Antennas & Receivers in Radio Astronomy

Bob Hayward, Senior Engineer, NRAO, Socorro, NM

Thirteenth Synthesis Imaging Workshop

May 28 - June 5, 2012

Antennas & Receivers - Outline

- A Little History
- Types of antennas
- Antenna fundamentals
- Reflector antennas
- Antenna performance
  - Aperture efficiency
  - Pointing
  - Polarization
- Single-Dish, Phased-Arrays and Interferometers
- The JVLA's…
  - Feeds & Receivers
  - Polarizers
  - Ka-Band Receiver
  - Signal Conversion Path
- System Noise Temperature
- JVLA Sensitivity

While past *Antennas & Receivers* talks have usually been generic presentations, this year saw the re-dedication of the Jansky VLA.

To take note of this event, most of today's slides will be devoted to NRAO's newly upgraded instrument.

It will also be geared more towards the receiver side of things than earlier Summer School talks were.

If you want to find out more information about antennas, check out the presentations by…

Peter Napier (2002, 2004 & 2006)

Mark McKinnon (2008 & 2010)

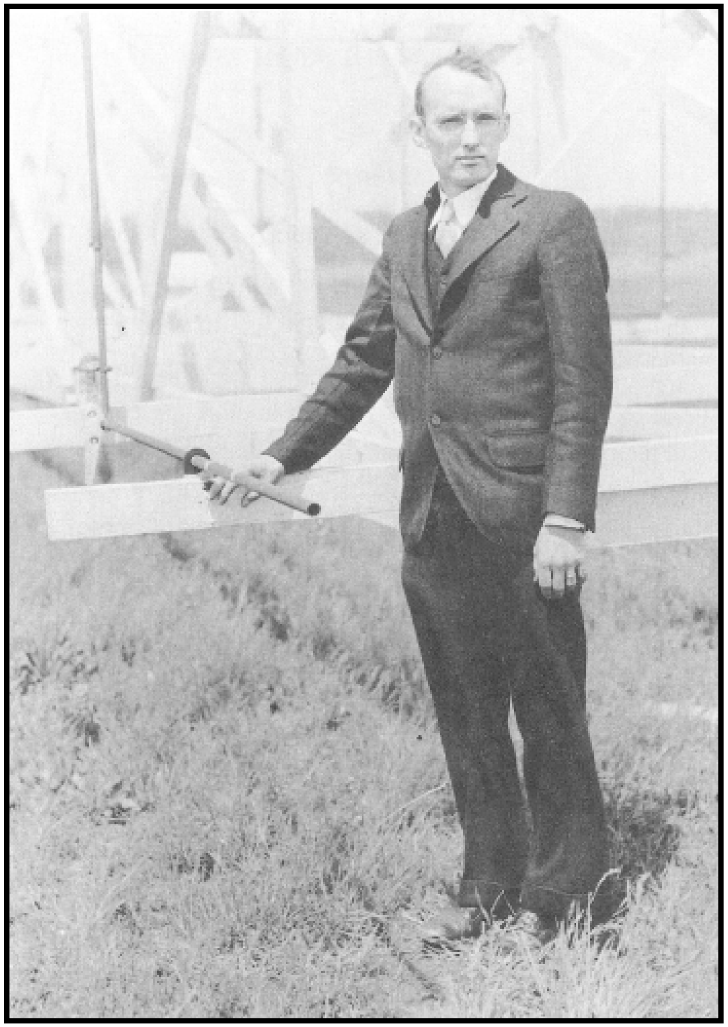
The Primary Antenna Elements, P.J. Napier,
Synthesis Imaging in Radio Astronomy II,
Edited by Taylor, Carilli, & Perley.
ASP Conference Series, Vol. 180, 1999, p. 37
http://articles.adsabs.harvard.edu/full/1999ASPC..180...37N

The Receiver System -- cm Regime, R.D. Norrod.
Single-Dish Radio Astronomy: Techniques and Applications,
Edited by Stanimirovic, Altschuler, Goldsmit & Salterh,
ASP Conference Proceedings, Vol. 278, 2002, p. 91
http://adsabs.harvard.edu/full/2002ASPC..278...91N

History Lesson

1932

Karl Jansky's "Star Static" 80 Years Ago



Karl Jansky with his antenna

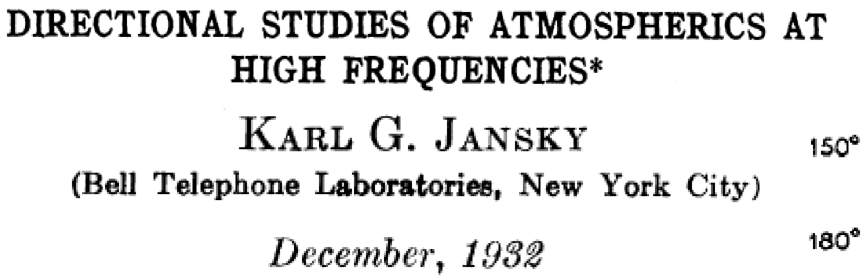
- Karl Jansky joined *Bell Labs* in 1928.
- He worked at the *Radio Research Field Station* at Holmdel, NJ.
- His principle assignment was to investigate sources of atmospheric static that might interfere with *short-wave* (3-30 MHz) telephone radio links that were being used for transatlantic telephone communications.
- While listening for the noise coming from thunderstorms, he discovered…

  "*noise of extraterrestrial origin*"
- He was to refer to it in his published papers as "*star static*".
- His famous - albeit serendipitous - discovery was made in 1932.
- Karl Jansky is now recognized as the *Father of Radio Astronomy*.

Classics in Radio Astronomy, W.T. Sullivan, D. Reildel Publishing Company, 1982, p. Frontispiece

Jansky's Antenna

1932



DIRECTIONAL STUDIES OF ATMOSPHERICS AT HIGH FREQUENCIES*

KARL G. JANSKY

(Bell Telephone Laboratories, New York City)

December, 1932

Frequency

14.6 meters
or
20.5 MHz

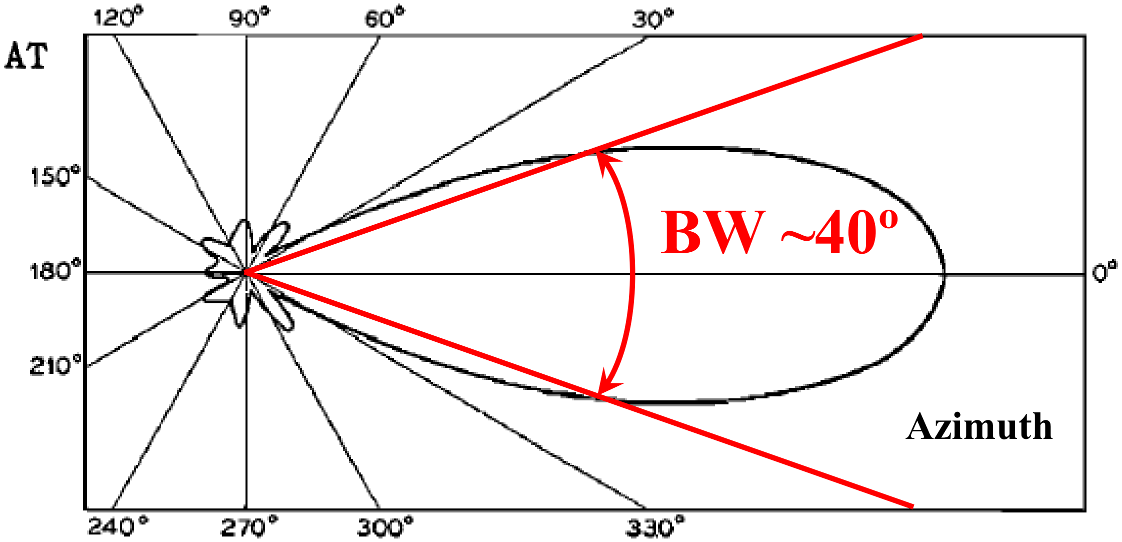


Fig. 3—Directional characteristic of array at 14.6 meters.

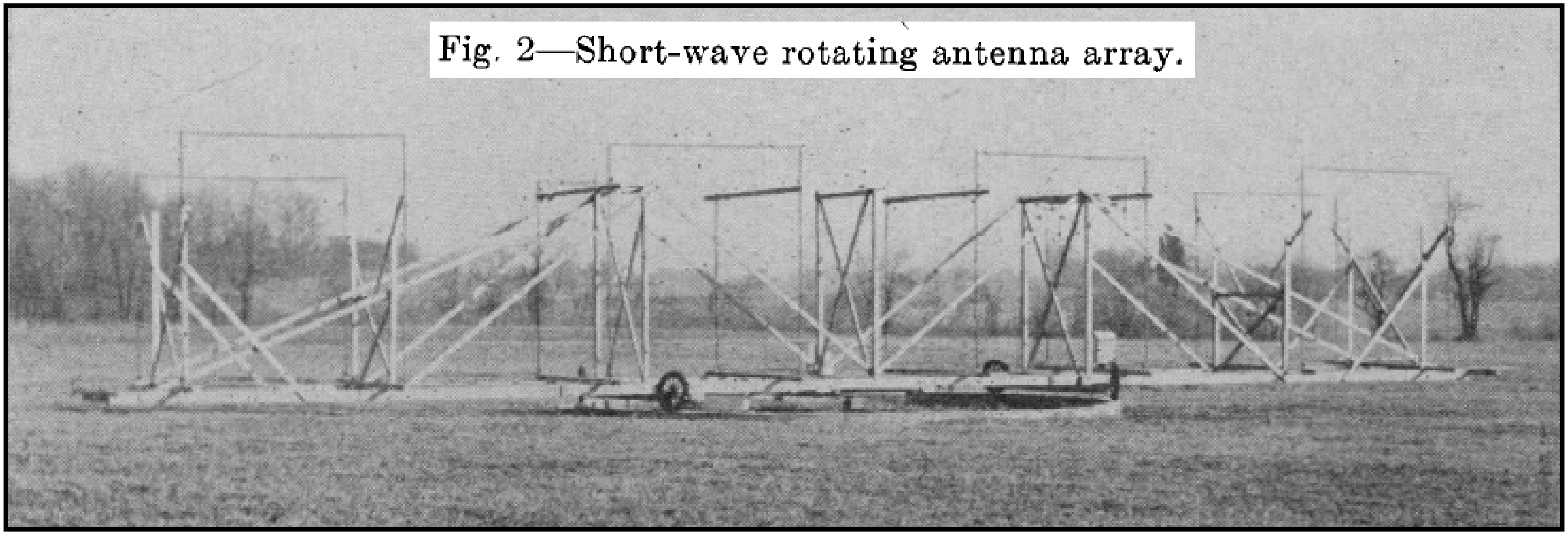


Fig. 2—Short-wave rotating antenna array.

Directional Studies of Atmospherics at High Frequencies, K.G. Jansky, Proc. of the IRE, Vol. 20, No. 12, Dec. 1932, p. 1920

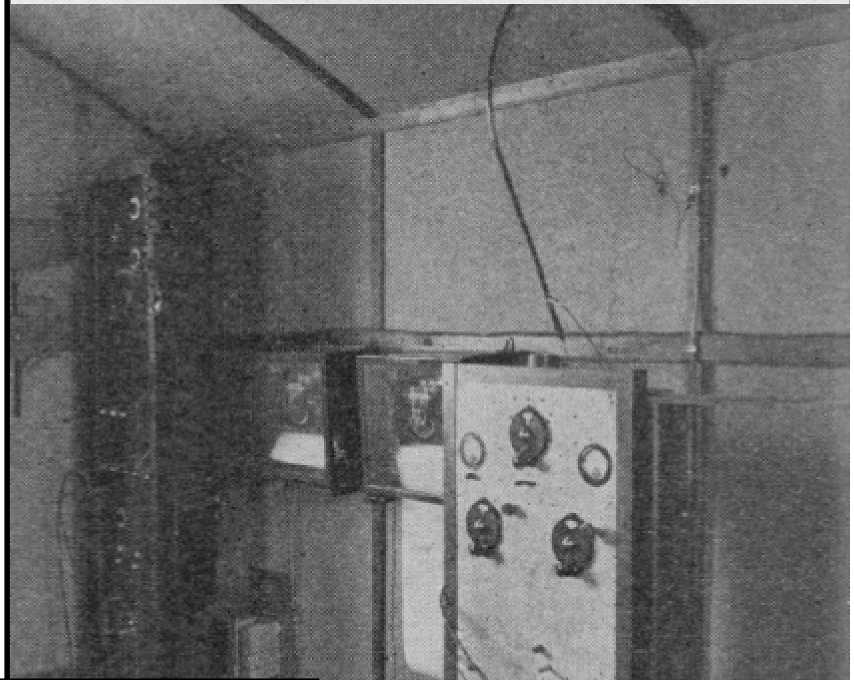
Jansky's Receiver

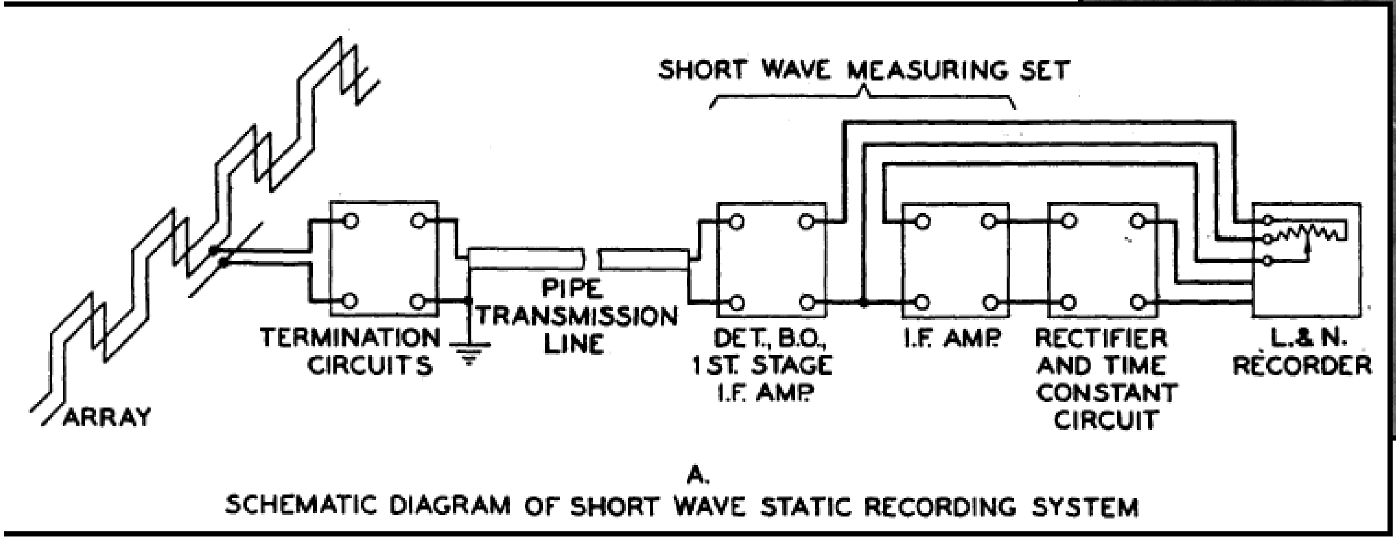
1932

DIRECTIONAL STUDIES OF ATMOSPHERICS AT
HIGH FREQUENCIES*

While Jansky's equipment was very primitive by today's standards, it was still up to the task for his serendipitous discovery of what he was to call *"star static"*.

Fig. 5—Long- and short-wave static recording systems.





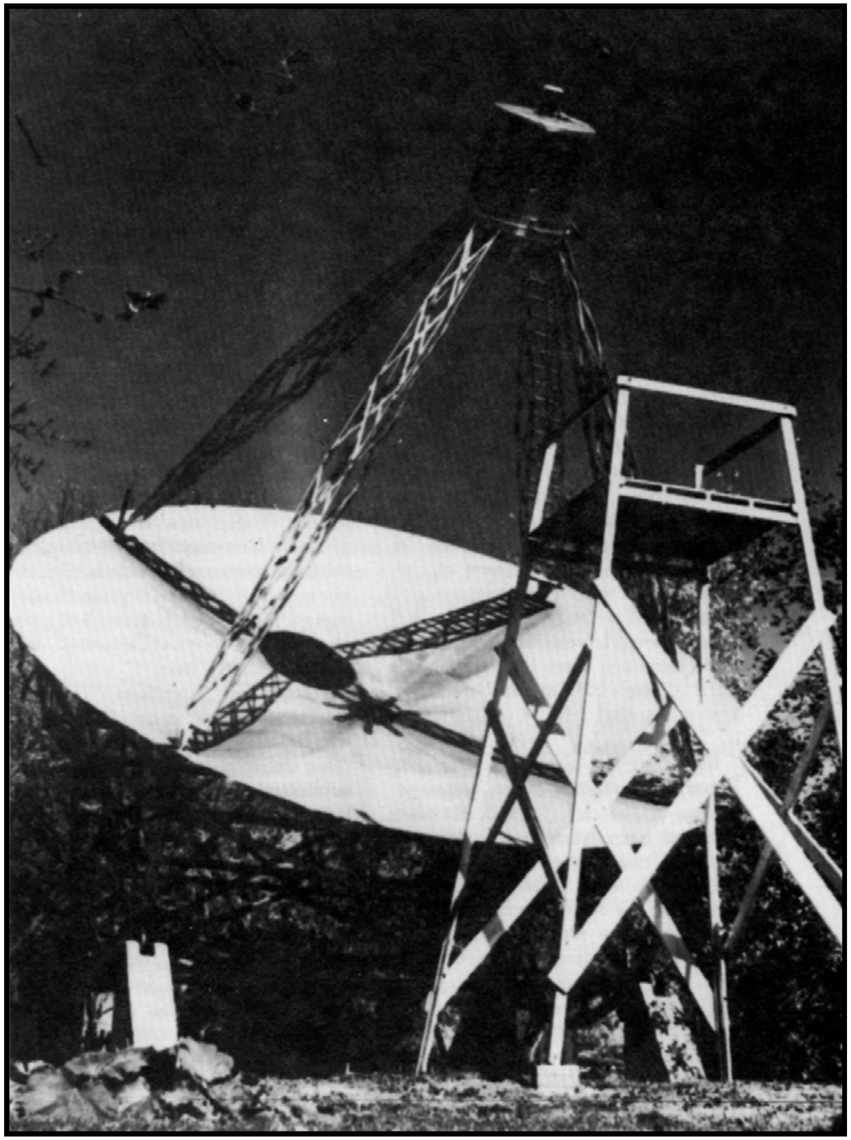
A.
SCHEMATIC DIAGRAM OF SHORT WAVE STATIC RECORDING SYSTEM

Directional Studies of Atmospherics at High Frequencies, K.G. Jansky, Proc. of the IRE, Vol. 20, No. 12, Dec. 32, p. 1920

Grote Reber – World's 1st Radio Astronomer

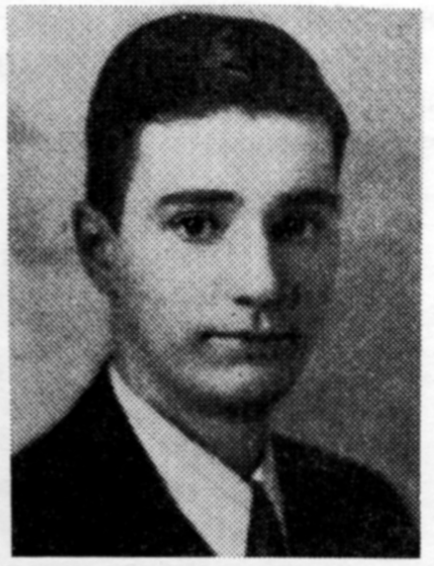
1939

- Grote Reber, a radio engineer & avid radio amateur, had read Jansky's articles. By 1938, he constructed a 31-foot parabolic dish in his back yard in Wheaton, IL and had begun observations of the celestial sky.
- Drift scans at both 9-cm & 33-cm produced negative results, so he built a new 1.9-m receiver. In April 1939 he found what he termed *cosmic static* from the center of the Milky Way. He then embarked on the first survey of the radio sky in 1941.
- Reber worked by day designing radio receivers at a factory in nearby Chicago. Taking the train was an hour each way. After supper he slept until midnight, and then sat in his basement and recorded the output meter readings of his receiver at one minute intervals until he left for work the next morning.
- By 1941 he had purchased a strip chart recorder.

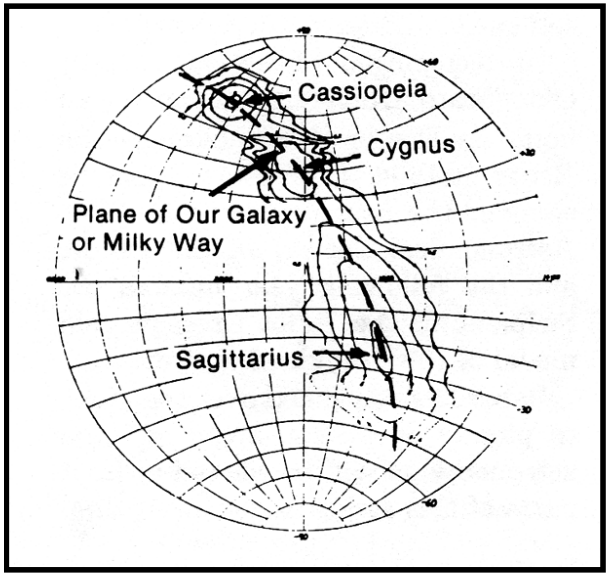


http://www.bigear.org/CSMO/HTML/CS13/cs13p14.htm

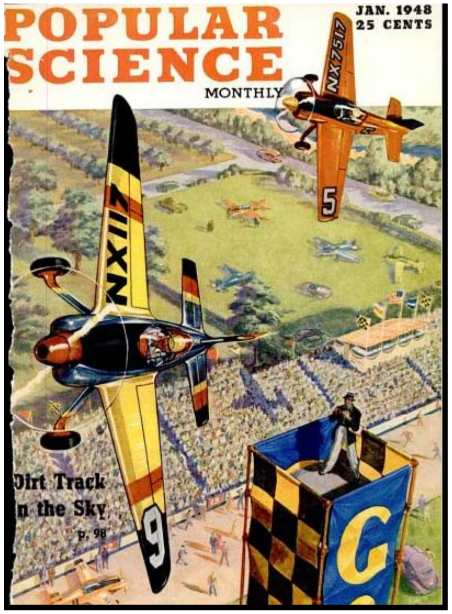
Grote Reber : A Radio Astronomy Pioneer, K. I. Kellermann, in *The New Astronomy - A Meeting to Honor Woody Sullivan on his 60th Birthday,* edited by W. Orchiston, Springer, 2005



Grote Reber circa 1940.



Reber's 1944 Radio Sky at 1.9m



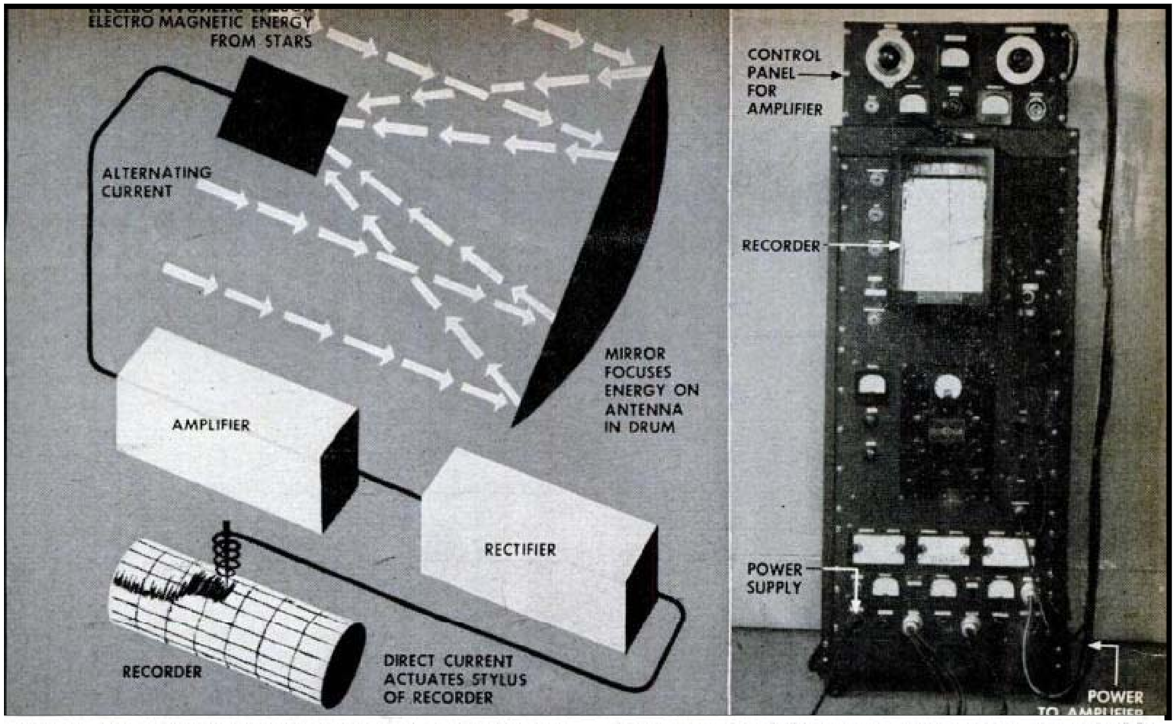
Because a radio ham heard strange sky noises, we may get better FM and television—and learn more about our universe.

