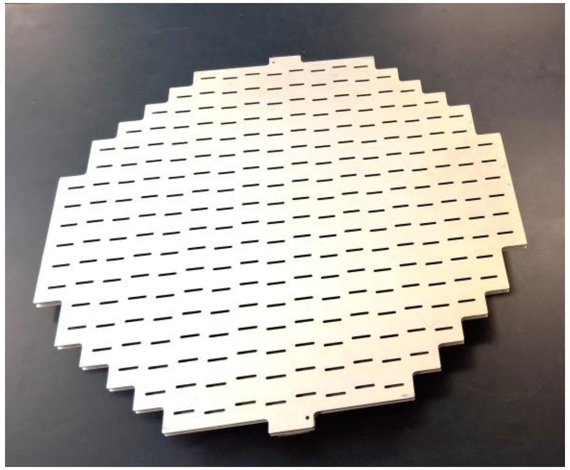
Radio Design 201 Microwave Circuits and Antennas

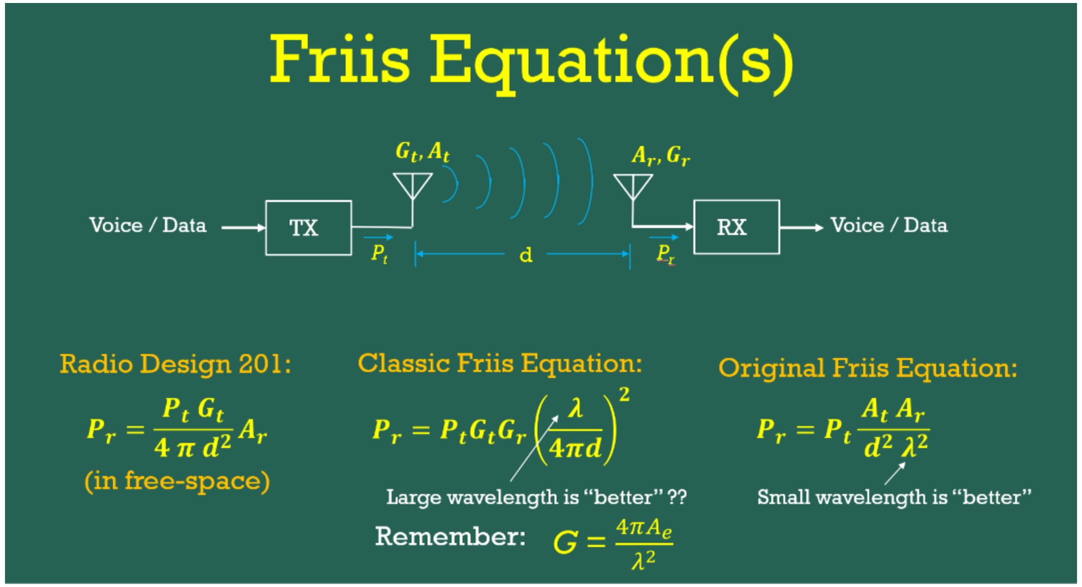
Episode 8 Phased-Arrays and Dish Antennas

Slides downloaded from: https://ecefiles.org/

Companion videos at: https://www.youtube.com/playlist?list=PL9Ox3wpnB0kpOb7NdpHAK-jDpsZm3Xedx

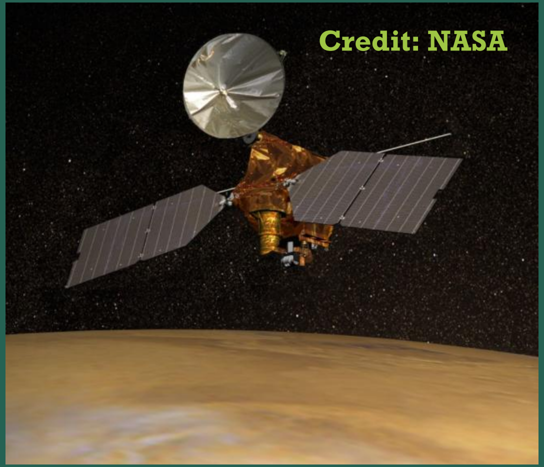
This video provides a relatively comprehensive overview of how phased-array and parabolic dish antennas work. Derived from a university course, the material includes essential math formulas, but the presentation is intended for a wide audience from students, to radio amateurs, to practicing professionals. Several real-world examples are presented to provide a good grounding in this field.





Microwave Circuits and Antennas

Radio Design 201 #8



Phased-Arrays and Dish Antennas

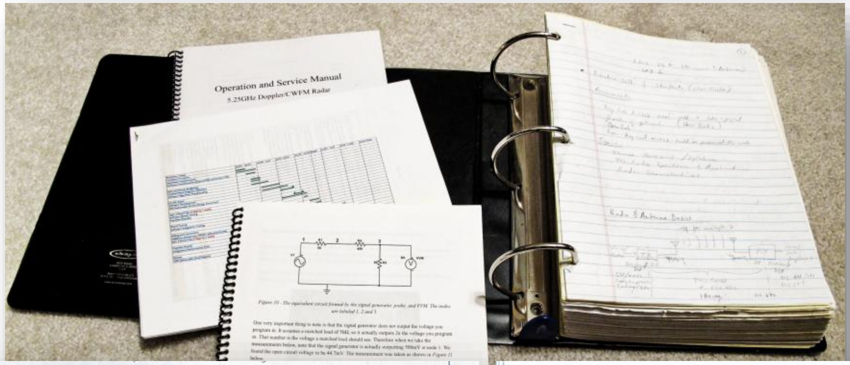
MegawattKS - YouTube

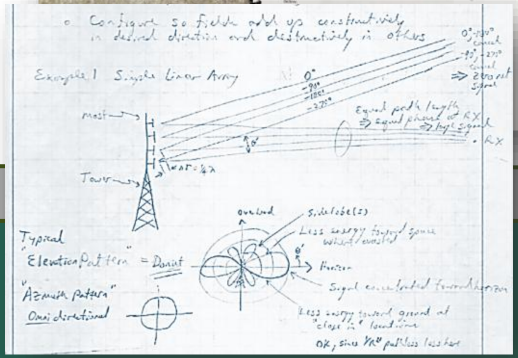
https://ecefiles.org

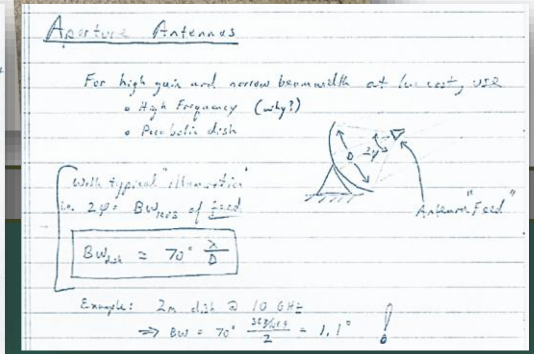
Today's "Lecture" Topics

Announcements

Review material from prior Episodes







Topics

Phased Arrays ***(Theory and Measurement)***

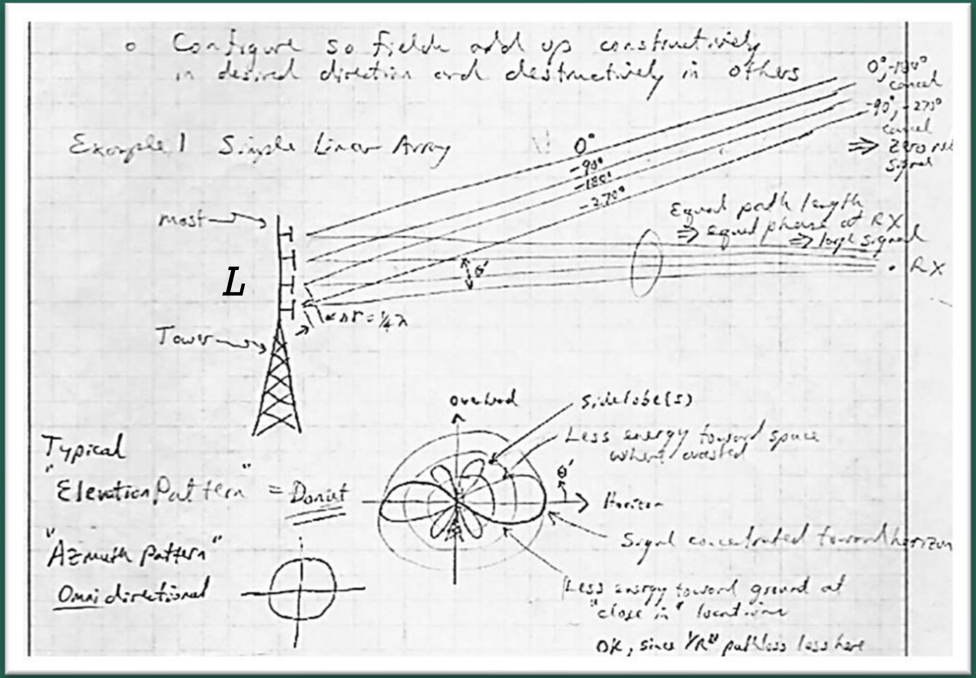
Benefits of using Microwaves

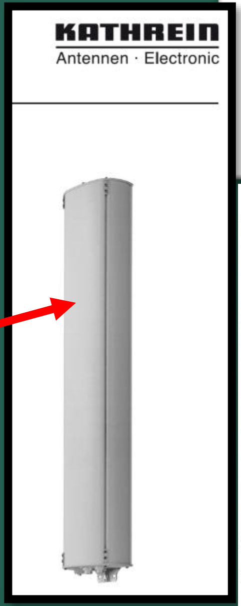
Derivation of Beamwidth & Gain Formulas

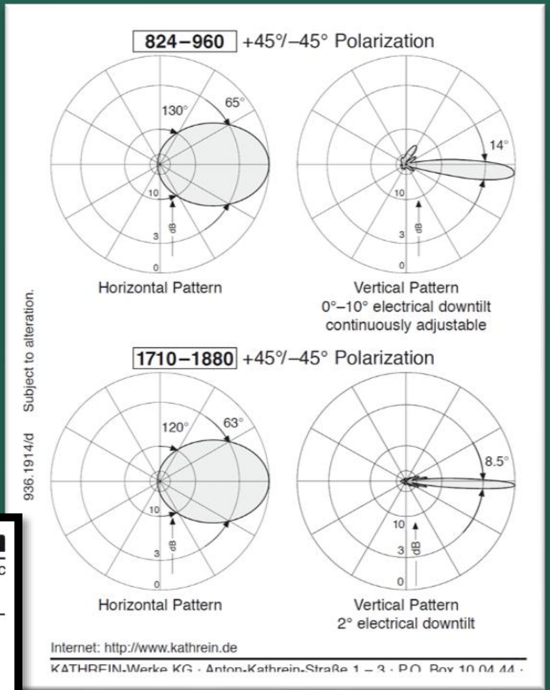
- ***1D Discrete Arrays***
- ***Extension to 2D Aperture Antennas***
- ***Dish antennas (Illumination-angle, gain, sidelobes, …)***
- ***Feeds (Horns, Helix, Dipole/corner-reflector, …)***

