Very Low Noise Amplifiers for Radio Astronomy and Space Communications

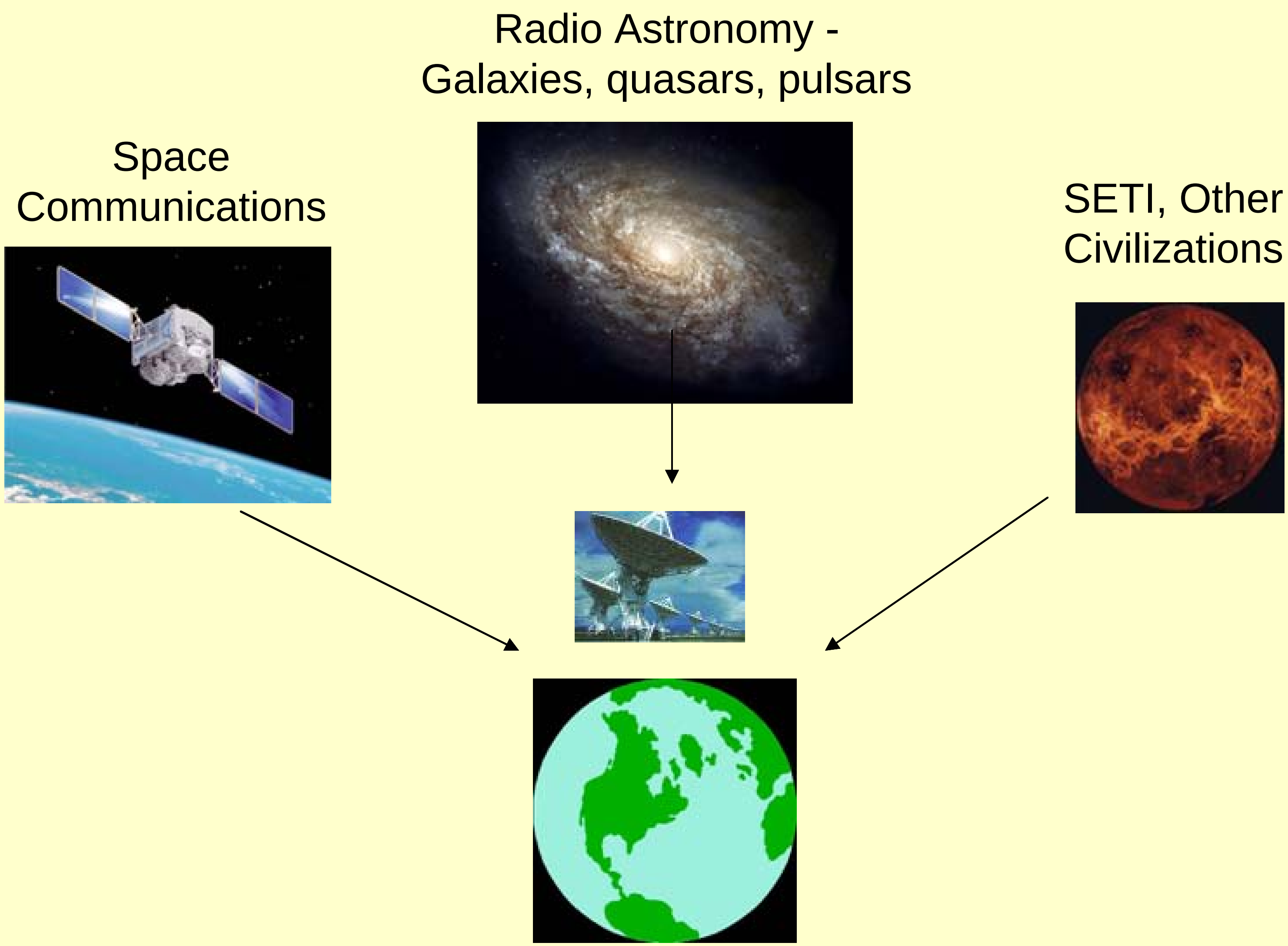
Sander Weinreb and Niklas Wadefalk

Outline

1. Rational for large arrays
2. Preview of IMS2005 Workshop on Large Arrays
3. Rationale for very low noise
4. Decade bandwidth antenna feeds
5. Low noise research projects at Caltech
   A. <10K noise at room temperature?
   B. Thermoelectric cooling to 200K
   C. Cryogenically cooled feed and LNA
6. LNA Design and results (Wadefalk)

Radio Waves Impinge Upon the Earth from Many Distant Sources

Our Sensitivity to These Waves is Proportional to the Collecting Area on Earth



Methods to Increase Microwave Collecting Area

Larger Antennas or Arrays of Smaller Antennas?

Green Bank 100m Antenna

Array of 12m Antennas

More Microwave Collecting Area is Needed
Why Use Arrays?

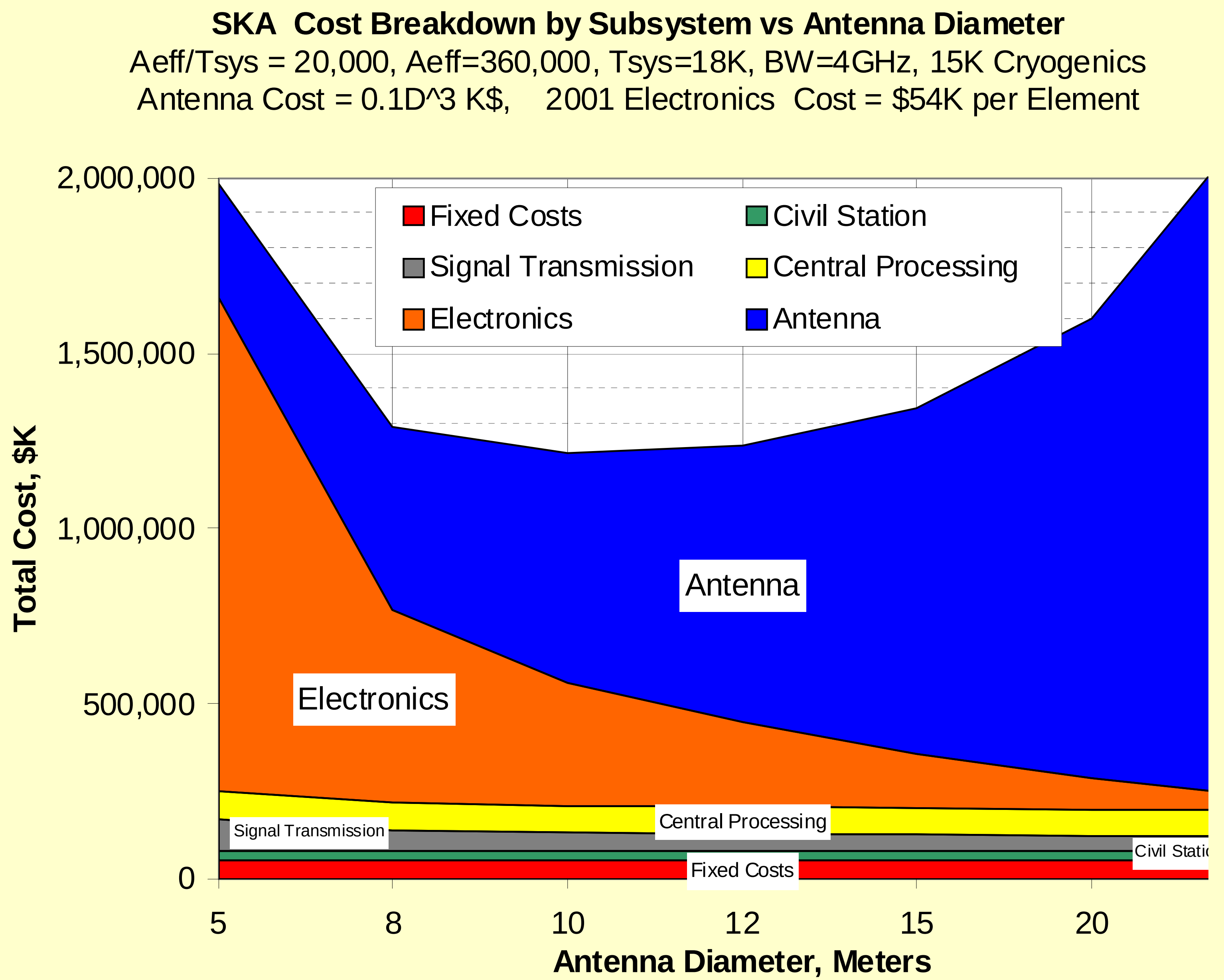
- Costs of large antennas are proportional to diameter to a power in the 2.7 range; thus to increase collecting area it is less expensive to have large numbers of small antennas.