Static from the Stars

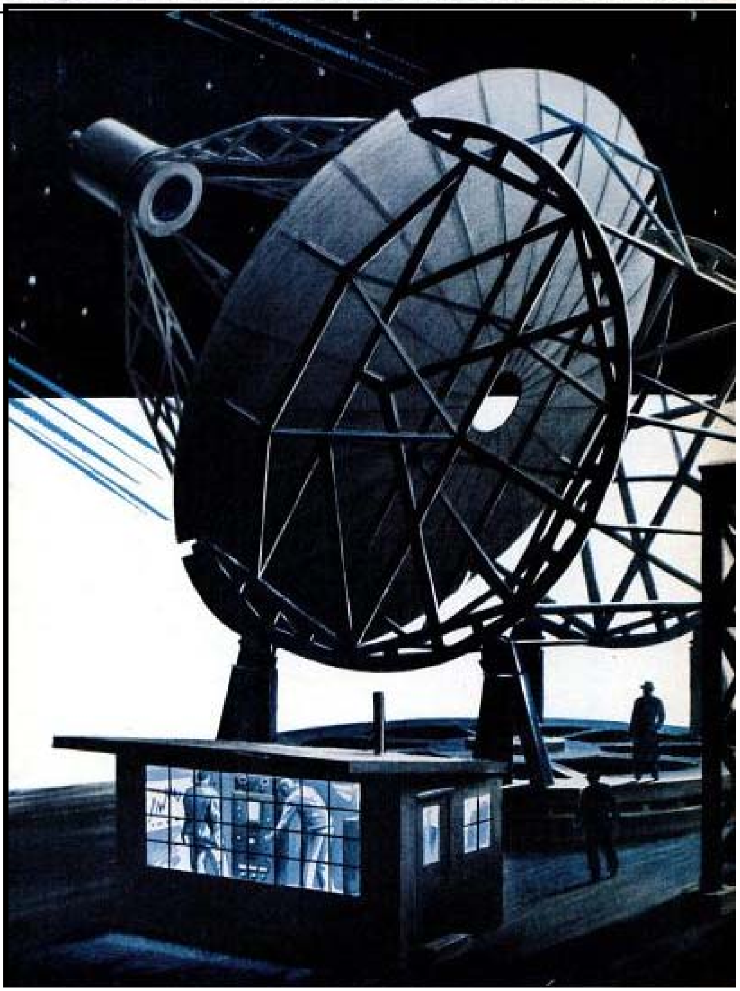
Reber—the first *e* is long, as in *receiver*—has designed and built a huge radio mirror that traps radio waves from the stars the same way that an ordinary telescope mirror traps light waves. The radio waves can be used for the same job—to explore the universe. After 10 years of experimenting

Tomorrow's telescopes may be huge mirrors that gather faint electronic radiations from stars.

JANUARY, 1948



Conversion of radiation into AC is shown in diagram at left, above. Actually, both amplifier and rectifier are inside the little knob that sticks out from drum at focal point. At right, above, is the laboratory apparatus. Top holds controls for amplifier; center, automatic recorder that charts time and intensity of radiation reception; bottom panel, power supply unit.



Interferometer Block Diagram

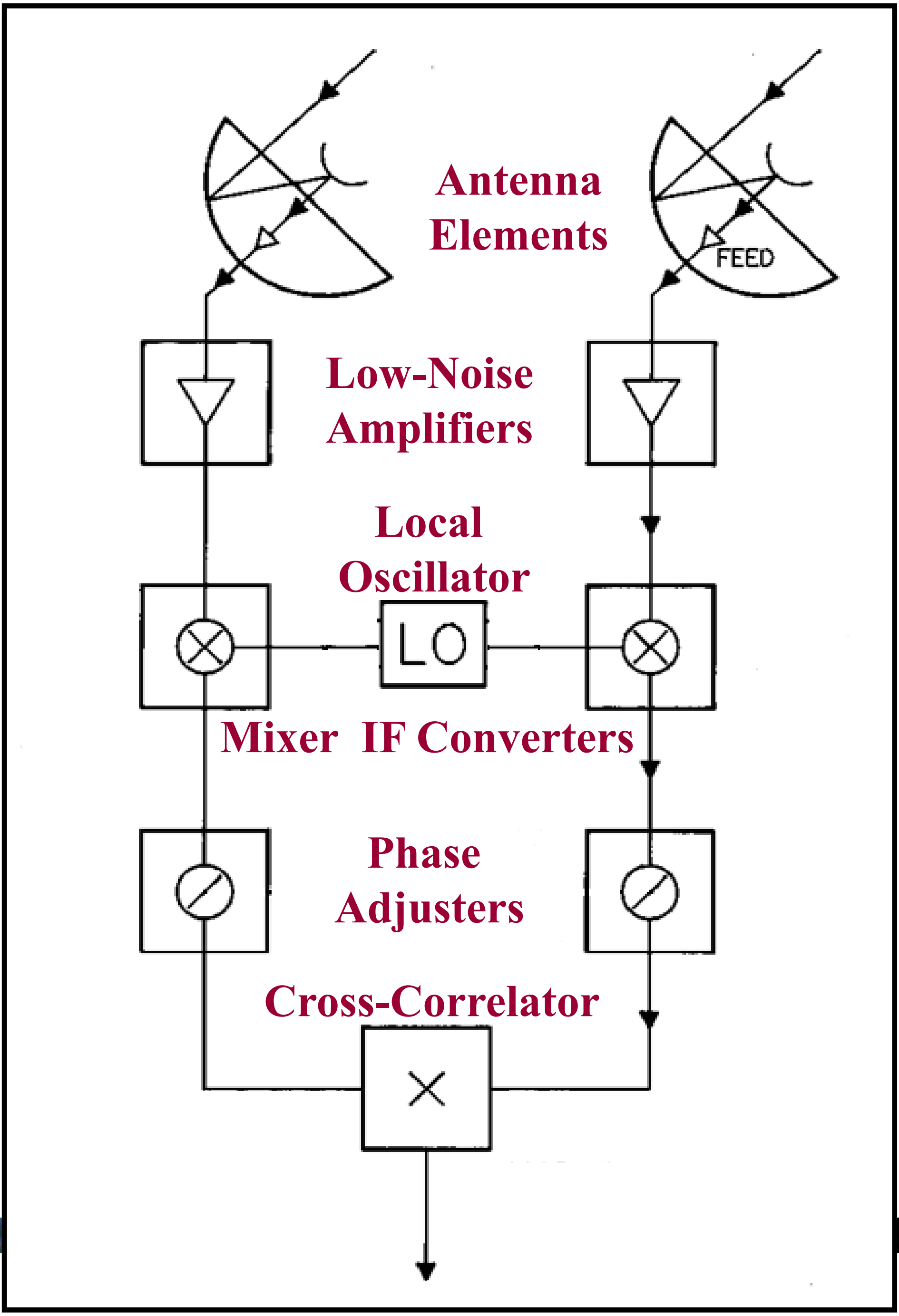
Advantages of Interferometry:

- Increases resolution
- Increases collecting area

Example : JVLA

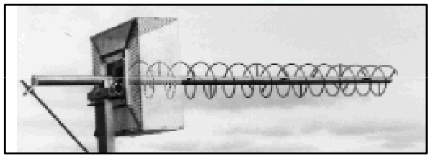
Electronically combining its
27 x 25-m (85-ft)
dishes results in…

- the resolution of an antenna up to 36 km (22 miles) across
- the sensitivity equivalent to a single dish with a diameter 130-m (422-ft)

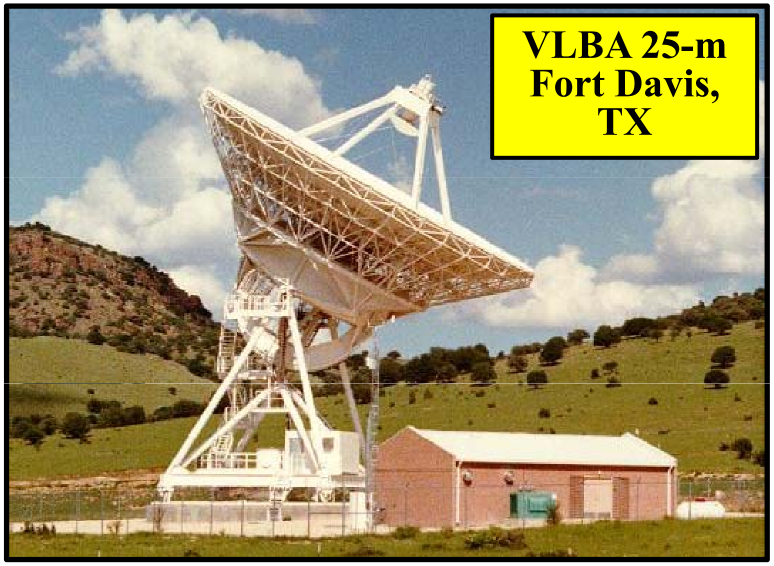


Types of Antennas

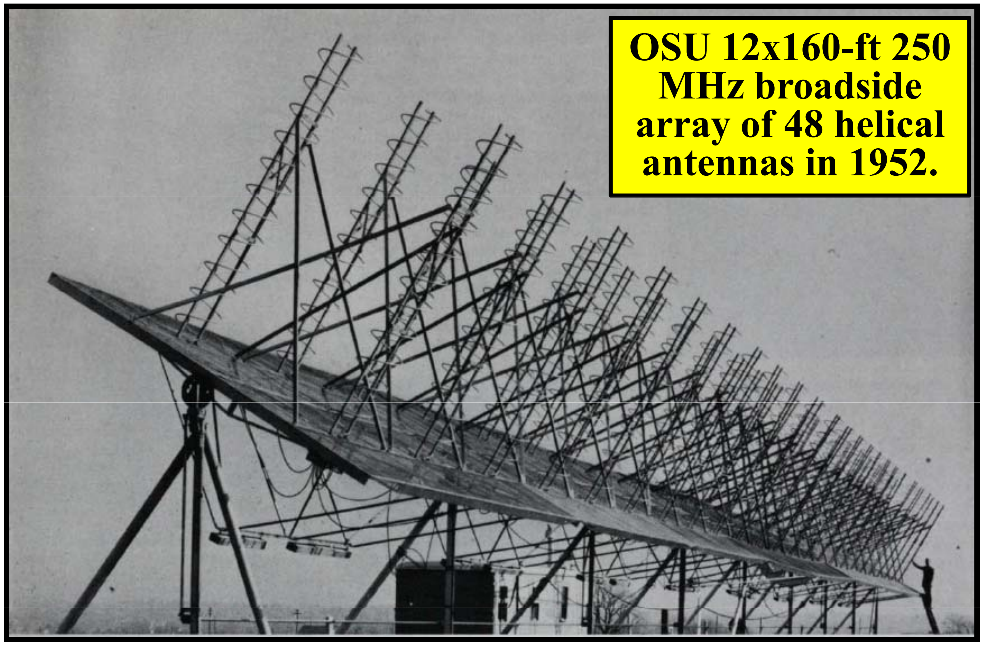
- Wire antennas $(\lambda > 1\text{m})$
  - Dipole
  - Yagi
  - Helix



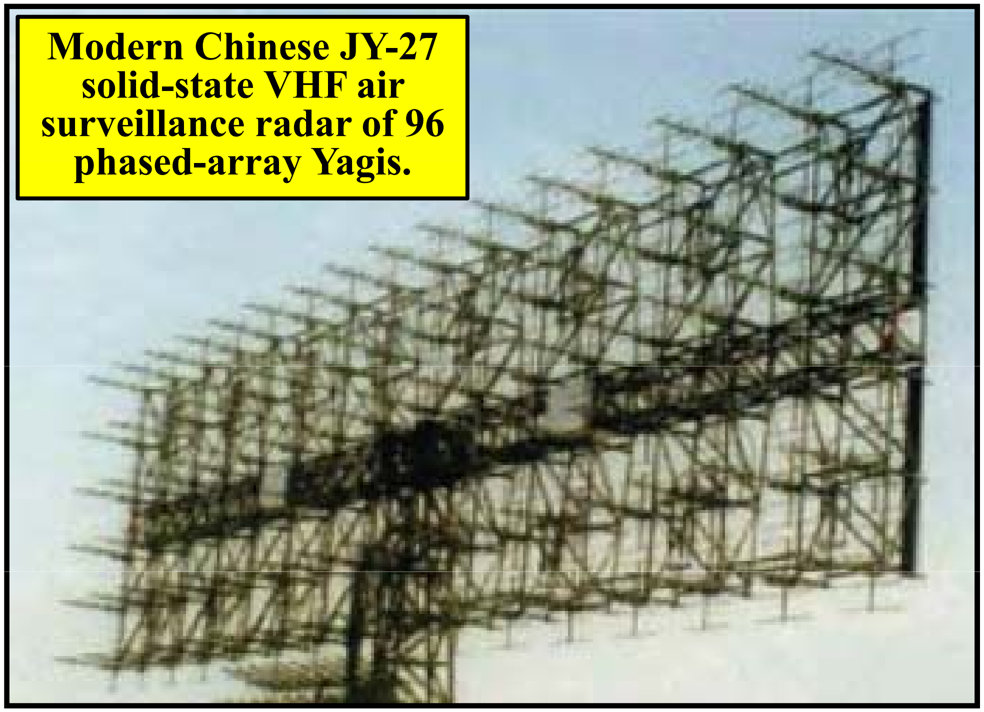
- Arrays of the Above
  - Broadside Arrays
  - Phased-Arrays
- Reflector antennas $(\lambda < 1\text{m})$



VLBA 25-m Fort Davis, TX



OSU 12x160-ft 250 MHz broadside array of 48 helical antennas in 1952.

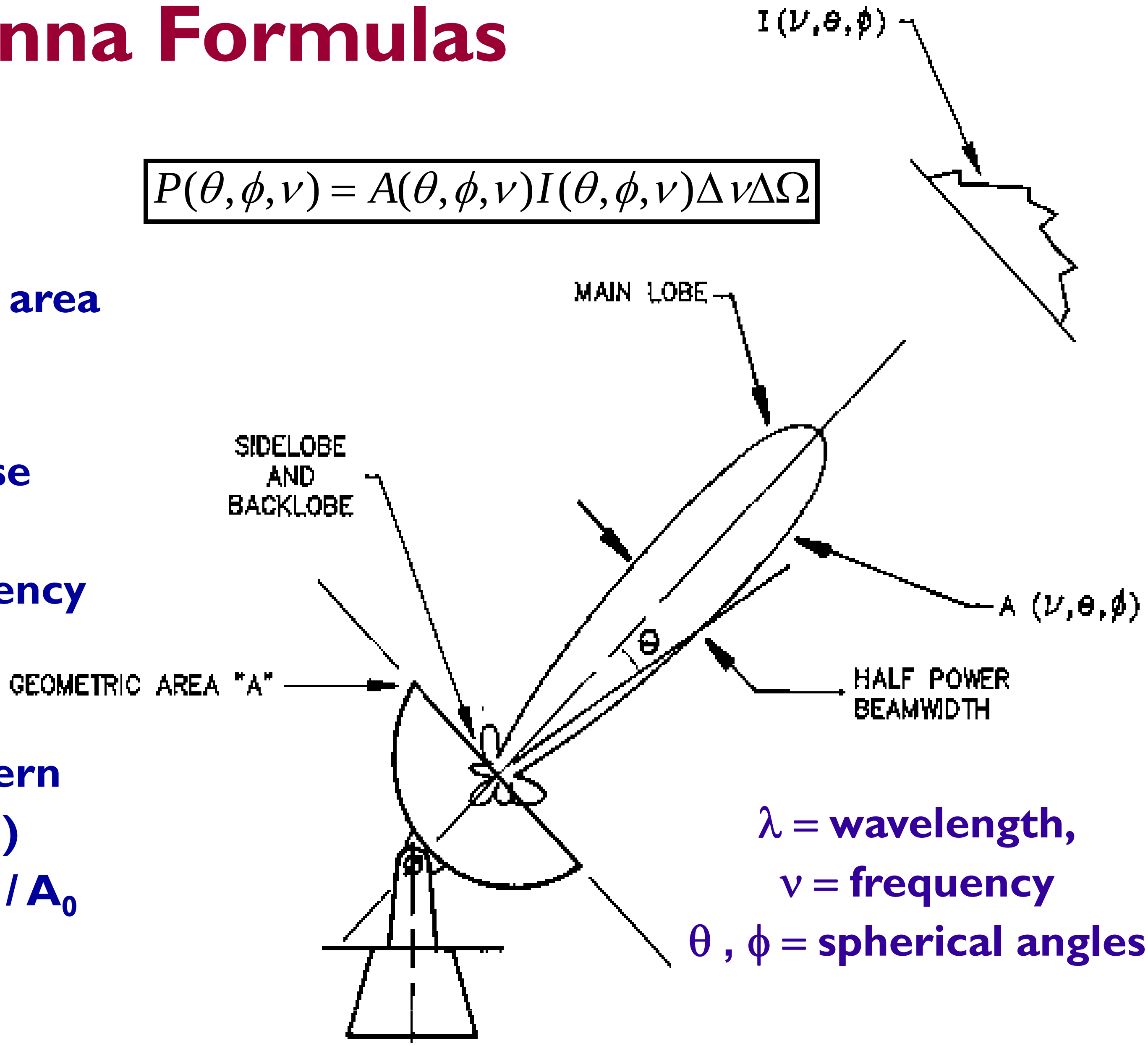


Modern Chinese JY-27 solid-state VHF air surveillance radar of 96 phased-array Yagis.

The Ohio State Radio Telescope, J.D. Kraus, Sky & Telescope, April 1953, p. 157
http://www.microwavejournal.com/articles/931-radar-today

Basic Antenna Formulas

$$\boxed{P(\theta,\phi,\nu) = A(\theta,\phi,\nu) I(\theta,\phi,\nu) \Delta\nu \Delta\Omega}$$



Effective collecting area

$\mathrm{A}(\nu,\theta,\phi)$ m^2

On-axis response

$\mathrm{A}_0 = \eta \mathrm{A}$

η = aperture efficiency

Normalized pattern

(primary beam)

$\mathit{A}(\nu,\theta,\phi) = \mathrm{A}(\nu,\theta,\phi) / \mathrm{A}_0$

λ = wavelength,

ν = frequency

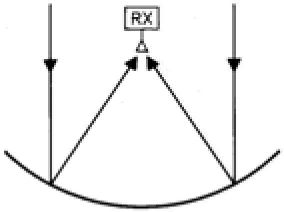
θ , ϕ = spherical angles

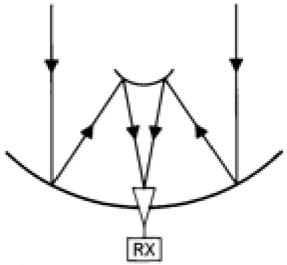
Importance of the Antenna Elements

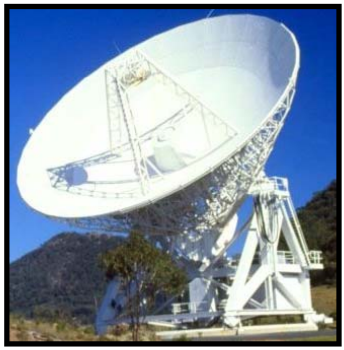
- **The shape of the *antenna pattern* will cause both the <u>amplitude</u> and <u>phase</u> to vary across the source.**
- **Antenna *pointing errors* can cause both <u>amplitude</u> and <u>phase</u> errors that vary with time.**
- ***Noise pickup* from the ground can cause time variable <u>amplitude</u> errors.**
- **Deformations of the antenna surface due to *gravity*, *wind* or *temperature* can cause <u>amplitude</u> and <u>phase</u> errors (especially at short wavelengths).**
- **The *polarization* properties of the antenna will modify the apparent <u>polarization</u> of the source.**

Examples of Antenna Reflector Optics

Prime
Focus
(GMRT)

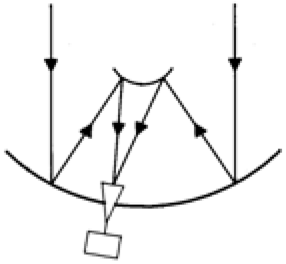


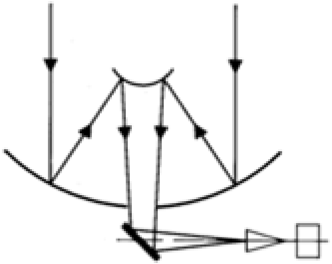




Cassegrain
Focus
(ATCA)

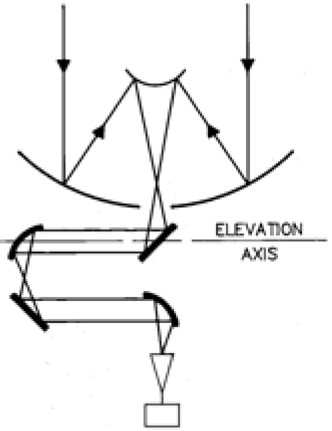
Offset
Cassegrain
(JVLA)

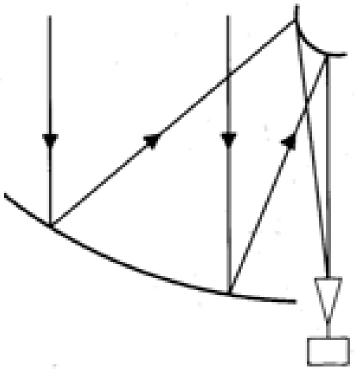




Naysmith
Focus
(OVRO)

Beam
Waveguide
(NRO 40m)





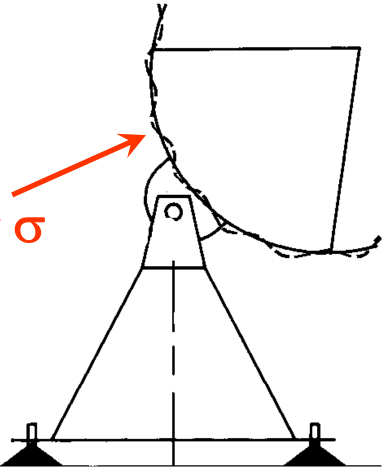
Dual
Offset
(GBT)

Reflector Optics: Limitations

- **Prime focus:**
  - Over-illumination of the primary reflector can increase system temperature due to ground pick-up (spillover).
  - Number of receivers, and access to them, is limited.
- **Subreflector systems:**
  - Can limit low frequency capability because the feed horns need to be large in order to illuminate the subreflector properly.
  - Over-illumination by the feed horn can cause unwanted sidelobes which may limit the dynamic range of the image when strong sources lie a few degrees away from a weak source.
- **Offset optics:**
  - Support structure for the offset feed arm can be complex and expensive, especially in large telescopes.

Antenna Performance:

Aperture Efficiency & Surface Accuracy



rms error σ

On axis response: $A_0 = \eta A$

Efficiency: $\eta = \eta_{sf} \cdot \eta_{bl} \cdot \eta_s \cdot \eta_t \cdot \eta_{misc}$

Where..

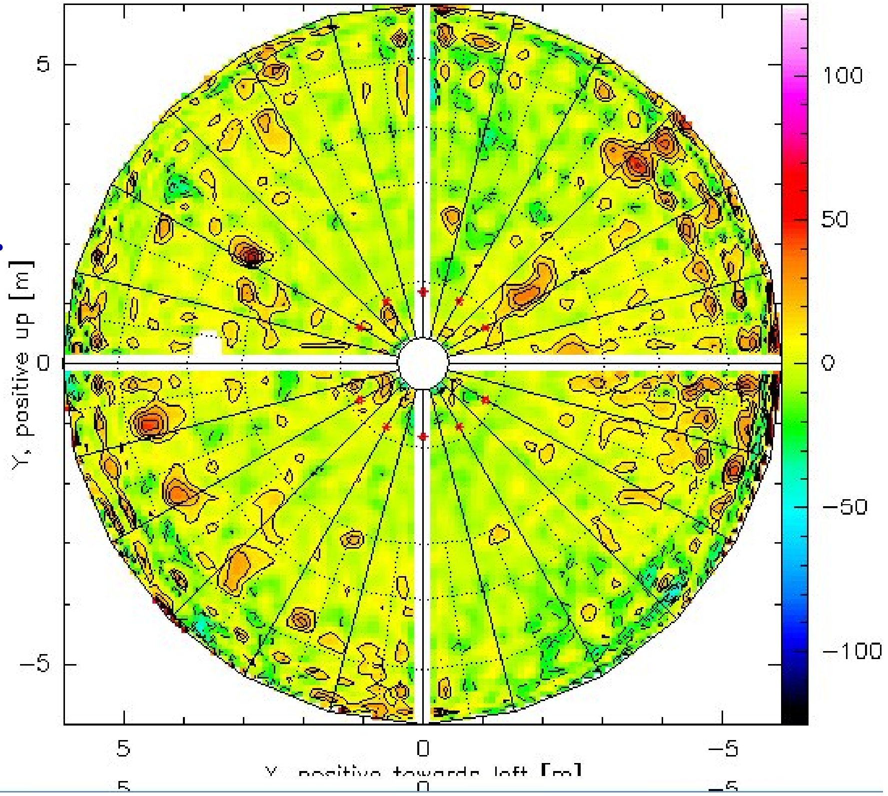
η_{sf} = Reflector surface efficiency, due to imperfections in reflector surface.

η_{bl} = Blockage efficiency caused by the subreflector and its support structure.

η_s = Feed spillover efficiency, the fraction of power radiated by feed intercepted by subreflector.

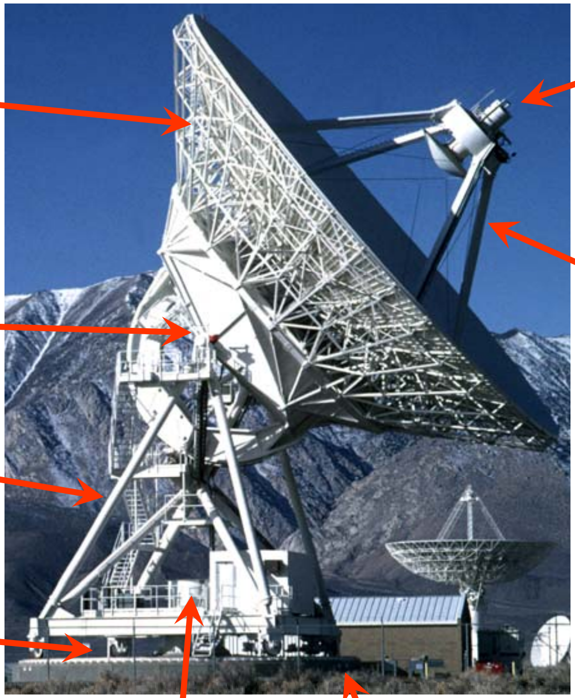
η_t = Feed illumination efficiency (outer parts of reflector illuminated at lower level than inner part.

