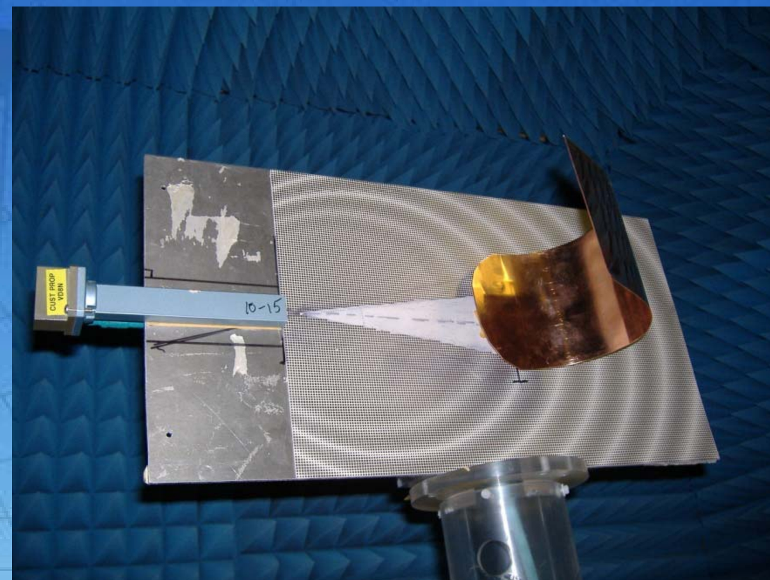


All three approaches can be applied to reduce real world structural obstructions/scattering pattern degradations

AIS Technology Benchmark Metrics

- Beam squint– angle / frequency ratio
- Peak angle
- 3 dB beamwidth
- Peak intensity


n0_1p50 HISA board simulations (w / 10" long board) (-) vs. measurement (---)
Radiation, dB
theta, degrees
0
-5
-10
-15
-20
-25
0
10
20
30
40
50
60
70
80
10
10.4
10.8
11.2
11.6
12


10-15

AIS Fundamental Theory

AIS Fundamental Theory

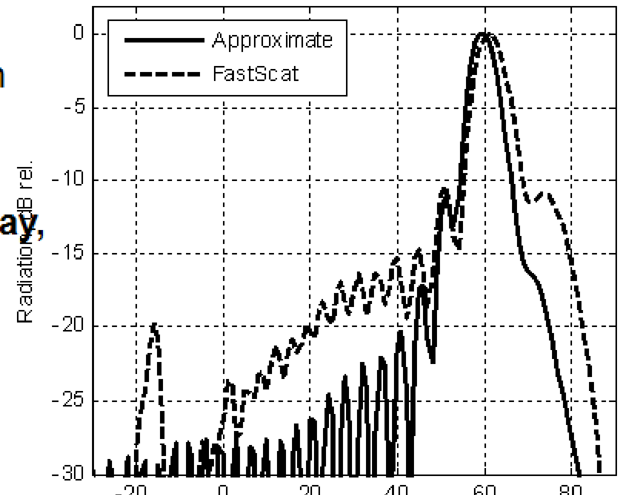
- Compute integral of the fields due to the surface wave currents

$$\vec{\mathbf{E}}_{rad}\left(\vec{\mathbf{k}}\right) \sim \int_{AIS} \left[\left(\hat{\mathbf{k}} \times \vec{\mathbf{J}}_{sw}\left(\vec{\mathbf{r}}\right)\right) \times \hat{\mathbf{k}}\right] \; e^{-i\vec{\mathbf{k}}\bullet\vec{\mathbf{r}}} \, d^2 r$$

- For flat AISA can simplify to $\vec{\mathbf{E}}_{rad}\left(\vec{\mathbf{k}}\right) \sim \int_{AIS} \left[\left(\hat{\mathbf{k}} \times \hat{\mathbf{j}}_{sw}\left(\vec{\mathbf{r}}\right)\right) \times \hat{\mathbf{k}}\right] \; e^{i\left[k\int_0^r n_{sw}(\vec{\mathbf{r}}')\,dr' - \vec{\mathbf{k}}\bullet\vec{\mathbf{r}}\right]} d^2 r$
- The field term can be written as a product of the surface current's magnitude, $j_{sw}\left(\vec{\mathbf{r}}\right)$, and the field's angular distribution, $\vec{\mathbf{P}} = \left[\left(\hat{\mathbf{k}} \times \hat{\mathbf{j}}_{sw}\left(\vec{\mathbf{r}}\right)\right) \times \hat{\mathbf{k}}\right]$
- The radiation angular range limitation is

$$\vec{\mathbf{P}} = \begin{cases} \cos(\phi-\phi_r)\cos(\theta)\,\hat{\theta} \; - \sin(\phi-\phi_r)\,\hat{\phi}; & TM \\ -\cos(\phi-\phi_r)\,\hat{\theta} \; - \sin(\phi-\phi_r)\cos(\theta)\,\hat{\phi}; & TE \end{cases}$$

  - Vertical polarization is practically limited to 75° from normal by cosine term
  - No limitation on horizontal polarization
- **Making some approximations of surface wave decay, the far field pattern good approximation for engineering studies**
  - Implemented approximation integral in Matlab
  - Good correlation with FastScat simulation for main beam angle and firs few sidelobes

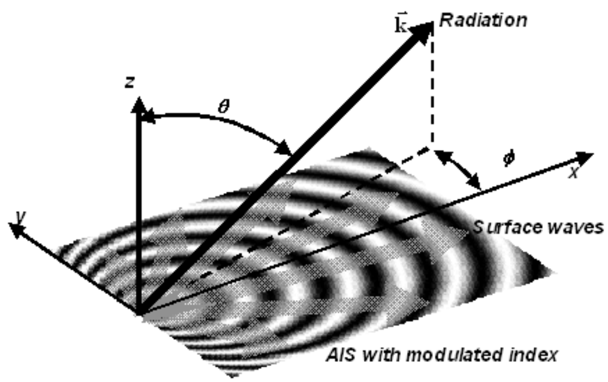


AIS Design Algorithm

- Match the surface wave index to the desired plane wave with the AIS grid momentum

$$k_{sw} = k_o \sin\theta_o - k_p \qquad k_p = \frac{2\pi}{\lambda_p} = k_o\left(n_o - \sin\theta_o\right)$$

  - k_o is the radiation's free-space wavenumber at the design frequency
  - θ_o is the angle of the desired radiation with respect to the AIS normal,
  - $k_p=2\pi/\lambda_p$ is the AIS grid momentum where λ_p is the AIS modulation period,
  - $k_{sw}=n_o k_o$ is the surface wave's wavenumber, where n_o is the surface wave's refractive index averaged over the AIS modulation