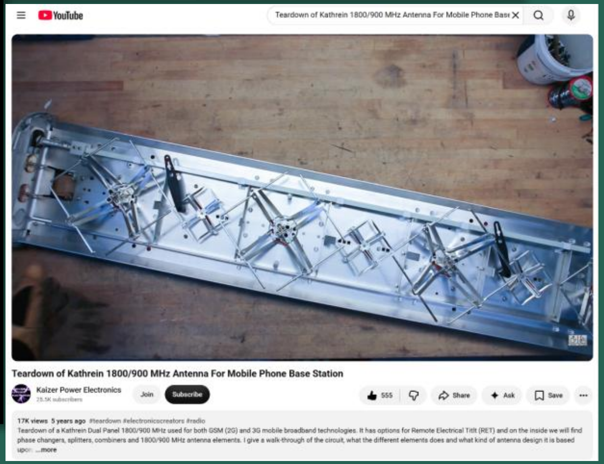
Application to Real-World Products/Design

Patterns, Beamwidth, and Gain









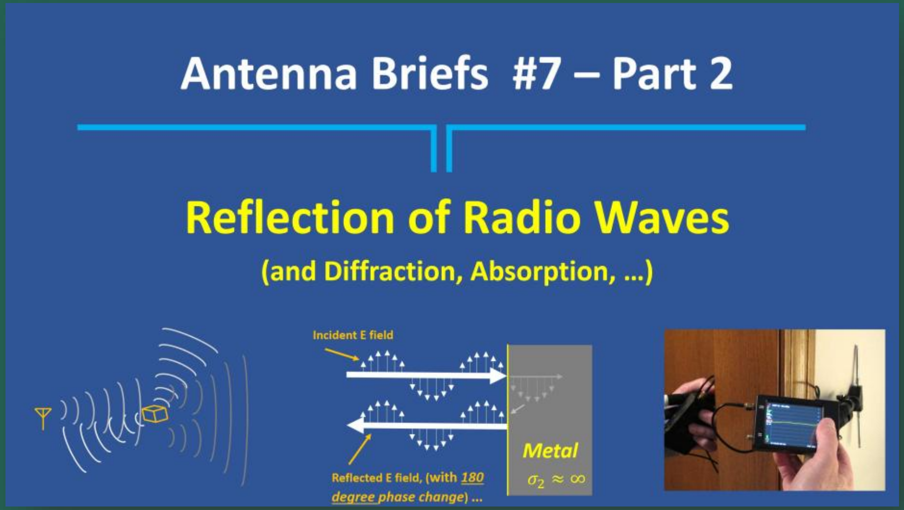
Beamwidth

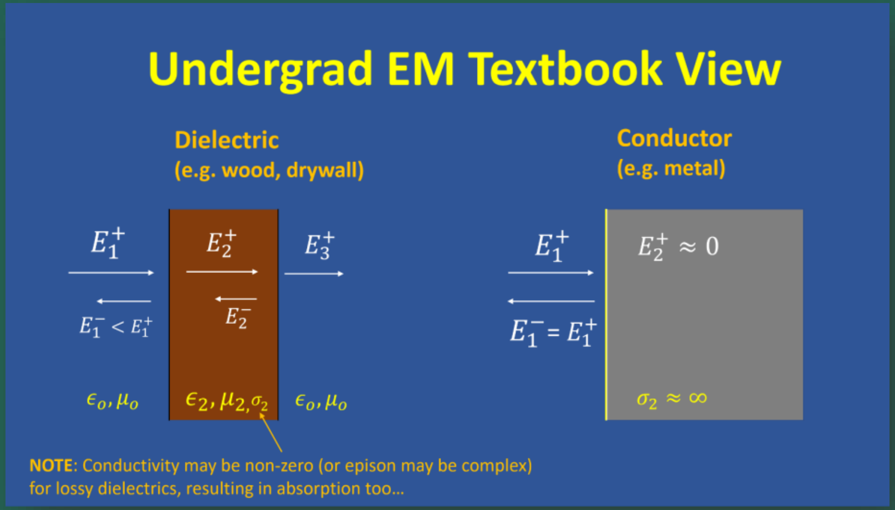
$$\theta_{3dB} \approx 50^{o}\frac{\lambda}{L}$$

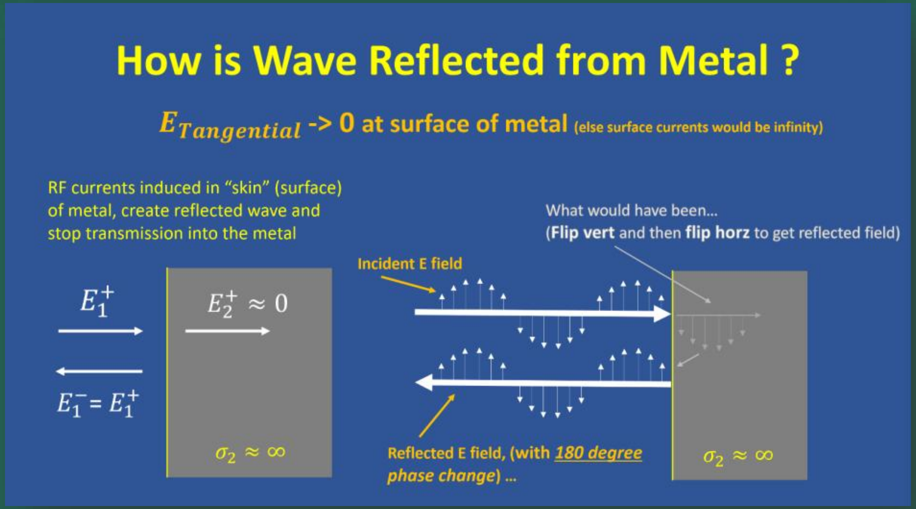
Directivity Gain

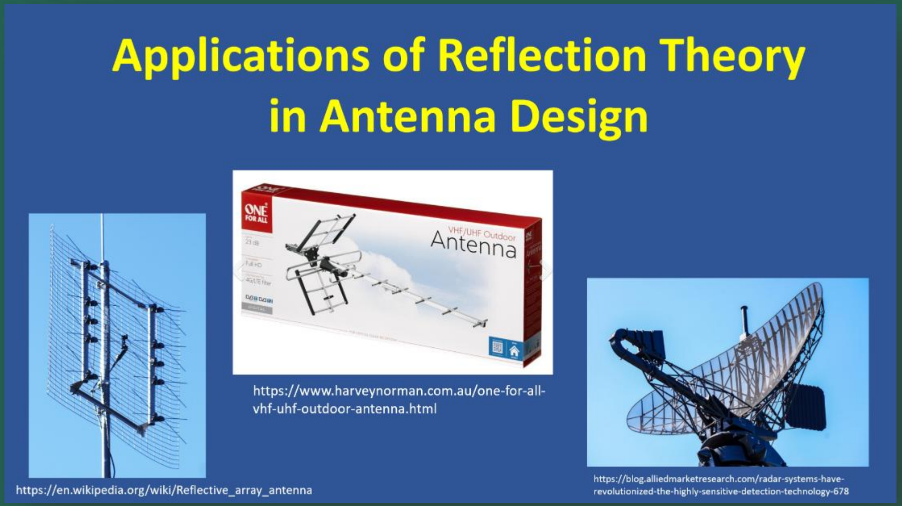
$$\mathbf{G} \approx (200^{o})^{2}\frac{1}{\theta_{el}\ \theta_{az}}$$