η_{misc}= Reflector diffraction, feed position phase errors, feed match and loss



Surface accuracy of an ALMA antenna measured with holography = 10um rms

Antenna Performance : Pointing



Reflector Structure

Elevation Encoder

Alidade Structure

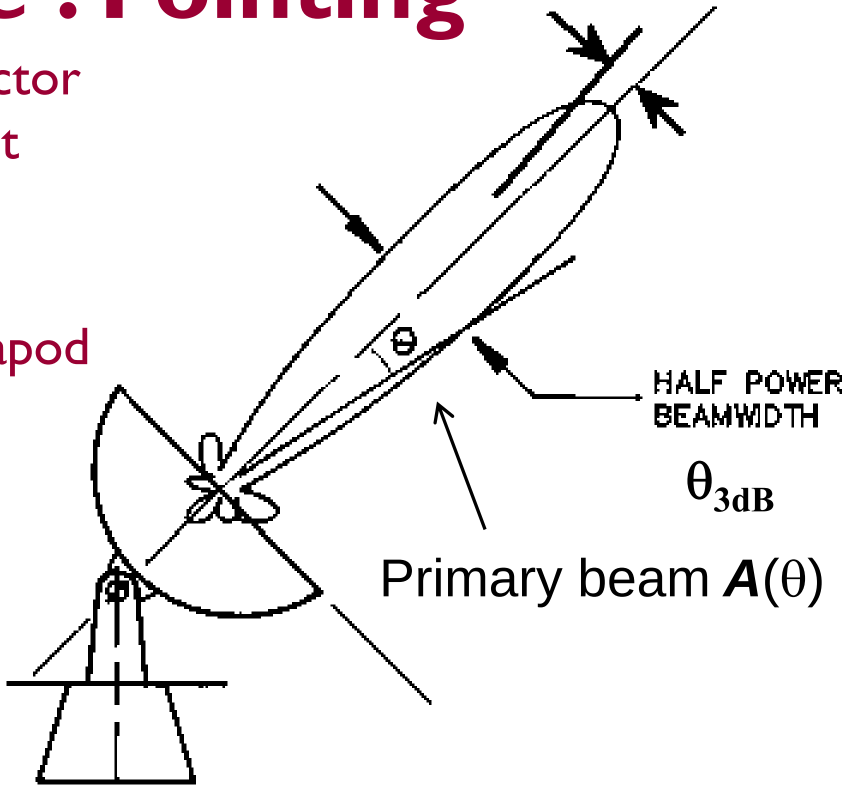
Rail flatness

Subreflector Mount

Quadrapod

Azimuth Encoder

Foundation



Pointing Accuracy : $\Delta\theta$ rms pointing error

At center of beam, $\Delta\theta < \theta_{3dB}/10$ is acceptable (beam response only varies $\boldsymbol{A}(\theta_{3dB}/10) \sim 0.97$

But at half power point in beam, beam varies by

$$\boldsymbol{A}(\theta_{3dB}/2 +/- \theta_{3dB}/10) / \boldsymbol{A}(\theta_{3dB}/2) = +/-0.3$$

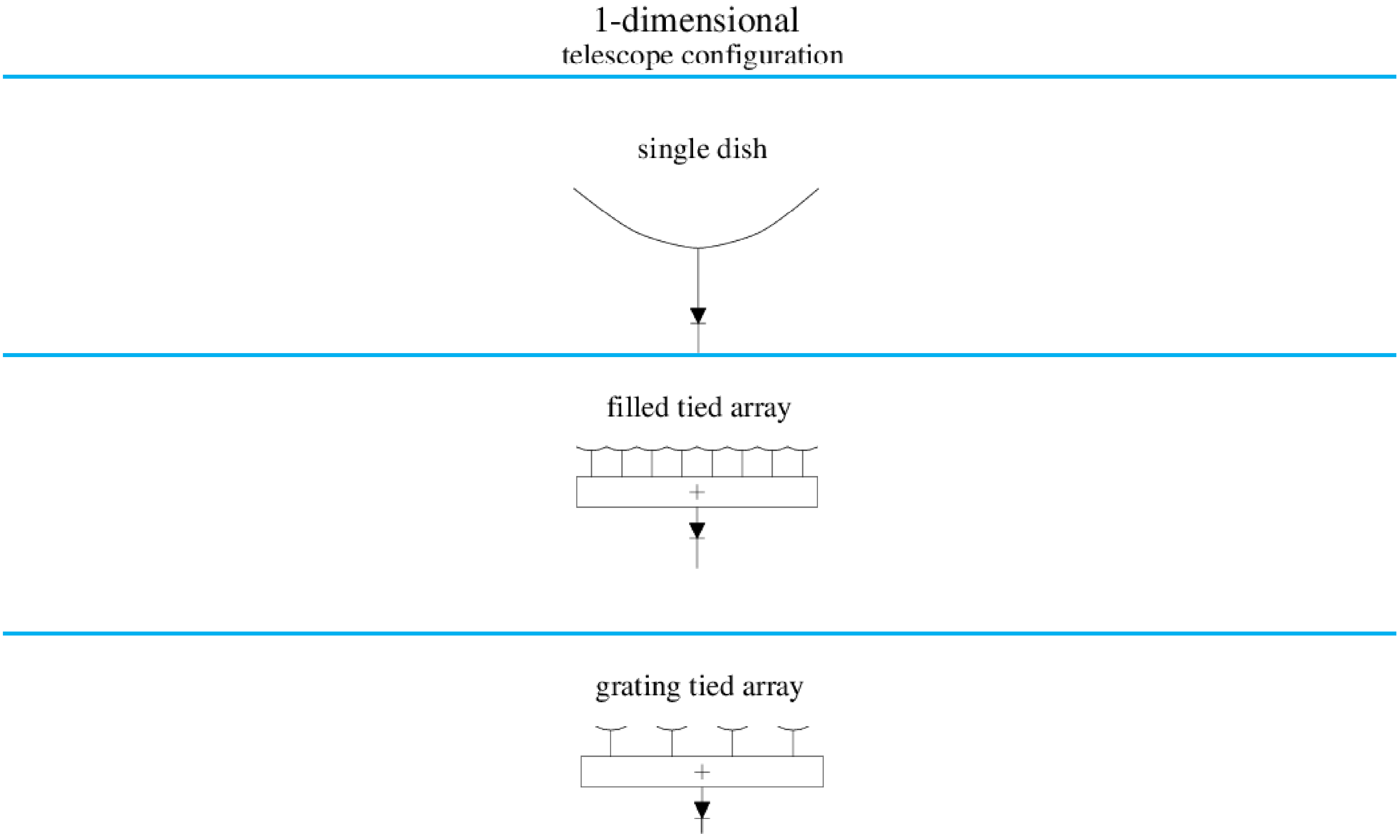
- JVLA Pointing:
  - "Blind", ~10" during Nighttime
  - "Blind", ~ 30" during Daytime
  - Reference Pointing, ~ 7" (Day)
  - $\Delta\theta$ = 3" = $\theta_{3dB}/17$ @ 50 GHz
- ALMA meets the "All-Sky" spec for pointing of < 2" rms

Antenna Performance : Polarization

Both the antenna and the receiver can modify the apparent polarization properties of the source:

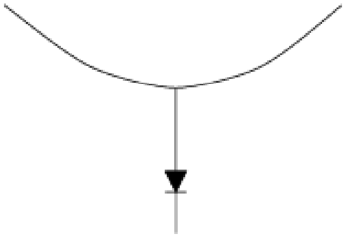
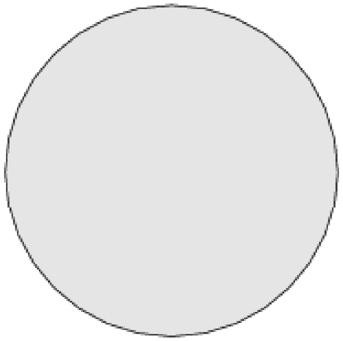
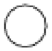
- Antenna structure:
  - Symmetry of the optics ?
  - Reflections in the optics ?
  - Curvature of the reflectors ?
- Quality of the Polarizer (usually linear or circular):
  - Leakage between orthogonal polarizations ?
- Typically the feed radiation pattern will have small instrumental polarization on-axis but the cross-polarization (i.e., leakage) will vary across the beam.

Single-Dish, Phased-Arrays & Interferometers



Instrumental Techniques in Radio Astronomy, **Johan Hamaker, Dwingeloo, NL - http://www.astron.nl/%7Ehamaker/les4.ps**

Physical aperture

1-dimensional		2-dimensional	
telescope configuration	beam cross-section	telescope configuration	beam projection
single dish 			

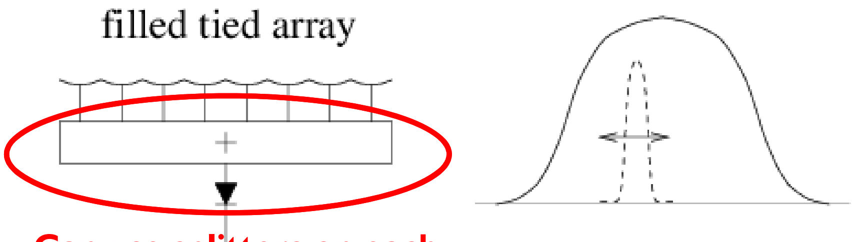
“Orange-Peel” Antenna

CSIRO Parkes 210-ft Telescope, Australia

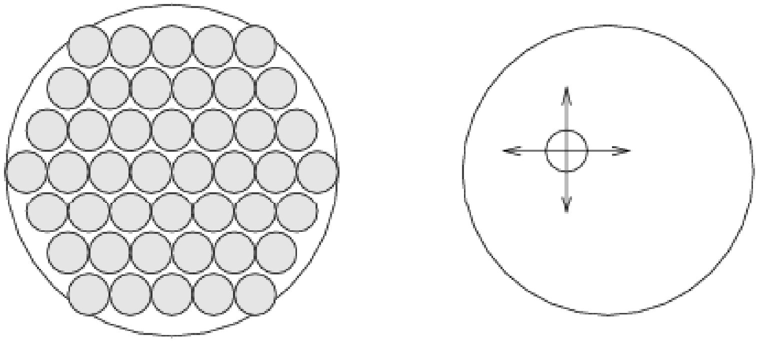
Instrumental Techniques in Radio Astronomy, Johan Hamaker, Dwingeloo, NL - http://www.astron.nl/%7Ehamaker/les4.ps
http://en.wikipedia.org/wiki/File:Antenna_radar_L-band_TAR_Finland.JPG
http://www.thelivingmoon.com/45jack_files/03files/Australia_Siding_Spring_Observatory.html

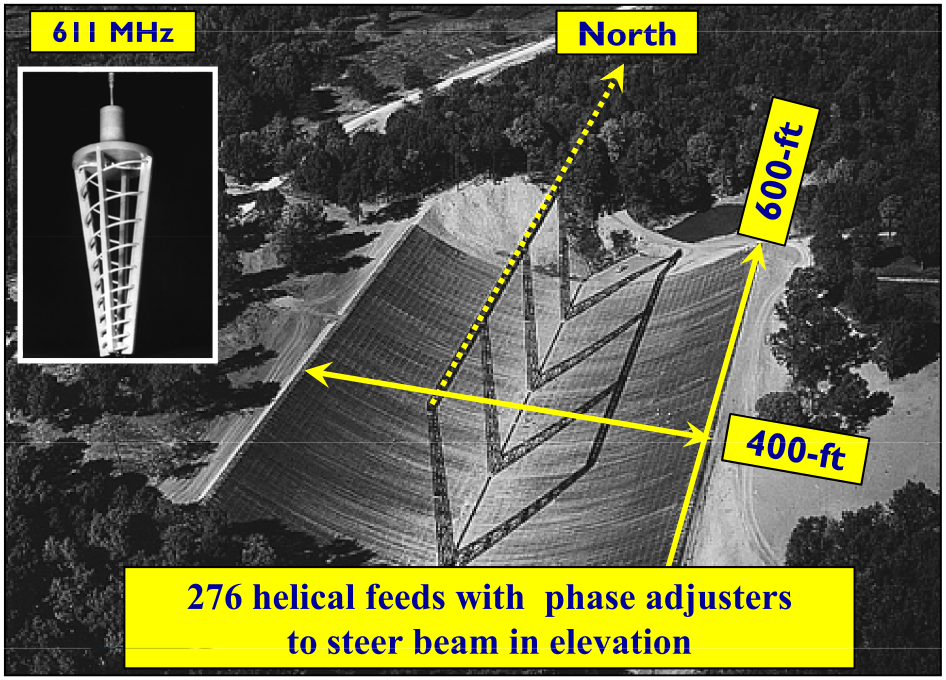
1-dimensional **Physical aperture** 2-dimensional

telescope configuration | beam cross-section | telescope configuration | beam projection



Can use splitters on each antenna output to connect multiple beamformers.





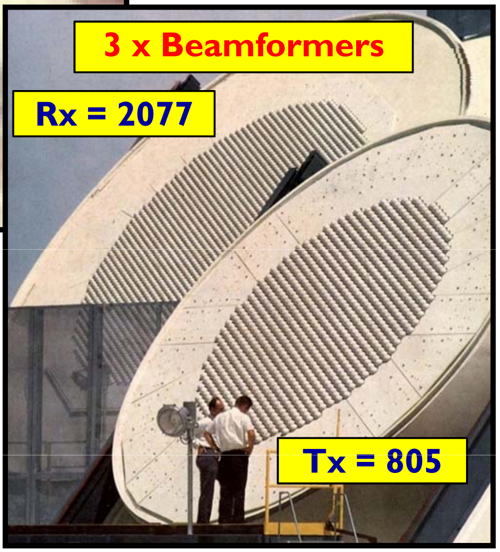
276 helical feeds with phase adjusters to steer beam in elevation

University Illinois 400-ft Telescope (1960)

Nike-X MAR-I

Multifunction Array Radar (Prototype)

WSMR, NM (1964)



L-Band (1200-1400 MHz)
25-ft Receiver Array Face
2077 active elements.

First "hardened" ABM radar & the source of the "Colgate Paramps" used in radio observatories around the world.

Instrumental Techniques in Radio Astronomy, Johan Hamaker, Dwingeloo, NL - http://www.astron.nl/%7Ehamaker/les4.ps ; http://www.ece.illinois.edu/about/history/reminiscence/400ft.html
MAR-I Photo courtesy of Doyle Piland, WSMR Archive ; *What Price Nike-X?*, FORTUNE Magazine, Nov 196

1-dimensional

Physical aperture

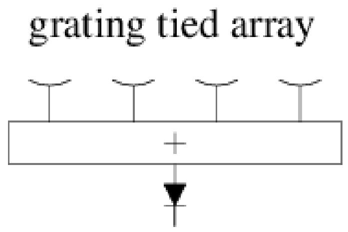
2-dimensional

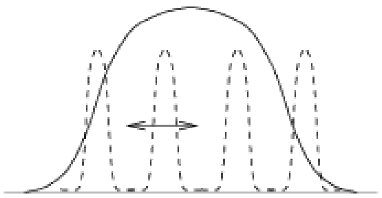
telescope configuration

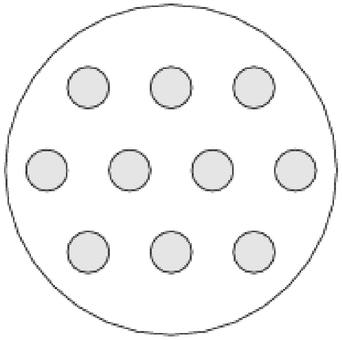
beam cross-section

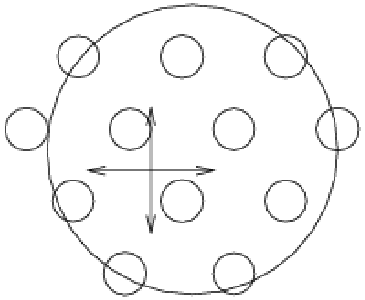
telescope configuration

beam projection

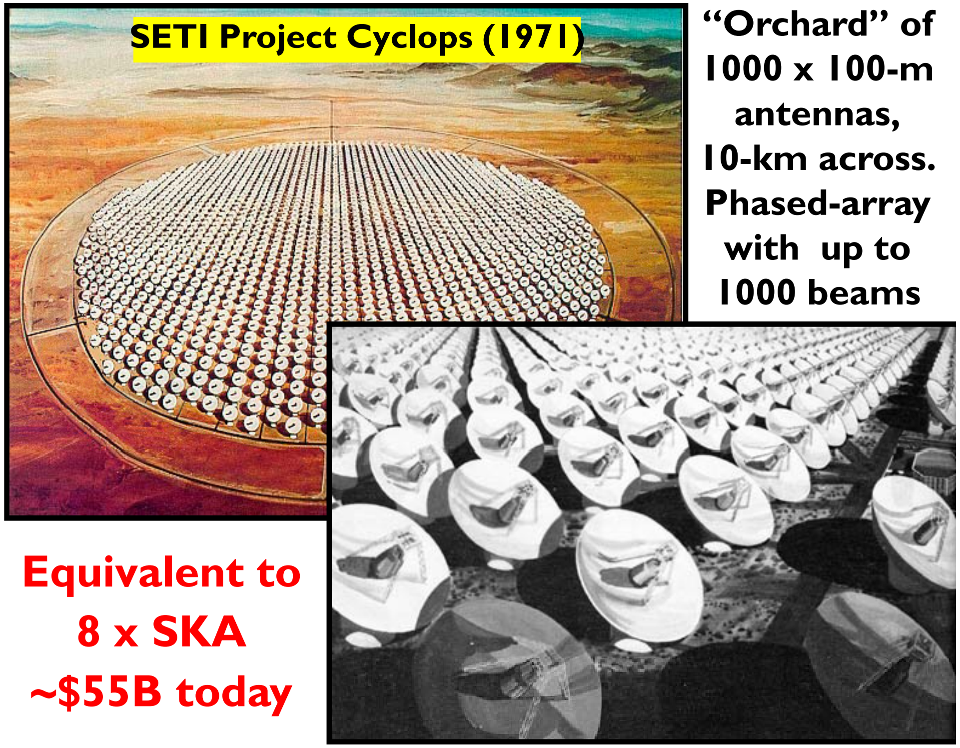








Algonquin 32-Element Solar Interferometer



SETI Project Cyclops (1971)

"Orchard" of 1000 x 100-m antennas, 10-km across. Phased-array with up to 1000 beams

Equivalent to 8 x SKA ~$55B today

Instrumental Techniques in Radio Astronomy, Johan Hamaker, Dwingeloo, NL - http://www.astron.nl/%7Ehamaker/les4.ps
http://www.flickr.com/photos/that_fat_bloke/2393400712/sizes/l/in/photostream/
http://news.discovery.com/space/are-aliens-eavesdropping-on-us-not-likely.html

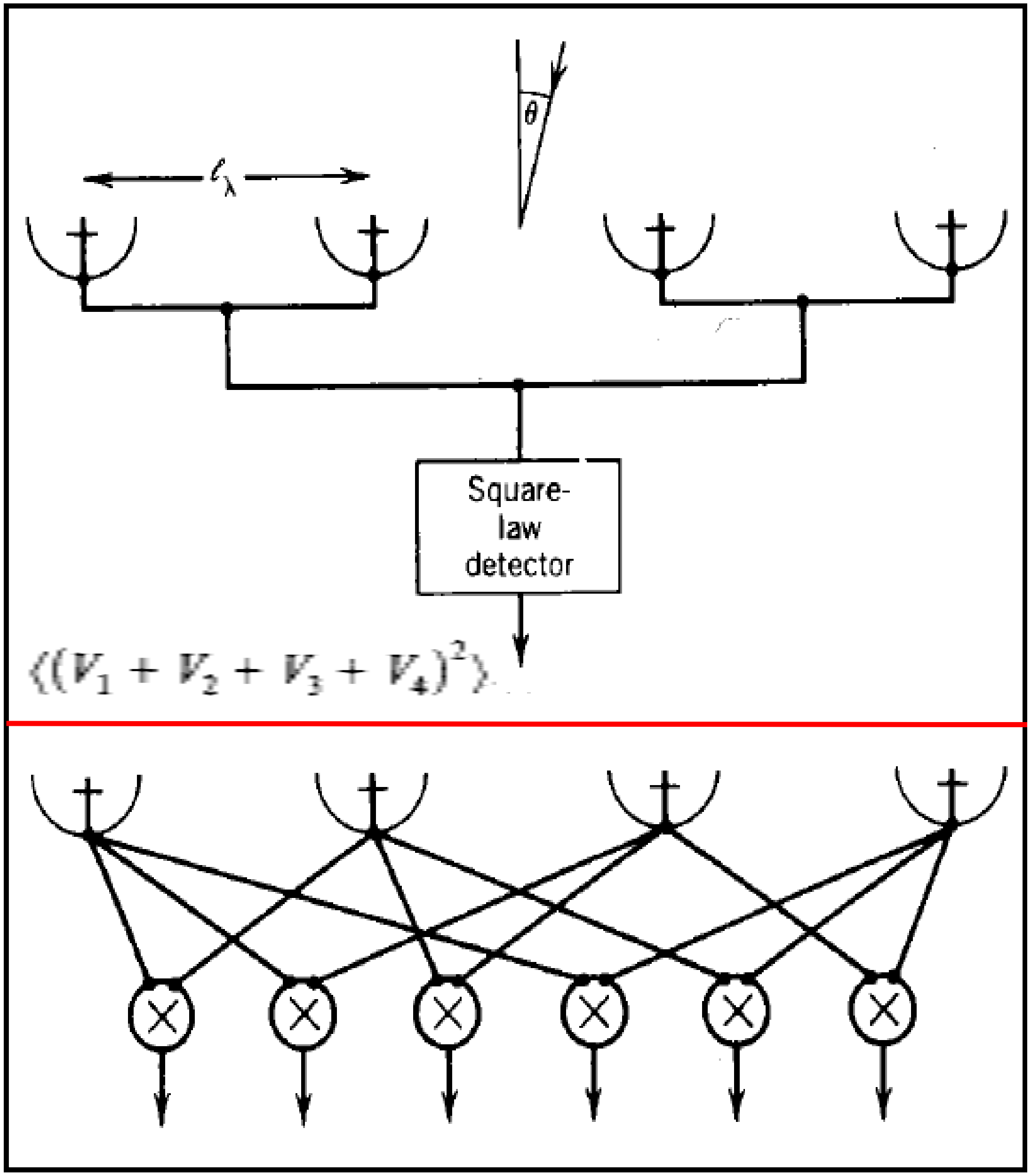
Distinction Between Phased & Correlator Arrays

Phase Array:

- The voltage signals from the antennas are combined in a branching network which forms the sums in the square-law detector.
- The beam pattern can be scanned across the sky by inserting phase-shifters on the antenna outputs.

Correlator Array:

- The correlator generates the cross products of all the signal voltages.
- Each produces an output which is one component of the Fourier Transform of the spatial distribution of the brightness of the observed object.
- All the same terms in the expanded phased-array expression are present except for the self-products (i.e., representing spatial frequencies near the u,v origin).
- A correlator array gathers data at much greater rate than a phased array unless the latter is equipped to form many beam simultaneously. In fact the phased array would be slightly more sensitivity because it measures the self products.
- It is cheaper to do the Fourier Transform in software than it is to built large numbers of beamformers.



Interferometry and Synthesis in Radio Astronomy, Thompson, Moran & Swenson, 1998, p.122

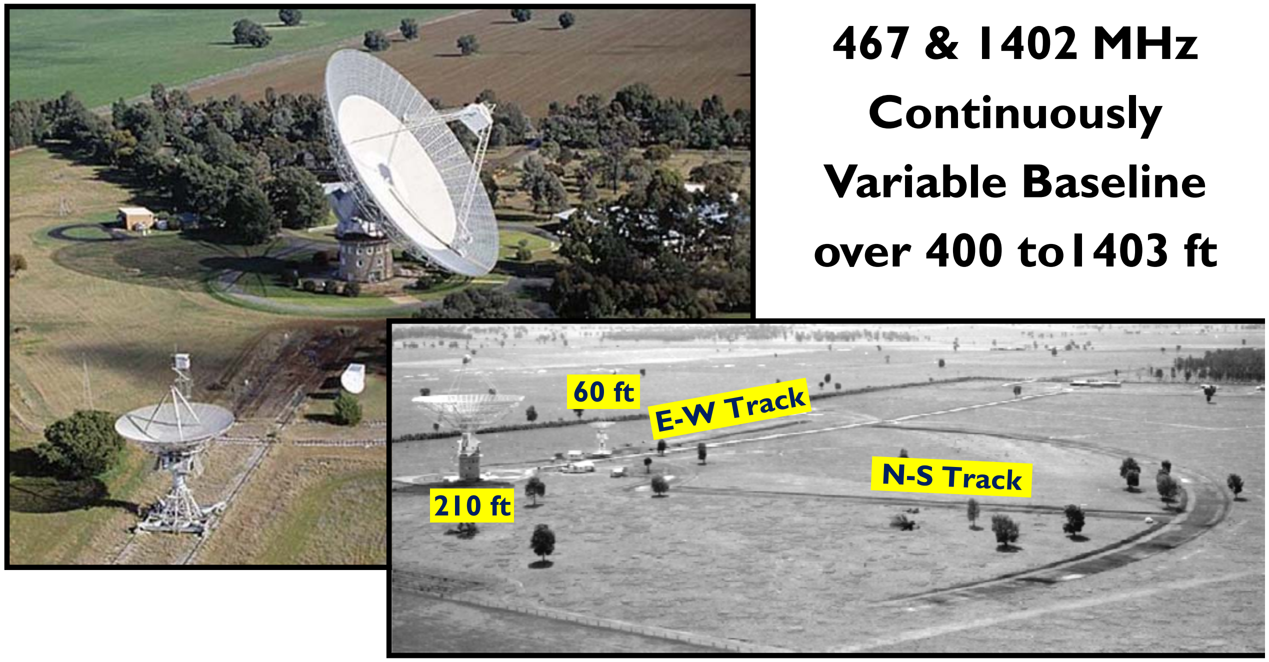
Variable Spacing Interferometer

telescope configuration

Visibility aperture

variable-baseline interferometer

Owens Valley 1600 ft Interferometer (1958)



467 & 1402 MHz

Continuously

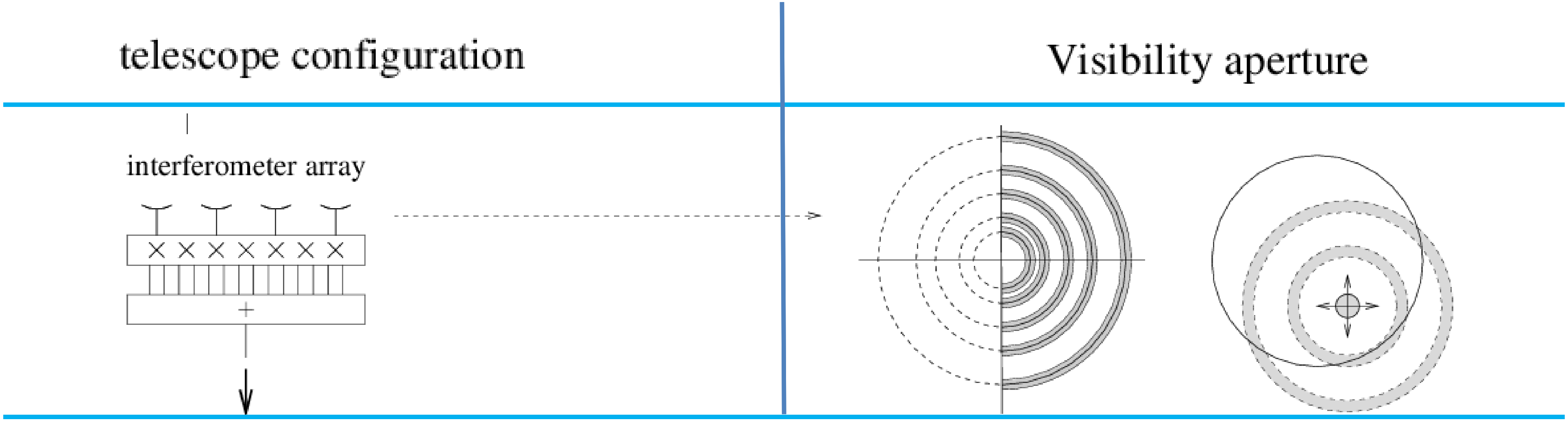
Variable Baseline

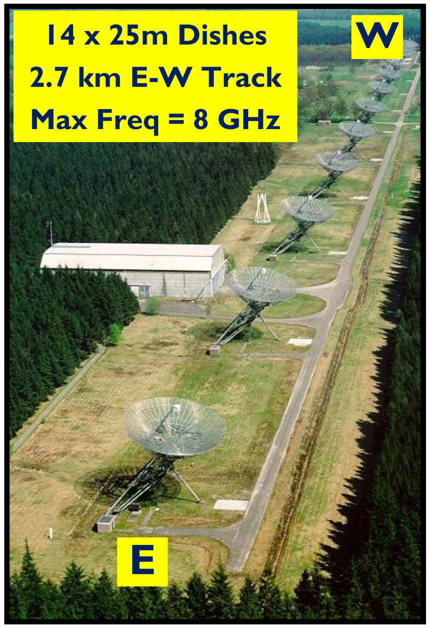
over 400 to1403 ft

Parkes 210/60-ft Interferometer (1965)