- Replace k_p by integral multiple of the first equations

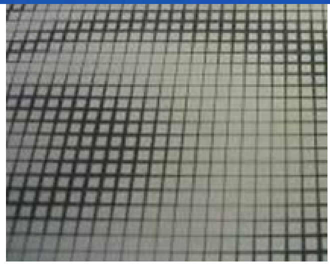
$$\sin(\theta_m) = n_o - m k_p / k, \quad m = 1, 2, 3, \ldots \mathrm{int}\left(\frac{k}{k_p}(n_0 + 1)\right)$$

  - the beam peaks of all modes can be determined, m = 1 is the main lobe
  - This equation can be used to quantify the AISA beam squint which limits bandwidth

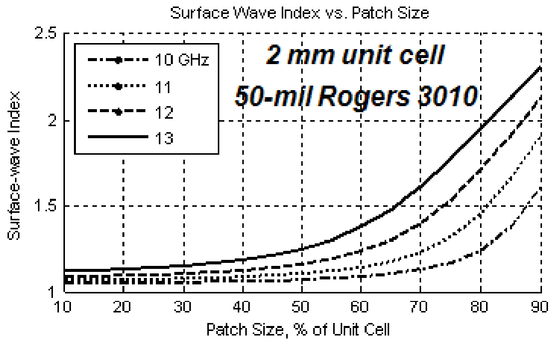
- The wavenumber k_o can be expressed as periodic variation in the surface-wave propagation index

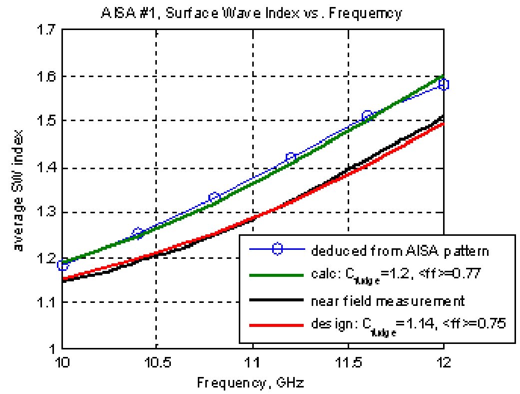
$$n_{sw}(\bar{\mathbf{r}}) = n_o + dn\cos(k_o n_o r - \bar{\mathbf{k}}_o \cdot \bar{\mathbf{r}})$$

- Control surface wave index with a grid of metal patches
  - Values can be computed with analytic expressions in many cases
    - ➢ Patch size large relative to substrate thickness
    - ➢ Surface wave phase shift per unit cell not close to 180 deg.
  - Can be computed with unit cell simulation



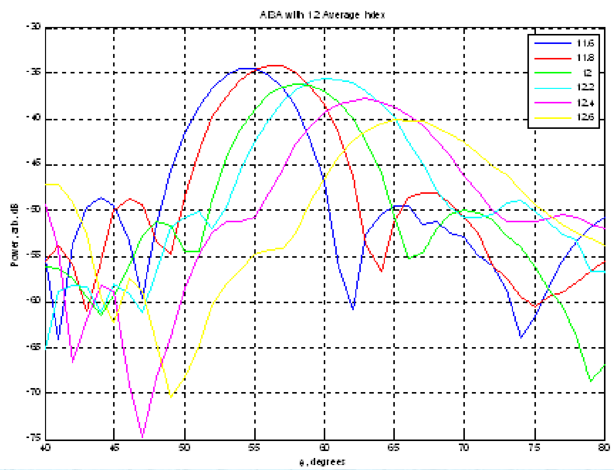
- Index has strong dependence on frequency, especially for higher indexes; this dominates beam squint

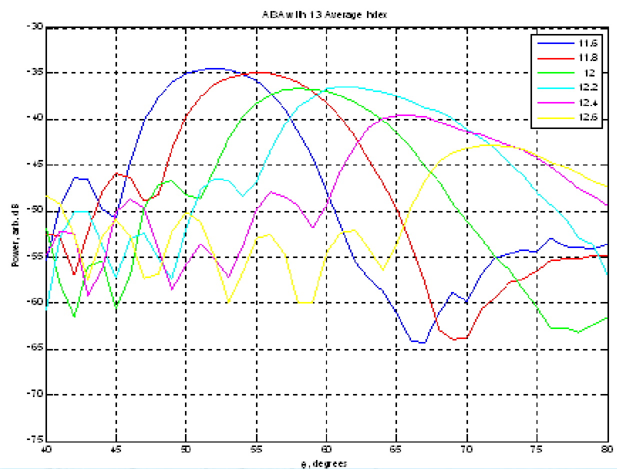




- Experience has shown need for scaling factors to match theory with measurements, but once determined (for substrate and freq.) can be used for design
  - Exact reasons not clear, but think it is related to
    - ➢ Finite surface affects
    - ➢ Varying index
  - This is topic area for future research

- AIS beam squint can be expressed as $\frac{d\theta}{dk} = \frac{1}{\cos(\theta)}\left(\frac{dn_o}{dk} + {k_p}/{k^2}\right)$
- Two components are
  - AIS's index dispersion
  - AIS modulation's Floquet term
- To eliminate beam squint would need negative dispersion $\frac{dn_o}{dk} = -{k_p}/{k^2}$
  - Possible with active circuits?
  - Topic area for further research
- From our experience the AIS's dispersion is significant
- Most straight forward way to increase bandwidth is to reduce the average AIS index