- Arrays can multibeam or image a region of sky whereas this is difficult to do with single antennas.

- New technology – low cost small antennas, microwave integrated circuits, fiber-optic signal transmission, and enormous advances in digital signal processing have enabled large arrays.

- In summary, arrays have become cost effective by substituting electronics for steel

Example of Array Cost for a Given Total Area

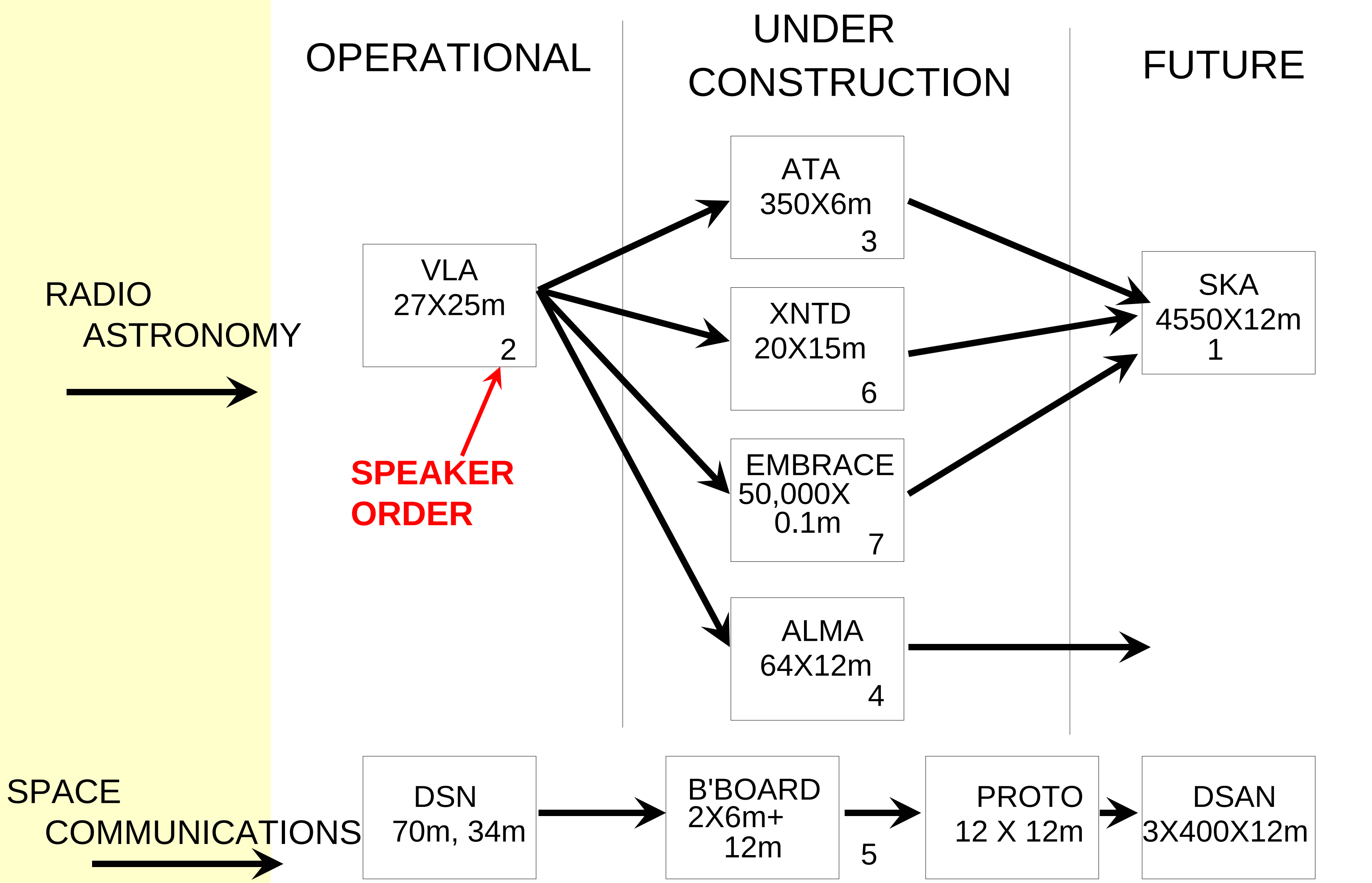


Comparison of Existing Large Antennas and Future Arrays

Antenna	Elements	Effective Area	Upper Frequency	Tsys	**A/Tsys**	Year Finished
DSN 70m	1 x 70 m	2,607	8 GHz	18	**145**	1965
GBT	1 x 100 m	5,700	100 GHz	20	**285**	2000
VLA	27 x 25 m	8,978	43 GHz	32	**280**	1982
Arecibo	1 x 305 m	23,750	8 GHz	25	**950**	1970
ALMA	64 x 12 m	4,608	800 GHz	50	**92**	2011
ATA	350 x 6 m	6,703	11 GHz	35	**192**	2007
DSN	**400 x 12m**	**32,000**	**38 GHz**	**18@8GHz 42@32GHz**	**1760 754**	**2013**
SKA	**4550 x 12m**	**327,600**	**22 GHz**	**18**	**20,000**	**2016**

ATA - Allen Telescope Array
DSN - Deep Space Network
VLA - Very Large Array
SKA - Square Km Array

Array Workshop Roadmap



Program - IEEE 2005 MTTS Workshop WFF

Long Beach, CA, June 17, 2005, 8AM-Noon

Very Large Microwave Arrays for Radio Astronomy and Space Communications

1. Introduction and Overview, S. Weinreb, Caltech/JPL

Rationale and requirements for new arrays. Comparison of current and future instruments. Space communication and radio astronomy applications. Introduction to SETI and the Square Km Array (SKA). Array technology.

2. Expansion of the Very Large Array (VLA) P. Napier, NRAO

The VLA with 27x25m telescopes in central New Mexico has been the premier instrument in radio astronomy for the past 20 years. The large improvement program with regards to frequency and bandwidth is described.

3. Allen Telescope Array (ATA) D. DeBoer, SETI Institute

The ATA is an array of 350 x 6m antennas under construction in northern California. It is pioneering new technology in terms of relatively low cost hydroformed reflectors and feeds and low noise amplifiers with instantaneous bandwidth of 0.5 to 11 GHz.

Workshop WFF Program Continued

4. Atacama Large Millimeter Array (ALMA) L. D'addario, JPL

ALMA is an array of 64 antennas of 12m diameter for astronomy at millimeter and submillimeter wavelengths. It is now under construction at 5000m elevation in northern Chile. Receivers use superconducting mixers in most bands. The system design and components will be described

5. An Array Based Deep Space Network (DSN) M. Gatti, JPL

The data return from space probes to Mars and beyond are limited by the present DSN system using 34m and 70m antennas. An array of 400 x 12 antennas is being considered to provide a factor of 40 increase in data rate.