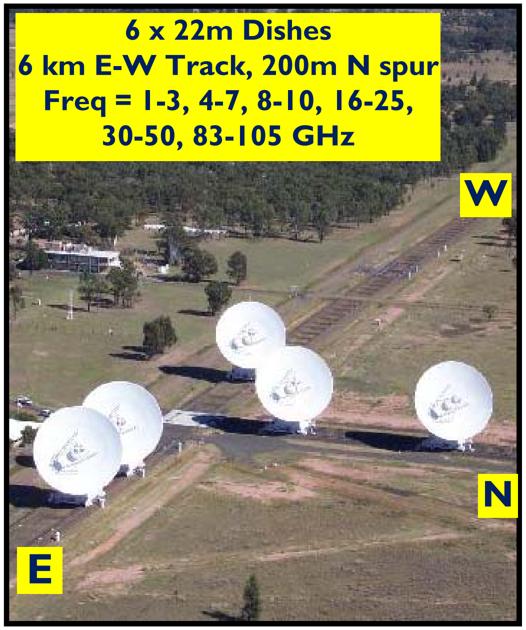
Instrumental Techniques in Radio Astronomy, Johan Hamaker, Dwingeloo, NL - http://www.astron.nl/%7Ehamaker/les4.ps
http://en.wikipedia.org/wiki/File:OVSA2.jpg
http://www.thelivingmoon.com/45jack_files/03files/Australia_Siding_Spring_Observatory.html
http://www.atnf.csiro.au/research/conferences/Parkes50th/RonEkers.pdf

Correlation Interferometer

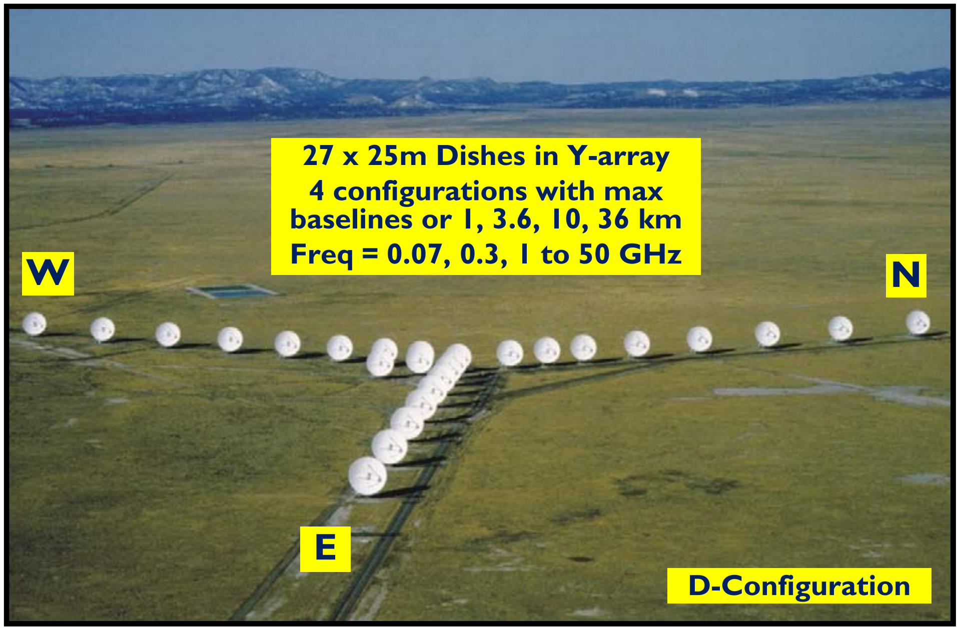



14 x 25m Dishes
2.7 km E-W Track
Max Freq = 8 GHz

Westerbork Synthesis Radio Telescope (1970)


6 x 22m Dishes
6 km E-W Track, 200m N spur
Freq = 1-3, 4-7, 8-10, 16-25, 30-50, 83-105 GHz

Australia Telescope Compact Array (1988)

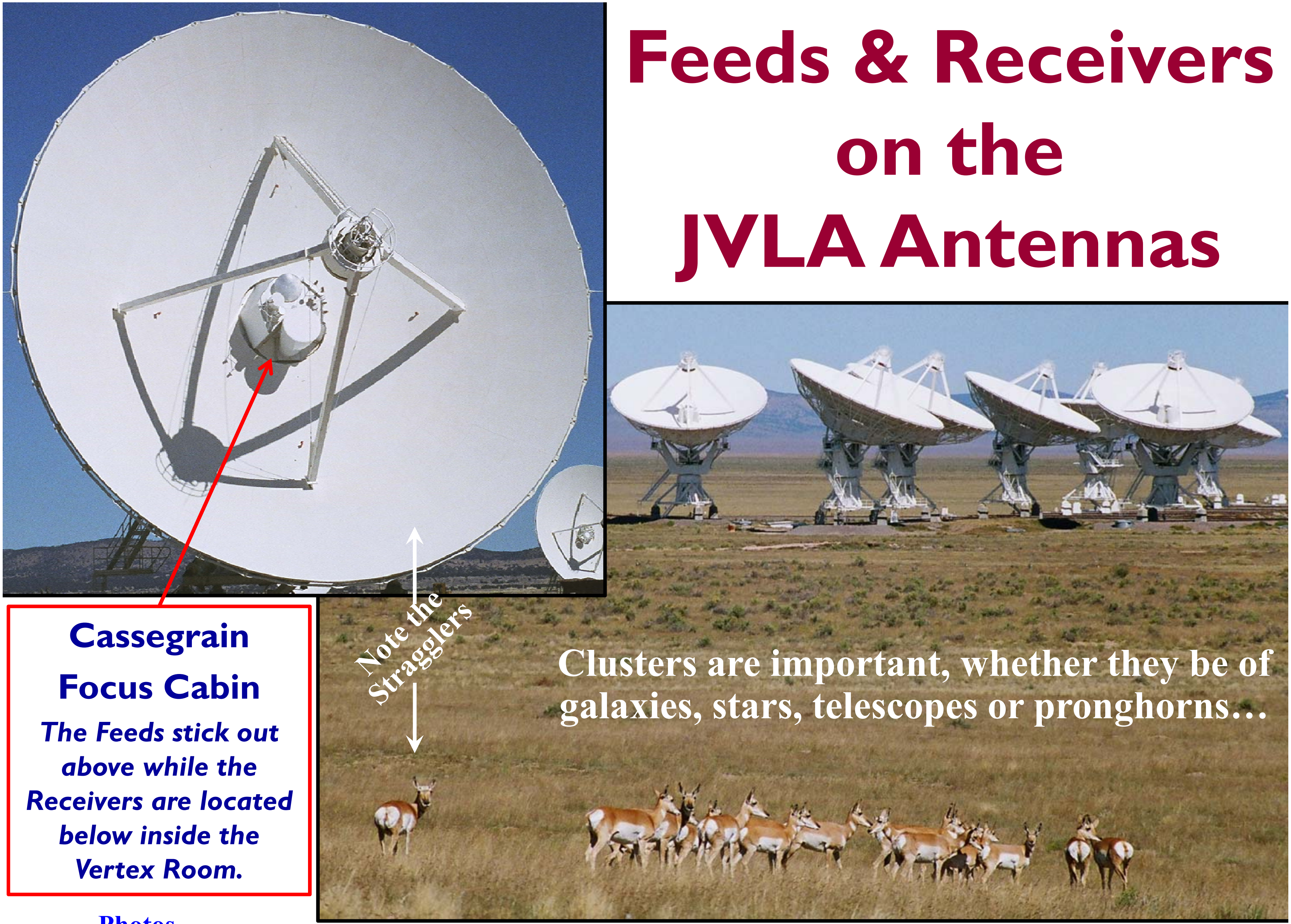

27 x 25m Dishes in Y-array
4 configurations with max baselines or 1, 3.6, 10, 36 km
Freq = 0.07, 0.3, 1 to 50 GHz

D-Configuration

Jansky Very Large Array (1980)

Instrumental Techniques in Radio Astronomy, Johan Hamaker, Dwingeloo, NL - http://www.astron.nl/%7Ehamaker/les4.ps
http://www.astronomie.nl/beeldbank/30/379/westerbork_synthese_radiotelescoop.html
http://astronomy.swin.edu.au/cosmos/A/ATCA ; http://images.nrao.edu/object/index.php?id=307

Feeds & Receivers on the JVLA Antennas



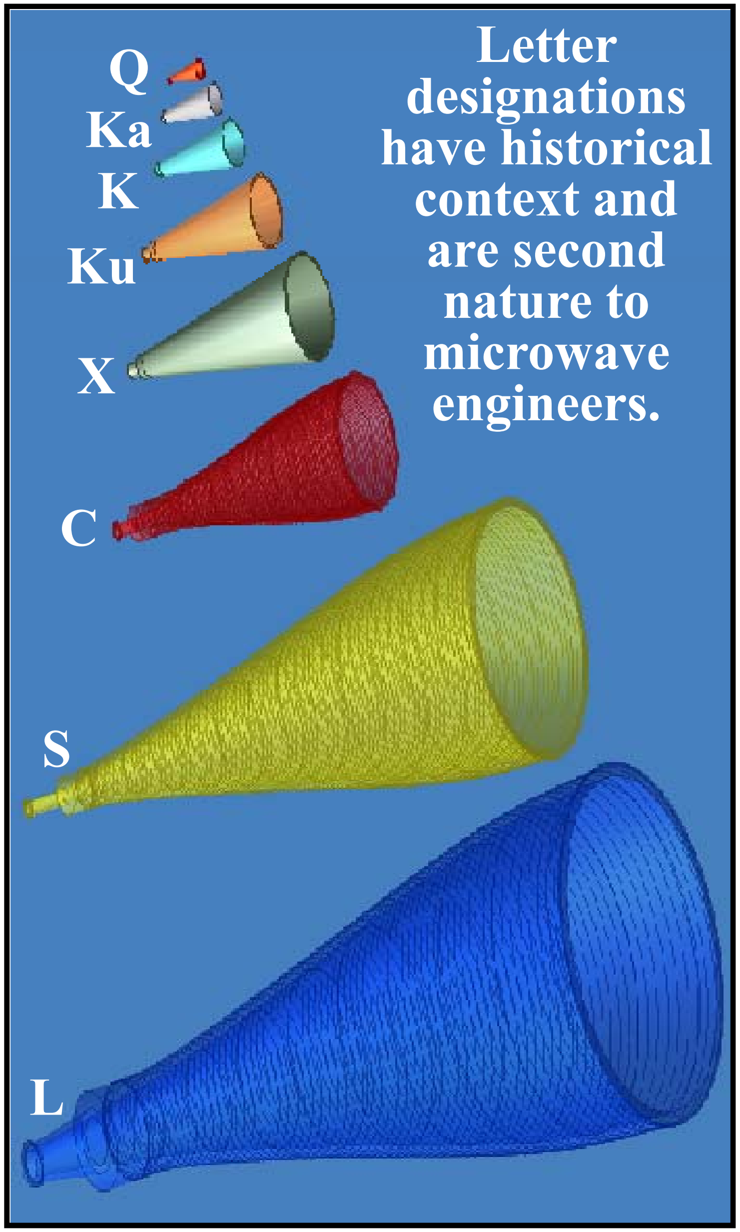
Cassegrain Focus Cabin

The Feeds stick out above while the Receivers are located below inside the Vertex Room.

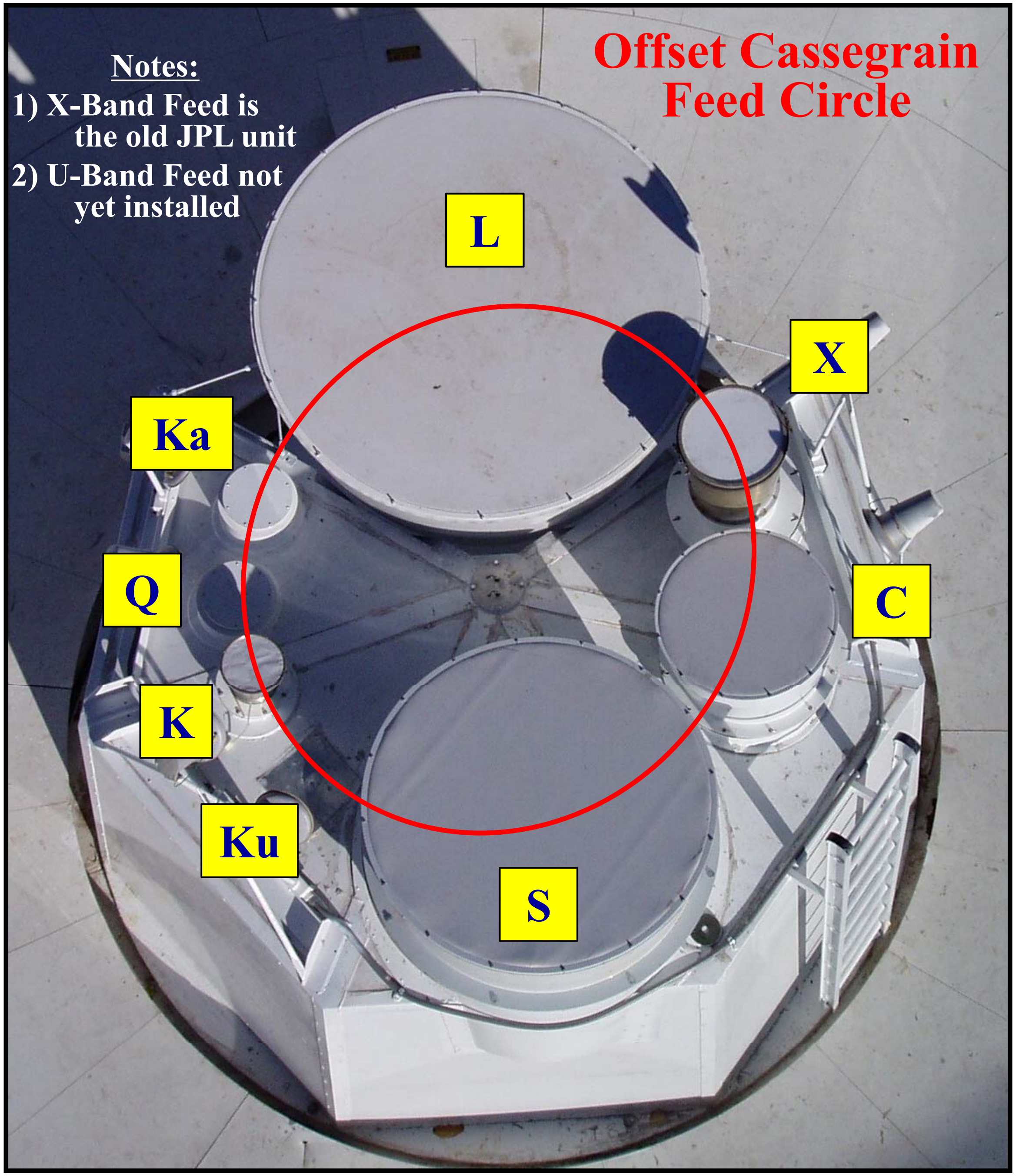
Clusters are important, whether they be of galaxies, stars, telescopes or pronghorns…

Photos
R. Hayward (2009)

JVLA Feeds



Letter designations have historical context and are second nature to microwave engineers.



Offset Cassegrain Feed Circle

Notes:

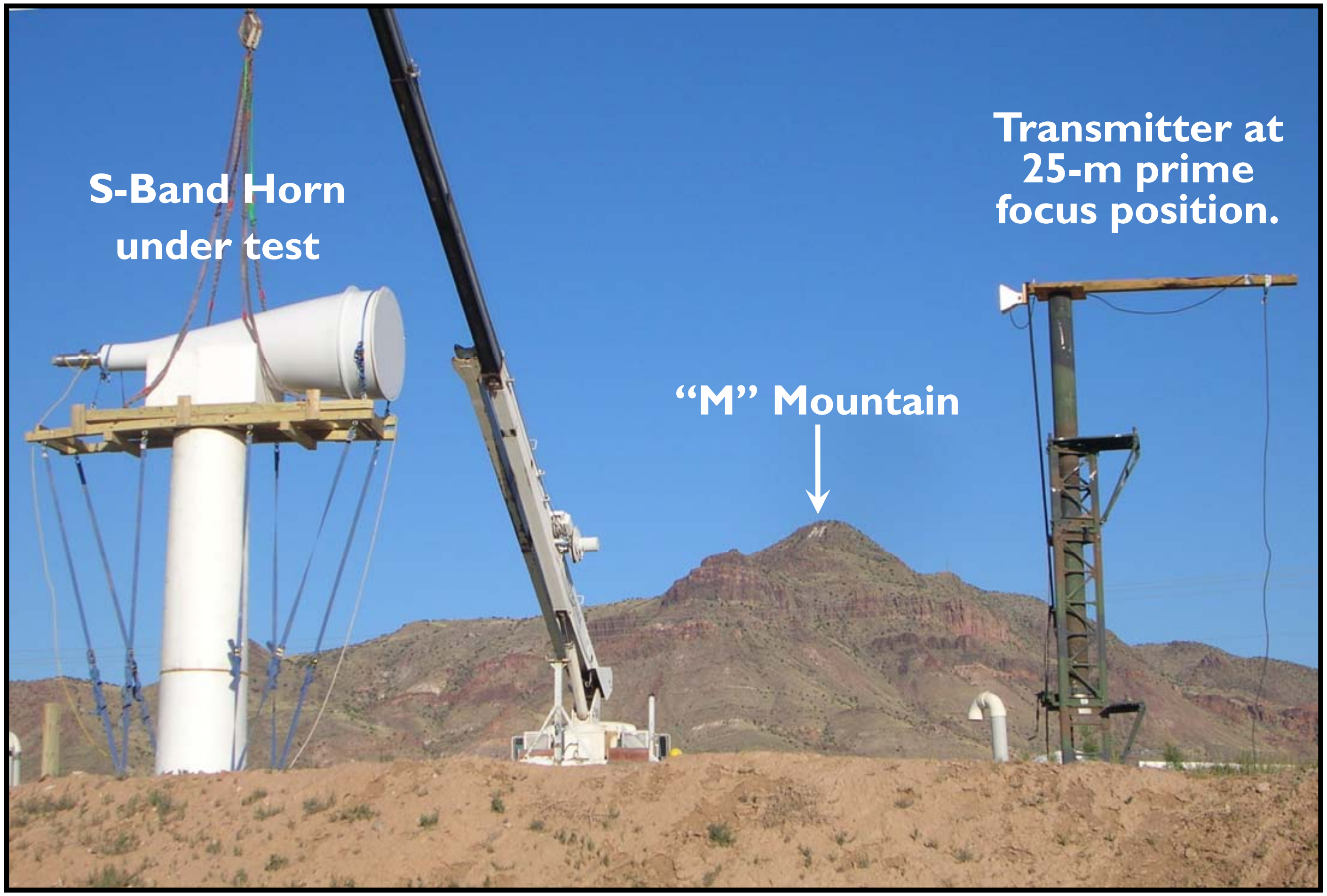
1) X-Band Feed is the old JPL unit

2) U-Band Feed not yet installed

Jim Ruff's Web Pages - http://www.aoc.nrao.edu/~jruff/A1Vertex.jpg

Outdoor Antenna Test Range

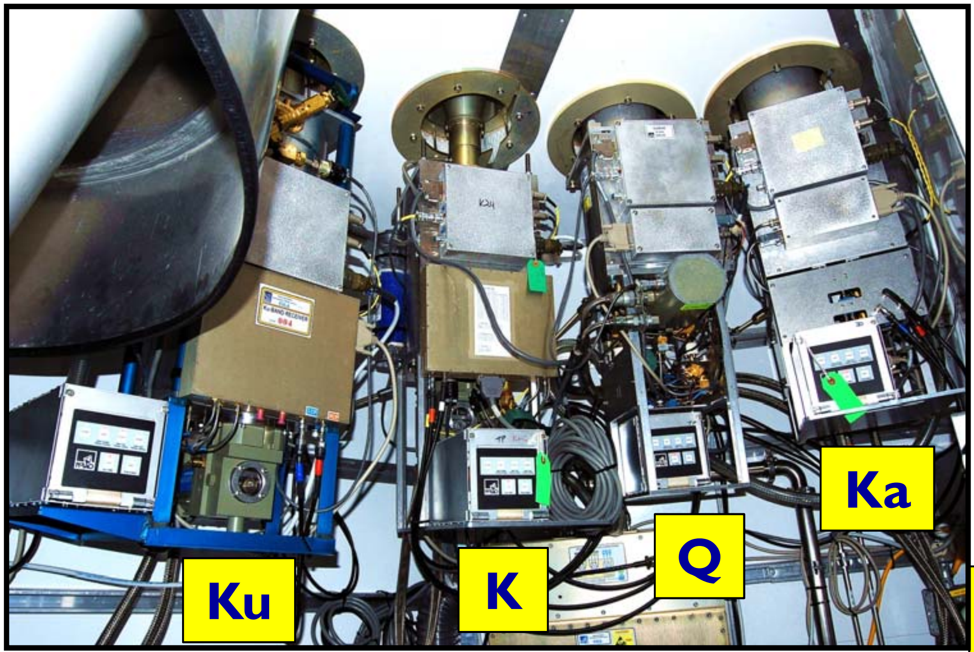
Prototype S-Band Feed - Pattern Measurements & VSWR Tests



**OATR Used for
L, S & C-Band Feeds**

Acknowledgments
Sri Srikanth
Jim Ruff
Dan Mertely
Hollis Dinwiddie
Tanner Oakes
Colton Dunlap
Brian Bonnett
Ryan Davis
Cody Griffee
Derrick Monroy
Tsama Parsons
Jesse Pomeroy
John Wall
Troy Jensen

JVLA 1-50 GHz Cryogenic Receivers



<u>Upper Level</u>

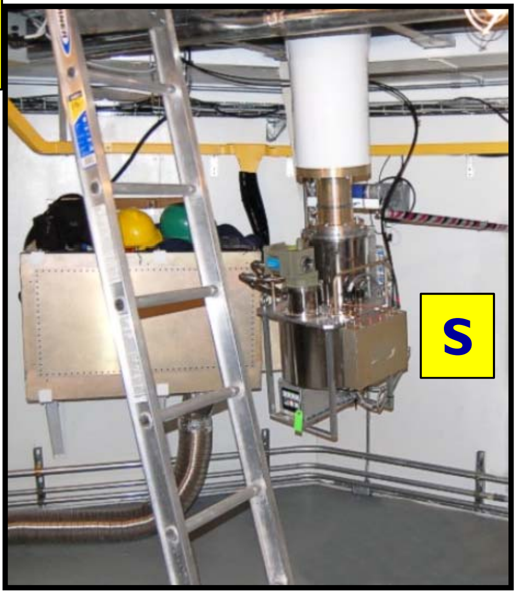
C = 4 - 8 GHz
X = 8-12 GHz
Ku = 12-18 GHz
K = 18-26 GHz
Ka = 26-40 GHz
Q = 40-50 GHz

Vertex Cabin

<u>Lower Level</u>

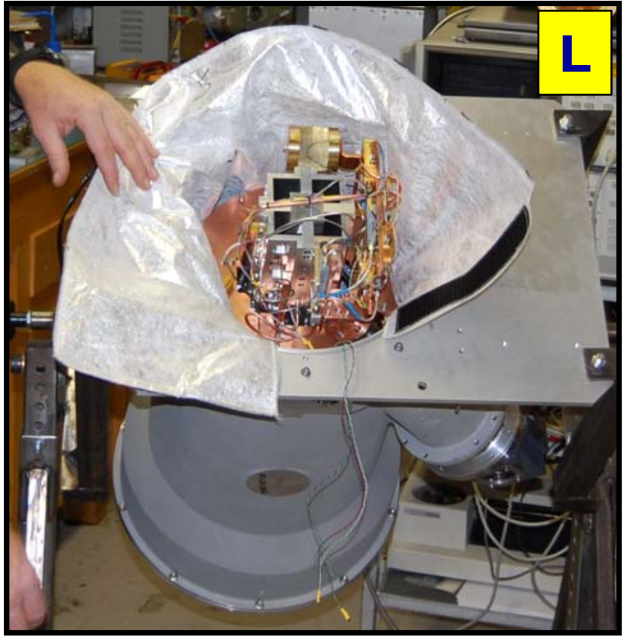
L = 1-2 GHz
S = 2-4 GHz

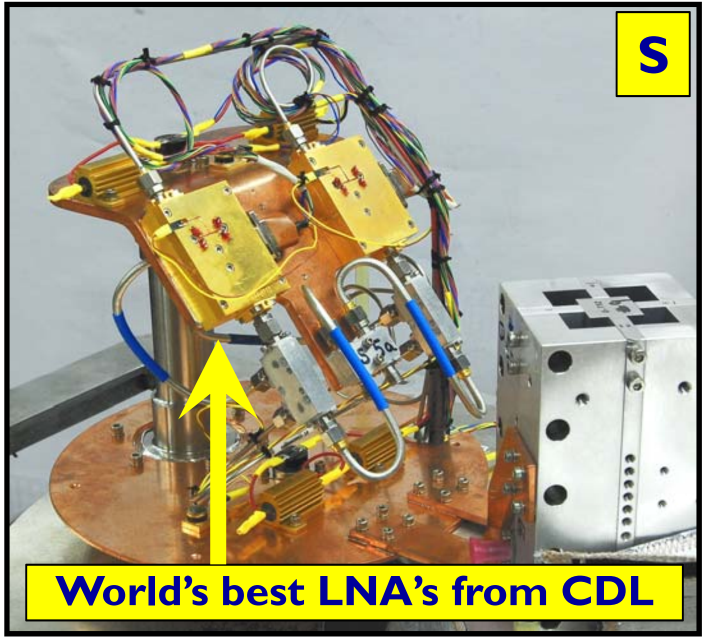
Total number of JVLA cryogenic receivers = 8 x 30 = 240