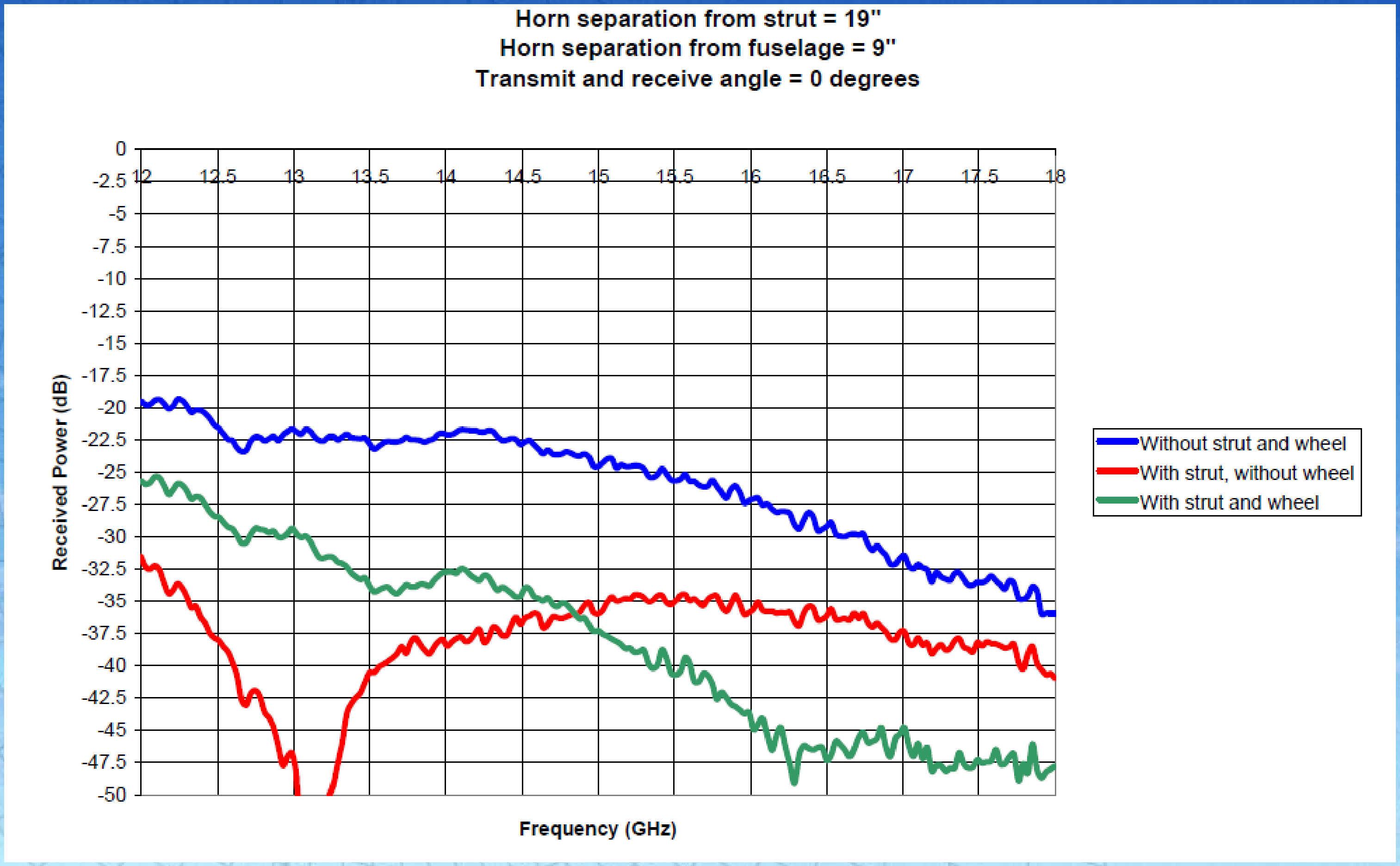




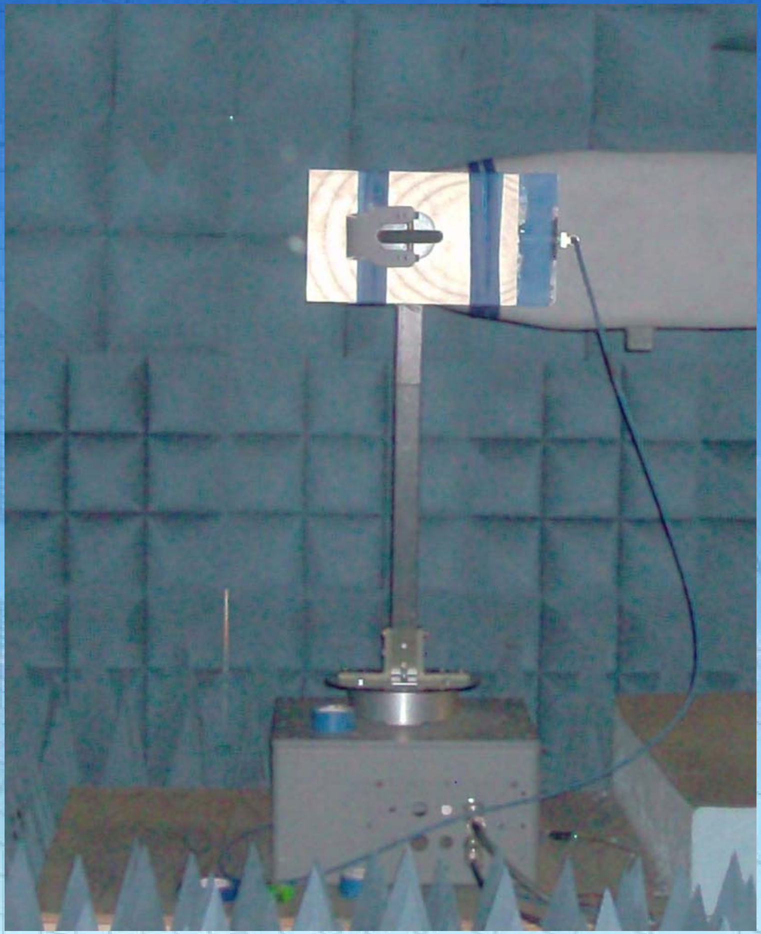
AISA Platform Integration

Obstruction Characterization

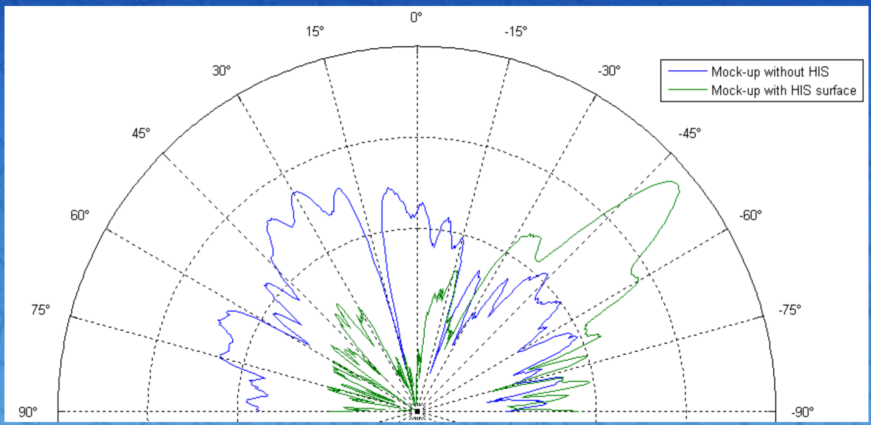
Obstruction Characterization



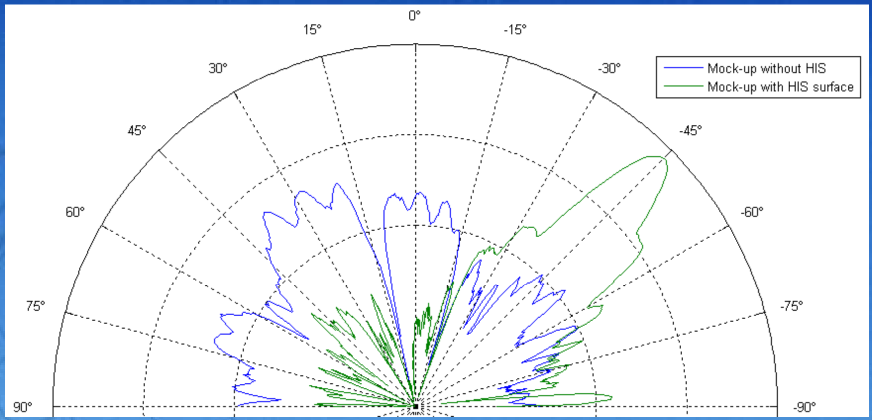
AISA
Characterization Setup