6. Large Array with Focal-Plane Array Feeds for the SKA J. Kot, CSIRO

An array of 15m antennas with 100-element focal-plane array feeds on each antenna is being considered as an SKA approach which achieves large collecting area and also a wide instantaneous field-of-view for the 0.8 to 1.7 GHz frequency range. The program plan and initial concepts of the feeds and receivers will be described.

Workshop Program Continued

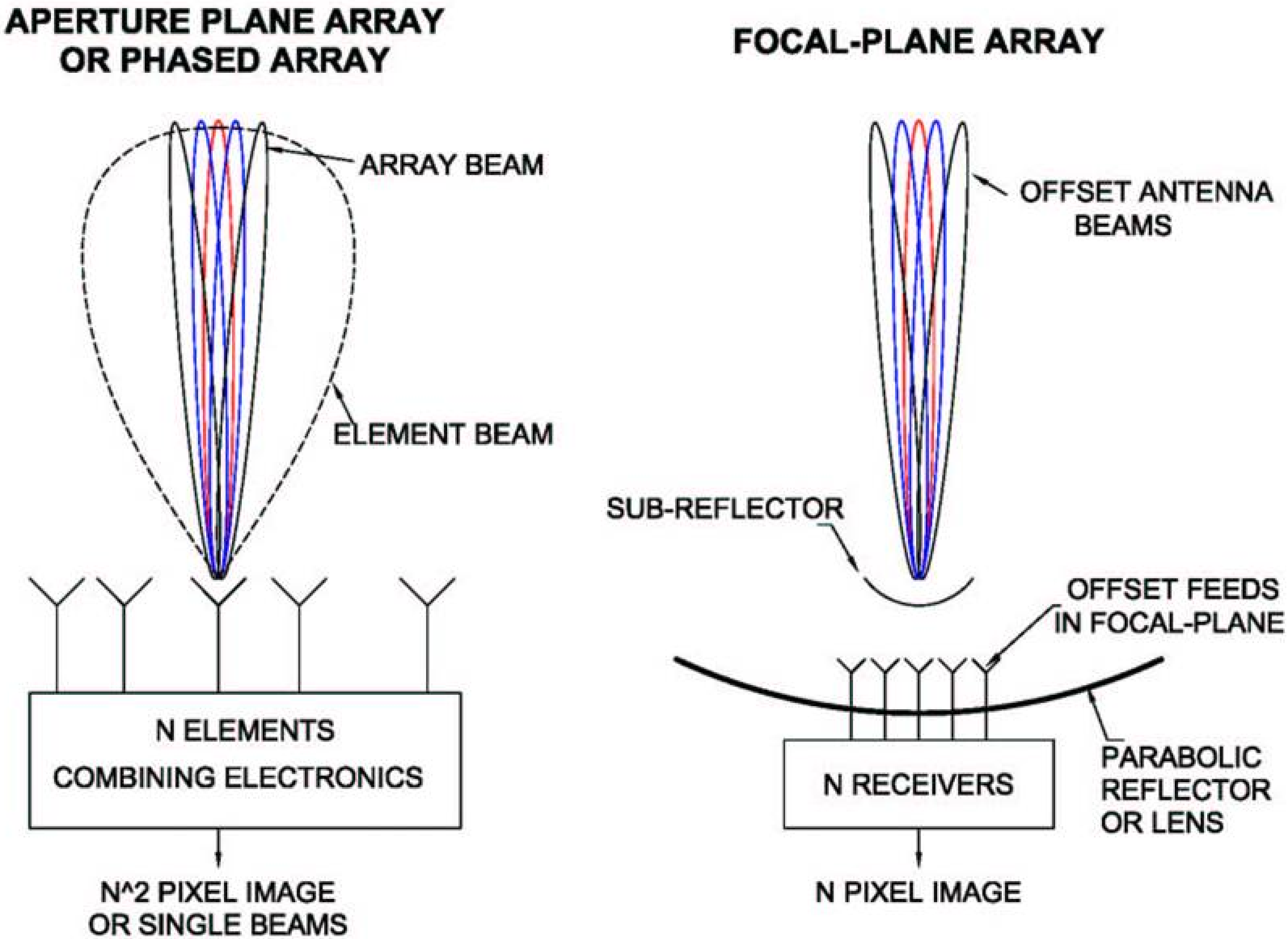
7. Phased-Array with All-Sky Imaging Capability J. Bi deVaate, Astron

A phased-array consisting of 50,000 small Vivaldi antennas operating in the 0.4 to 1.5 GHz range is described as an SKA demonstration project.

8. Very Low Noise Amplifiers for Very Large Arrays N. Wadefalk, Caltech

The design and current test results for wide bandwidth cryogenic and room temperature MMIC LNA's and active baluns for the 0.5 to 40 GHz range will be presented.

Types of Imaging Arrays

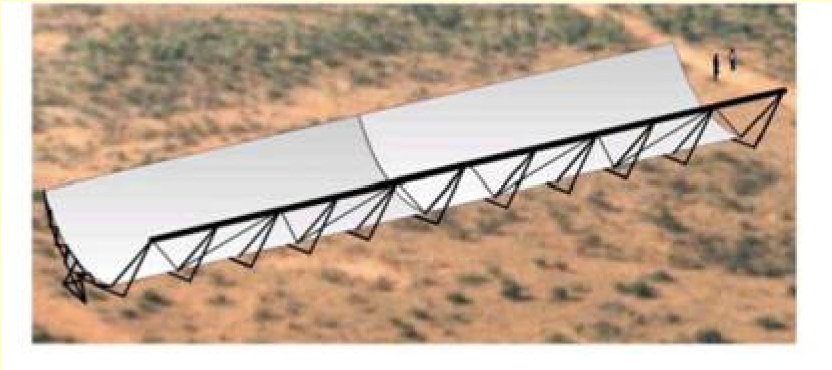


SKA Organization, Funding, and Time Line

- SKA is a 15-country international collaboration with a director, steering committee, and engineering working groups
- World-wide $34M has been funded for SKA development and $91M is in proposals
- Expectation is for international funding at a level of the order of $1B with roughly 1/3 from the US, 1/3 from Europe, and 1/3 from the rest of the world. (ALMA is currently internationally funded at a level in the $0.6 to $1B range from the US, Europe, Canada, and Japan.)
- Timeline is currently:
  - Site selection in 2006
  - Concept selection in 2008
  - Construction start in 2011
  - Initial operations in 2015
  - Full operations in 2020
- Alternatives such as splitting into high and low frequency arrays in northern and southern hemispheres are being considered