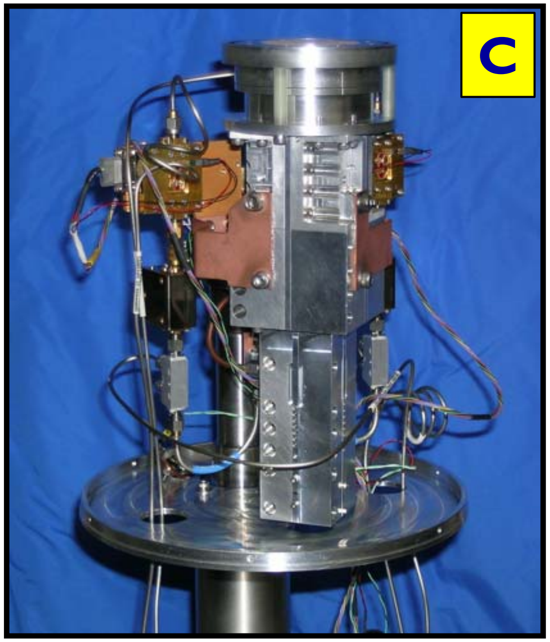
Paul Harden's JVLA Front-End Web Pages - http://www.aoc.nrao.edu/~pharden/fe/fe.htm

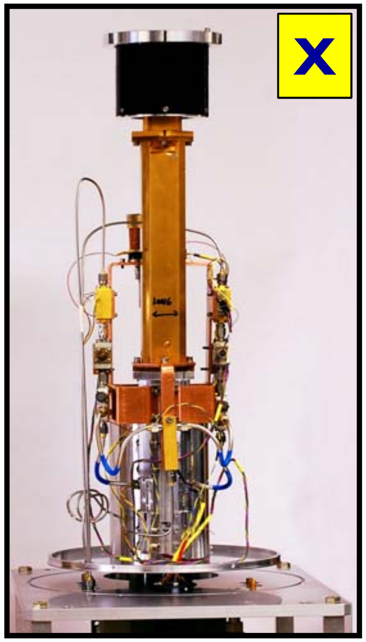
Rogues Gallery of (Naked) JVLA Receivers

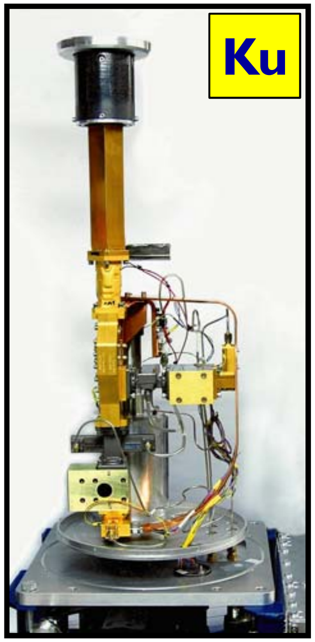


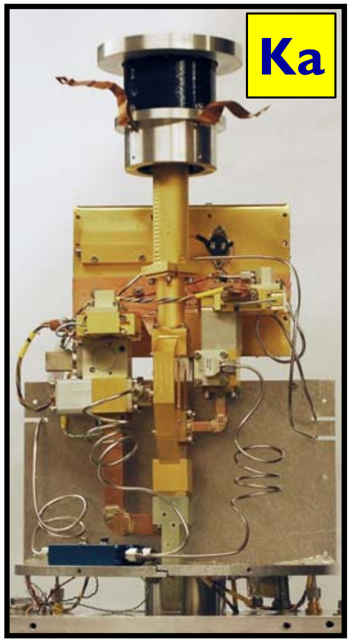


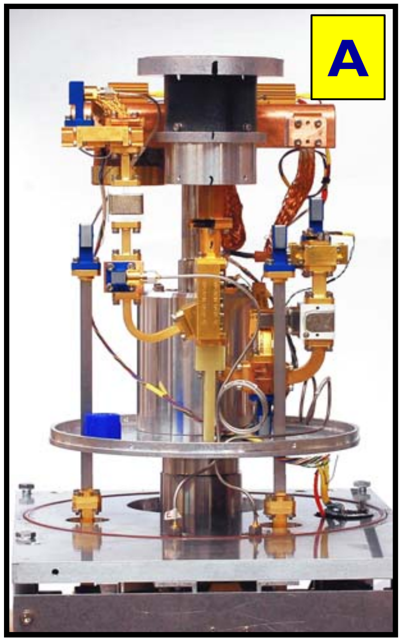
World's best LNA's from CDL

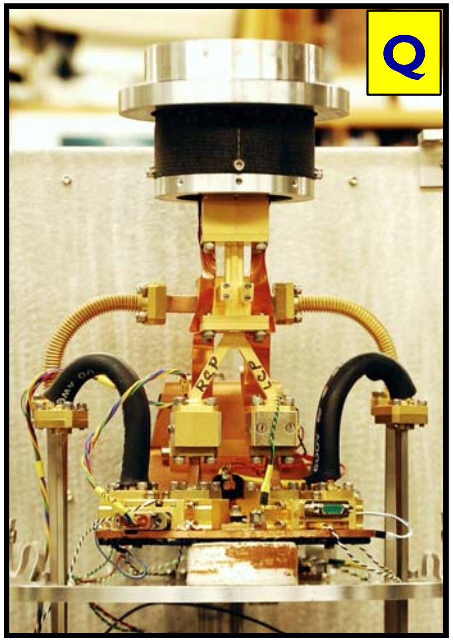












http://www.aoc.nrao.edu/~pharden/fe/fe.htm

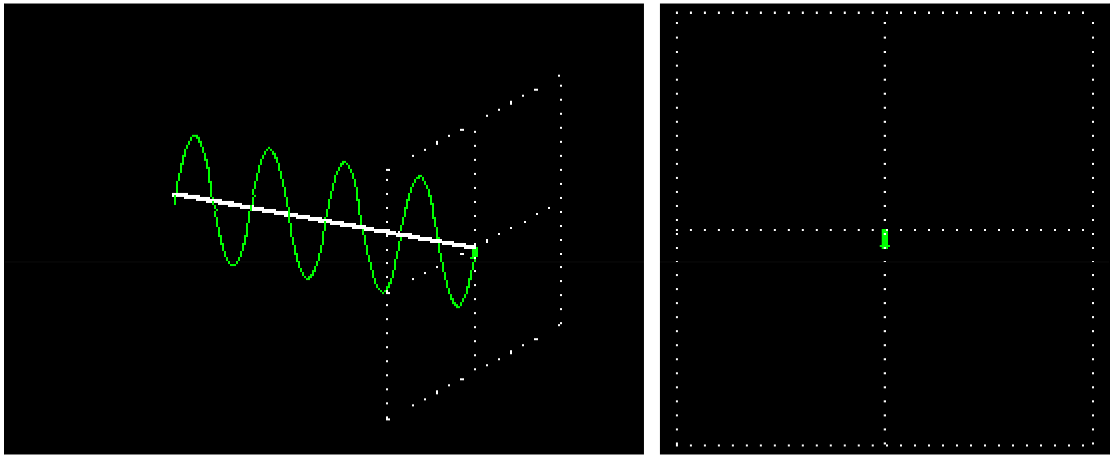
Circular vs. Linear Polarization on the JVLA

- The original VLA used circular polarizers.
- Most new arrays use linear (e.g. , ATCA & ALMA).
- At the beginning of the EVLA upgrade there was discussion whether we should switch to linear. We decided to remain with circular…
  - Easier to calibrate the gains, particularly for 'snapshot' observations.
  - Imaging of the Stokes Q and U are simpler.
  - Avoids a mixed system, with linear at most bands but circular at some existing bands (18-26 and 40-50 GHz).
  - Avoids a hybrid system during the transition period
    - VLA circular vs. EVLA linear
- The price that we pay is…
  - Wideband circular polarizers are more complicated and expensive than linear polarizers.
  - Circular polarizers require additional devices which will (slightly) degrade performance (i.e., reduced bandwidth and sensitivity).

Primer - Linearly Polarized Signals

Vertical

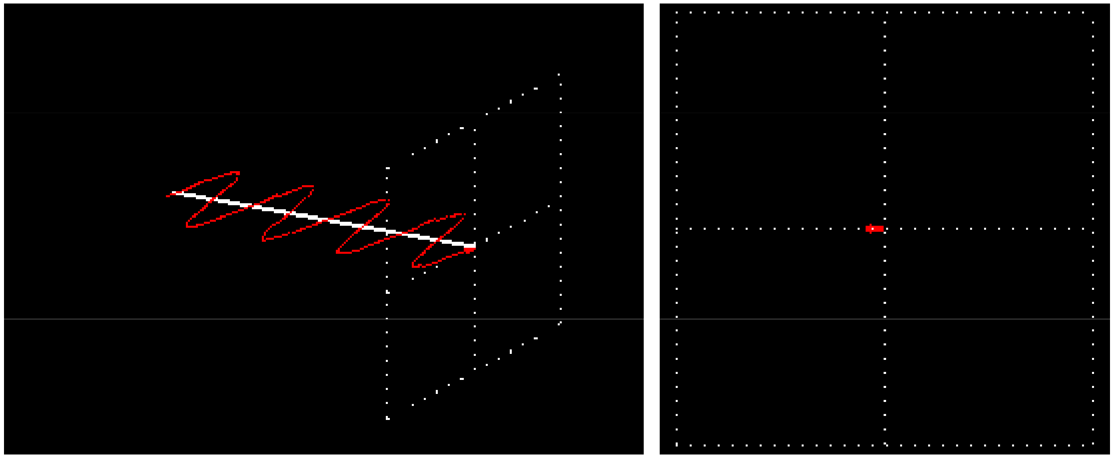
$$E_y = A\sin(x/\lambda - \omega t)$$



A device called an Orthomode Transducer is needed to separate both linear polarizations simultaneously.

Horizontal

$$E_z = A\sin(x/\lambda - \omega t)$$



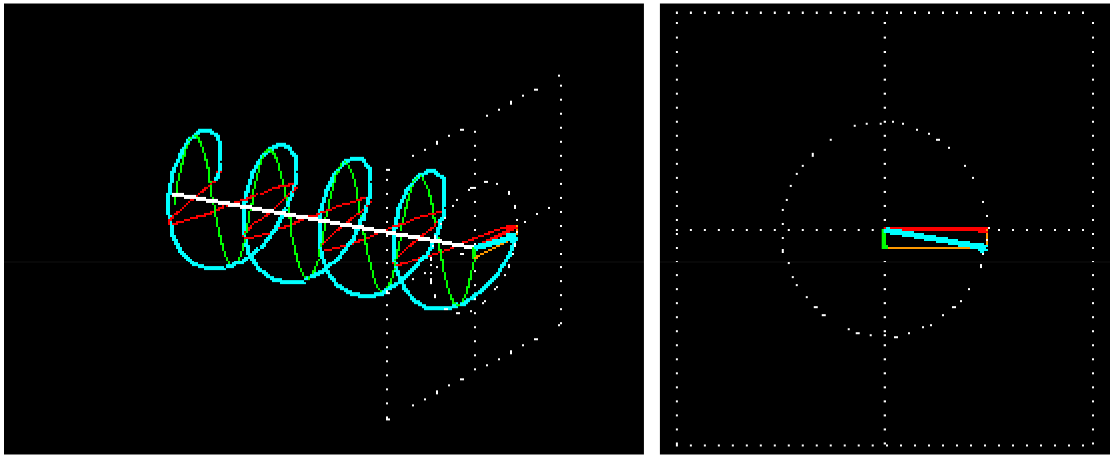
Interactive animations of electromagneticwaves, András Szilágyi, Institute of Enzymology, Hungarian Academy of Sciences
http://titan.physx.u-szeged.hu/~mptl11/Proceedings/InteractiveAnimationsOfElectromagneticWaves.ppt

Primer - Circularly Polarized Signals

Left Circular

$$E_y = A\sin(x/\lambda - \omega t + 90^\circ)$$

$$E_z = A\sin(x/\lambda - \omega t)$$



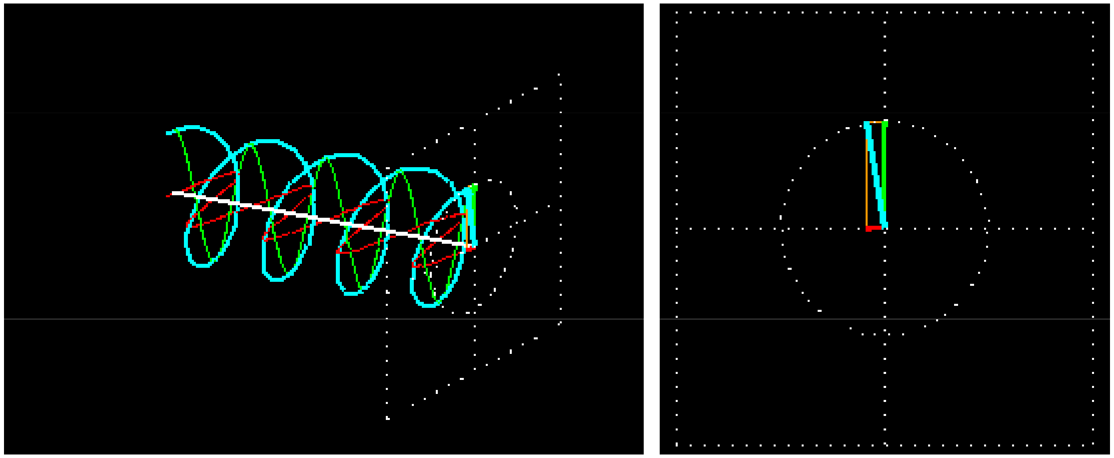
Radio Astronomy Definition

To convert linear to circular, a 90 degree phase-shifter is needed which retards one of the linear polarizations.

Right Circular

$$E_y = A\sin(x/\lambda - \omega t - 90^\circ)$$

$$E_z = A\sin(x/\lambda - \omega t)$$



Interactive animations of electromagneticwaves, András Szilágyi, Institute of Enzymology, Hungarian Academy of Sciences
http://titan.physx.u-szeged.hu/~mptl11/Proceedings/InteractiveAnimationsOfElectromagneticWaves.ppt

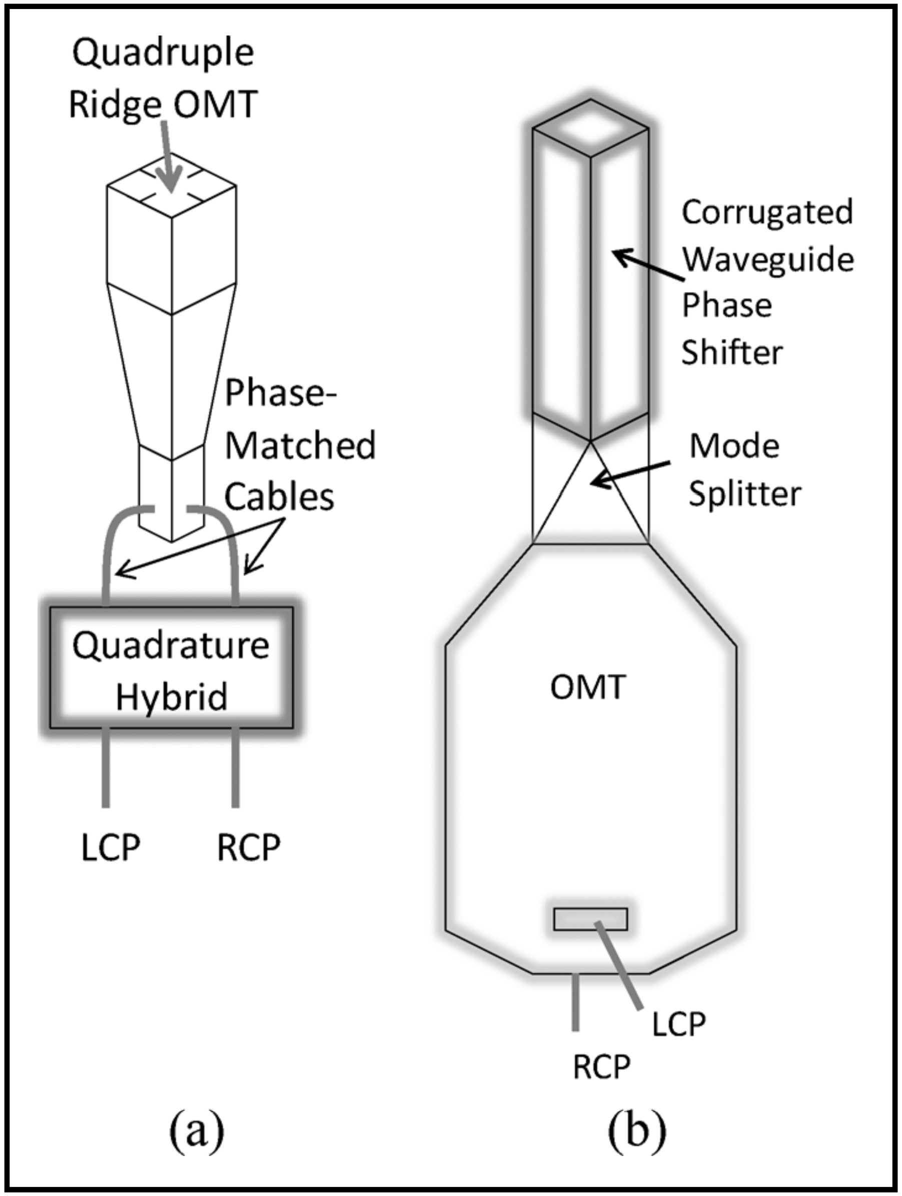
JVLA Wideband Circular Polarizers

- **The JVLA's polarizers essentially generate Left and Right circular polarizations from the two orthogonal linear polarizations.**

- **Fig (a) :The *Circular Polarizers* used at lower frequencies (e.g., L, S & C-Band) consist of**
  - **a quadruple-ridge OMT (which separates the signal into 2 linear polarizied coaxial outputs)**
  - **and a coaxial quadrature hybrid (which retards one of the linear signals by 90°)**
  - **to produce LCP & RCP.**

- **Fig (b) :The *Circular Polarizers* used at higher frequencies (e.g., Ku, K, & Ka-Band) consist of**
  - **a corrugated waveguide phase shifter (which retards one of the linear polarizations by 90°)**
  - **and a linear polarizier (a twofold symmetric waveguide OMT)**
  - **to produce LCP & RCP.**

- **Two remaining frequency bands:**
  - **X-Band uses a waveguide phase-shifter followed by a quadridge OMT**
  - **Q-Band uses a relatively narrowband waveguide circular polarizer known as a sloping septum polarizer.**

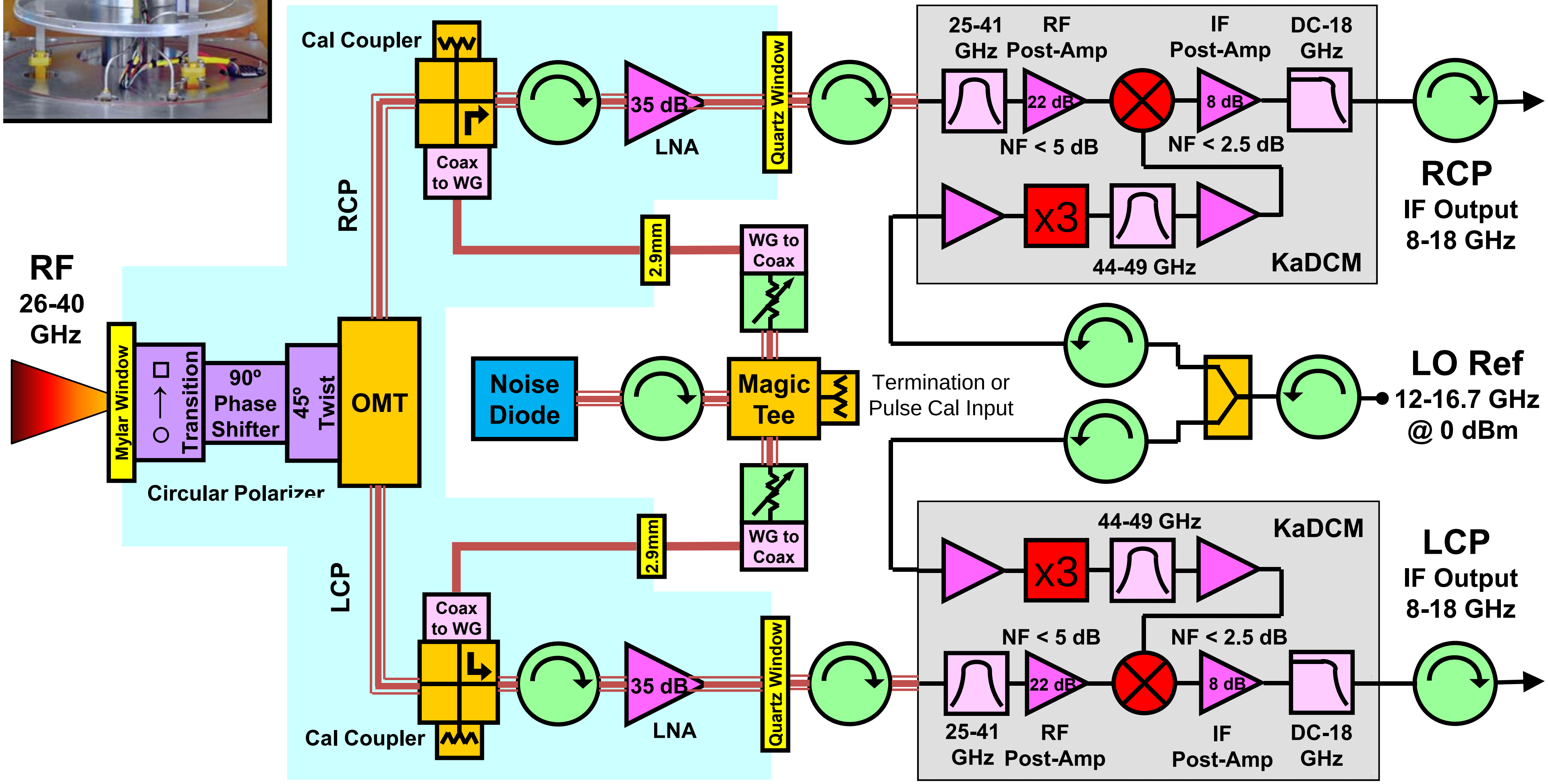


Wideband Diagonal Quadruple-Ridge Orthomode Transducer for Circular Polarization Detection, G. Coutts, IEEE Transactions on Antennas and Propagation, Vol 59 , Issue: 6, June 2011, p. 1902-1909

JVLA Ka-Band (26-40 GHz) Receiver Block Diagram

Key:

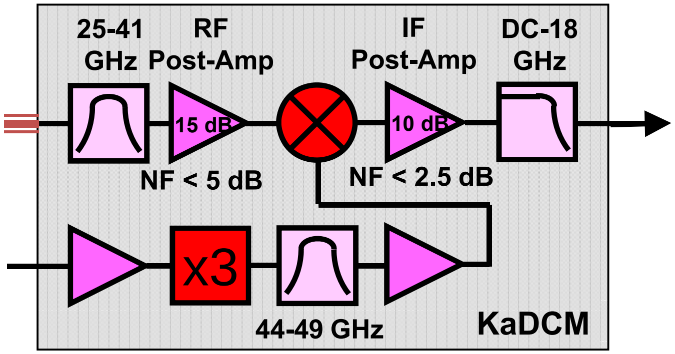
- 🟦 Cryogenic Dewar
- 🟨 Vacuum Window
- ▨ MMIC Module
- ═ WR-28 Waveguide
- ▬ Coaxial Cable, 2.9mm
- — Coaxial Cable, SMA



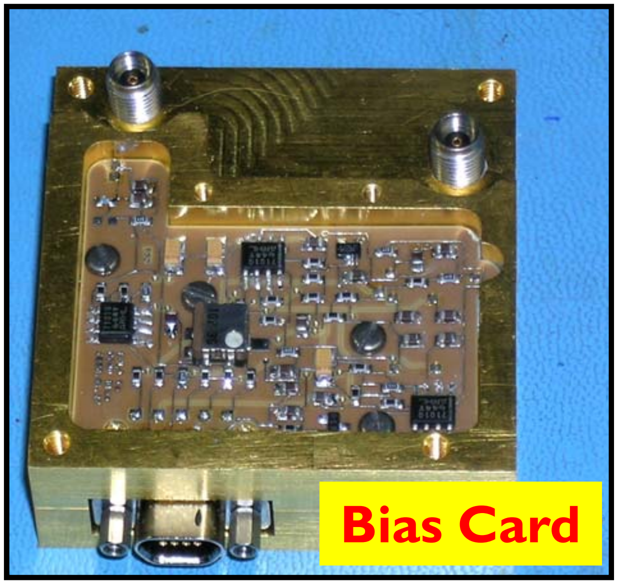
Ka-Band Down-Converter Module (KaDCM)

MMIC-based multifunction modules can save both money and space.