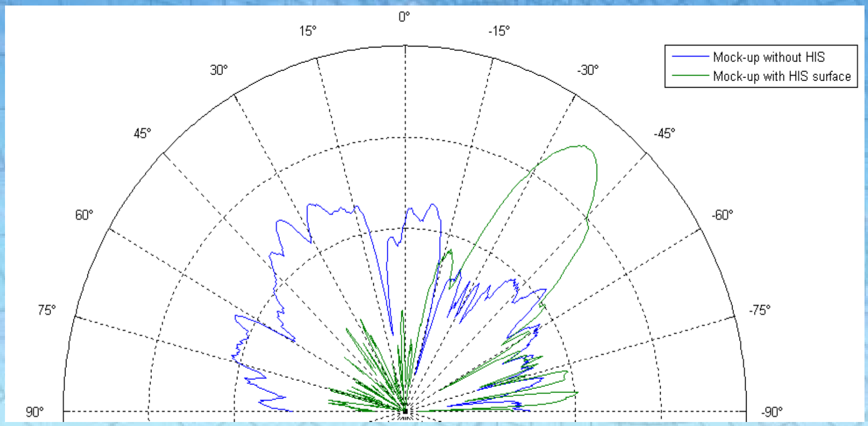
ACIN Elevation Characterization



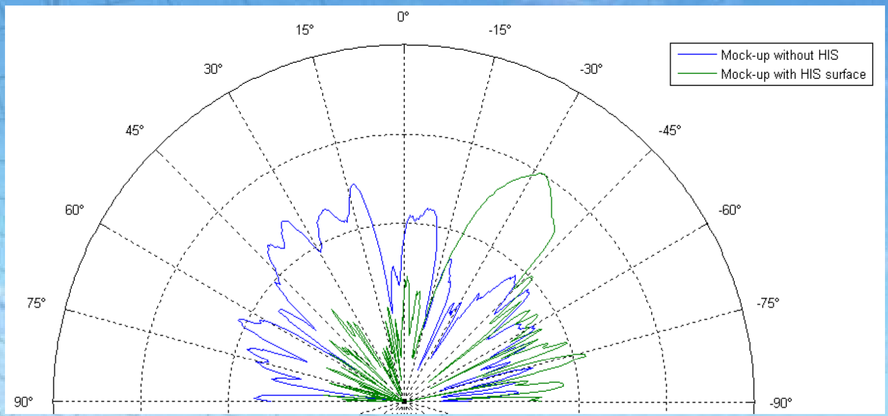
10.6 GHz



11 GHz



11.4 GHz

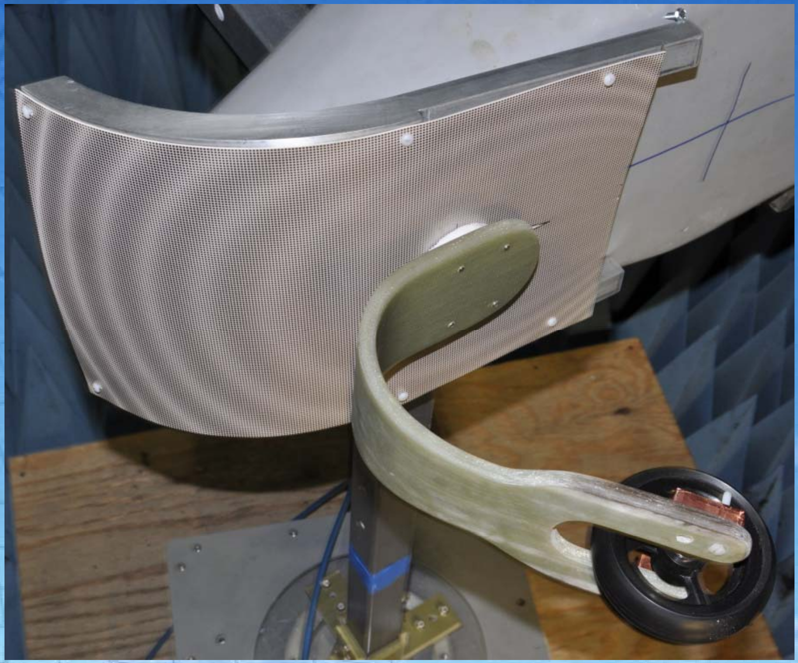


11.8 GHz

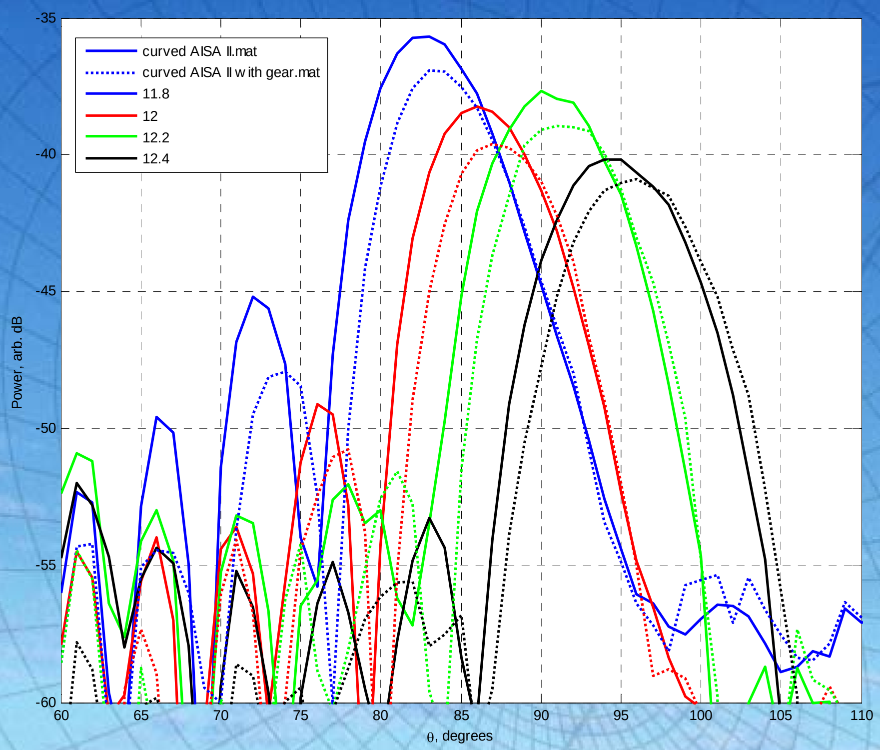
AIS Design Approach

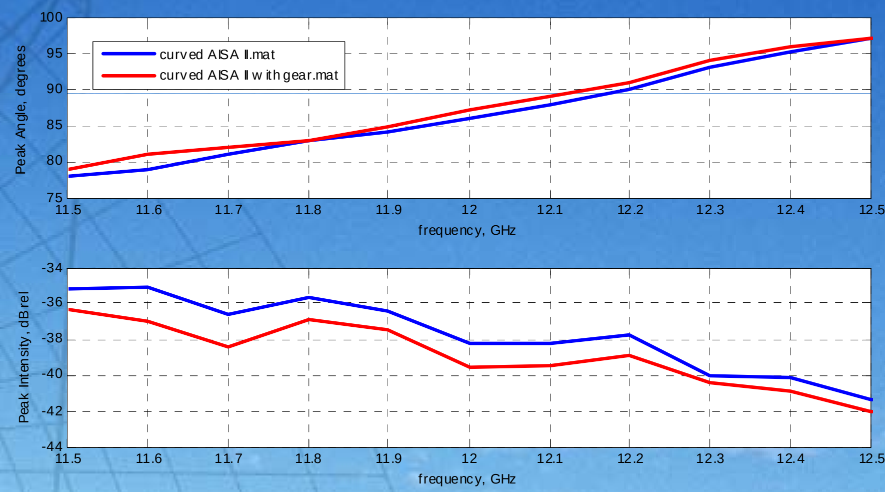
- Empirically derive surface wave and modulation indices
  - Characterize Flat Panel Designs
  - Optimize AIS bandwidth / decrease beam squint
- Curve AISA to achieve near horizon coverage
  - Compensate for finite ground plane
  - Extend coverage beyond AIS angle limitations
- Optimize pattern on AIS to mitigate the obstacles