EM Wave Reflection

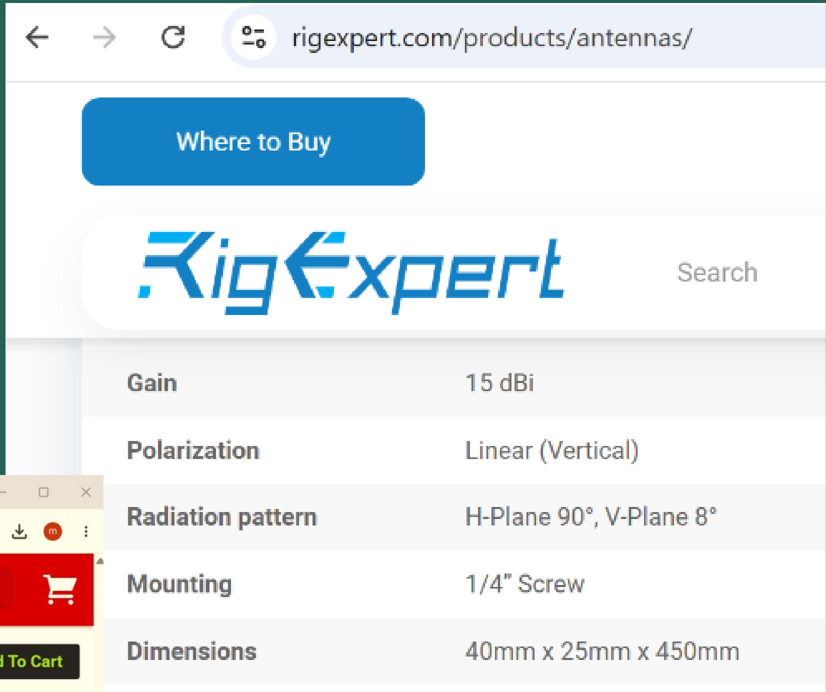


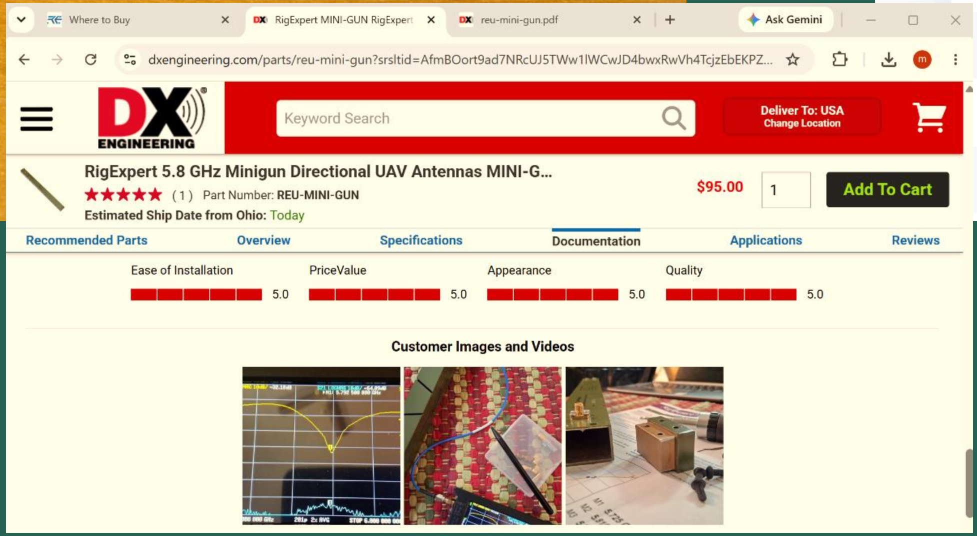




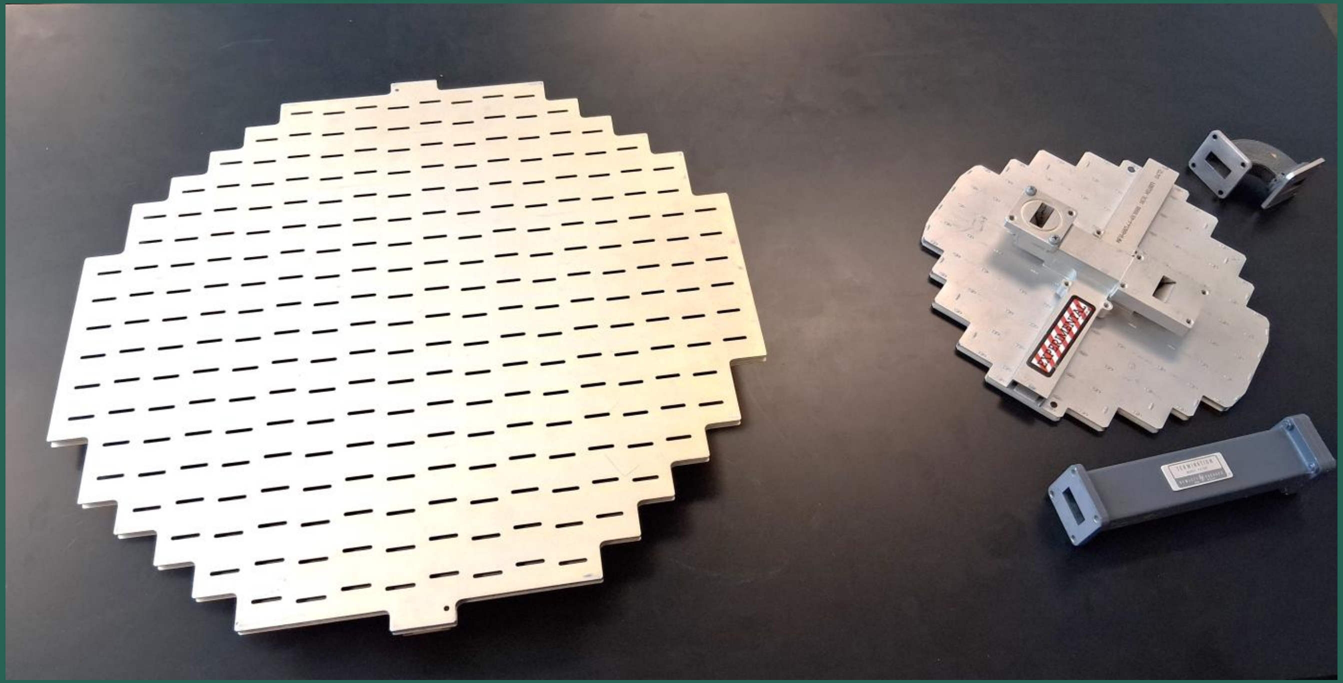


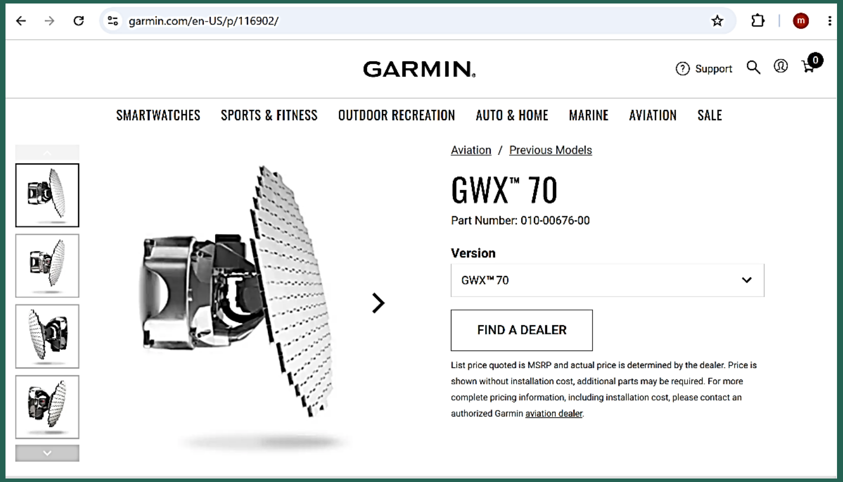
Microwave 1-D "Slot Array"





Microwave 2-D Slot Arrays





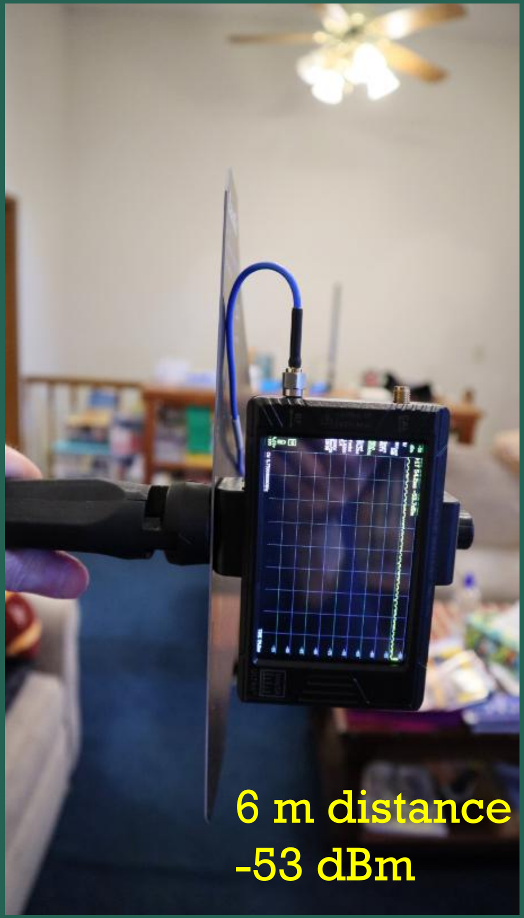
For Doppler Storm Tracking in Aircraft

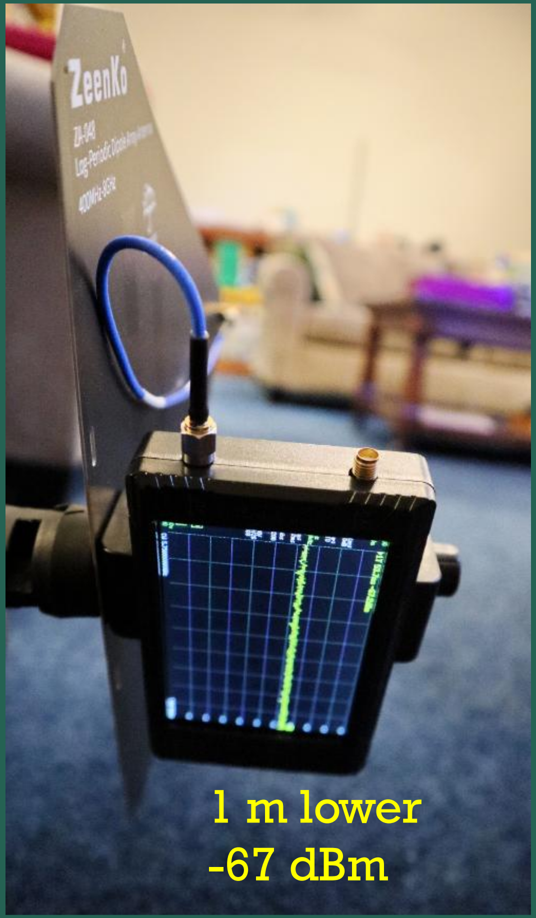
$$\theta \geq 50^o \frac{\lambda}{D}$$

$$\mathbf{G} \approx (203^o)^2 \frac{1}{\theta_{el}\ \theta_{az}}$$

Home-Lab Indoor "Antenna Range" Measurements ☺

Transmitter is LiteVNA in CW mode at 5.75 GHz





Receiver is TinySA Ultra in zero-span mode at 5.75 GHz with -50 dBm Ref level and 5 dB/div vert

Should be in the Far-Field, which for this "electrically large" antenna means a distance of:

$$D > \frac{2\,L^2}{\lambda} = \frac{(2)\,0.3m^2}{0.052m} = 3.5m$$

Need line of sight and minimal multi-path reflections

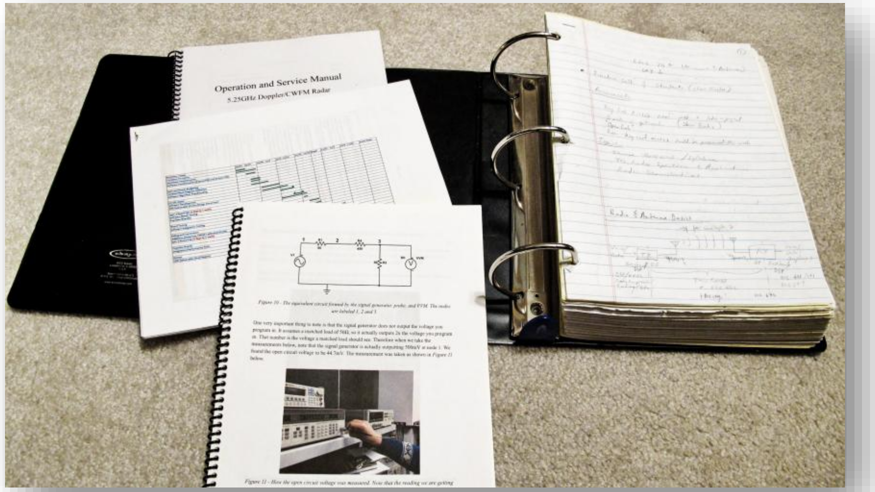
We measured -14 dB at an elevation angle of $tan^{-1}(-1m/6m)$ = -13°

Receive antenna is a wideband log-periodic

Today's "Lecture" Topics

Announcements

Review material from prior Episodes



Topics

Phased Arrays (Theory and Measurement)

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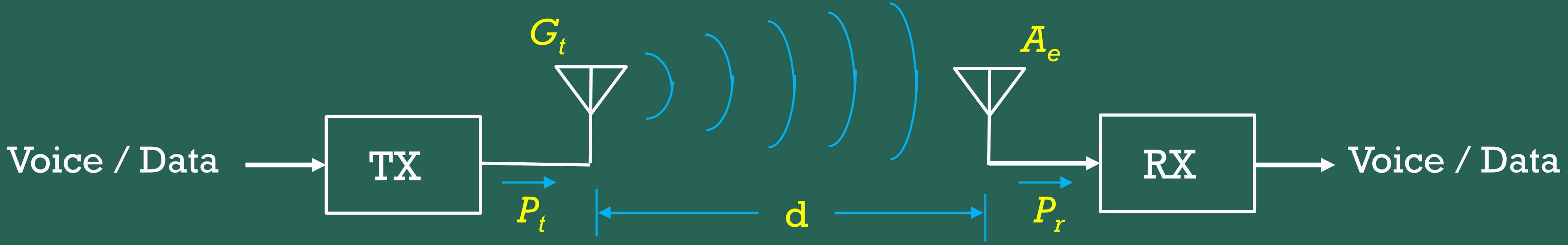
Application to Real-World Products/Design

Microwave Links and Received Signal Power

(from Episode 5)



$$P_r = \frac{P_t\, G_t}{4\, \pi\, d^n} A_e$$

Make these large for maximum range

⇒ *Highly directional antennas !*

⇒ *Use Microwave frequencies (if n=2)*

n=2 for free-space with line-of-sight

Gain and A_e vs Antenna Type

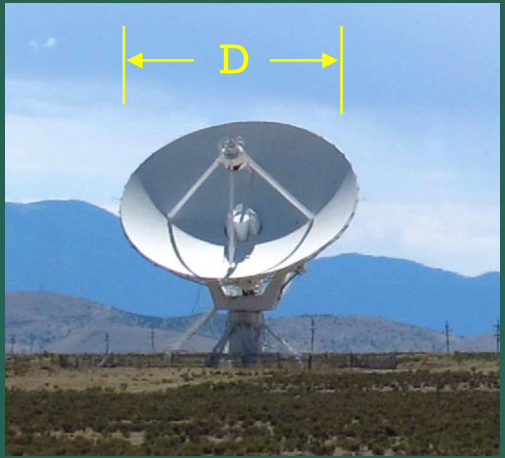
(from Episode 5)