Antenna Concepts Proposed for SKA

Fixed Small Antennas - Netherlands



Cylindrical Paraboloid - Australia

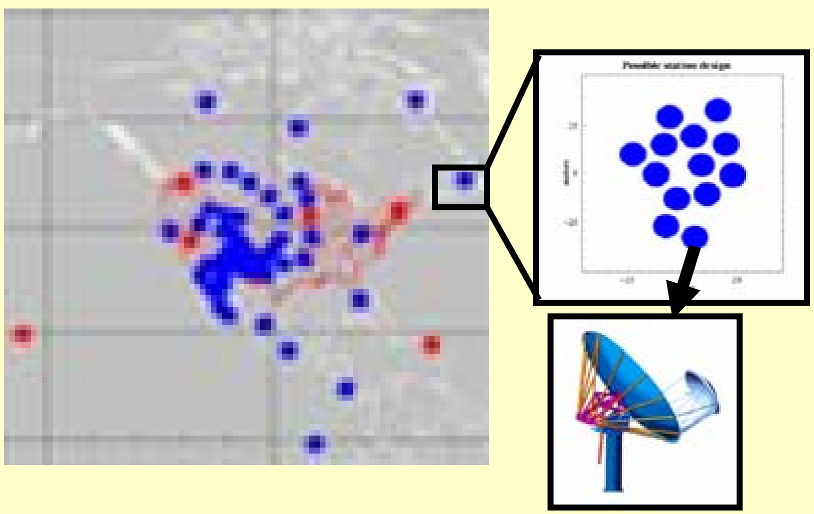
Mesh Antenna – India, Australia

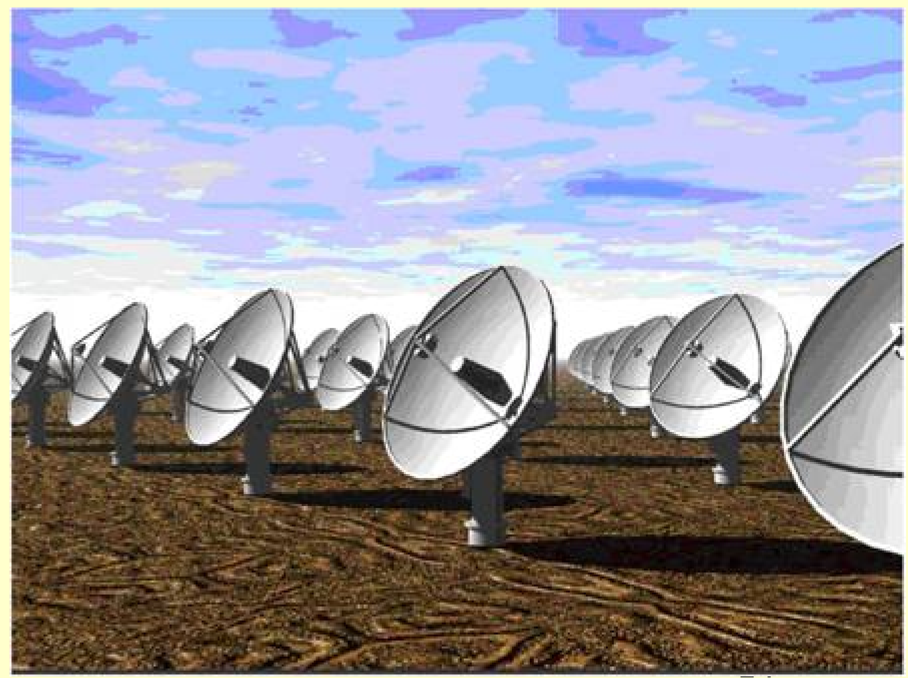
Aerostat Supported Focal Plane Array
Feed over Tilting Reflectors - Canada

Arecibo-Type Actuated Reflectors - China

US Concept for SKA

• 4550 12m antennas covering 0.15 to 34 GHz
Configured with 50% of antennas within 35 km, 25% in next 35 to 350 km, and 25% in 350 to 3500 km range
Site not selected but US southwest is most likely

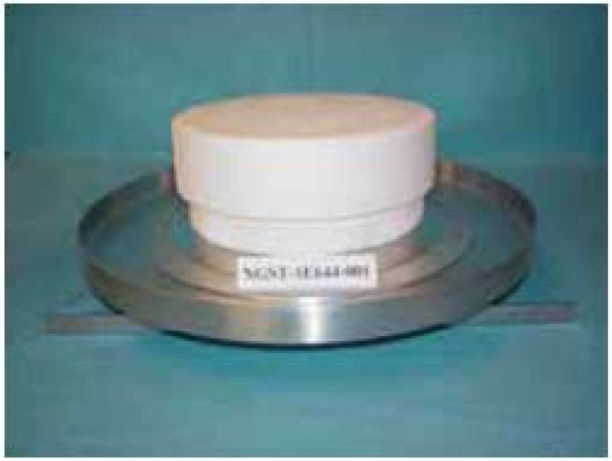




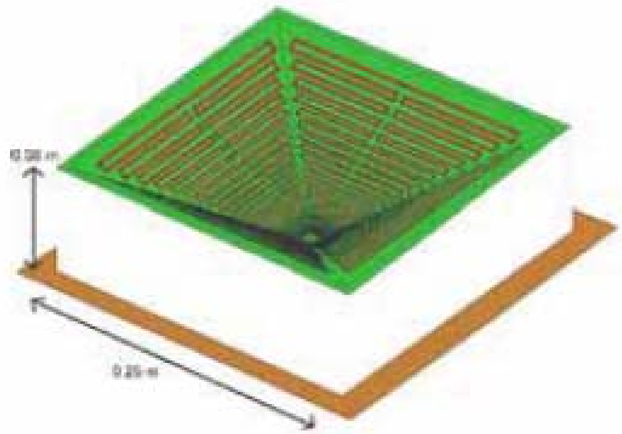
Candidate Decade-Bandwidth Feeds for the SKA

The entire 0.1 to 34 GHz frequency range will be covered with 3 wideband receivers.

ATA



Ingersen



Kildal

Figure IV.1.3 - Candidate feeds for the SKA. All have a width of approximately half the longest wavelength of operation but the ATA feed is much longer than the others. At present, the Ingersen and Kildal feeds have unacceptable impedance variations with frequency but the short length and terminal locations are much more compatible with low noise operation in a cryogenics dewar.