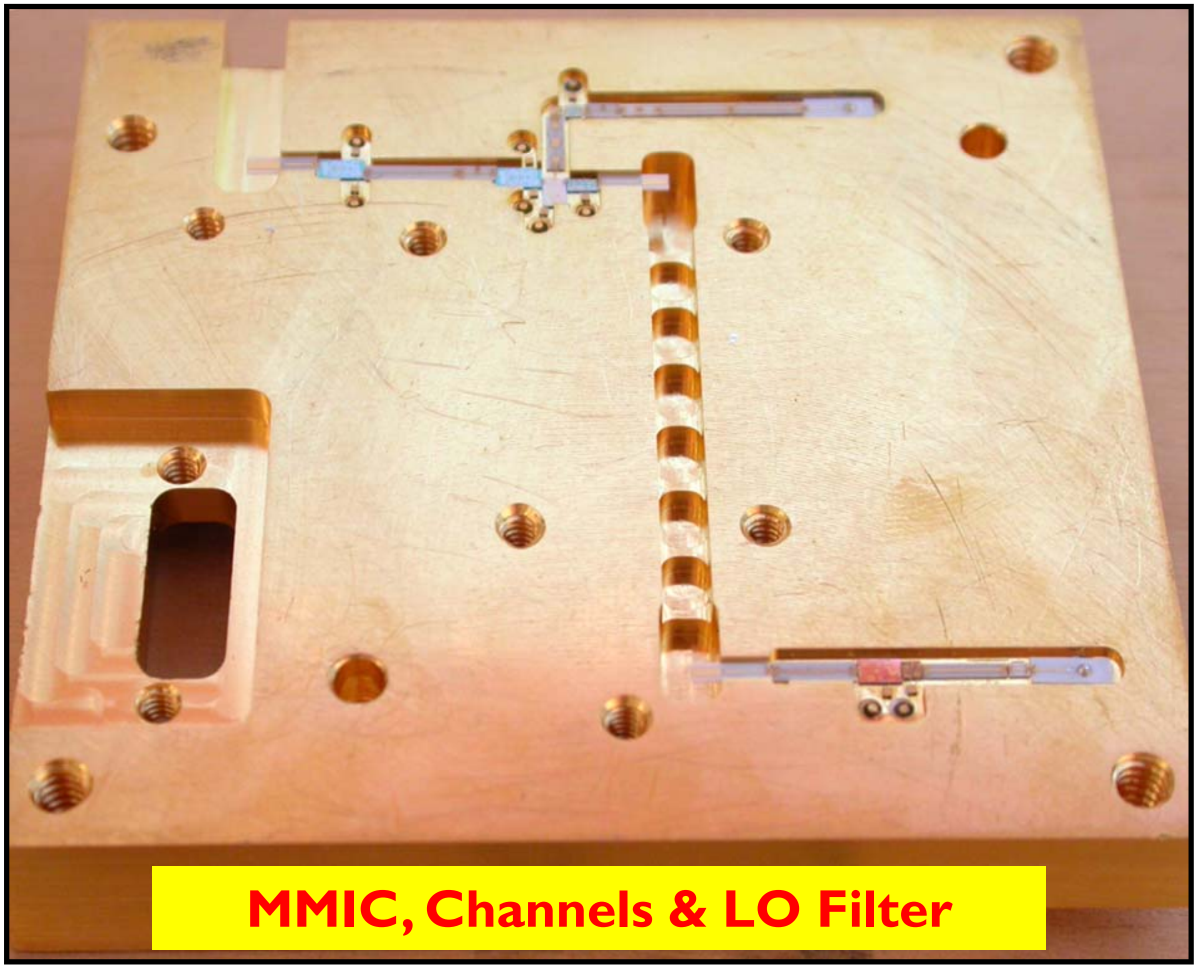
KaDCM Block Diagram



Module



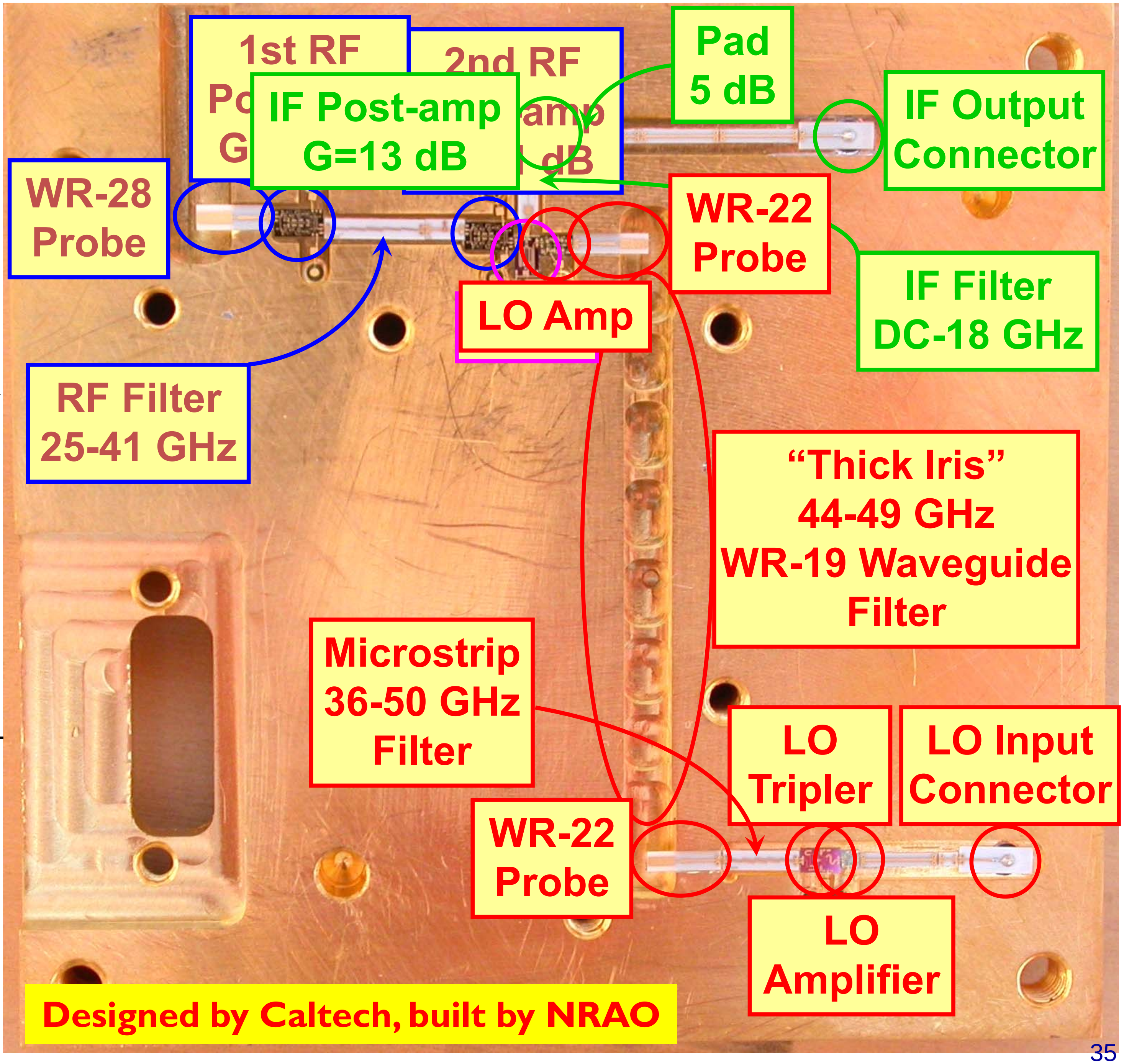
Bias Card



MMIC, Channels & LO Filter

Inside the KaDCM

Co-Planar Waveguide (CPW) Circuit Board & MMIC Component Layout

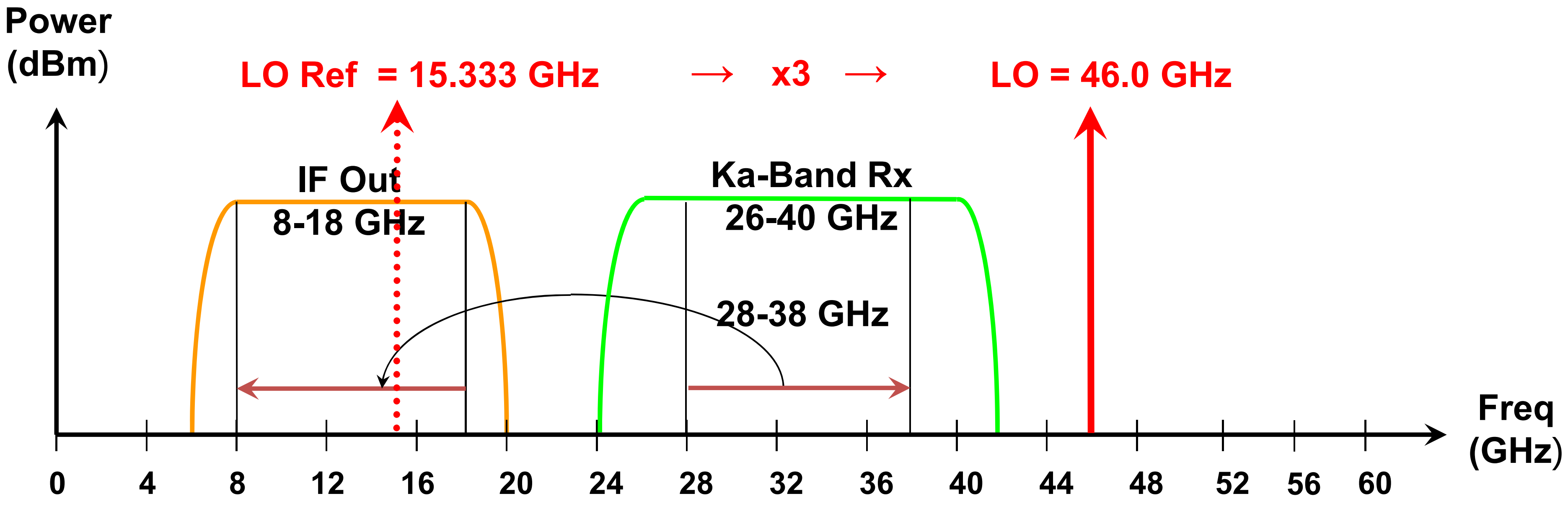


Designed by Caltech, built by NRAO

KaDCM contains:

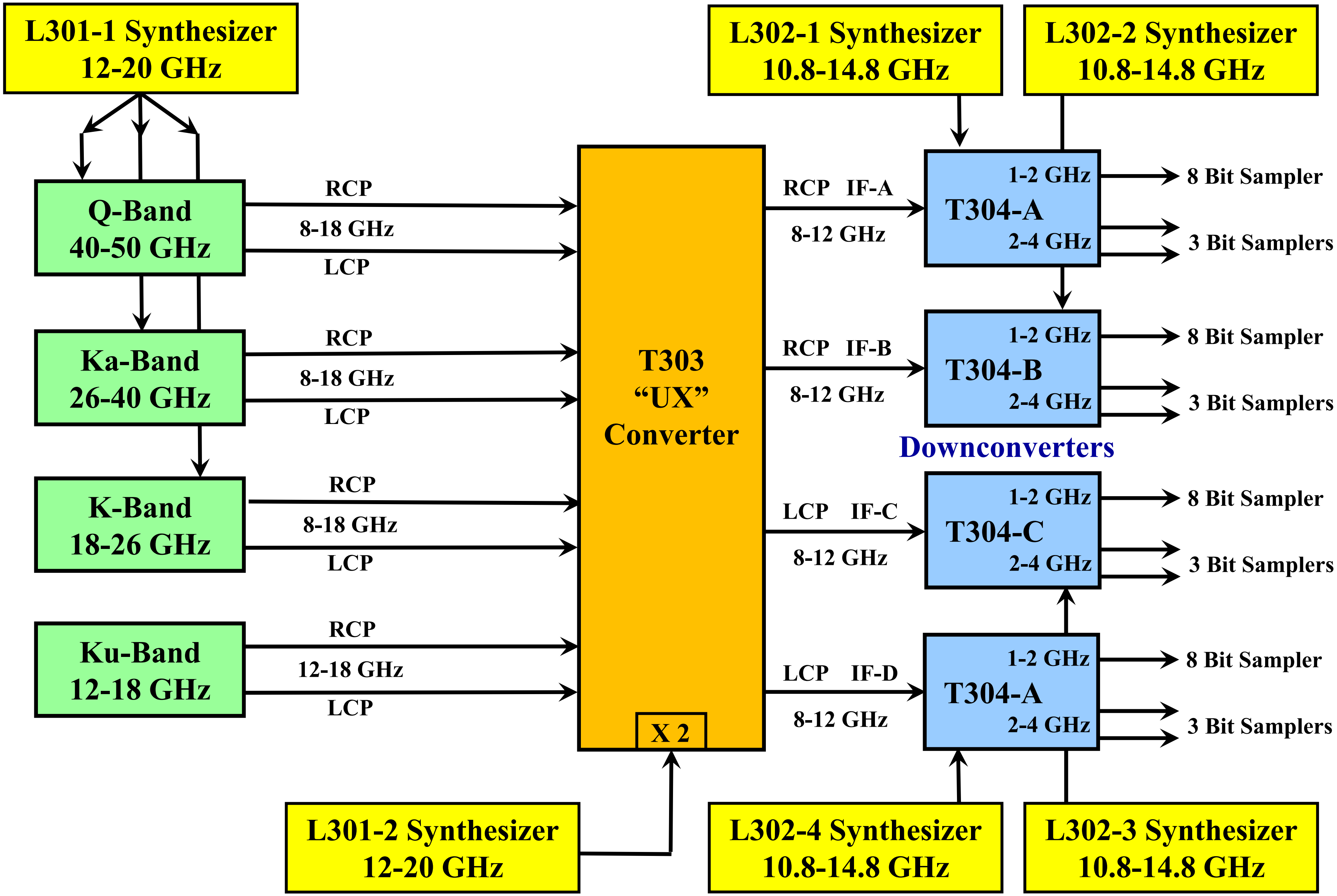
- 7 MMIC Devices
  - 5 Amplifiers
  - 1 Mixer
  - 1 Tripler
- 14 CPW Boards
- ~75 Wire Bonds

Ka-Band Receiver Block Conversion Frequency Diagram

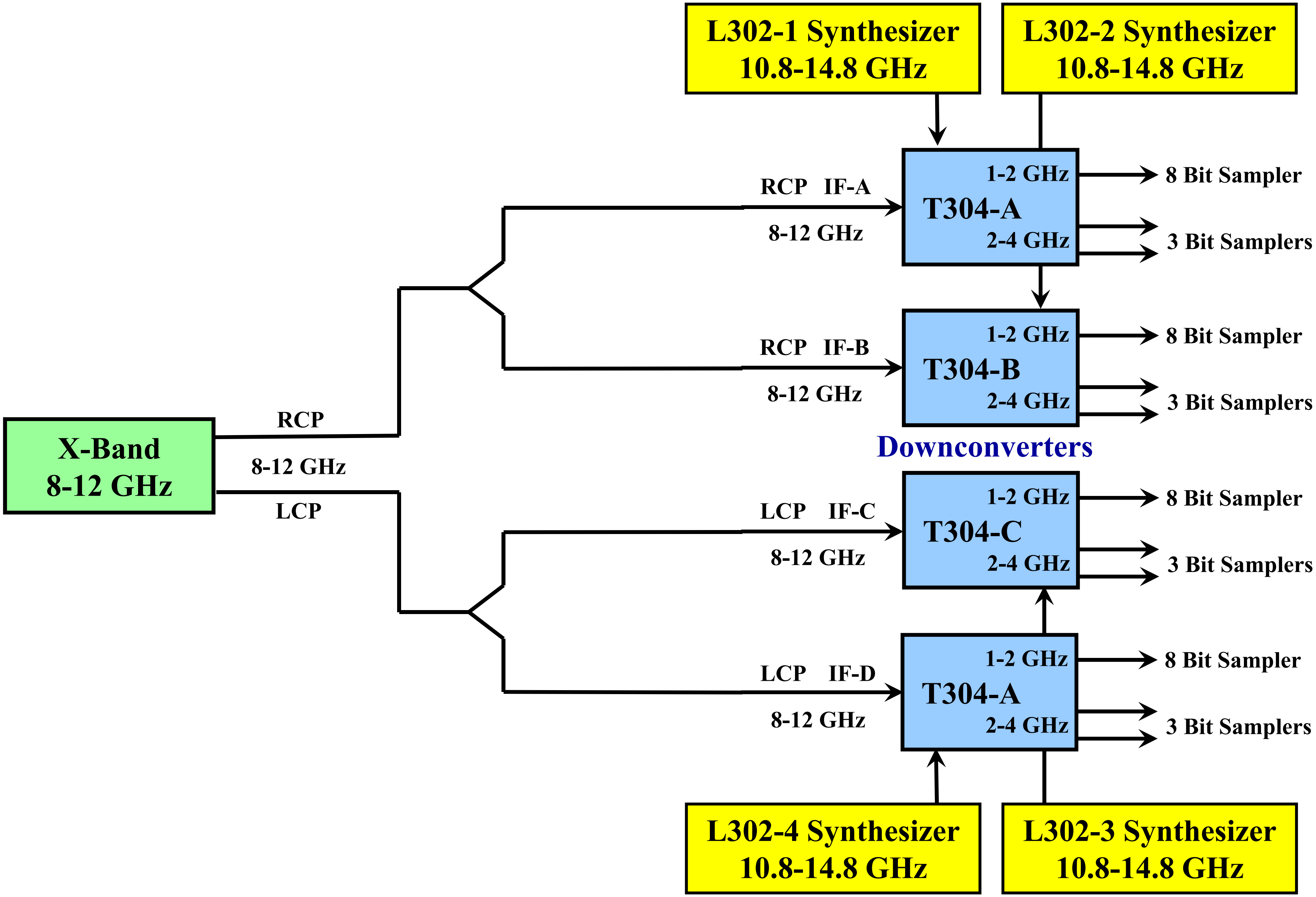


- Translation of 28-38 GHz down to 8-18 GHz
- LO Ref 15.333 GHz x 3 = 46 GHz
  - **Closest L301 Lock Point is actually 15.232 GHz**

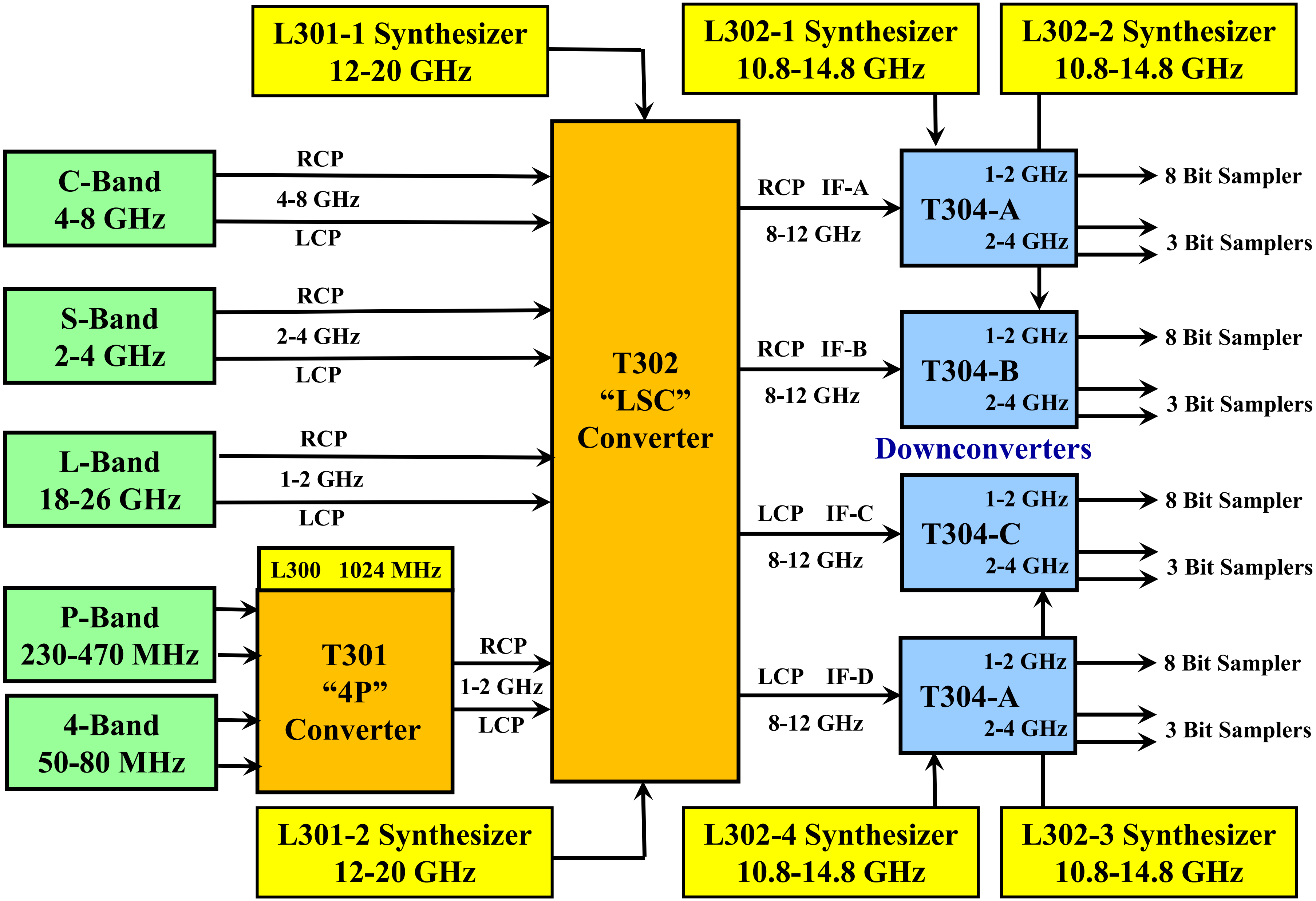
JVLA Ku, K, Ka & Q-Band Conversion



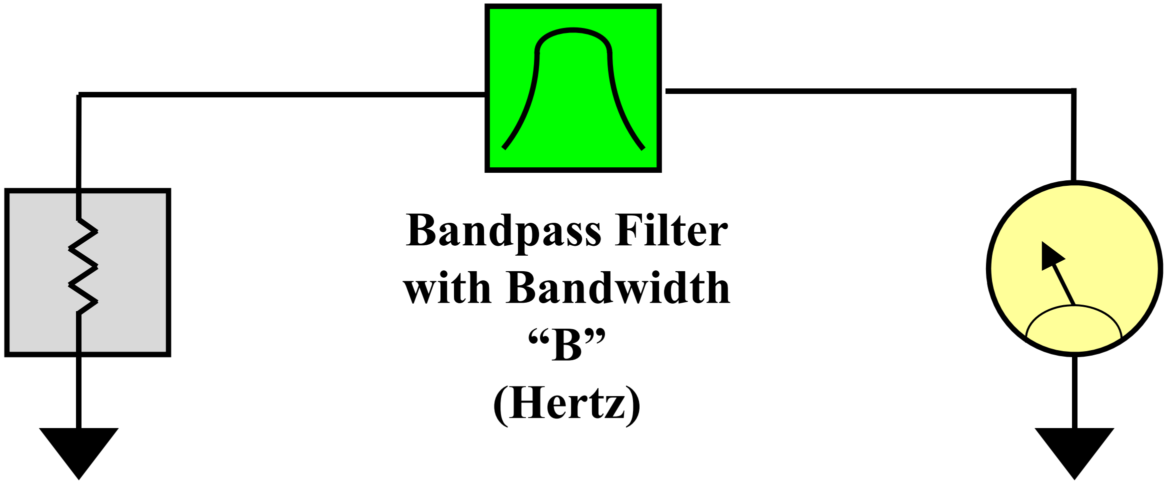
JVLA X-Band Conversion



JVLA 4, P, L, S, C-Band Conversion



Thermal Noise of a Device



"Hot" Resistor at Temperature "T" (Kelvin)

Bandpass Filter with Bandwidth "B" (Hertz)

Power Meter Indicating Power "P" (Watts)

Absolute Zero	=	0°K	= -273°C	= -460°F
Liquid Nitrogen	=	77°K	= -196°C	= -321°F
Room Temp	=	295°K	= 22°C	= 71°F

P_dBm = 10 · log (P_Watts * 1000)

1 mW → 0 dBm

1 µW → -30 dBm

1 W → +30 dBm

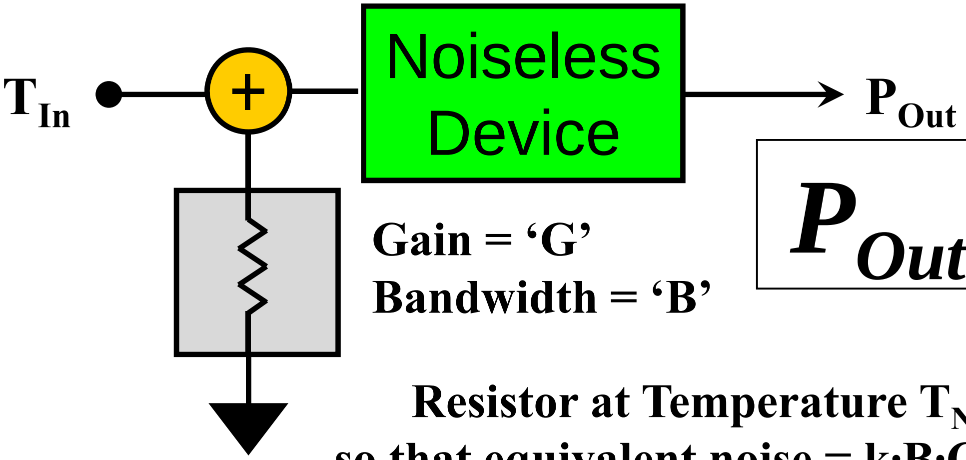
$$P = k \cdot B \cdot T$$

where "k" is Boltzmann's Constant $= 1.38 \times 10^{-23}$ Joules/Kelvin

For T = 1°K & B = 1 Hz, a resistor will produce 0.0000000000000000000000138 Watts or -198.6 dBm

Noise Temperature of an Amplifier

Consider the noise in an amplifier to look like this:



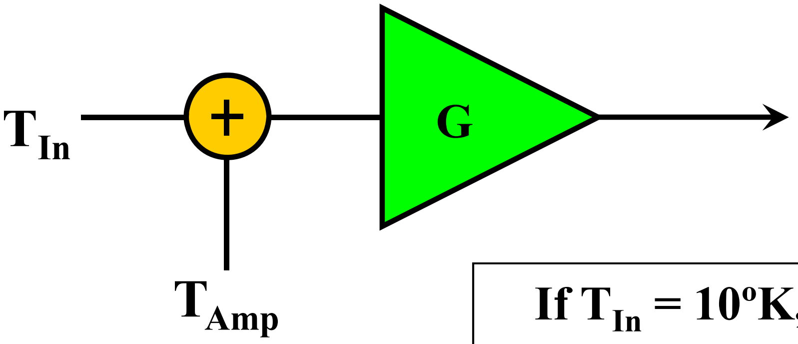
Gain = ‘G’
Bandwidth = ‘B’

Resistor at Temperature T_N
so that equivalent noise = $k{\cdot}B{\cdot}G{\cdot}T_N$

$$\boxed{P_{Out} = k{\cdot}B{\cdot}G{\cdot}(T_{In}+T_N)}$$

T_N is the effective
Noise Temperature
of the Device

A Real-world Amplifier with Internal Noise:

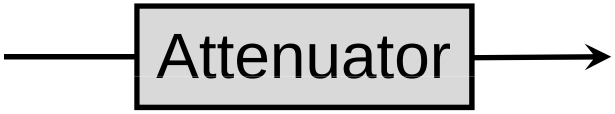


$T_{Out} = T_{In} + T_{Amp}$
$P_{Out} = k{\cdot}B{\cdot}(T_{In} + T_{Amp}){\cdot}G$

If T_{In} = 10ºK, G = 20 dB, B = 100 MHz & T_{Amp} = 100ºK
Then T_{Out} = 110ºK & P_{Out} = -78.19 dBm

Noise Temperature of an Attenuator

(i.e., The Effect of Resistive Losses)



Temperature = ‘T_o’
Attenuation = ‘L’

$$L = 10^{\left(Att\_dB \big/ 10\right)}$$

This is the amount the signal is reduced.

$$T_{Att} = T_o \cdot (L - 1)$$

This is the amount of resistive thermal noise added to the signal.