Single (half-wave) dipoles are relatively isotropic

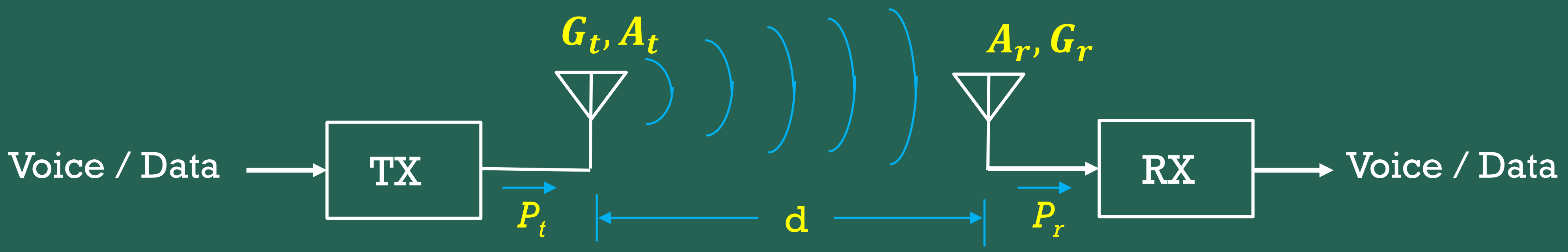
$$G \approx 1.6 \ \ \text{(2 dBi), and} \ \ A_e \approx \frac{1}{\pi}\left(\frac{\lambda}{2}\right)^2$$

Dish antennas can have large effective apertures and very large gain at microwave frequencies

$$A_e \approx \pi\left(\frac{D}{2}\right)^2 \ \ \text{and} \ \ G = \frac{A_e}{A_{ei}} = \frac{4\pi A_e}{\lambda^2}$$



Friis Equation(s)



Radio Design 201:

$$P_r = \frac{P_t\, G_t}{4\,\pi\, d^2} A_r$$

(in free-space)

Classic Friis Equation:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2$$

Large wavelength is "better" ??

Original Friis Equation:

$$P_r = P_t \frac{A_t\, A_r}{d^2\, \lambda^2}$$

Small wavelength is "better"

Remember: $G = \frac{4\pi A_e}{\lambda^2}$

System-Level Examples

Mars Global Surveyor*

$$P_r = P_t \frac{G_t}{4\pi d^2} A_e$$

$$> \quad Pnoise = k\,T\,B$$

d = 378E9 meters (230 Million Miles)

P_t = 100 W
f =8.4 GHz
$\lambda = 0.036\ m$
3m dish
Ae=4.9 m²
$G_t \approx$ 48,000 (47 dB)
(@ 70% aperture efficiency)

*Rough estimates based on web search results

Goldstone 70m DSN dish
$A_e \approx 3800\ m^2$

P_r = 1.0E-14 W (-110 dBm)

kTB = 1.4E-16 W* (-129 dBm)

$SNR = 71 \quad (19\ dB)$

* Assuming System noise temperature T = 21 K, downlink bandwidth= 500 kHz (e.g. 500 kbps BPSK)

Rover Relay Operations

Rovers included a UHF whip antenna, and a Microwave dish.

UHF was used for most proximity data transmission.

Why?

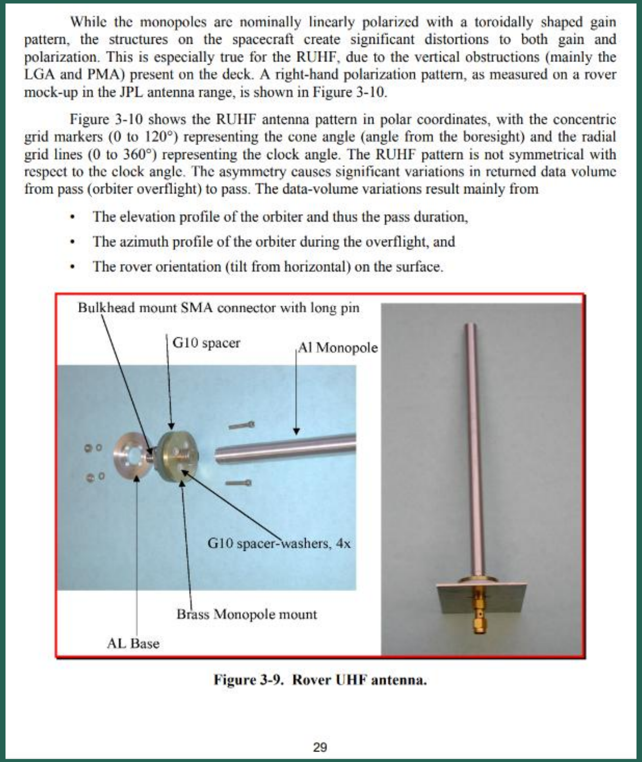

While the monopoles are nominally linearly polarized with a toroidally shaped gain pattern, the structures on the spacecraft create significant distortions to both gain and polarization. This is especially true for the RUHF, due to the vertical obstructions (mainly the LGA and PMA) present on the deck. A right-hand polarization pattern, as measured on a rover mock-up in the JPL antenna range, is shown in Figure 3-10.

Figure 3-10 shows the RUHF antenna pattern in polar coordinates, with the concentric grid markers (0 to 120°) representing the cone angle (angle from the boresight) and the radial grid lines (0 to 360°) representing the clock angle. The RUHF pattern is not symmetrical with respect to the clock angle. The asymmetry causes significant variations in returned data volume from pass (orbiter overflight) to pass. The data-volume variations result mainly from

- The elevation profile of the orbiter and thus the pass duration,
- The azimuth profile of the orbiter during the overflight, and
- The rover orientation (tilt from horizontal) on the surface.

Figure 3-9. Rover UHF antenna.

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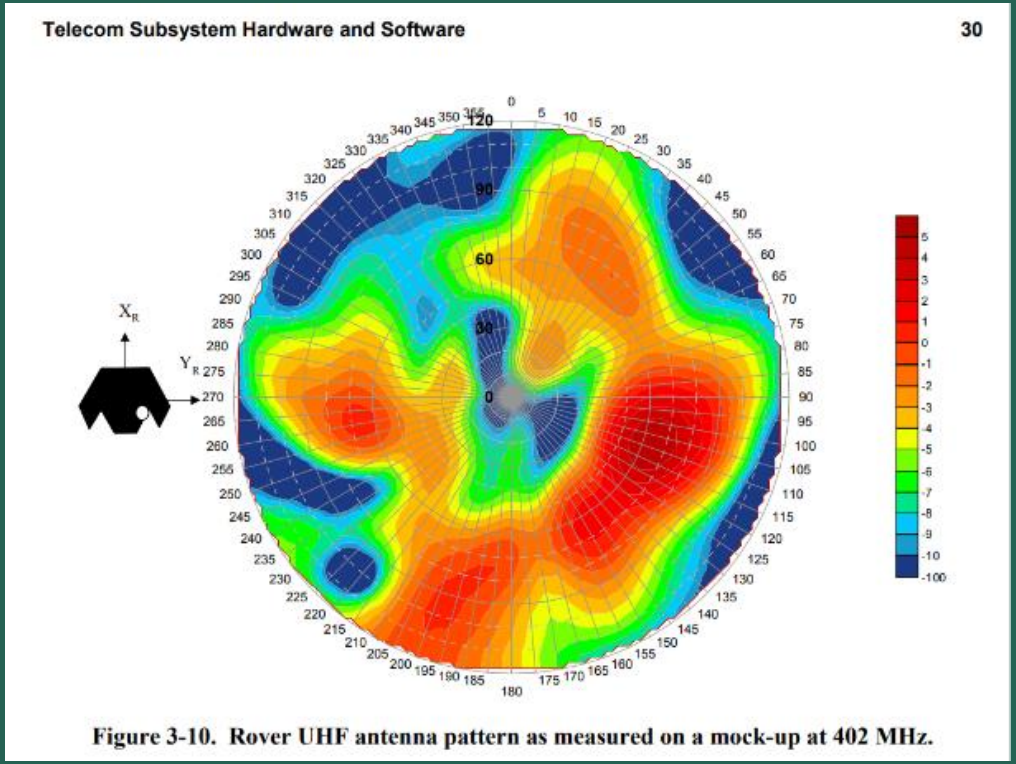
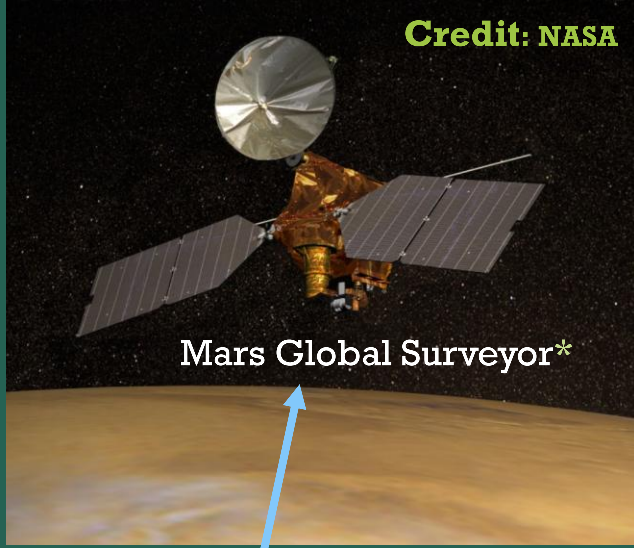


Figure 3-10. Rover UHF antenna pattern as measured on a mock-up at 402 MHz.



https://descanso.jpl.nasa.gov/DPSummary/MER_article_cmp20051028.pdf

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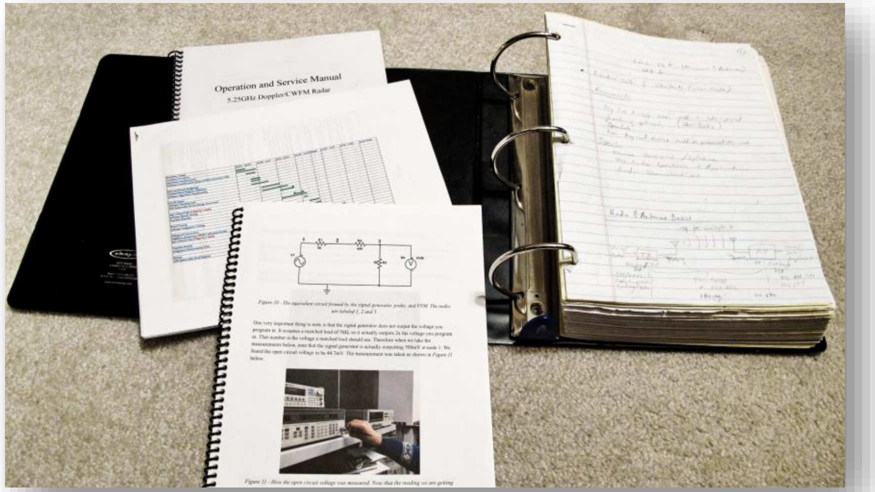

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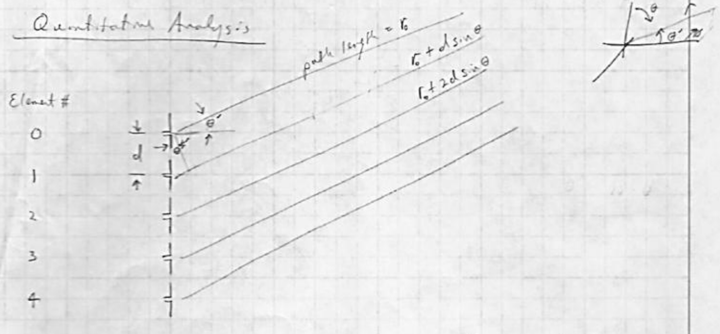
Application to Real-World Products/Design

Discrete Array Beamwidth Derivation

Quantitative Analysis



Field at observation point (r, θ') from element n is (for short dipole)

$$E_n(r,\theta) \approx 30\, I_n\, L\, \beta \cos\theta' \frac{1}{r_n} e^{-j\beta r_n} \quad \text{where} \quad \beta = \frac{\omega}{c} = \frac{2\pi}{\lambda}, \quad r_n = r_0 + nd\sin\theta$$

(I_n: phasor!)