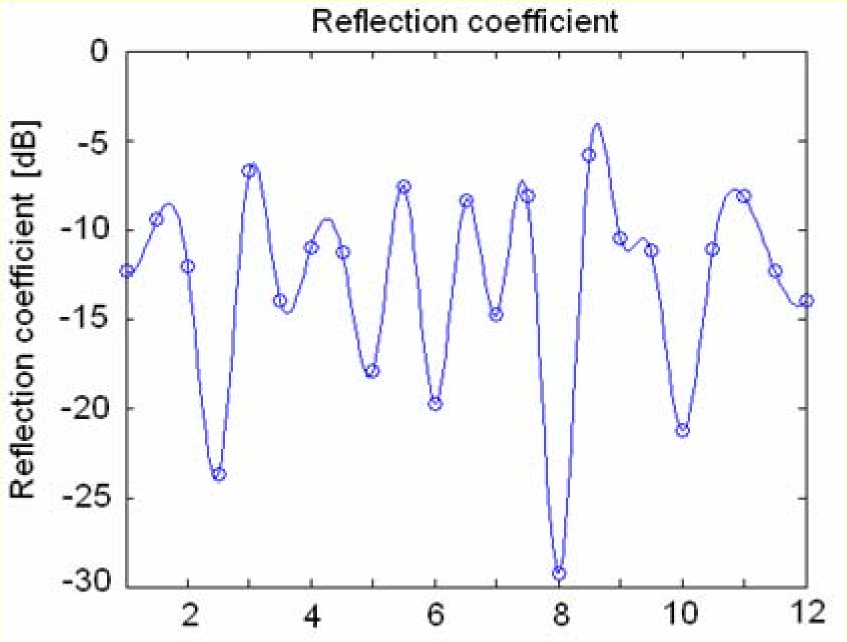
Chalmers 1.2 to 11 GHz Feed

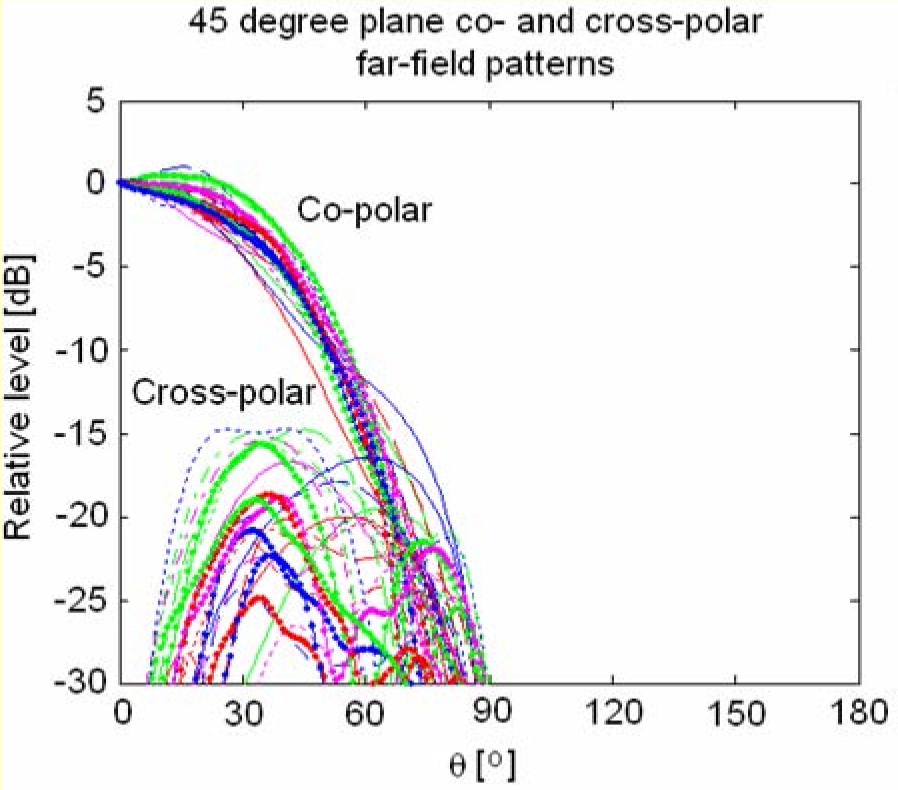
Feed is under tests at Chalmers and can be integrated with a cryogenic active balun and tested on an ATA antenna in early phases of the SKA.

Chalmers Feed Study Computed Results

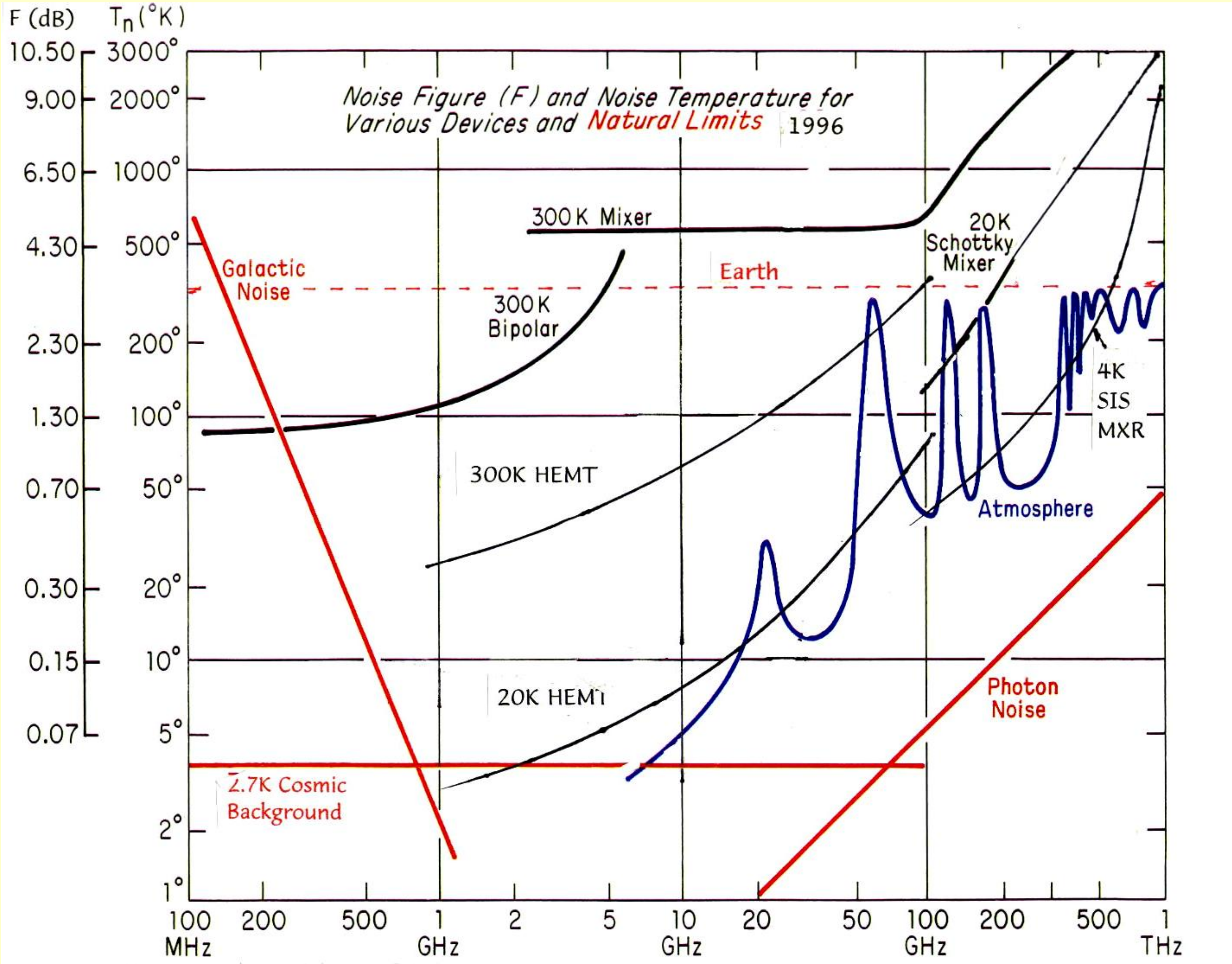
• Calculated pattern gives 57% prime focus efficiency, 3K spillover, and 0.3K mesh leakage in 12/16m symmetric antenna from 0.5 to 1.5 GHz

• Gain is 10.5 +/- 0.5 dB and reflection coefficient better than 6 dB over 1:12 frequency range. Provides 65% efficiency at half-angles of 42° to 55°





Limits to Noise in Receiving Systems



LNA Development Projects at Caltech

.

- Most projects utilize 0.1um InP HEMT MMIC's fabricated at Northrop Grumman (NGST). WIN GaAs mHEMT's and IBM SiGe HBT's are also being investigated