Curved AIS Design

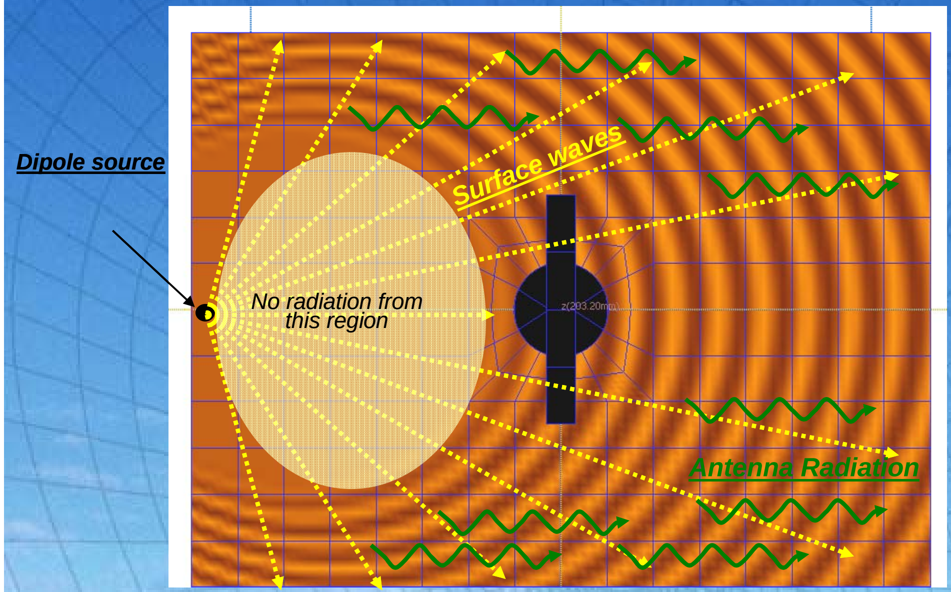


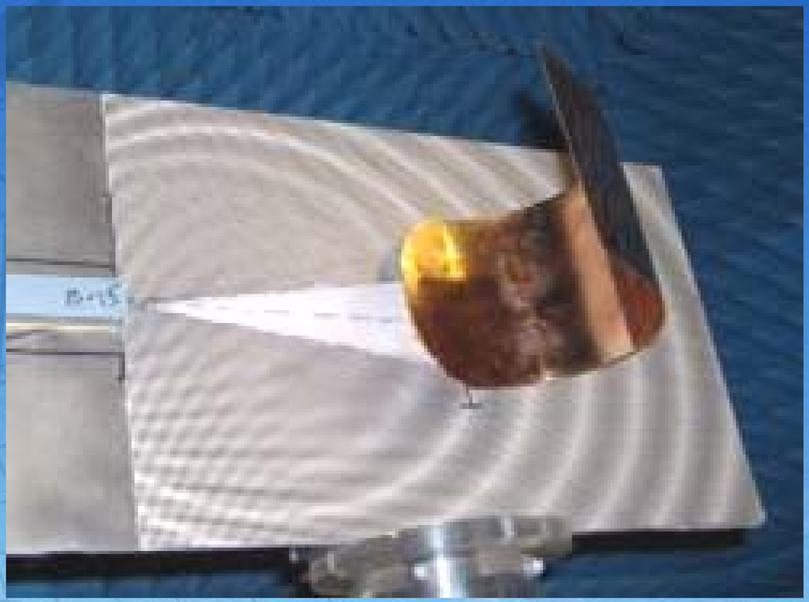
Curved AIS Design Results





Strut Effect

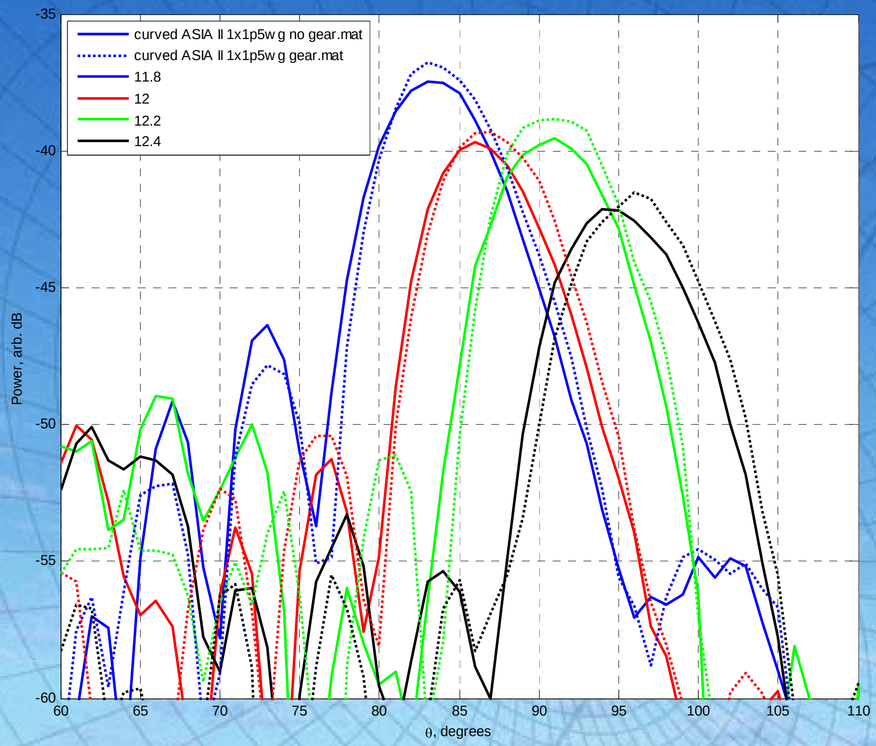


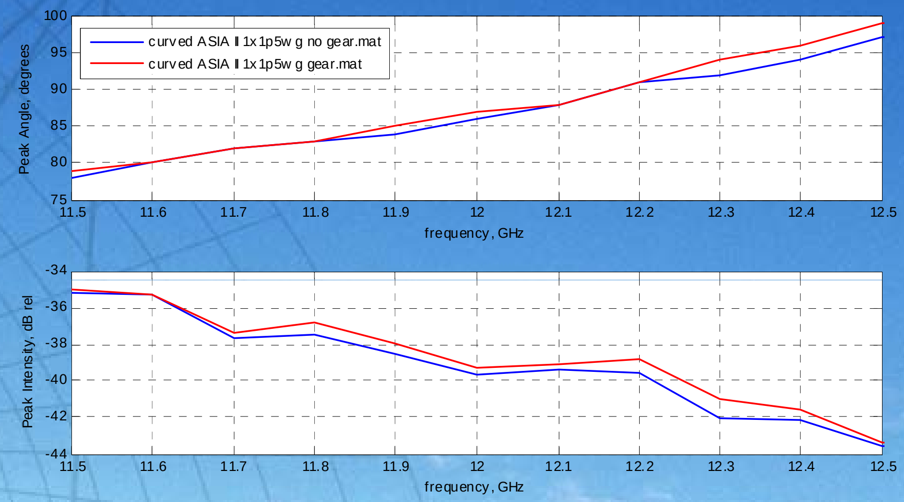


Surface Waveguide

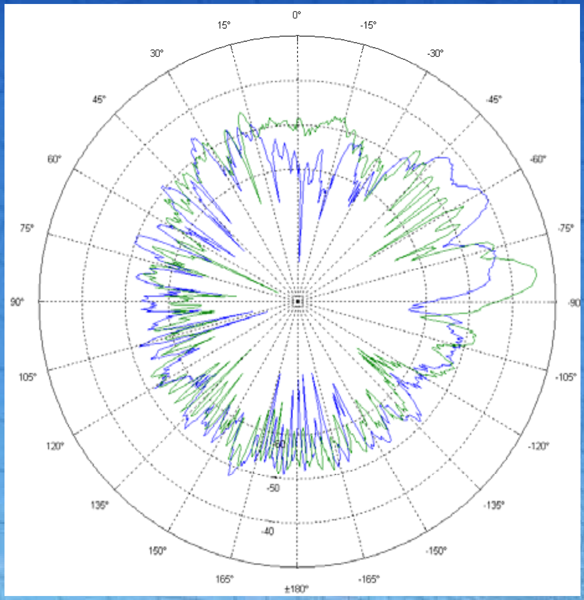
- Index is tailored by selectively removing metal to produce a region of comparatively low surface-wave index.
  - Low-index region guides surface-wave energy away from it
  - Physically analogous to a dielectric waveguide