OR, in general,

$$= F(\theta') \frac{1}{r_n} I_n e^{-j\beta r_n}$$

And total field is

$$E_{tot} = \sum_{n=0}^{N-1} F(\theta') \frac{1}{r_n} I_n e^{-j\beta r_n}$$

(N: # of elements)

$$= F(\theta') \sum_{n=0}^{N-1} \frac{1}{r_0 + nd\sin\theta} I_n e^{-j\beta(r_0 + nd\sin\theta')}$$

$$\approx \underbrace{F(\theta') \frac{1}{r_0} e^{-j\beta r_0}}_{\text{Field of single element}} \underbrace{\sum_{n=0}^{N-1} I_n e^{-jn\underbrace{\beta d \sin(\theta')}_{\Omega}}}_{\text{"Array Factor"}}$$

NOTES: Array Factor ~ (discrete) Fourier Transform of Excitation currents I_n w/ $\beta d\sin(\theta) = \Omega$

⇒ Can pick I_n to give desired pattern using FT theory!

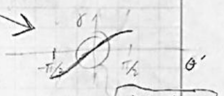
Examine Array Factor (substitute $\frac{2\pi}{\lambda} = \beta$)

$$\sum_{n=0}^{N-1} I_n e^{-jn 2\pi \frac{d}{\lambda} \sin\theta'}$$

with equal $I_n = I_0\ \forall n$ & $d/\lambda = 0.5$.

$$\Rightarrow AF = I_0 \sum_{n=0}^{N-1} e^{-jn\pi\sin\theta'}$$

To simplify sum, let $\sin\theta' = \gamma$



$\boxed{\gamma \approx \theta' \text{ for small } \theta'}$ ($\leq \pm 30°$) within 5%

$$\Rightarrow AF = I_0 \sum_{n=0}^{N-1} e^{-jn\pi\gamma}$$

OPT

$$= I_0 \sum_{n=0}^{\infty} e^{-jn\pi\gamma} - \sum_{n=N}^{\infty} e^{-jn\pi\gamma}$$

$$= I_0 \sum_{n=0}^{\infty} e^{-jn\pi\gamma}\left[1 - e^{-jN\pi\gamma}\right]$$

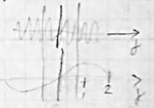
Recall $\sum_{n=0}^{\infty} r^n = \frac{1}{1-r}$

$$= I_0 \frac{1}{1 - e^{-j\pi\gamma}}\ 1 - e^{-jN\pi\gamma}$$

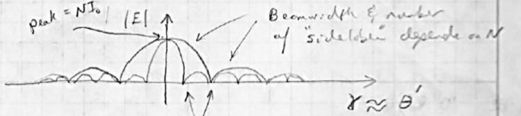
$$= I_0 \frac{e^{-j\frac{N}{2}\pi\gamma}\left(e^{j\frac{N}{2}\pi\gamma} - e^{-j\frac{N}{2}\pi\gamma}\right)}{e^{-j\frac{\pi}{2}\gamma}\left(e^{j\frac{\pi}{2}\gamma} - e^{-j\frac{\pi}{2}\gamma}\right)}$$

$$= I_0 \underbrace{e^{-j\frac{N-1}{2}\pi\gamma}}_{\text{Phase Shift w/ magnitude}=1} \frac{\cancel{2}}{\cancel{2}} \underbrace{\frac{\sin\left(N\frac{\pi}{2}\gamma\right)}{\sin\left(\frac{\pi}{2}\gamma\right)}}_{\approx N\frac{\sin(Nx)}{Nx}}$$

for $\gamma \approx \theta' < 30°$ $\quad x = \pi/2\,\gamma$



⇒ Pattern =



$$\gamma_{1st\ null} \approx \theta'_{1st\ null} = \frac{2}{N} \text{ radians} = \frac{110}{N} \text{ degrees}$$

Example: Suppose $N = 8$

⇒ First null when

$$\theta' \simeq \gamma = \frac{2}{N} = \frac{2}{8}$$

⇒ $= 0.25$ radians

$= 15°$

⇒ Null-Null Beamwidth = 30° (actually 29°)

OPT if time permits

3dB point reached when

$$\frac{\sin\left(N\frac{\pi}{2}\gamma\right)}{\sin\left(\frac{\pi}{2}\gamma\right)} \approx 0.707\, N$$

(N: value of AF @ $\gamma = 0$)

⇒ $\gamma \approx 0.11$ (to give $N\frac{\pi}{2}\gamma = \pi/4$)

$\theta = \sin^{-1}(0.11) = 0.1102 \simeq 0.11$ ✓

$= 6.3°$!

⇒ 3dB Beamwidth ≈ 12.5° for $N = 8$

(Compare w/ ≈ 90° for single dipole element)

Note: Doubling # of elements halves beamwidth

Halving # of elements doubles "

N	BW_{3dB}	Array Dimension $L = N\frac{\lambda}{2}$
8	12.5°	4λ
16	6.3°	8λ
4	25°	2λ
2	50°	1λ

In general, (For uniform excitation & $N > 2$)

$$\boxed{BW_{3dB} \approx 50° \frac{\lambda}{L}}$$

L: Total array dimension $= N\frac{\lambda}{2}$ for min spacing

2 –D Array or Dish Beamwidth

Aperture Antennas

For high gain and narrow beamwidth at low cost, use
- High Frequency (why?)
- Parabolic dish

With typical "illumination"
i.e. $2\psi = BW_{NULL}$ of feed

$$\boxed{BW_{dish} \simeq 70^\circ \frac{\lambda}{D}}$$

Example: 2m dish @ 10 GHz

$\Rightarrow BW = 70^\circ \frac{3E8/10E9}{2} = 1.1^\circ$!

Recall that narrow beam concentrates power resulting in high Effective Isotropic Radiated Power

$EIRP = P_t\, G_t$ ← Directivity gain of dish ← Transmitter output power

Can be shown that

$$G_t \simeq 0.5 \left(\pi \frac{D}{\lambda}\right)^2$$

Example: 2m dish, 10 GHz, $P_t = 1\,W$

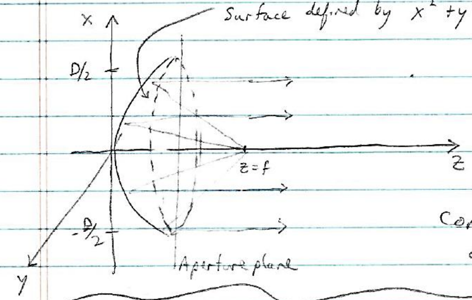
$\Rightarrow G_t = 0.5 \left(\pi \frac{2}{3E8/10E9}\right)^2 = 44{,}000$

$\Rightarrow EIRP = 44\,kW$!

Safety Concerns ! ?

Dish Geometry

Surface defined by $x^2 + y^2 = 4fz$ ← Focal Length

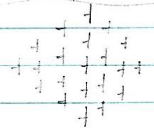


Commercial parabolic dishes described by f/D ratio ...

If dish "feed" antenna is at focal point ($z = f$),
- All rays leave dish parallel to z axis
- All path lengths are equal ⇒ equal phase

⇒ Field is uniform throughout aperture (if uniformly illuminated)

⇒ Similar to field from (2 D) discrete array



⇒ Similar far field pattern

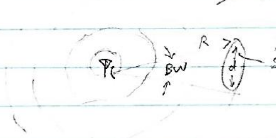
1-D	Dipole array	$BW = 50^\circ \frac{\lambda}{L}$
2-D	Dish	$BW = 70^\circ \frac{\lambda}{D}$ in both dimensions!

Non-uniform Excitation in aperture plane; Diameter takes place of length

Relationship between Bw & Gain

Combine BW & G_t formulas: $G \simeq 0.5 \left(\pi \frac{70^\circ}{BW}\right)^2$

This can be shown to be true in general



sphere around isotropic radiator $A_{sphere} = 4\pi R^2$

Directed Antenna Beamwidth: BW (radians) illuminates surface patch area $= \pi \left(\frac{d}{2}\right)^2$

$A_{patch} = \pi \left(\frac{R \cdot BW}{2}\right)^2$

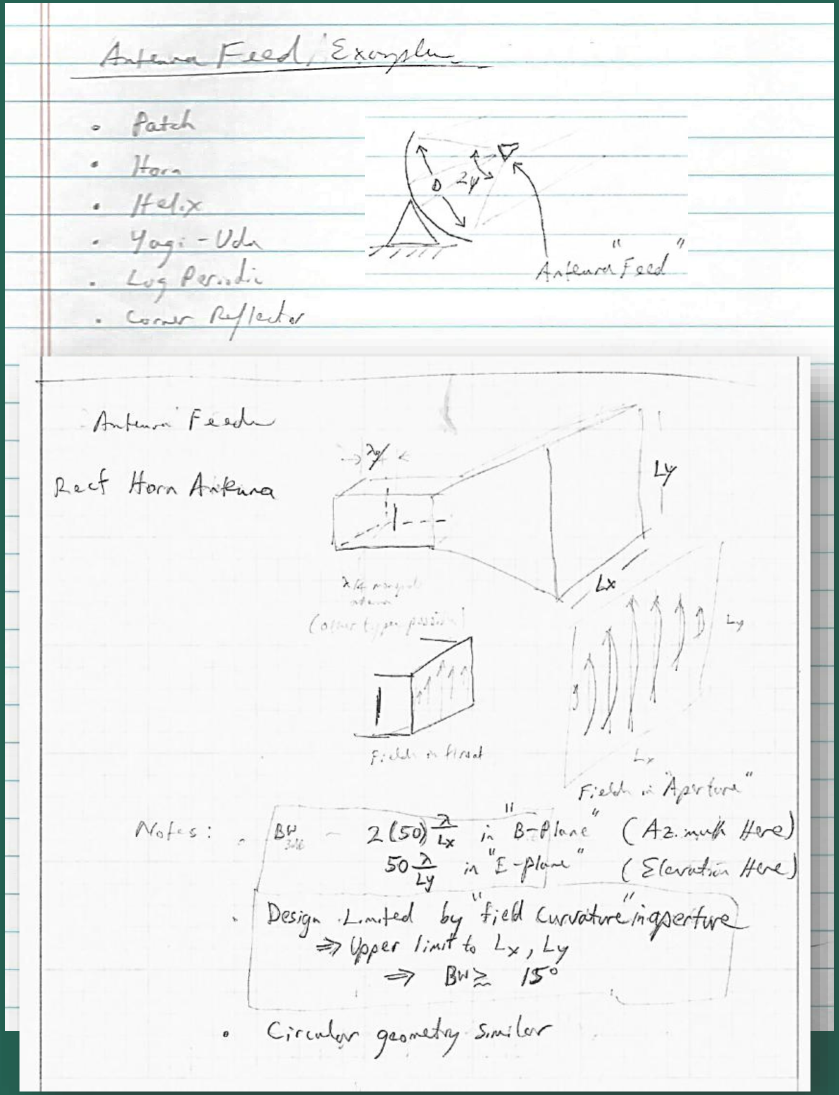
Directivity Gain is then $G_t = \frac{A_{sphere}}{A_{patch}} = \left(\frac{4}{BW}\right)^2$ radians