For an Attenuator…

With no Loss
0 dB → L= 1

With a “small” Loss
0.1 dB → L=1.023

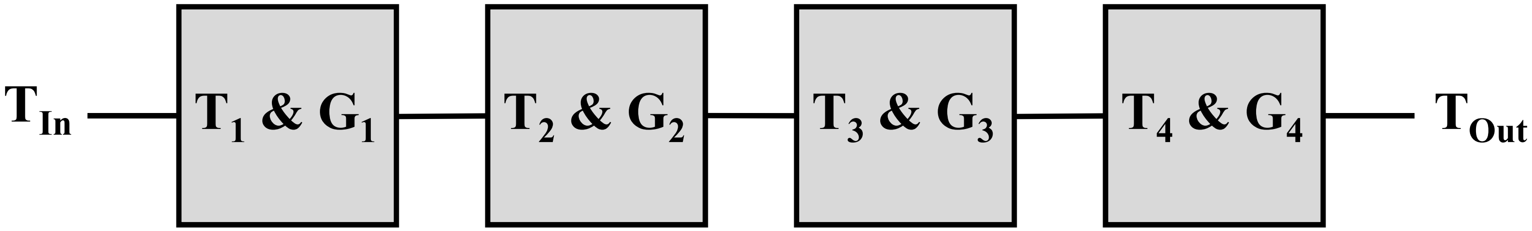
With a “large” Loss
20 dB → L=100

Examples:

If T_o = 300ºK and Insertion Loss = 3 dB
Then L = 2.0 and T_{Att} = 300ºK

If T_o = 15ºK and Insertion Loss = 0.1 dB
Then L = 1.0233 and T_{Att} = 0.35ºK

Noise Temperature of Cascaded Systems



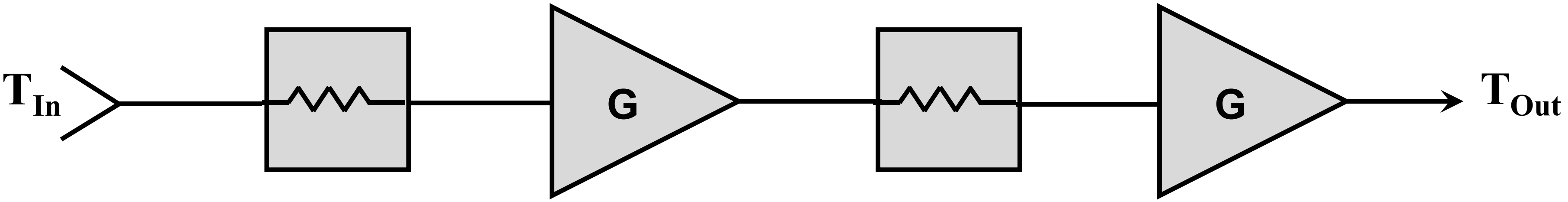
$$T_{Out} = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \frac{T_4}{G_1 G_2 G_3}$$

The devices need not just be amplifiers.
They are anything with loss or gain.
For Attenuators, G = 1/L

First formalized by Harald Friis (Jansky's boss) at Bell Labs in 1945.

Noise Temperature of a Receiver System

A Receiver System consisting of an antenna with a lossy line in front of the LNA, followed by more lossy cable between the LNA and a Postamp:

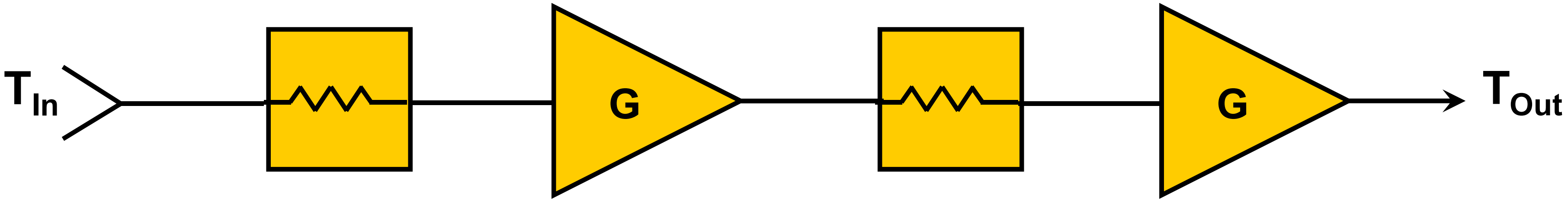


$$\underset{T_{Sys}}{\underset{\uparrow}{T_{Out}}} = \underset{T_{Ant}}{\underset{\uparrow}{T_{In}}} + \underbrace{\boxed{\overbrace{T_{Line}\cdot(L_{Line}-1)}^{T_{Line},\ L_{Line}} + \overbrace{T_{Amp}\cdot L_{Line}}^{T_{LNA},\ G_{LNA}}} + \overbrace{T_{Cable}\cdot\frac{L_{Line}}{G_{LNA}}\cdot(L_{Cable}-1)}^{T_{Cable},\ L_{Cable}} + \overbrace{T_{Postamp}\cdot\frac{L_{Line}\cdot L_{Cable}}{G_{LNA}}}^{T_{Postamp},\ G_{Postamp}}}_{T_{Rx}}$$

**"Double whammy"
from resistive losses
in front of the LNA.**

Noise Temperature of a Warm Receiver System

A non-cryogenically cooled Receiver System



$T_{\text{Line}} = 300^{o}K$
$L_{\text{Line}} = 1\ dB$

$\boxed{T_N = 77.7^{o}K}$

$T_{\text{LNA}} = 100^{o}K$
$G_{\text{LNA}} = 30\ dB$
$B = 1000\ MHz$

$\boxed{T_N = 125.98^{o}K}$

$T_{\text{Cable}} = 300^{o}K$
$L_{\text{Cable}} = 2\ dB$

$\boxed{T_N = 0.22^{o}K}$

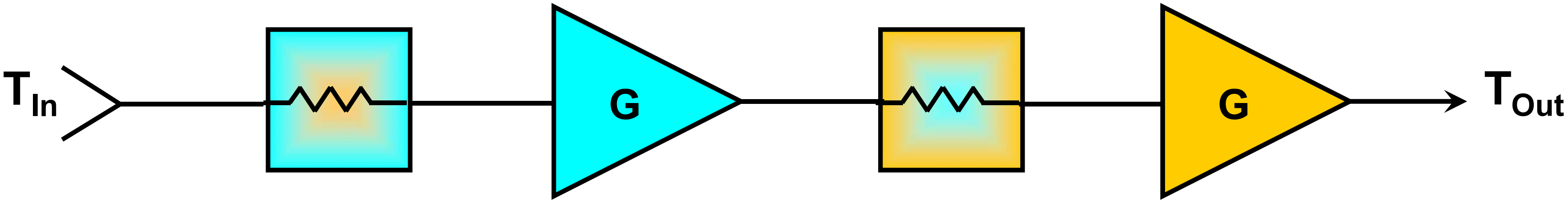
$NF_{\text{Postamp}} = 5\ dB$
$T_{\text{Postamp}} = 627^{o}K$
$G_{\text{Postamp}} = 30\ dB$

$\boxed{T_N = 1.27^{o}K}$

$$\boxed{T_{Rx} = 205^{o}K}$$

Noise Temperature of a Cold Receiver System

A cryogenically cooled Receiver System



$T_{\mathrm{Line}} = 50^{\circ}K$
$L_{\mathrm{Line}} = 0.2\ \mathrm{dB}$

$T_{\mathrm{LNA}} = 10^{\circ}K$
$G_{\mathrm{LNA}} = 30\ \mathrm{dB}$
$B = 1000\ \mathrm{MHz}$

$T_{\mathrm{Cable}} = 150^{\circ}K$
$L_{\mathrm{Cable}} = 2\ \mathrm{dB}$

$NF_{\mathrm{Postamp}} = 5\ \mathrm{dB}$
$T_{\mathrm{Postamp}} = 627^{\circ}K$
$G_{\mathrm{Postamp}} = 30\ \mathrm{dB}$

$T_N = 2.36^{\circ}K$

$T_N = 10.47^{\circ}K$

$T_N = 0.09^{\circ}K$

$T_N = 1.04^{\circ}K$

$$T_{Rx} = 14.0^{\circ}K$$

Noise Model for JVLA Ka-Band Receiver

EVLA Ka-Band Rx *(R. Hayward)* *(28 March 2006)*	P (1dB) (dBm)	P (1%) (dBm)	Temp (K)	NF/C (dB)	Loss/Gain (dB)	Loss/Gain (linear)	Delta T (K)	Trx (K)	BW (MHz)	Pnoise (dBm) for Tsky of 13.0 (K)	Headroom (dB) wrt P(1%)
									18000	-84.9	
Weather Window			300		0	1.0000	0.000			-84.9	
Feed Horn			300		-0.02	0.9954	1.385			-84.5	
Vacuum Window			300		-0.01	0.9977	0.695			-84.3	
Phase Shifter			13		-0.1	0.9772	0.305			-84.3	
OMT			13		-0.1	0.9772	0.312			-84.3	
Waveguide			13		-0.1	0.9772	0.319			-84.3	
Cal Coupler (IL)			13		-0.1	0.9772	0.327			-84.3	
Cal Coupler (Branch)			300	-30	0	1.0000	0.300			-84.3	
Isolator			13		-0.4	0.9120	1.385			-84.3	
LNA	-10	-22	10		35	3162.2777	12.106			-47.1	25.1
Stainless Steel W/G			156.5		-8	0.1585	0.318	17.45		-55.0	
Vacuum Window			300		-0.2	0.9550	0.034			-55.2	
Waveguide			300		-1	0.7943	0.196			-56.2	
Isolator			300		-0.5	0.8913	0.117			-56.7	
RF Post-Amp	15	3	637.9	5	11.5	14.1254	2.279			-44.9	47.9
RF Filter (25-41 GHz)			300		-1	0.7943	0.020		14000	-47.0	
Attenuator			300		0	1.0000	0.000			-35.4	
RF Post-Amp	15	3	637.9	5	11.5	14.1254	0.203			-35.4	38.4
Mixer (Level 10 - 5dB)	-2	-14	300		-14	0.0398	0.163			-49.4	21.4
IF Filter (DC-18 GHz)			300		-1	0.7943	0.044		14000	-50.4	
Post-Amp	18	6	229.6	2.5	13	19.9526	0.164			-37.4	43.4
Attenuator			300		-5	0.3162	0.023			-42.4	
Isolator			300		0.5	1.1220	-0.004	20.69		-41.9	

The Radiometer Equation

$$\Delta T = \frac{T_{Sys}}{\sqrt{B\cdot\tau}} = \frac{T_{Source}+T_{Ant}+T_{Rx}}{\sqrt{B\cdot\tau}}$$

Where…

ΔT	**is the sensitivity of the receiver.**
T_{Source}	**is the astronomical noise from the source of interest.**
T_{Ant}	**is the noise contribution from the sky, antenna spillover, etc.**
T_{Rx}	**is the noise contribution from the receiver.**
B	**is the detection bandwidth.**
τ	**is the integration time.**

The Radiometer Equation Consequences

$$\Delta T = \frac{T_{Sys}}{\sqrt{B \cdot \tau}} = \frac{T_{Source} + T_{Ant} + T_{Rx}}{\sqrt{B \cdot \tau}}$$

If the T_{Sys} is reduced by a factor of 2, the amount of integration required to achieve the same sensitivity level takes only 1/4th as much time.

In other words, you would be able to observe 4 times as many astronomical objects in the same amount of time.

Perspective:

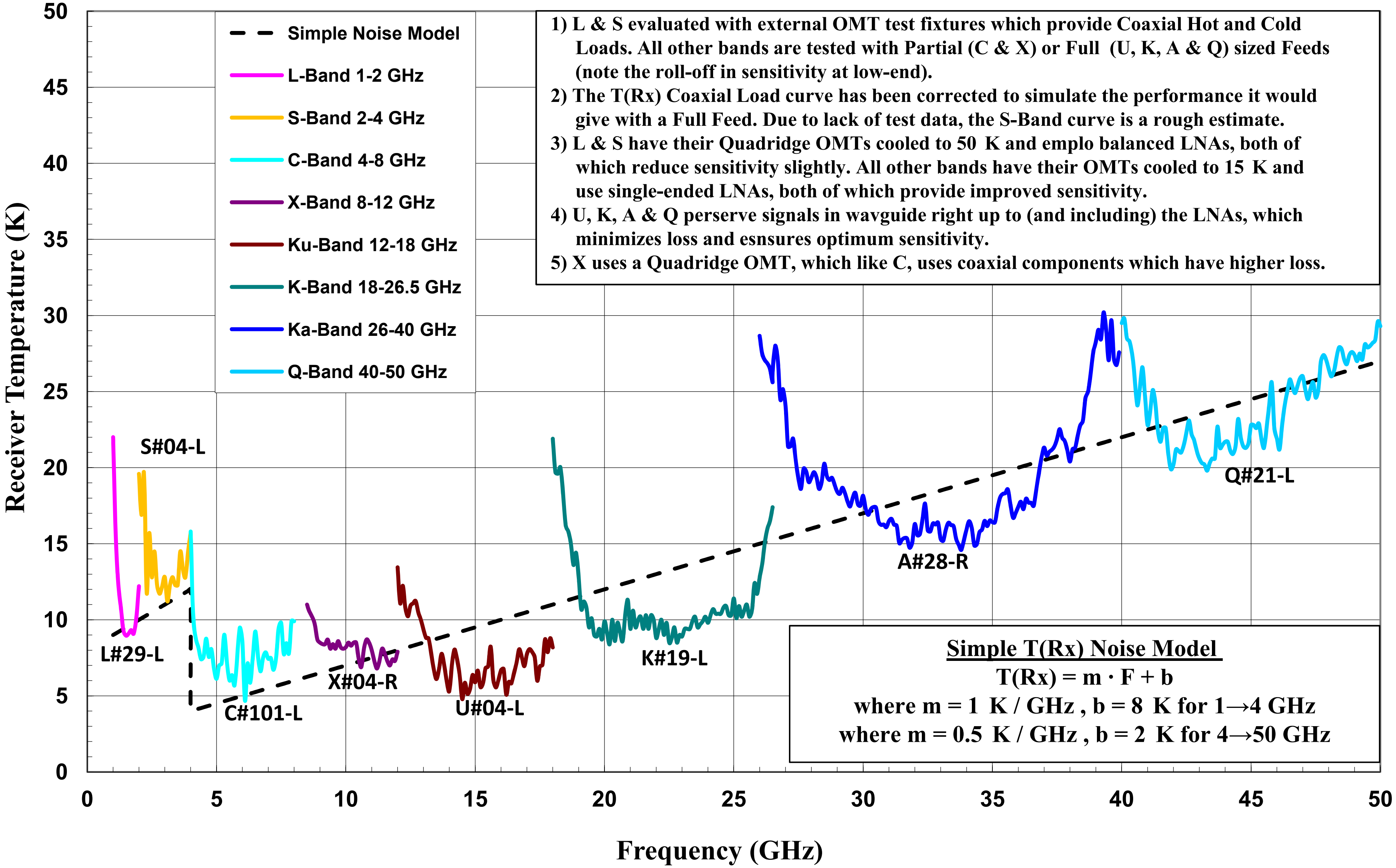
For the JVLA at C-Band, which has a T_{Sys} of about 25°K, a relatively strong astronomical source with a flux of 1 Jy (= 10^{-26} W m^{-2} Hz^{-1}) would cause about a 0.2°K increase in the system temperature – less than 1%.

Obviously astronomical sources contribute a very, very small amount to the overall noise power coming out of the antenna/receiver system.

T(Rx) vs. Frequency for JVLA Receiver Bands

Original EVLA Project Book - T_{Rx} Requirements (Band Center)

Band	L	S	C	X	Ku	K	Ka	Q
T_{Rx}	14	15	16	20	25	34	40	48



1) L & S evaluated with external OMT test fixtures which provide Coaxial Hot and Cold Loads. All other bands are tested with Partial (C & X) or Full (U, K, A & Q) sized Feeds (note the roll-off in sensitivity at low-end).

2) The T(Rx) Coaxial Load curve has been corrected to simulate the performance it would give with a Full Feed. Due to lack of test data, the S-Band curve is a rough estimate.

3) L & S have their Quadridge OMTs cooled to 50 K and emplo balanced LNAs, both of which reduce sensitivity slightly. All other bands have their OMTs cooled to 15 K and use single-ended LNAs, both of which provide improved sensitivity.

4) U, K, A & Q perserve signals in wavguide right up to (and including) the LNAs, which minimizes loss and esnsures optimum sensitivity.

5) X uses a Quadridge OMT, which like C, uses coaxial components which have higher loss.

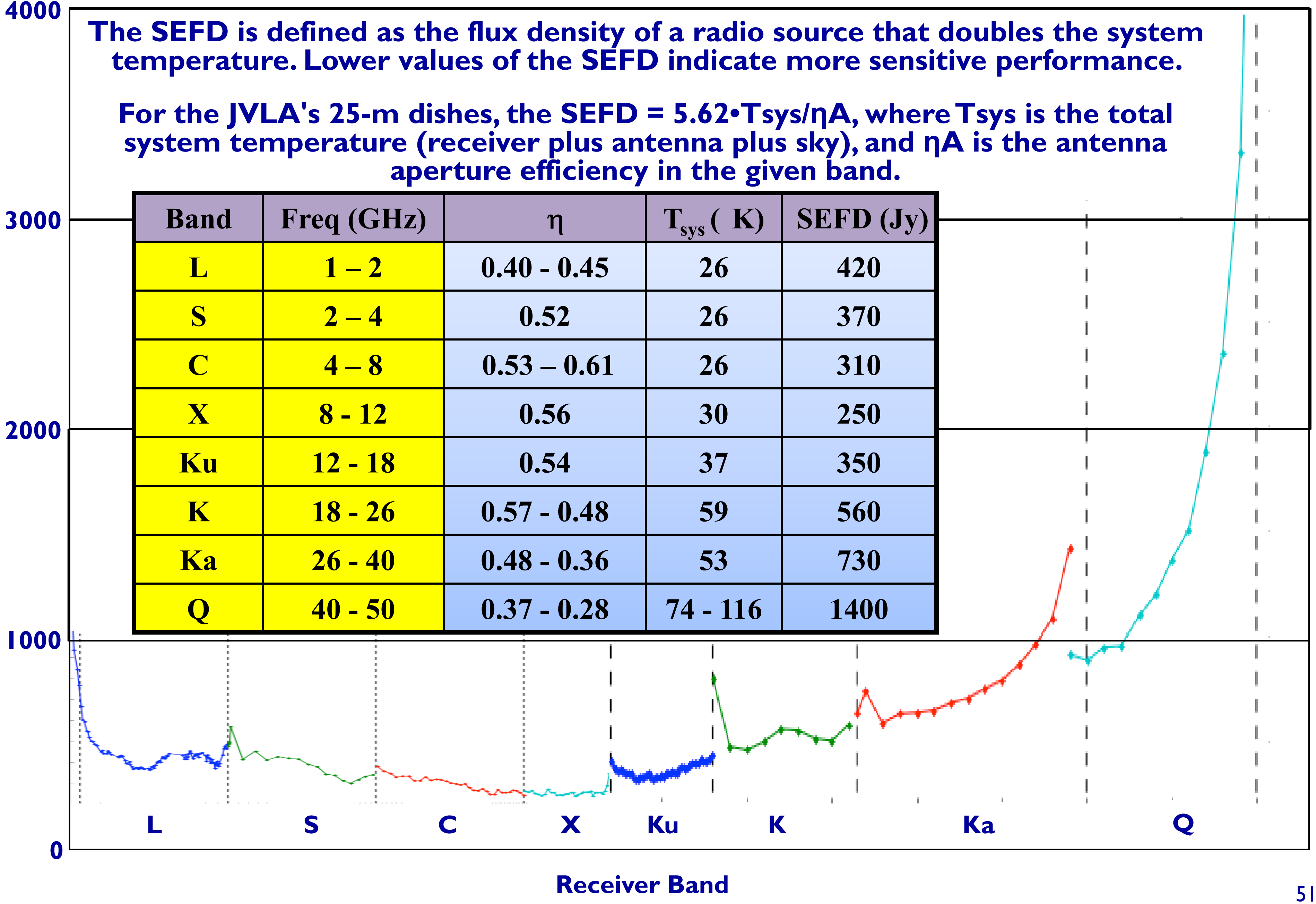
Simple T(Rx) Noise Model

$T(Rx) = m \cdot F + b$

where $m = 1$ K / GHz , $b = 8$ K for 1→4 GHz

where $m = 0.5$ K / GHz , $b = 2$ K for 4→50 GHz

JVLA *System Equivalent Flux Density* (SEFD)



The SEFD is defined as the flux density of a radio source that doubles the system temperature. Lower values of the SEFD indicate more sensitive performance.

For the JVLA's 25-m dishes, the SEFD = 5.62•Tsys/ηA, where Tsys is the total system temperature (receiver plus antenna plus sky), and ηA is the antenna aperture efficiency in the given band.

Band	Freq (GHz)	η	T_{sys} (K)	SEFD (Jy)
L	1 – 2	0.40 - 0.45	26	420
S	2 – 4	0.52	26	370
C	4 – 8	0.53 – 0.61	26	310
X	8 - 12	0.56	30	250
Ku	12 - 18	0.54	37	350
K	18 - 26	0.57 - 0.48	59	560
Ka	26 - 40	0.48 - 0.36	53	730
Q	40 - 50	0.37 - 0.28	74 - 116	1400

Questions

Backup Slides

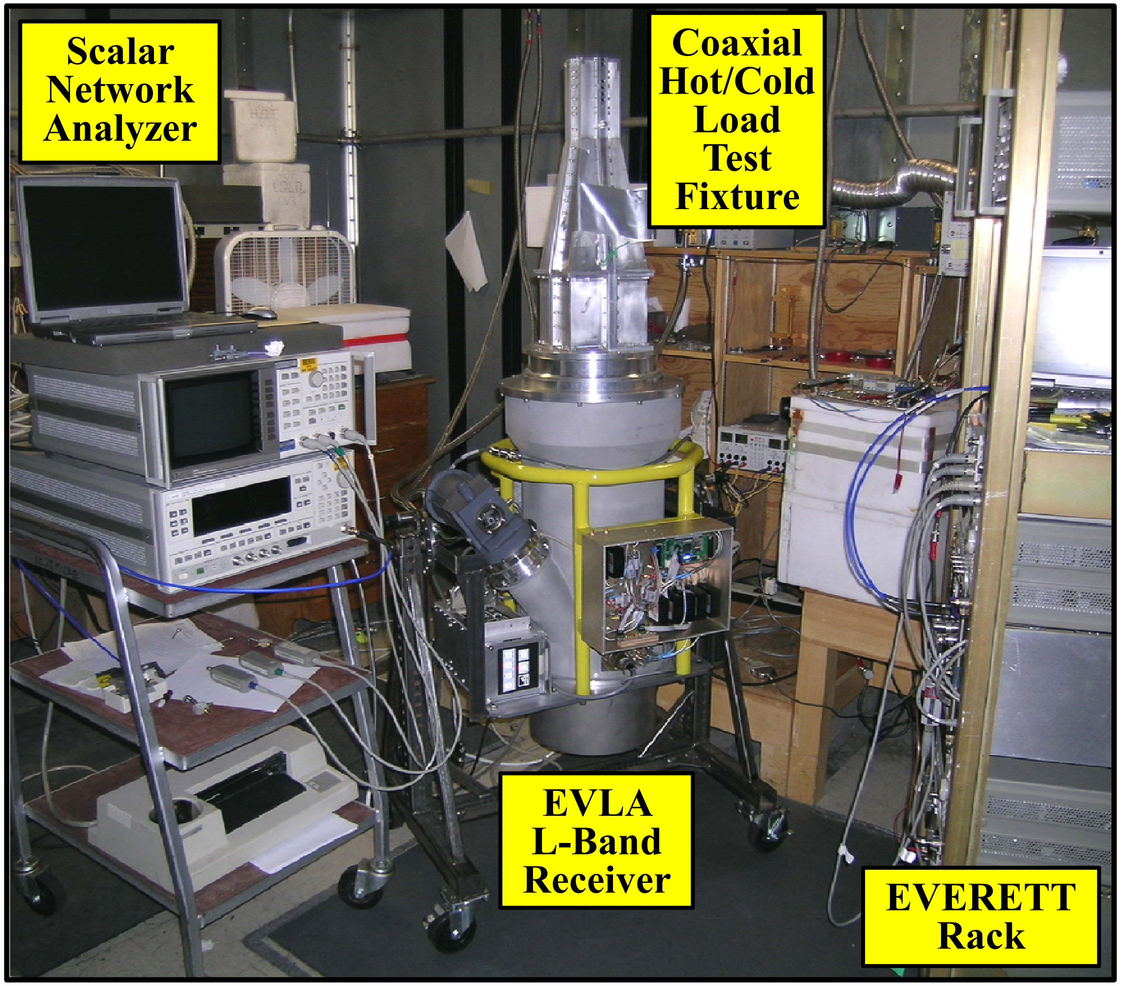
JVLA Receiver Test & Calibration Equipment

- To evaluate the new JVLA receivers, the Front-End Group uses two custom test racks known as…
  - SOIDA (*Stack of Obsolete Instruments Dithering Around*)
  - EVERETT (*Expanded Vla Enhanced Receiver Evaluation & Test Terminal*)
- These test racks consist of a data acquisition PC, two commercial frequency synthesizers, a power meter plus a custom designed Baseband Converter (BBC) unit.