Curved AIS with Optimized Waveguide

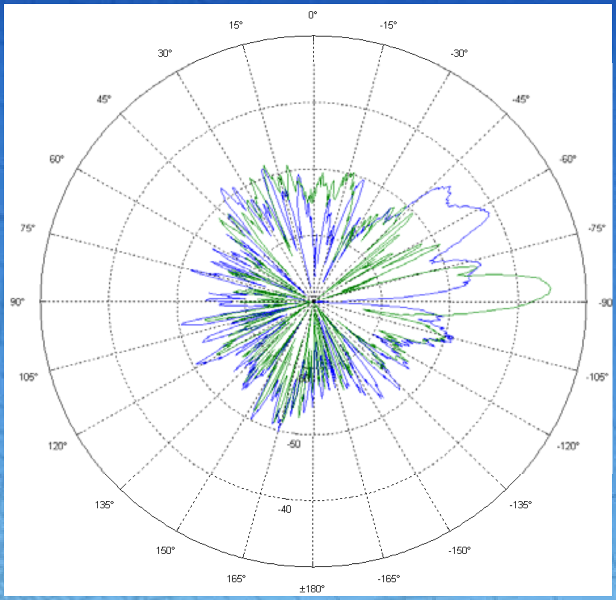




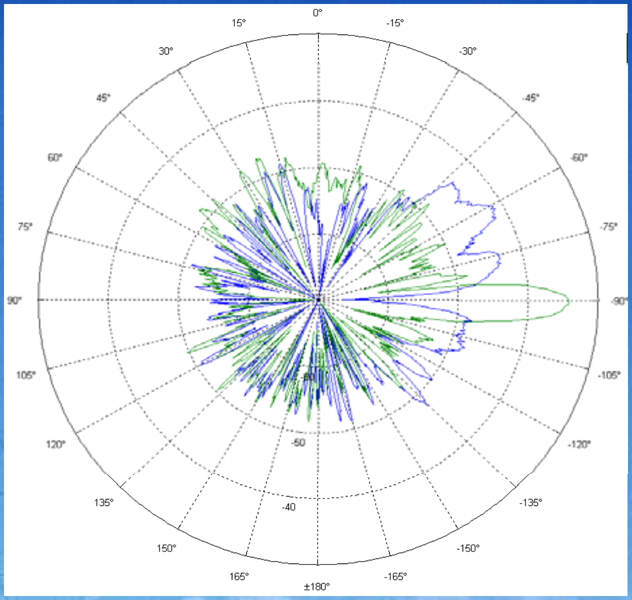
AIS Comparison to Aluminum Sheet



11.6 GHz



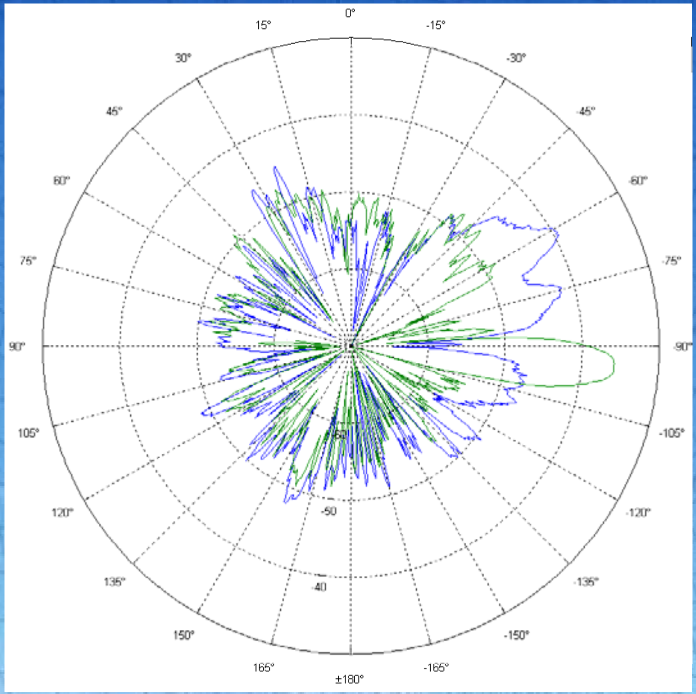
11.8 GHz



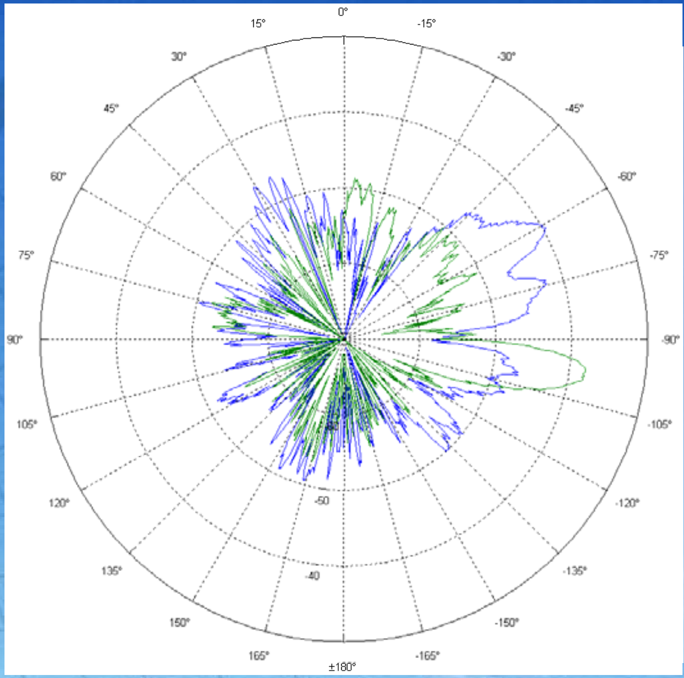
12 GHz

Aluminum Sheet
Waveguide Curved AISA

AIS Comparison to Aluminum Sheet



12.2 GHz

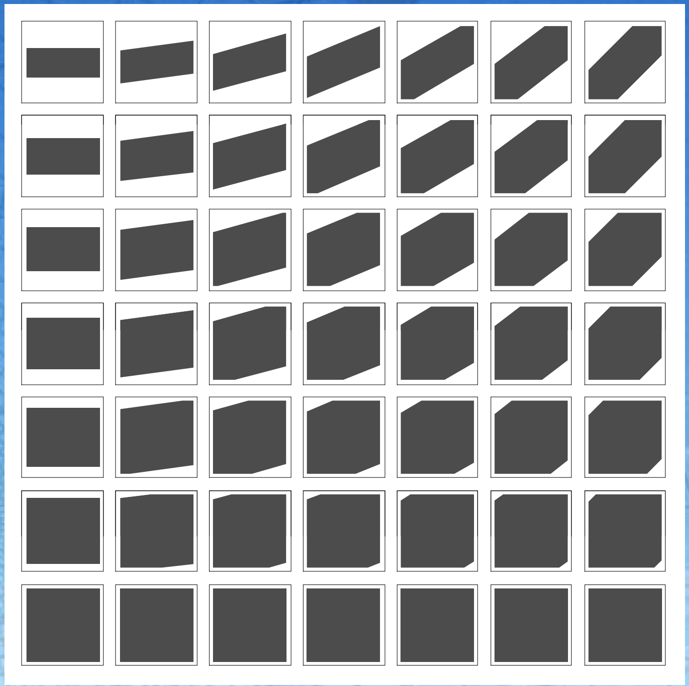


12.4 GHz

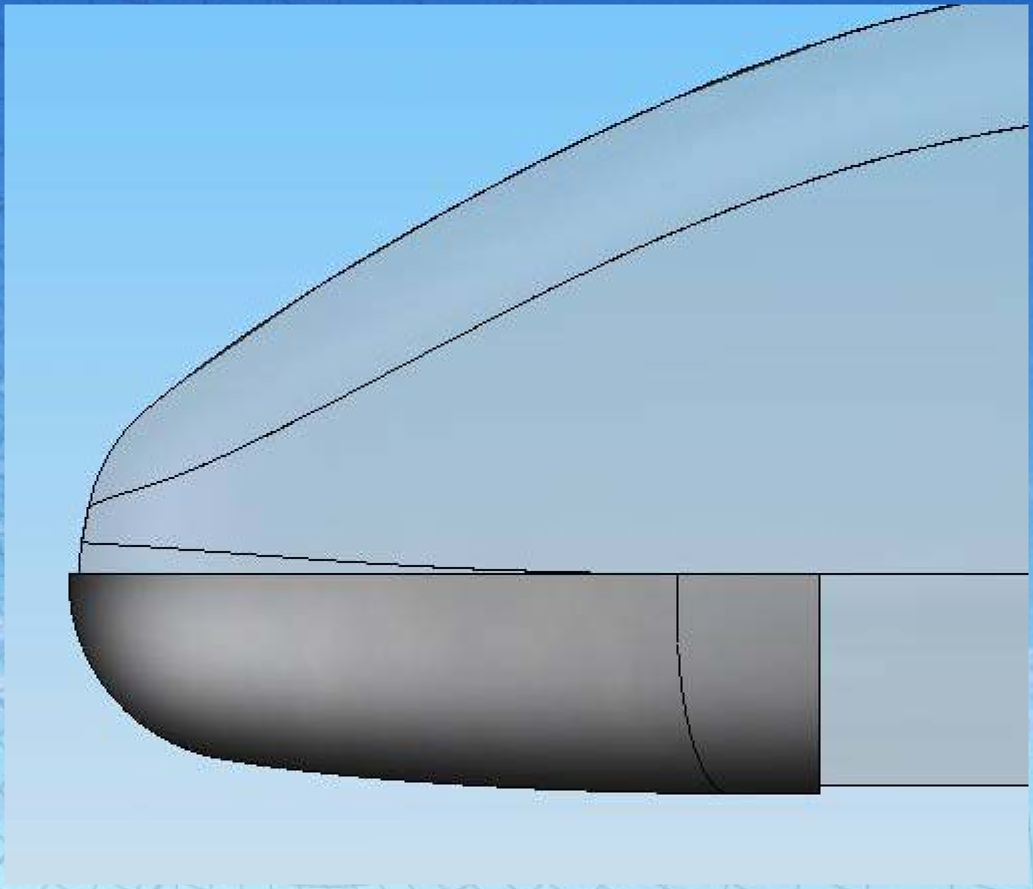
Aluminum Sheet
Waveguide Curved AISA

CURRENT AIS EFFORT

Circularly Polarized AIS Design



Conformal AIS applique



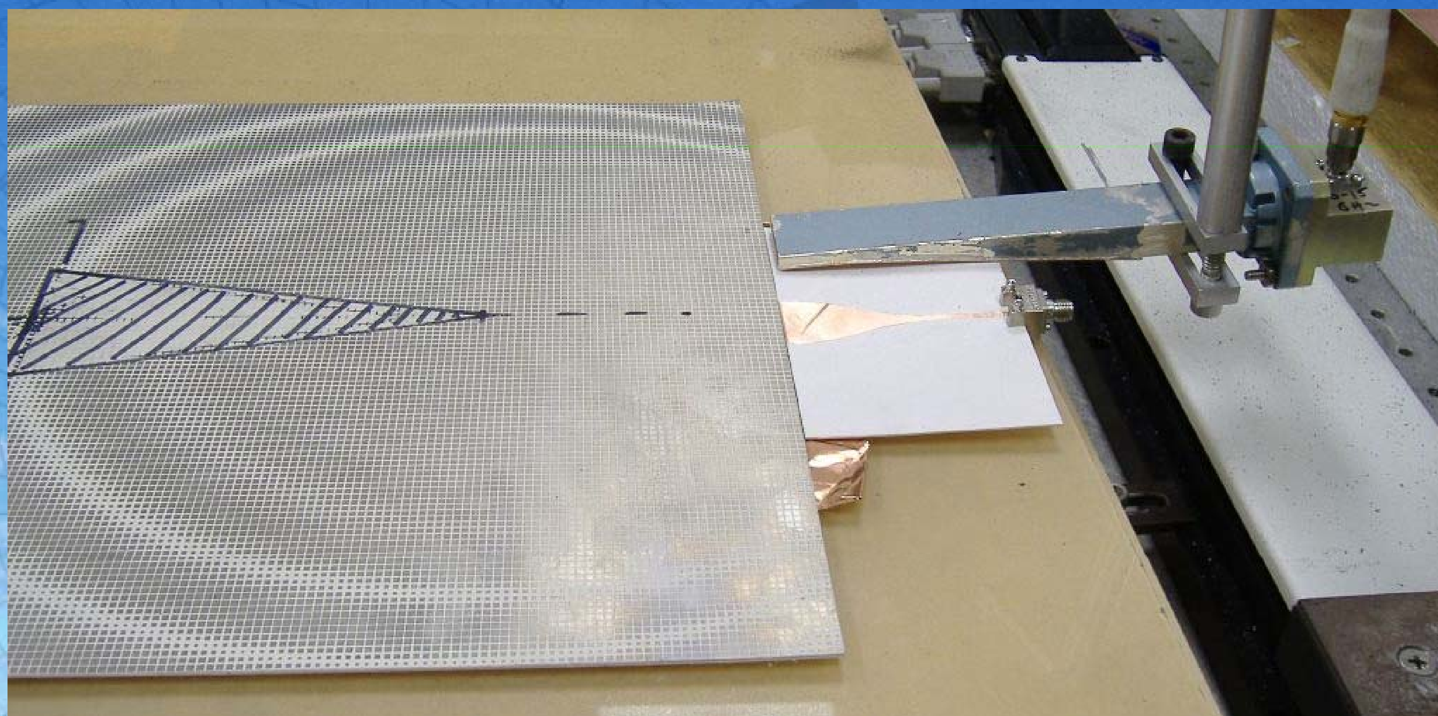
Conformal Applique

- Forming high dielectric material.
  - Existing substrates teflon impregnated
    - Vacuum-formable?
- Three dimensional transformation from flat panel to applique.

Lower Dielectric Materials

- Low dielectric materials cheaper, but require thicker material.
- Dielectric – material thickness ratio changes by square-root of initial dielectric / final dielectric ratio.
- Thermo-plastic material in this range.
  - Vacuum-forming process forms applique

Conformal Feeds



Proposed Future Development

- Investigate other frequency bands (Cellular, ISM, FRS)
- Integrate AIS onto other platforms
- Explore other commercial applications for technology
- Develop baseline AIS synthesis tools
- Environmentally qualify the AIS

Conclusions

- AIS is a cheap and versatile technology that minimizes RF obstructions
- Further research needed to expand bandwidth, theoretically predict indices, and optimize design techniques
- Lower dielectric material not explored

Questions