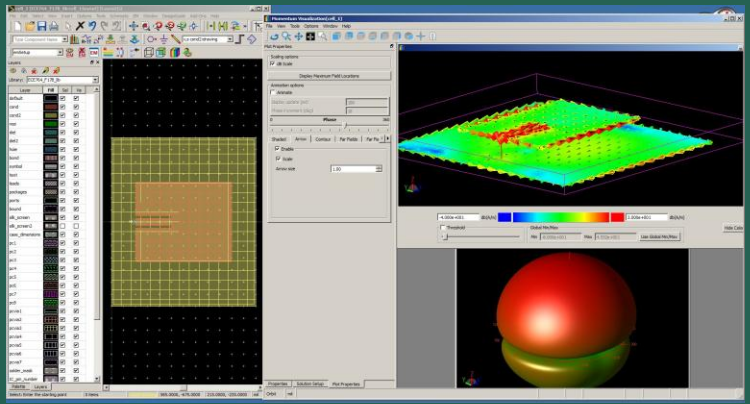
OR, for degrees: $G_t = \left(\pi \frac{73^\circ}{BW^\circ}\right)^2$ in degrees ✓

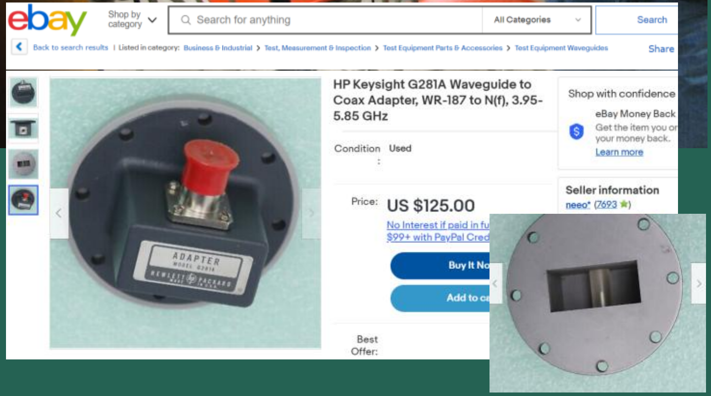
Benefits of Dish on Receive

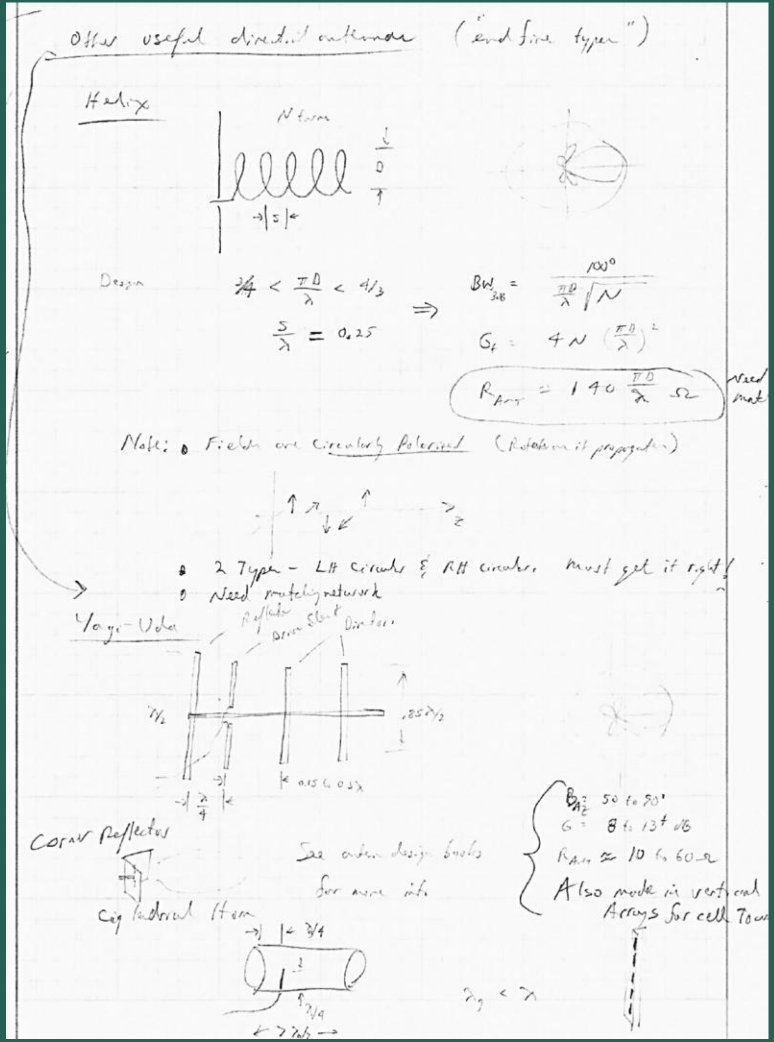
- Intercepts large area of passing EM wave
  ⇒ more power received $P_r = P\, A_e$ (Power Density; "Effective Aperture")
- Provides good angular discrimination (benefit ??)

Feed Antennas





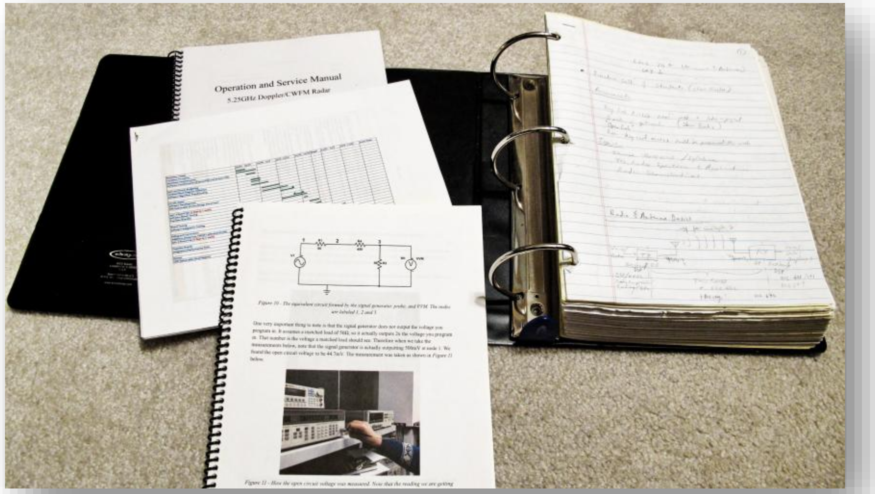




Today's "Lecture" Topics

Announcements

Review material from prior Episodes



Topics

Phased Arrays ***(Theory and Measurement)***

Benefits of using Microwaves

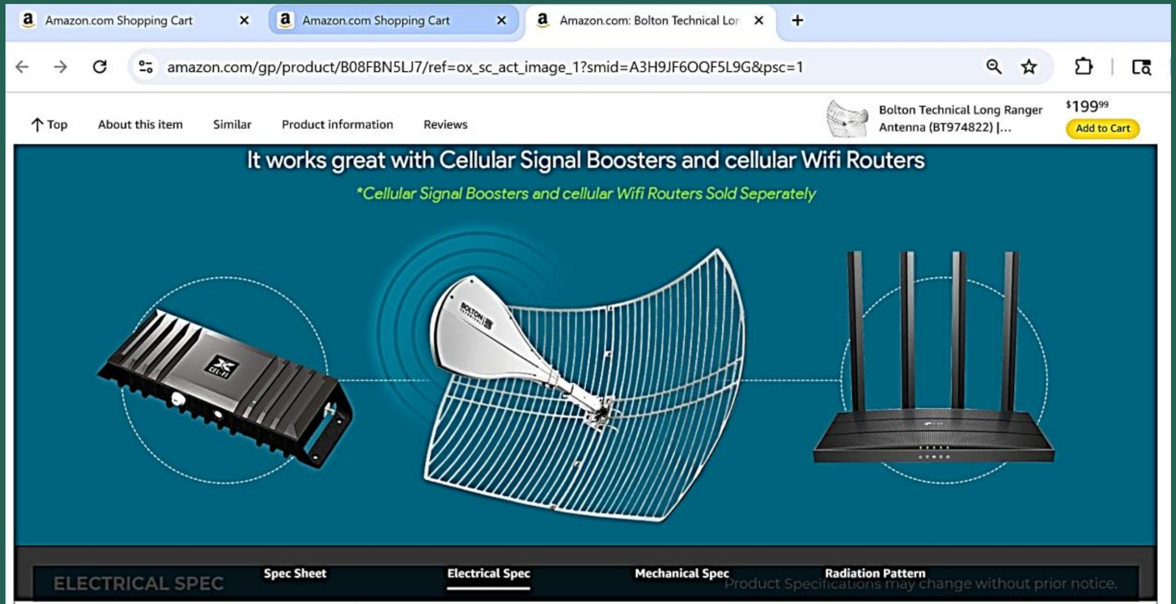
Derivation of Beamwidth & Gain Formulas

- ***1D Discrete Arrays***
- ***Extension to 2D Aperture Antennas***
- ***Dish antennas (Illumination-angle, gain, sidelobes, …)***
- ***Feeds (Horns, Helix, Dipole/corner-reflector, …)***

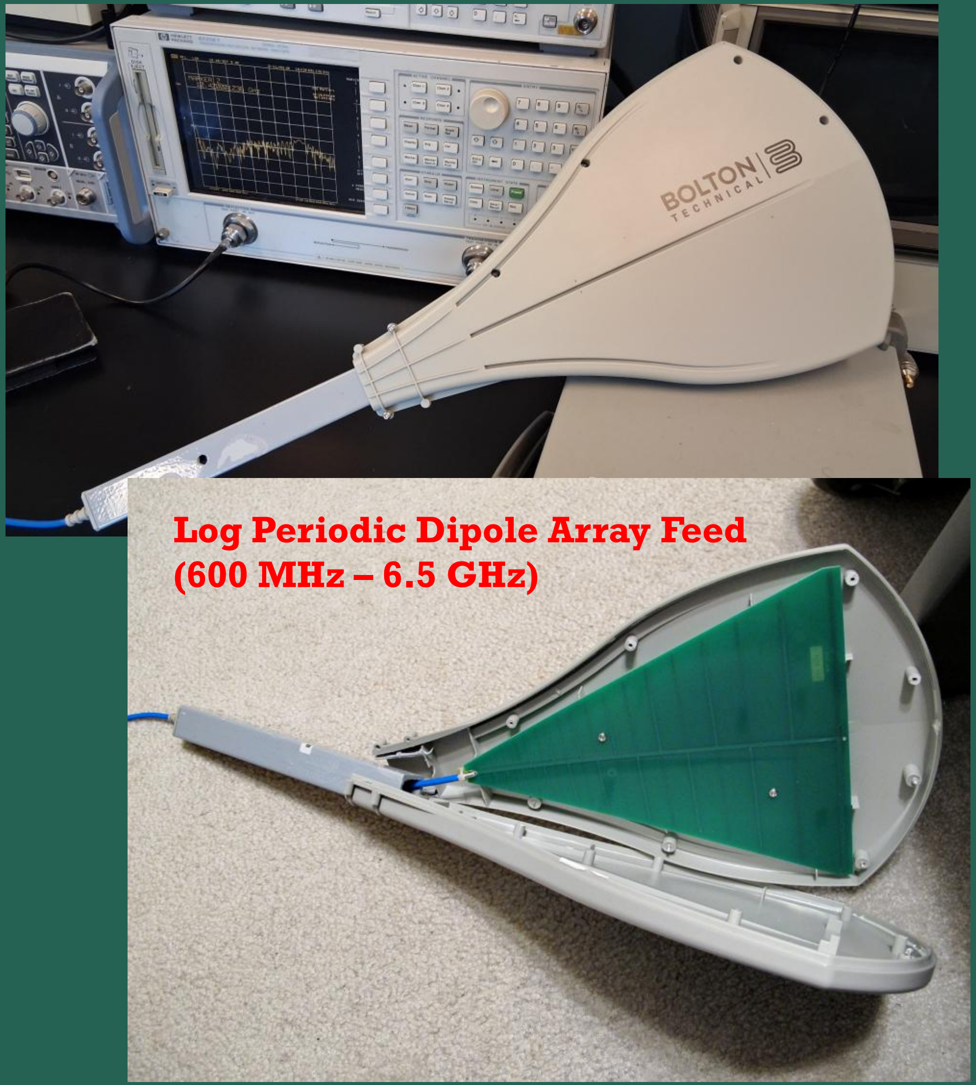
Application to Real-World Products/Design