- A Scalar Network Analyzer (SNA) is used for additional tests…
  - <u>Circular Polarization Purity</u>

    Axial Ratio
  - <u>Total Power Stability</u>

    Gain Fluctuations

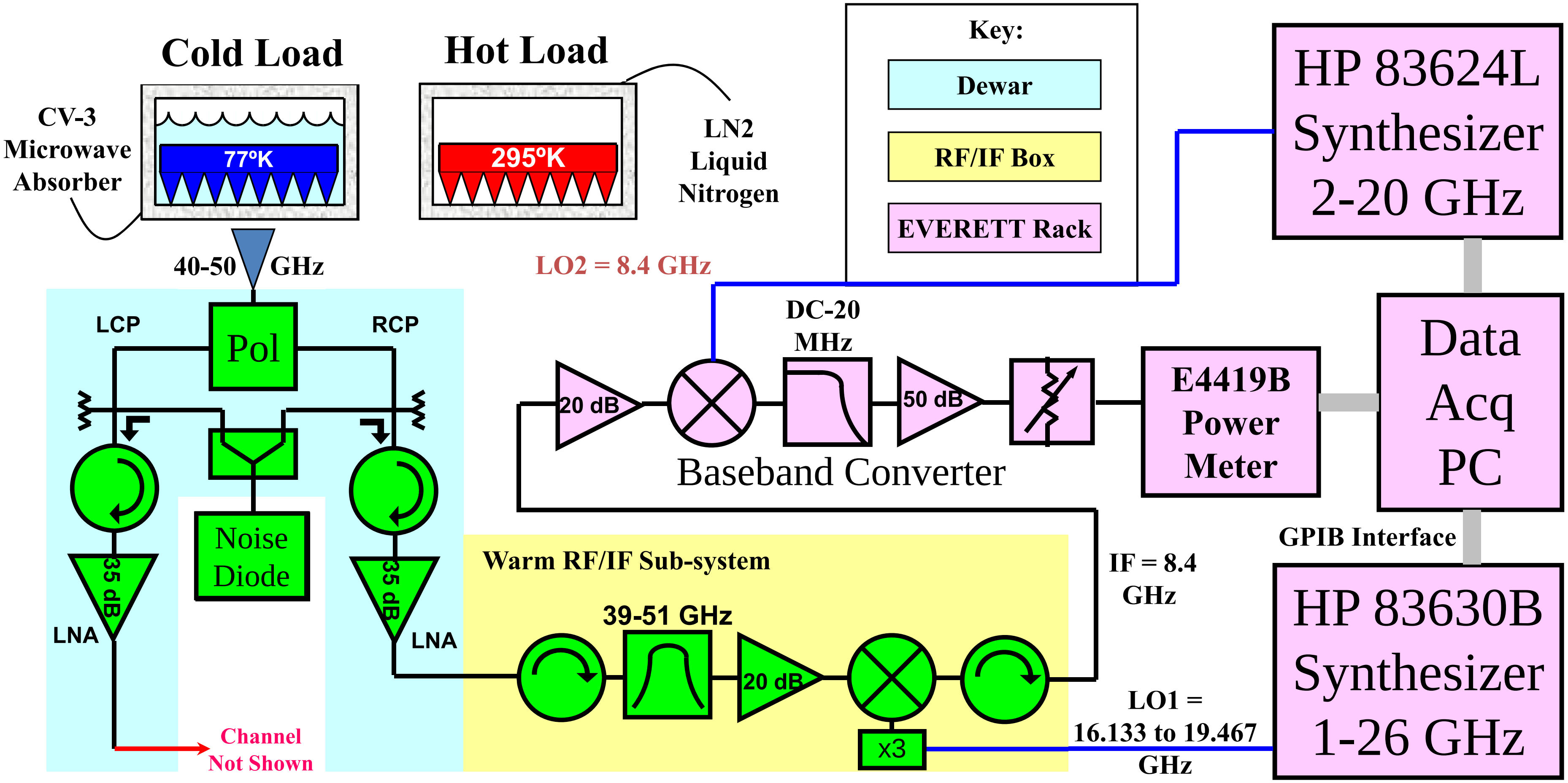


L-Band Receiver in Screen Room undergoing sensitivity, axial ratio & stability tests.

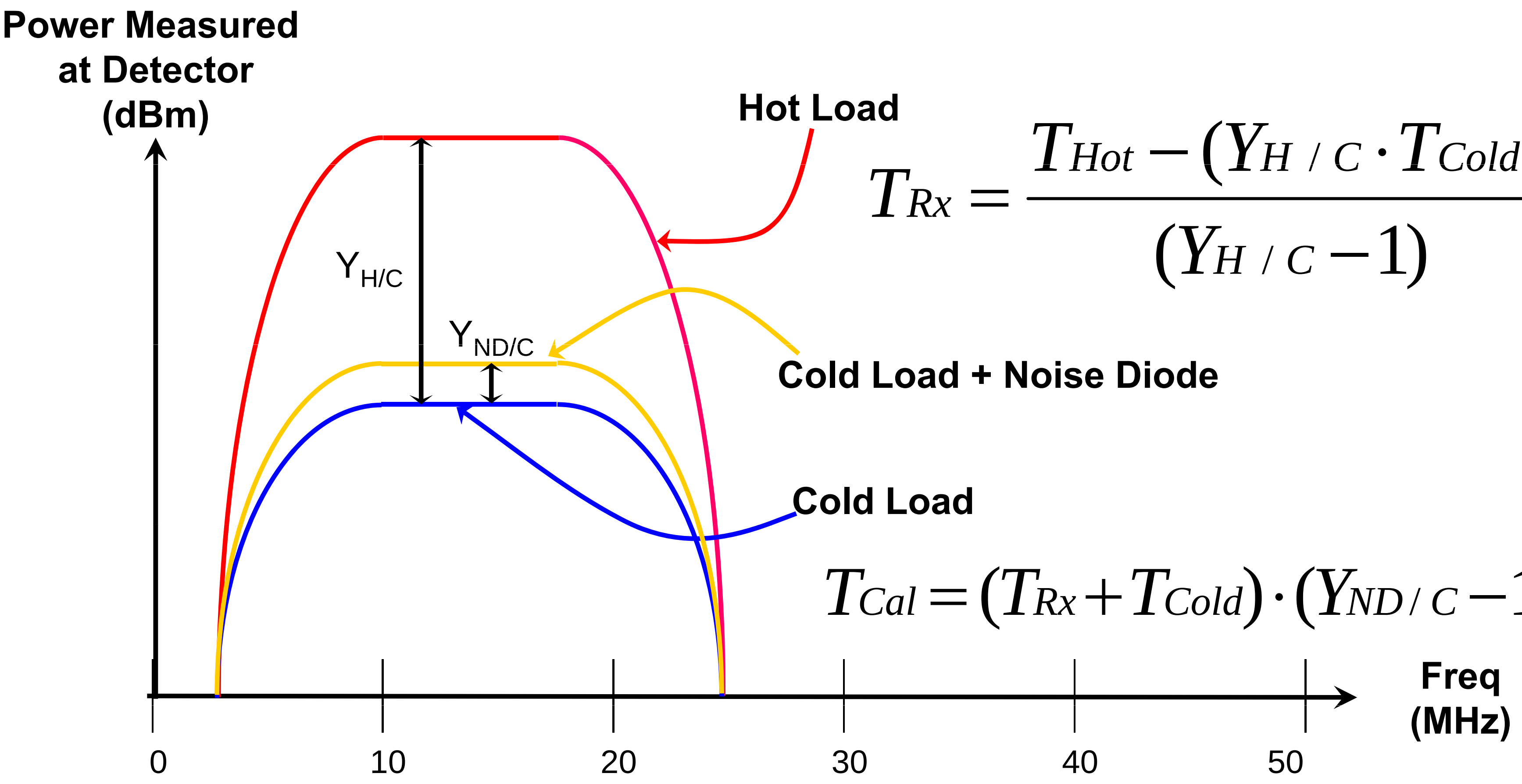
EVERETT Rack & Ku-Band S/N 21

- To properly characterize a receiver, we need to measure the…
  - Receiver Sensitivity T_{Rx} *vs. Freq*
  - Noise Diode Calibration T_{Cal} *vs. Freq*
- For the higher frequency receivers we use *Hot & Cold "Bucket" Loads* with convoluted CV-3 Absorber.
- The *Hot Load* is at room temp (295ºK)
- Copious amounts of Liquid Nitrogen are used to cool the *Cold Load* (77ºK).
- The boxes are made from low-loss HD30 Zotefoam.
- A metal plate is used to make the *Cold Load* look "colder" (by reducing leakage from the 300ºK ceiling).
- The *Cold Load is* elevated so a fan can help eliminate moisture from building up on the bottom surface.

"SOIDA" / "EVERETT" Rack Hot-Cold Load Q-Band Receiver Characterization



What SOIDA & EVERETT See…



$$T_{Rx} = \frac{T_{Hot} - (Y_{H/C} \cdot T_{Cold})}{(Y_{H/C} - 1)}$$

$$T_{Cal} = (T_{Rx} + T_{Cold}) \cdot (Y_{ND/C} - 1)$$

The Y-Factor Equation

- **Since the P = kBGT formula has two unknowns (G & T), we require two measurements to uniquely solve for T_{Rx}.**
- **We do this by placing two loads of known temperatures in front of the receiver and measuring the power ratio.**
- **This is known as the *Y-Factor*.**

- **Hot Load = Room Temperature**

  T_{Hot} = 295ºK

  Cold Load = Liquid Nitrogen

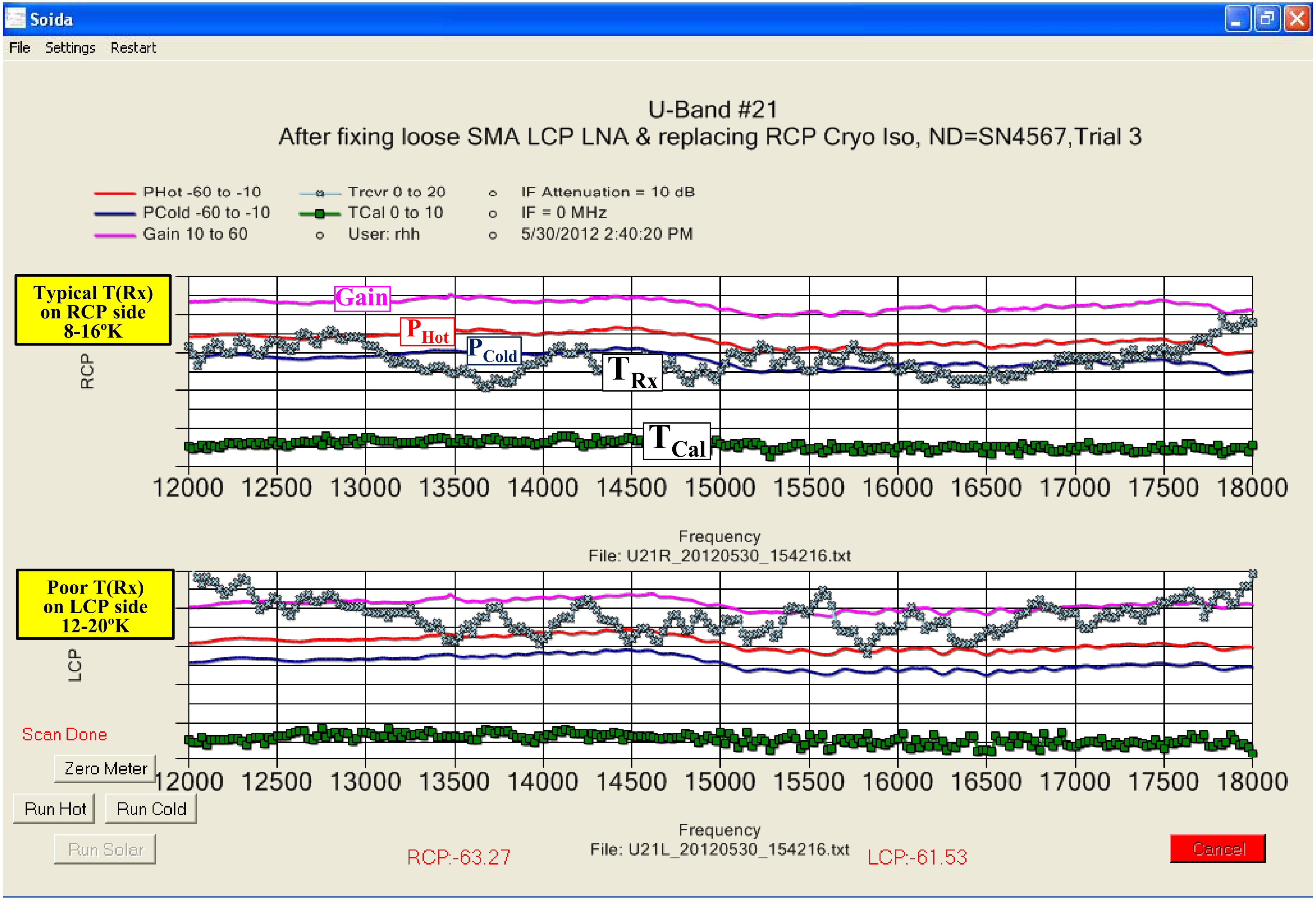
  T_{Cold} = 77ºK

$$\frac{P_{Hot}}{P_{Cold}} = \frac{kBG\cdot(T_{Hot}+T_{Rx})}{kBG\cdot(T_{Cold}+T_{Rx})}$$

$$Y_{H/C} = \frac{P_{Hot}}{P_{Cold}} = \frac{T_{Hot}+T_{Rx}}{T_{Cold}+T_{Rx}}$$

$$T_{Rx} = \frac{T_{Hot} - Y_{H/C}\cdot T_{Cold}}{(Y_{H/C}-1)}$$

Real-time EVERETT Display of a Ku-Band Rx Test



U-Band #21

After fixing loose SMA LCP LNA & replacing RCP Cryo Iso, ND=SN4567,Trial 3

PHot -60 to -10
PCold -60 to -10
Gain 10 to 60
Trcvr 0 to 20
TCal 0 to 10
User: rhh
IF Attenuation = 10 dB
IF = 0 MHz
5/30/2012 2:40:20 PM

Typical T(Rx) on RCP side 8-16ºK

File: U21R_20120530_154216.txt

Poor T(Rx) on LCP side 12-20ºK

Scan Done

RCP:-63.27

File: U21L_20120530_154216.txt

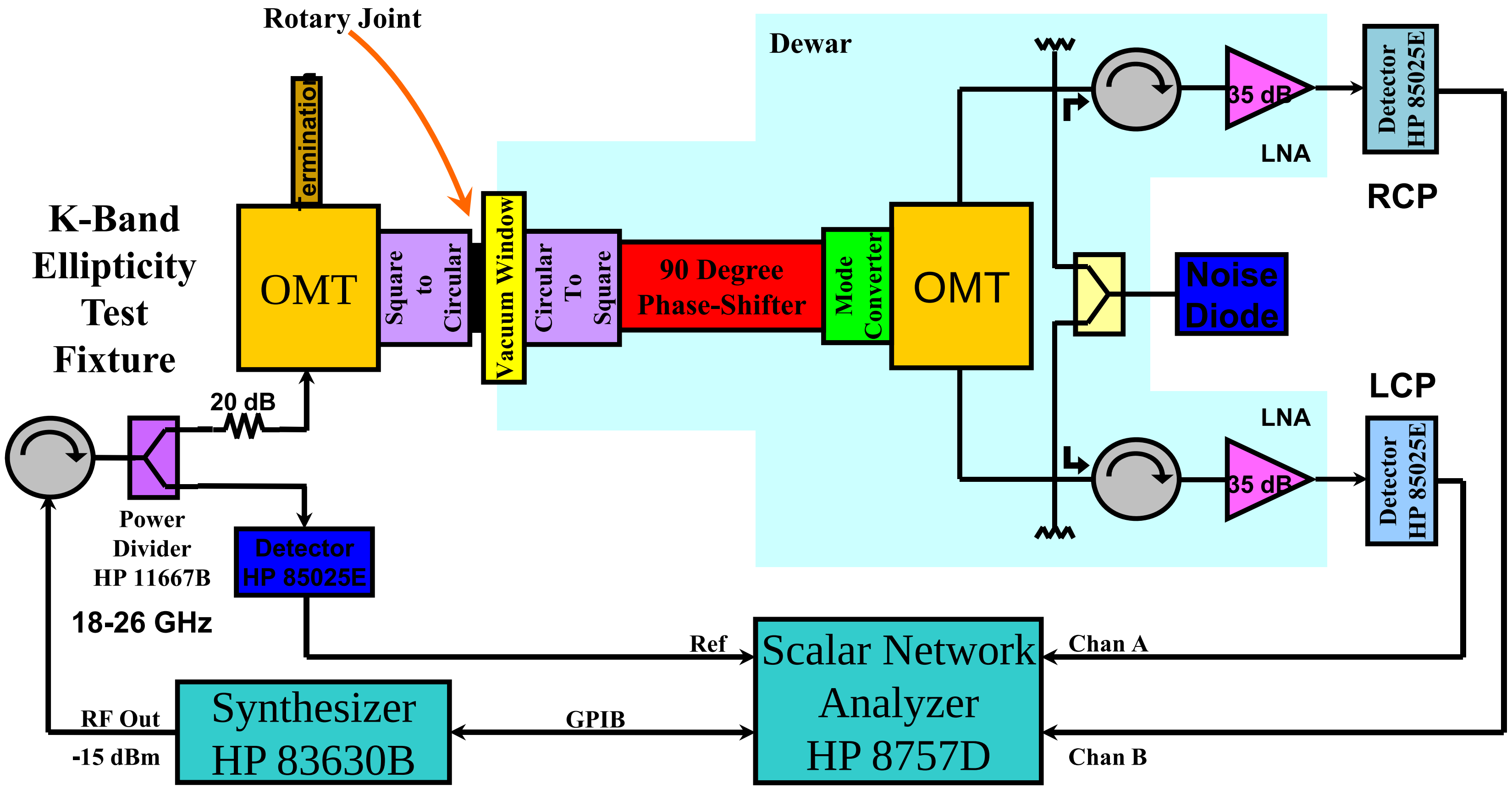
LCP:-61.53

Table of JVLA Circular Polarizers

Band	Freq (GHz)	Bandwidth Ratio	Circular Polarizer Type
L	1-2	2.00 : 1	Quadridge OMT (*Lilie*) + Commercial 90° Hybrid Coupler (*Mactech*)
S	2-4	2.00 : 1	
C	4-8	2.00 : 1	
X	8-12	1.50 : 1	PS (*Sri*) + Offset Quadridge OMT (*Coutts*)
Ku	12-18	1.50 : 1	Corrugated W/G Phase-Shifter (*Srikanth*) + 2-Fold Symmetric W/G OMT (*Wollack*)
K	18-26	1.44 : 1	
Ka	26-40	1.54 : 1	
Q	40-50	1.25 : 1	Commercial Sloping Septum (*Spacek*)

Axial Ratio vs. Frequency Measurements
K-Band Ellipticity Test Setup

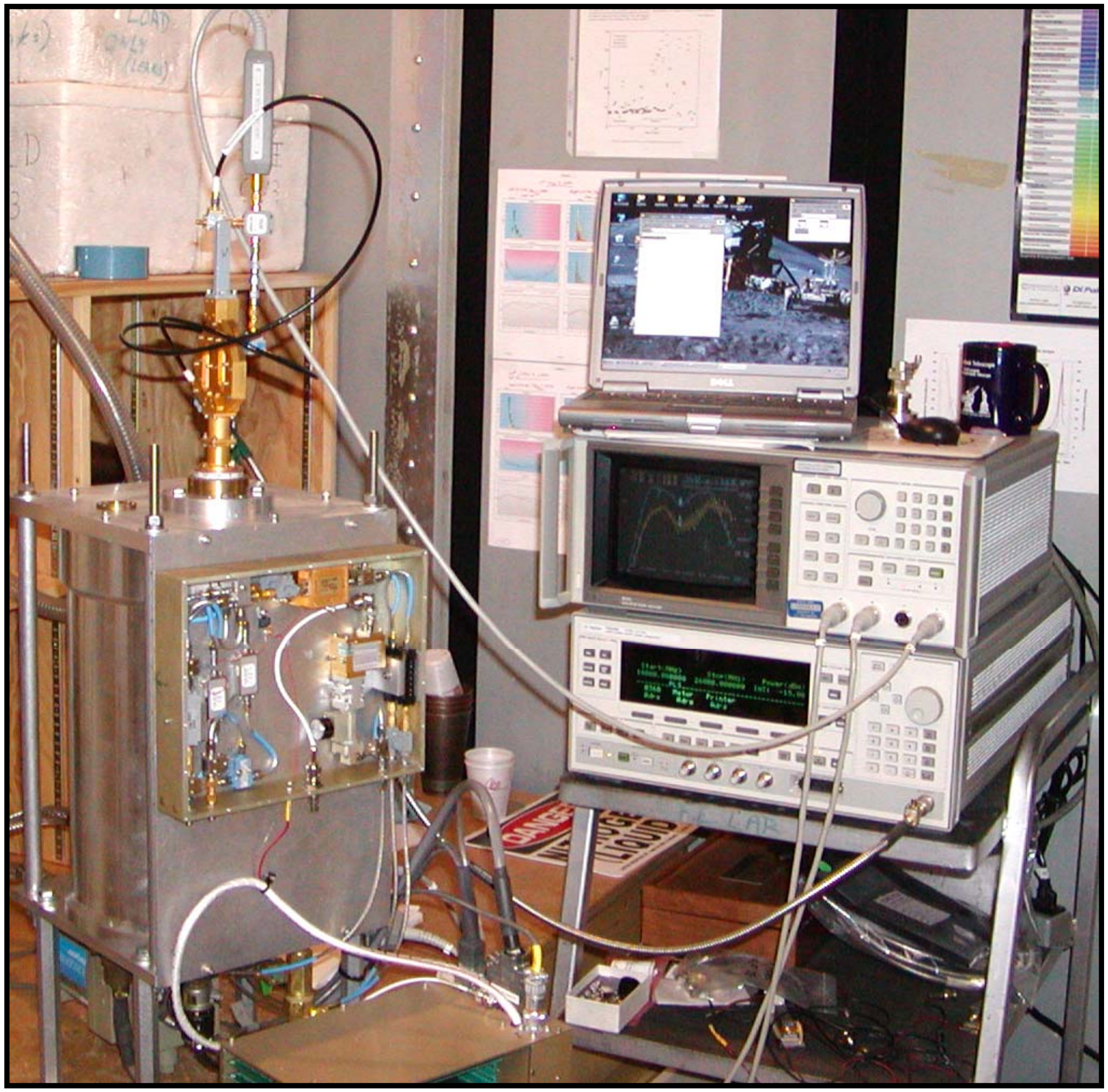
- Inject a single-component linearly polarized signal into the receiver, swept across 18-26.5 GHz, rotating the angle through a full circle in 22.5 degree steps (i.e., 17 fixed position angles) and recording the gain vs. freq response.
- A perfect circular polarizer would break a pure linear signal into equal left & right circular components, and would show no change with position angle.
- A circular polarizer with a 1 dB Axial ratio would show a power variation of 1 dB through the full position angle rotation in either or both circular polarizations.



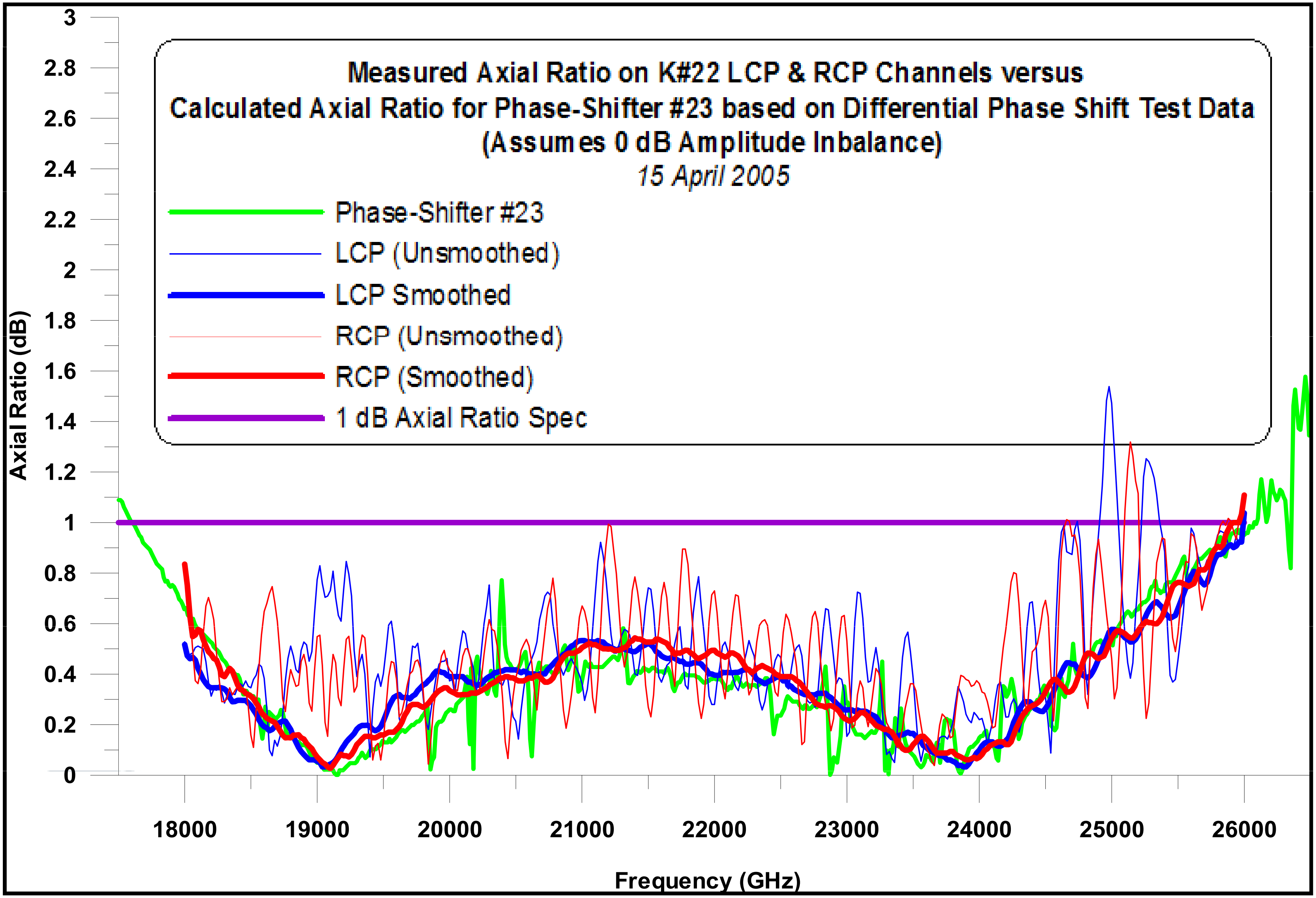
Note that an engineer's Axial Ratio of 1 dB corresponds to an astronomer's D-term of 6.1%.

K-Band Receiver S/N 22 Under Test

- **Axial Ratio test using the Scalar Network Analyzer…**
  - **Full frequency sweep taken at each Position Angle (every 22.5 degrees).**
  - **Using the SNA "Reference Channel" eliminates power variations from RF cable being twisted.**
  - **SNA data "grabbed" by laptop & written to Excel files.**
  - **A *super-spreadsheet* imports the nearly 100,000 data points and then calculates the axial ratio for each frequency point.**
  - **Freq resolution: L-Band = 2.5 MHz**
    Ka-Band = 35 MHz
  - **Scheme also allows smoothing of data before AR calculated so effect of freq ripple in the test setup can be reduced.**



Typical K-Band Axial Ratio Measurement



Effect of LNA Input Match on Axial Ratio

Receiver L#21 (Interim)
(17 Feb 2006)

VLA-style Quadridge OMT
& Hybrid Coupler

Simulated LNA Input Return Loss
Good = 30 dB
Poor = 10 dB

Tests like this indicated a match of better than -15 dB was required for the LNAs