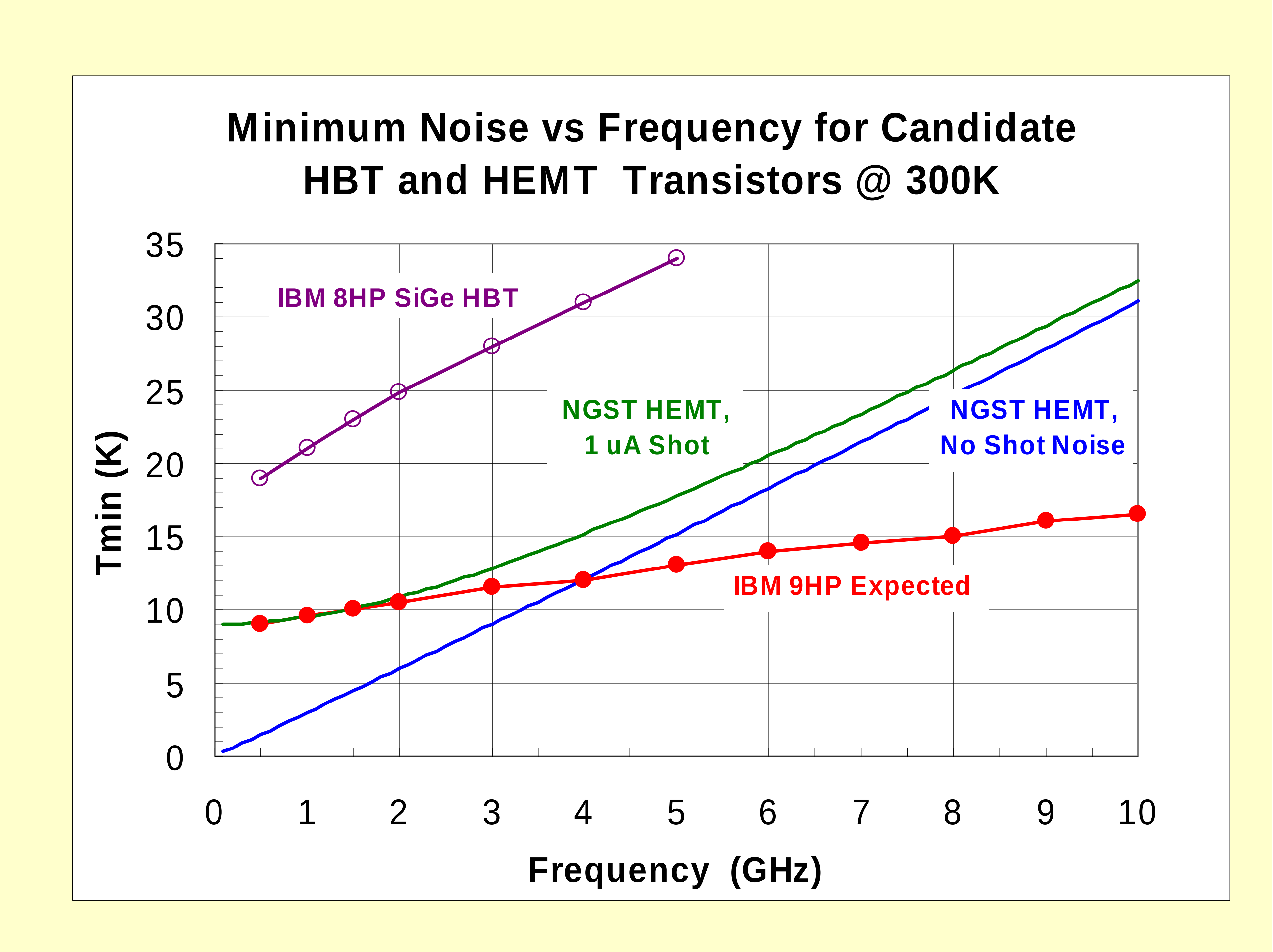
- 1.2 to 11 GHz cryogenic LNA's and active baluns for Allen Telescope Array
- 1.2 to 11 GHz cooled wideband feed and active balun for radio astronomy including SKA.
- 8.4 and 32 GHz LNA's for the NASA Deep Space Network (DSN)
- Uncooled 0.6 to 1.7 GHz, 10K noise LNA for radio astronomy
- Thermoelectric cooling of LNA's to 200K
- Cryogenic 2 to 8 GHz LNA's for U. of Arizona, 64 element, 345 GHz focal plane array
- Wideband LNA's for millimeter wave IF amplifiers in radio astronomy and atmospheric sensors

Issues with Achieving Very Low Noise at 300K

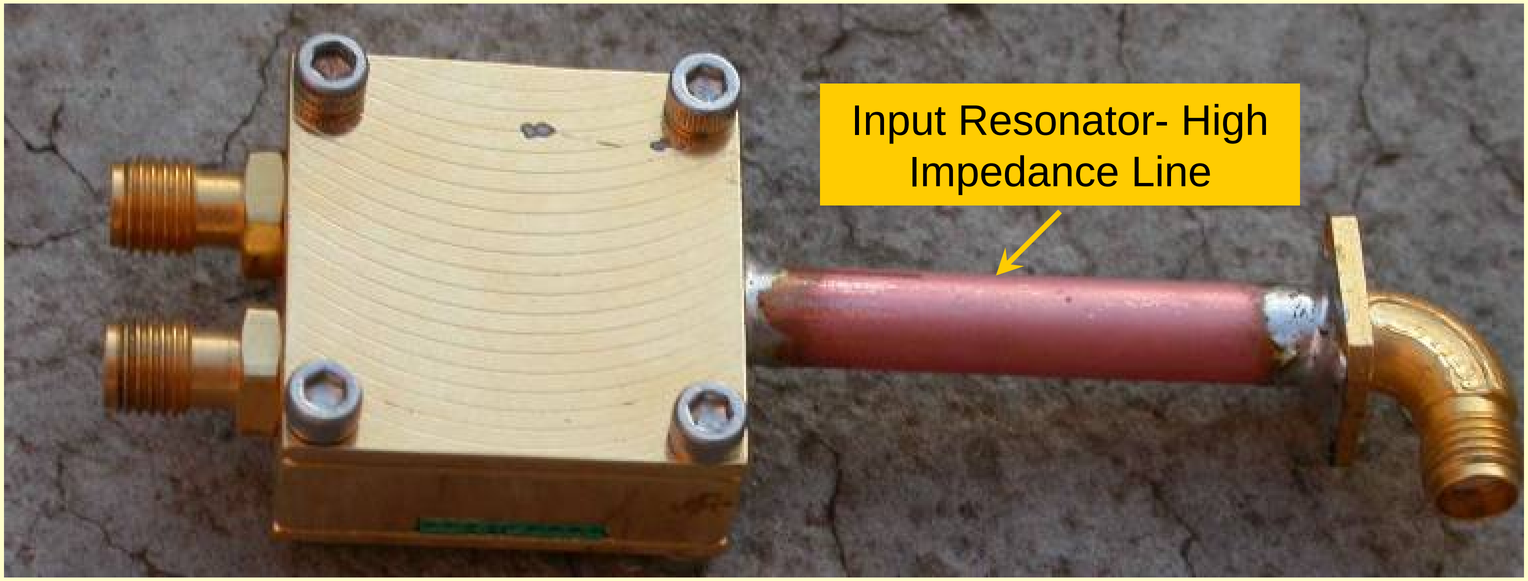
- **Noise Measurement Error** – It is very difficult to measure a room temperature transistor or LNA with a NF error of less than +/- 0.1 dB or a noise temperature error of less than +/- 7K. This clouds the data on available transistors and LNA's.

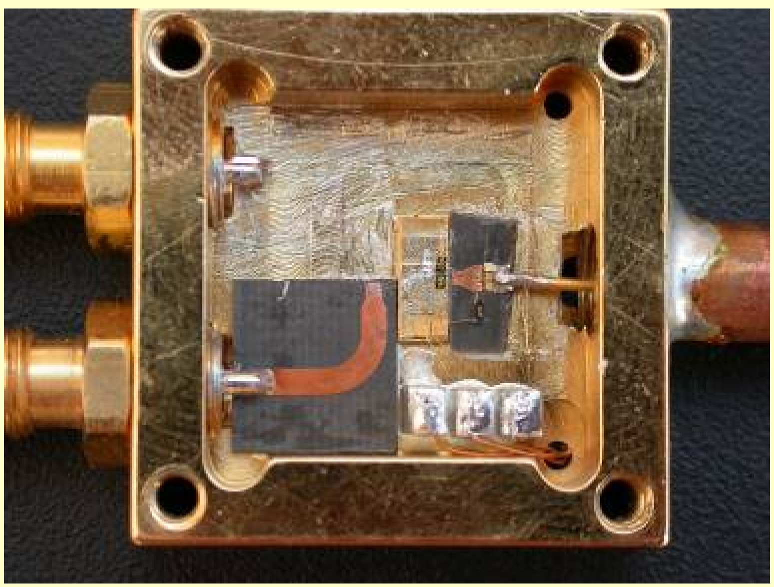
- **Loss –** A loss of 0.1 dB between LNA and feed increases the noise by 7K. This encourages integrating the LNA and feed.