Prime-Focus Dish with LPDA Feed

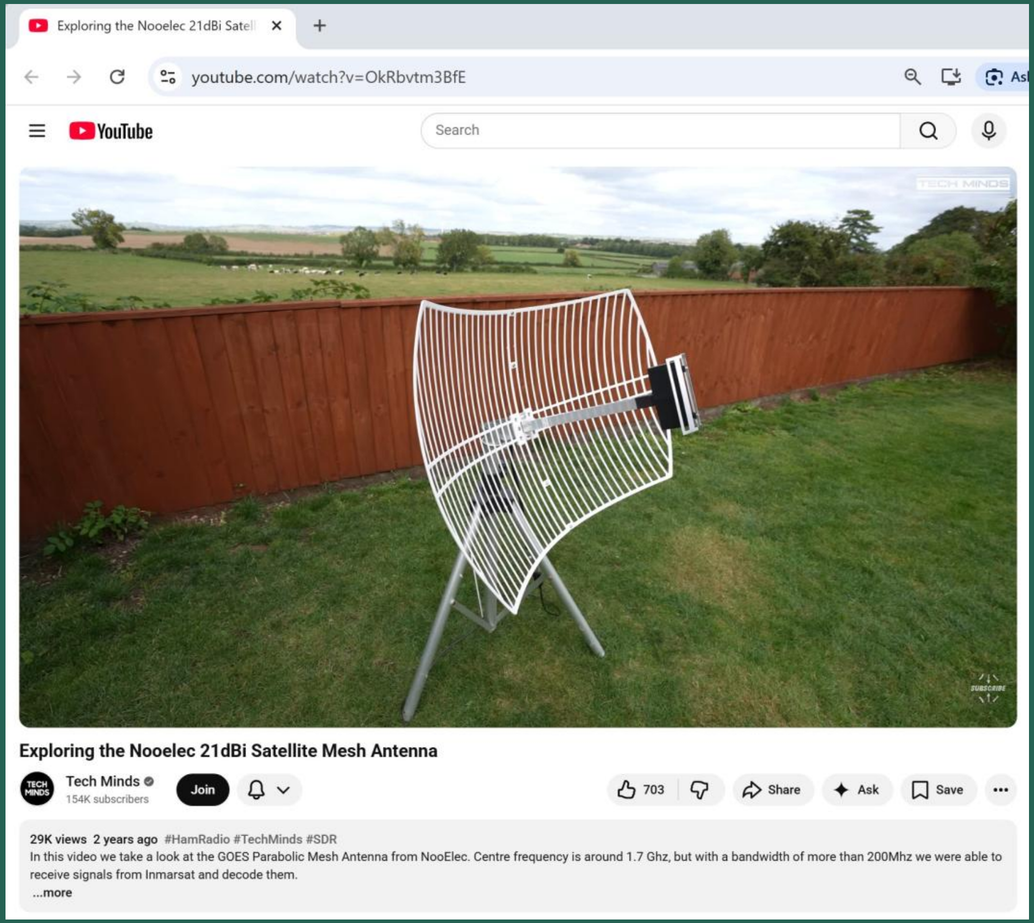
Bolton "Long Ranger" Parabolic Antenna

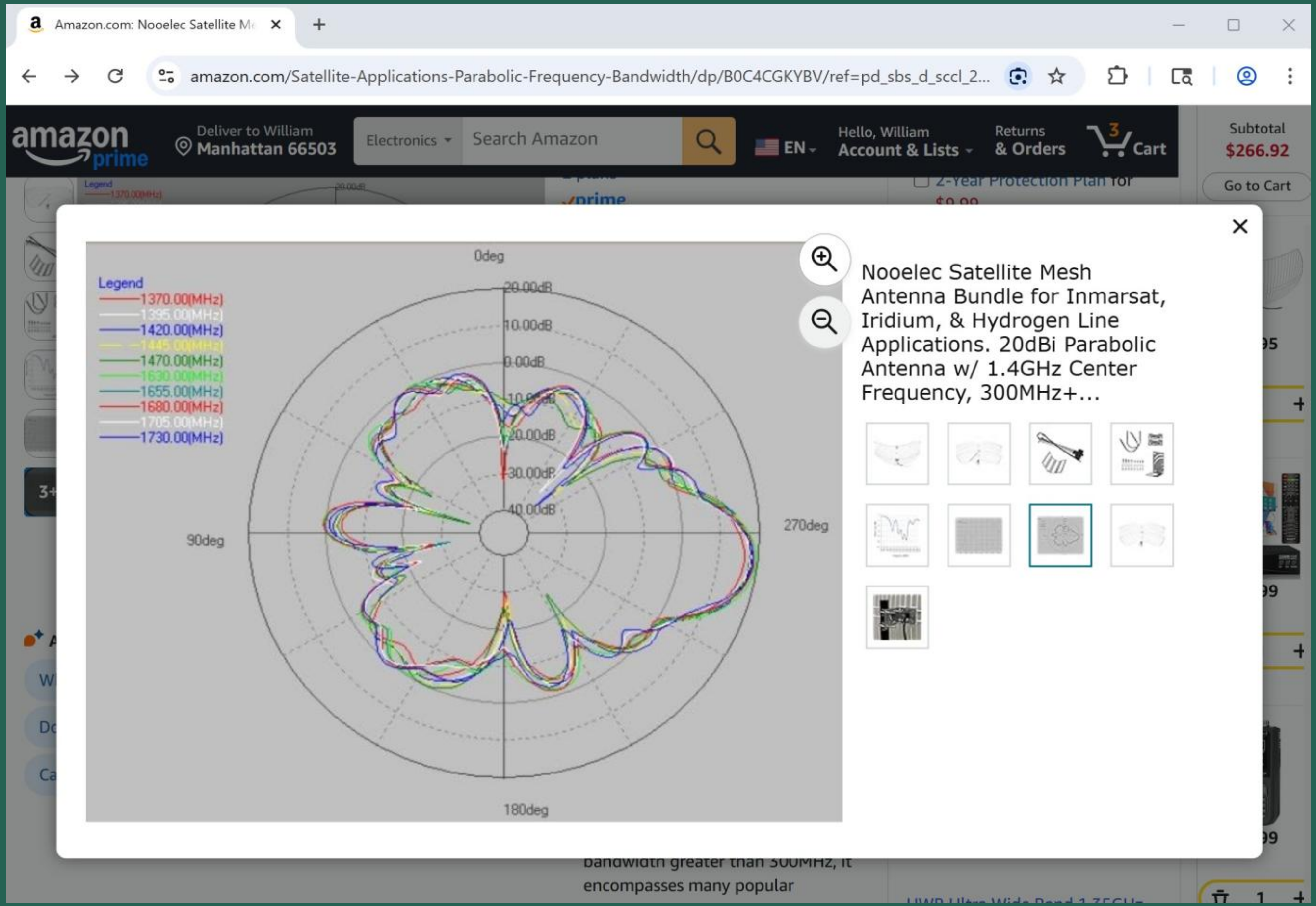


Item No.		BT974822			
Frequency Range		MHz	600-960	1700-2200	3000-6500
Gain		dBi	8-15	20-28	10-26
Polarization		Vertical or Horizontal			
Beam width	Horizontal	deg	23	10	7
	Vertical		35	13	9
VSWR			≤2.5	≤2.0	≤2.5
Front-To-Back Ratio		dB	>11	20	>10
Input Power, maximum		watt	100		
Impedance		ohm	50		

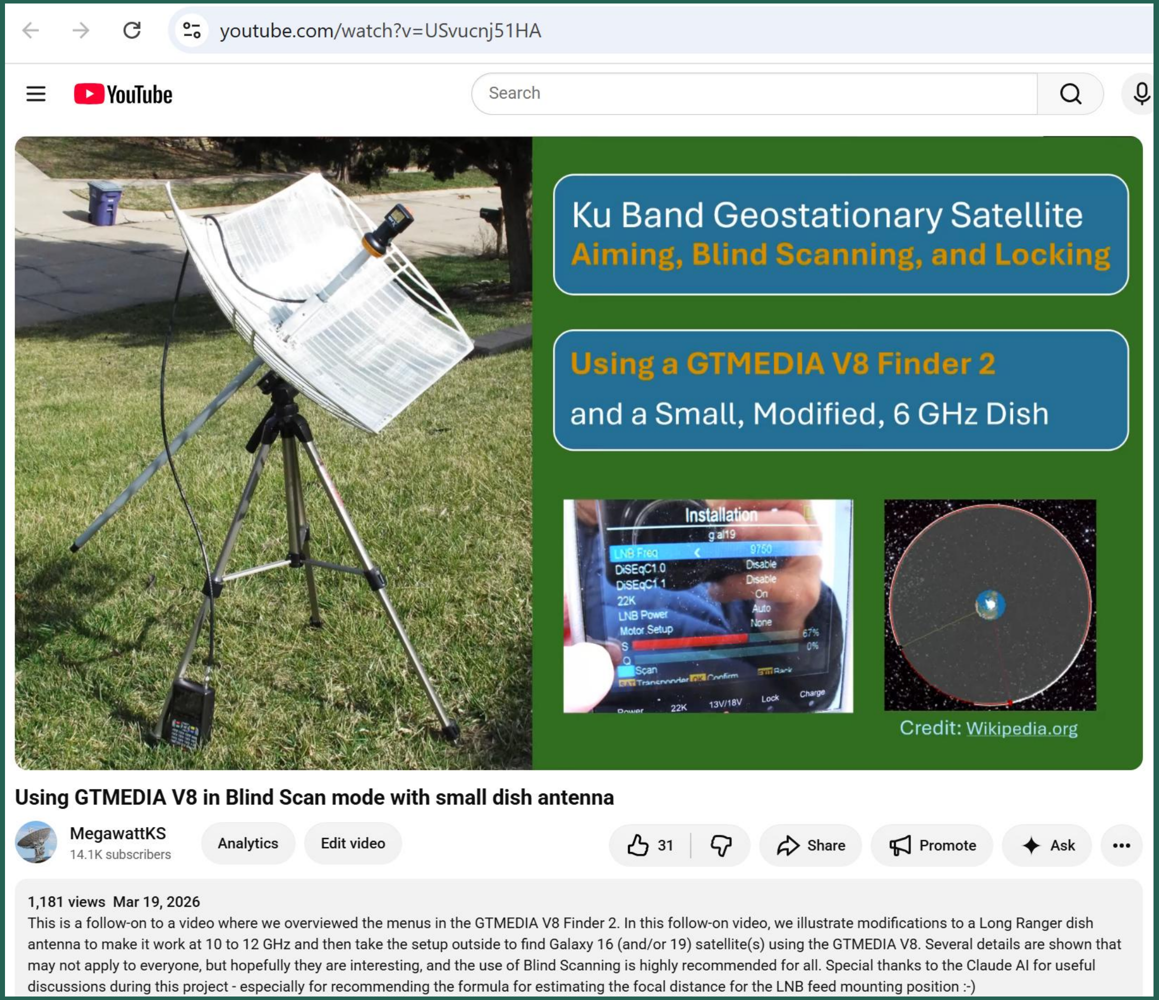


Inexpensive Dish with
1.4 GHz Dipole/Corner-reflector Feed

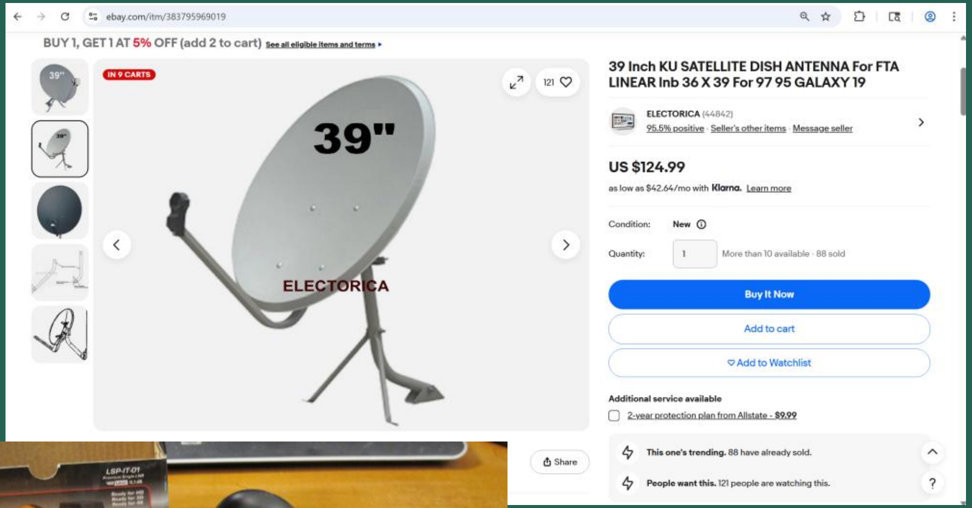




Experiments in Modifying Dish for 10 GHz Satellite TV



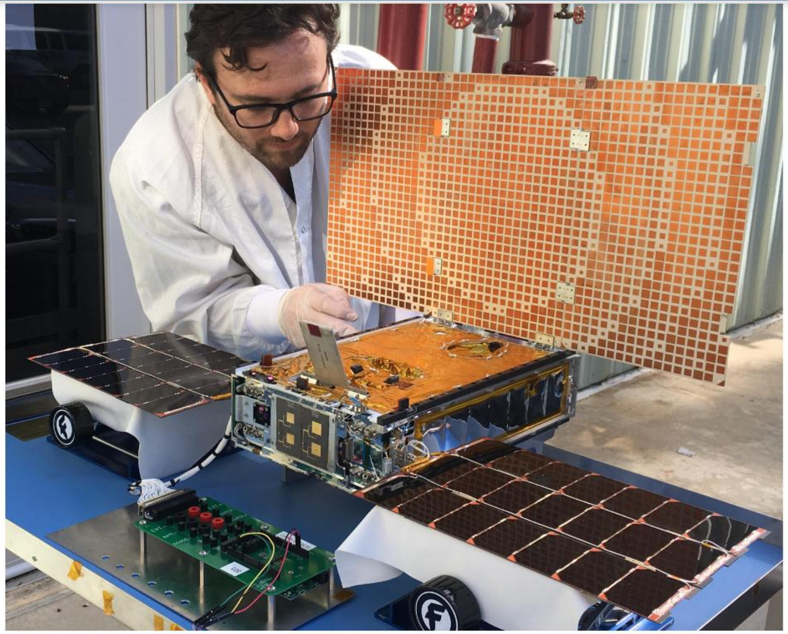
Alternative/Preferred “Offset-Feed” Type Dish



LNB with circular waveguide feed

Advanced Phased-Array Designs
(Microwave Aperture Antennas)

NASA SOLAR SYSTEM EXPLORATION



Engineer Joel Steinkraus uses sunlight to test the solar arrays on one of the Mars Cube One (MarCO) spacecraft.

https://solarsystem.nasa.gov/missions/mars-cube-one/in-depth/

https://arstechnica.com/information-technology/2021/11/starlink-unveils-2nd-generation-satellite-dish-and-new-wi-fi-router/

Starlink Teardown: DISHY DESTROYED!
YouTube · 380,000+ views · 11/25/2020
by Ken Keiter

https://www.youtube.com/watch?v=iOmdQnIlnRo

Automotive Radar – Status and Trends

Martin Schneider

Robert Bosch GmbH, Corporate Research, PO box 77 77 77, D-31132 Hildesheim, Germany, +49 5121 49 2543, Schneider.Martin@de.bosch.com

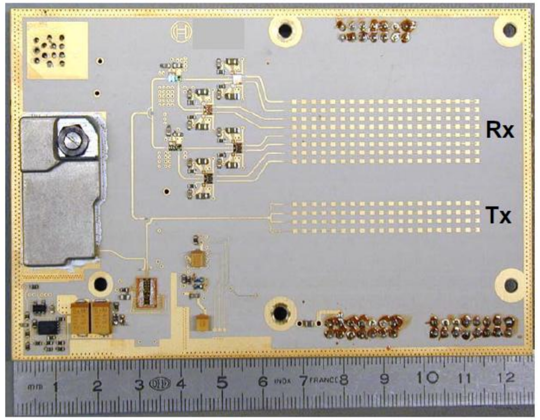


Fig. 5. Bistatic 77 GHz DBF front end with 8 patch antenna columns for receive and 4 columns (fed by a power splitter) for transmit

Fig. 6. Test vehicle with 77 GHz DBF demonstrator (also insert in right bottom corner)

www.scribd.com/document/94178930/5-3-Radar-Sensors

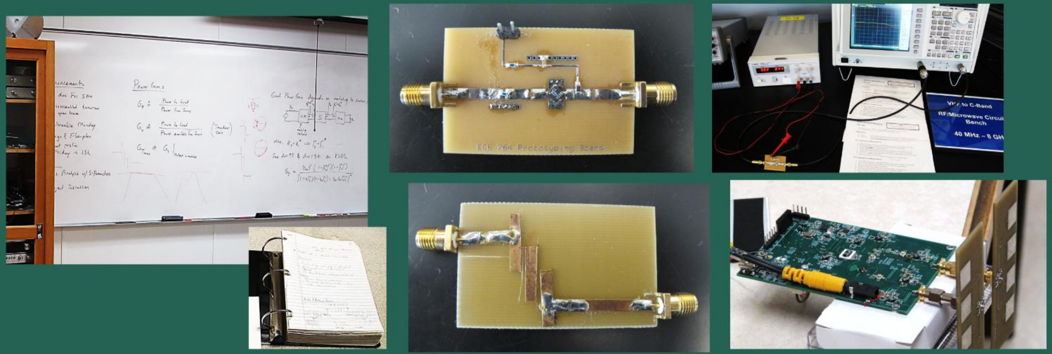
Future Episodes

Transmission-line Theory
Smith Charts
Microstrip
Microstrip Circuits
Radar or uWave Transverter Project

Radio Design 201 #3

Microwave Circuits and Antennas

Project-oriented Learning

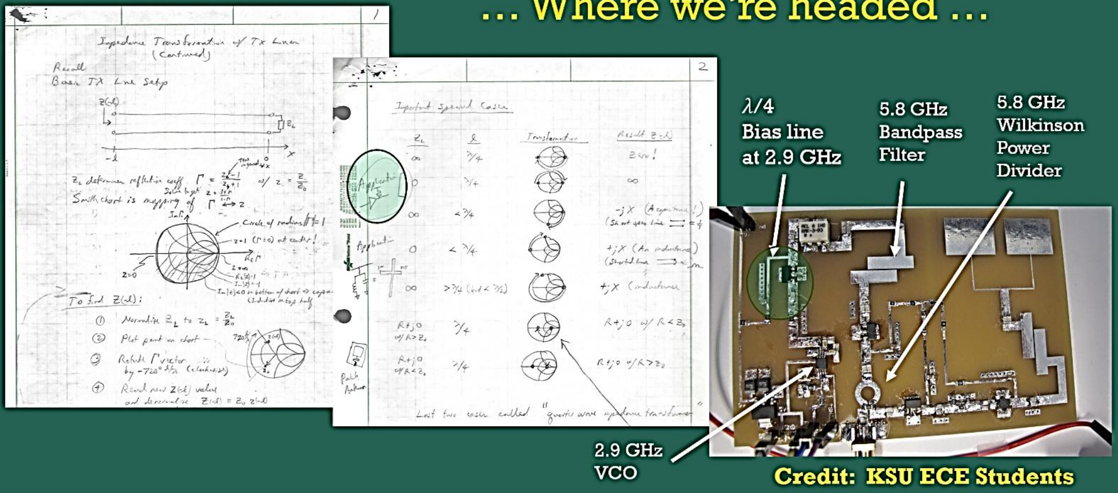


MegawattKS - YouTube

https://ecefiles.org

Microwave Circuits

… Where we're headed …

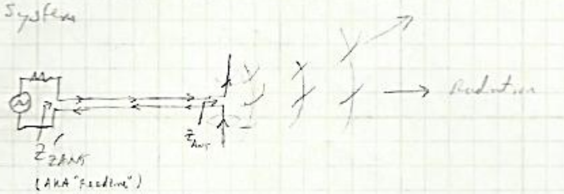


Credit: KSU ECE Students

1

Wires & Transmission Lines @ RF

Recall TX System

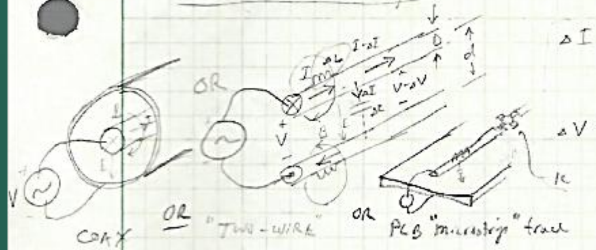


Transmission Line Characteristics

- "No" radiation ("if balanced feed & wires "closely spaced") $(d \ll \lambda/4)$
- Single connection $(Z'_{ANT} = Z_{ANT})$ if length $\ll \lambda/4$
- Distributed LC circuit if length $\geq 0.1\lambda$ $(\geq 0.1" @ 10 GHz)$ "Length of pin on an IC"

$\Rightarrow Z'_{ANT} \neq Z_{ANT}$ (except in special case of $Z_{ANT} \equiv Z_0$ of line)

TX Line modeling



$\Delta I = \frac{V}{1/j\omega\Delta C} = j\omega CV$ where $\Delta C = \mathcal{C}(\Delta x)$ — C per unit length (Typically 1 to 3 pF/inch)

$\Delta V = j\omega\Delta L\, I$ with $\Delta L = \mathcal{L}(\Delta x)$ (Typically 5-20 nH/inch)

Current ΔI drawn thru ΔC, Voltage "drop" ΔV across ΔL (but no power loss if L, C are "lossless" (V, I 90° apart))

$\Rightarrow$ V, I phase change along line

$\Rightarrow$ "Guided wave" propagates away from source toward load

IMPORTANT

$\boxed{\text{At RF \& microwave, any "node"} \gtrsim 0.05\lambda \text{ is NOT a node — it's a complicated LC network!}}$

At 2 GHz, $\lambda = \frac{3\times10^8}{2\times10^9} = 0.15$ m

$\Rightarrow \lambda/20 \approx 7$ mm! $= 1/3$ inch

Thanks For Watching !