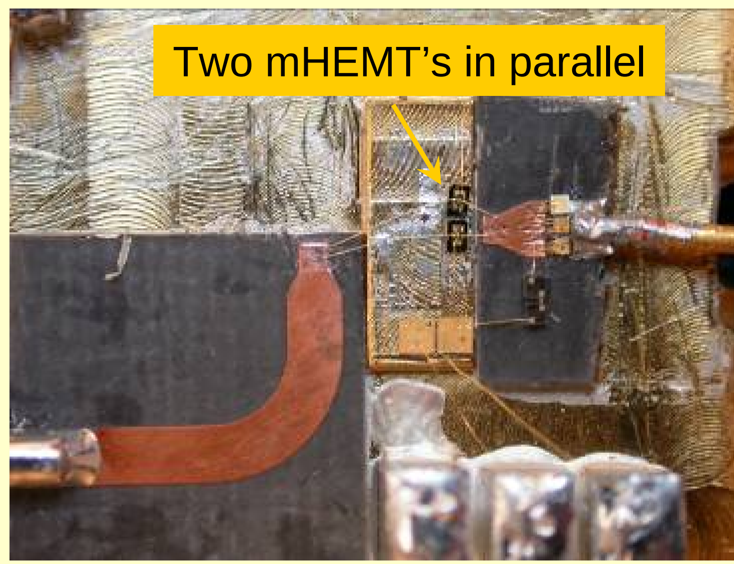
- **HEMT Leakage Current** – At low microwave frequencies the gate leakage current in a MESFET or HEMT transistor may limit the noise yet is an unspecified parameter which may vary greatly from one transistor to the next. It is uncertain at present whether to model the noise of this leakage current as shot noise or resistor thermal noise.


Minimum Noise vs Frequency for Candidate
HBT and HEMT Transistors @ 300K
Tmin (K)
Frequency (GHz)
0
5
10
15
20
25
30
35
0
1
2
3
4
5
6
7
8
9
10
IBM 8HP SiGe HBT
NGST HEMT,
1 uA Shot
NGST HEMT,
No Shot Noise
IBM 9HP Expected

Test Fixture for Noise Measurement of WIN mHEMT Transistor





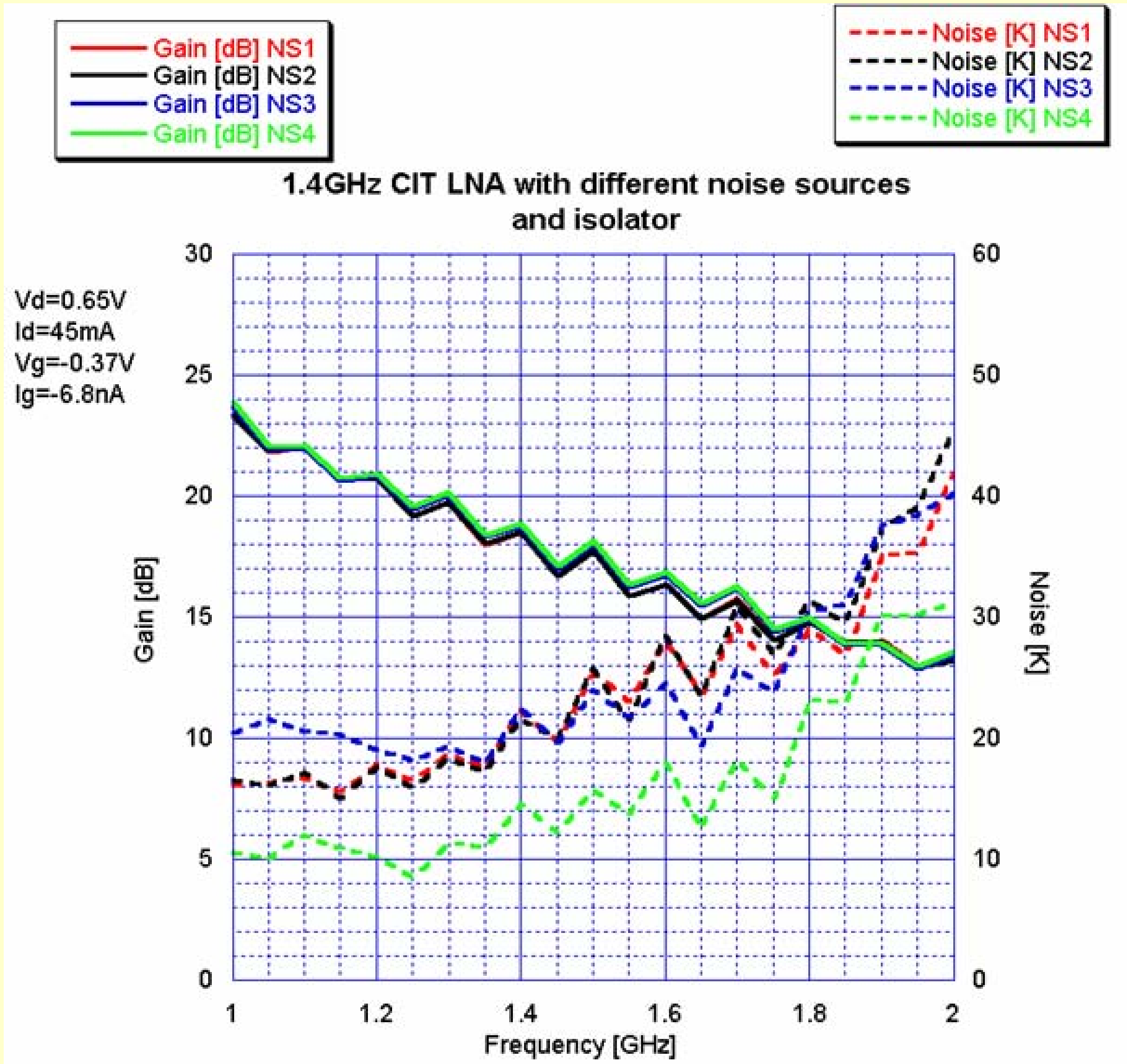


Test Data of Noise and Gain of LNA at 300K with WIN mHEMT

Jan 3, 2005

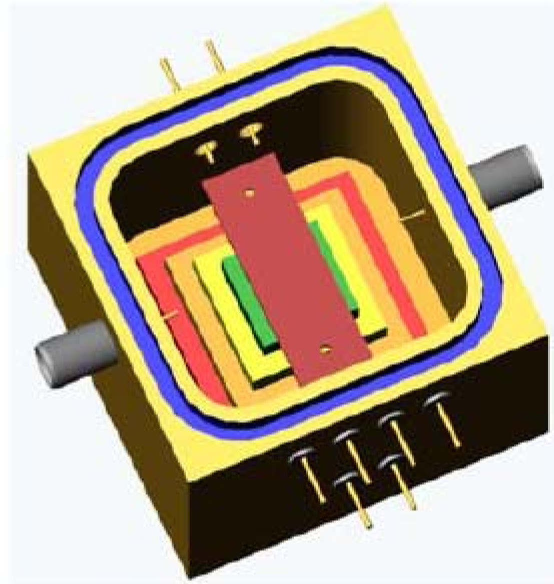
- Four different Agilent noise sources used with 3 agreeing at ~ 18K noise in the 1.2 to 1.4 GHz range.

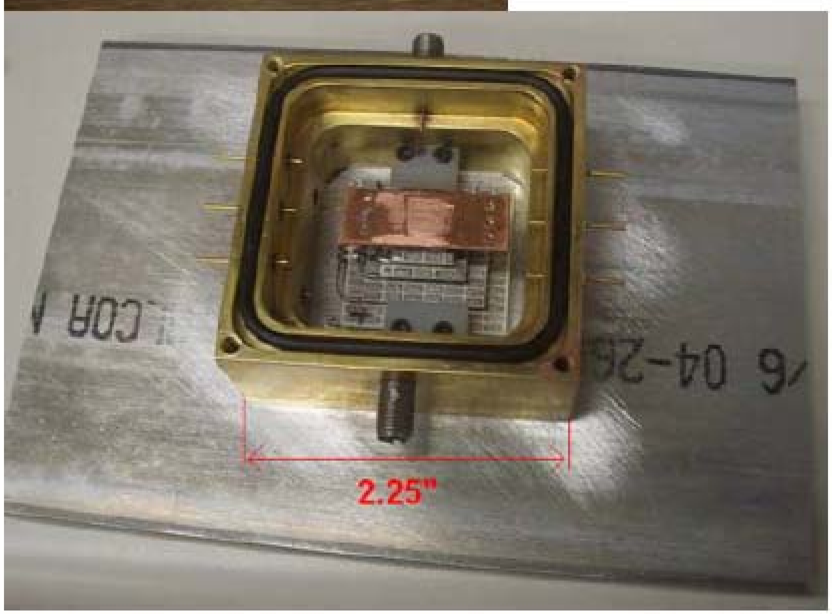
- This data is with an isolator between the noise sources and the LNA to reduce the effects of noise source on/off impedance upon gain.

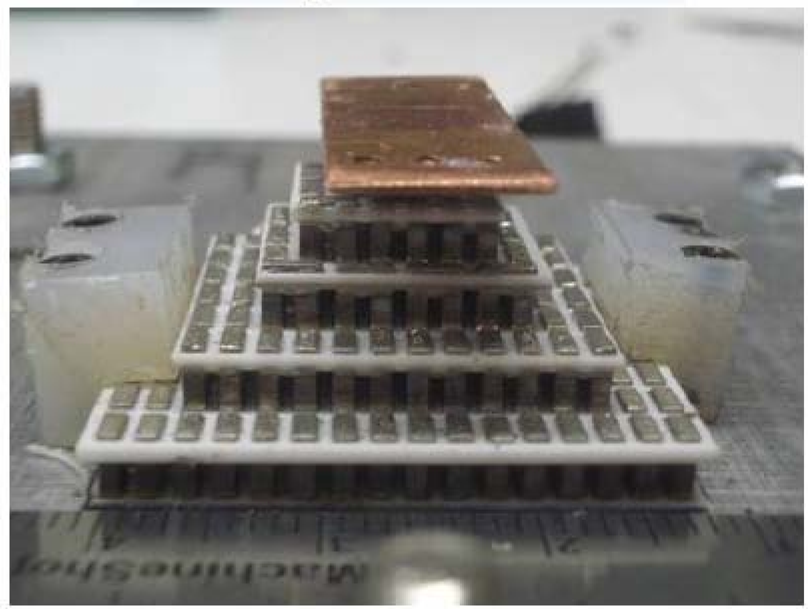


NS1: Agilent N4002A 15 dB ENR with Anritsu 10.10dB attenuator
NS2: HP 346C 15 dB ENR with Anritsu 10.1dB attenuator
NS3: Agilent N4000A 5dB ENR
NS4: HP 346A 5 dB ENR

Prototype Dewar for Thermoelectric Tests

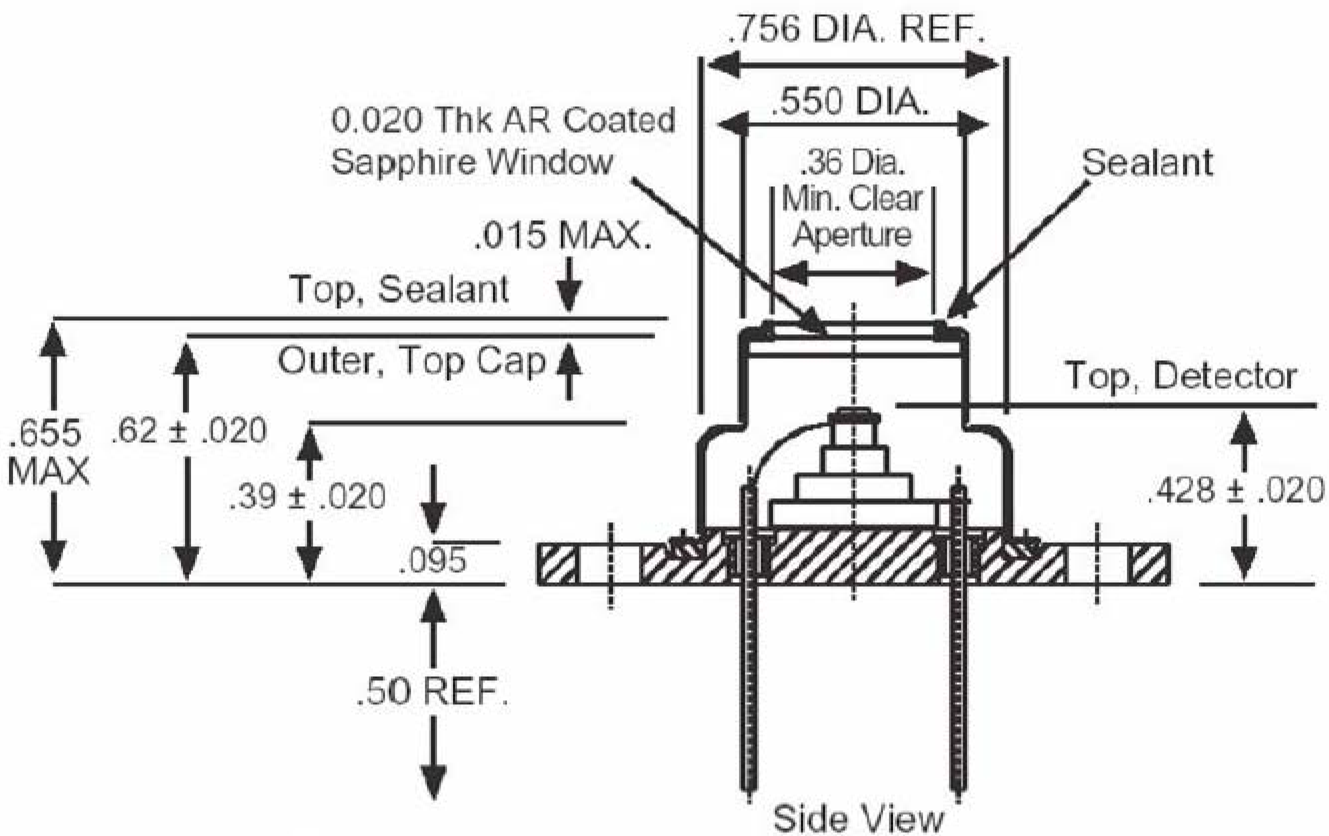






Thermoelectic Cooling within the Transistor Package

4 Stage TEC cooled IR detector operates at 200K
Ref: http://www.judsontechnologies.com/

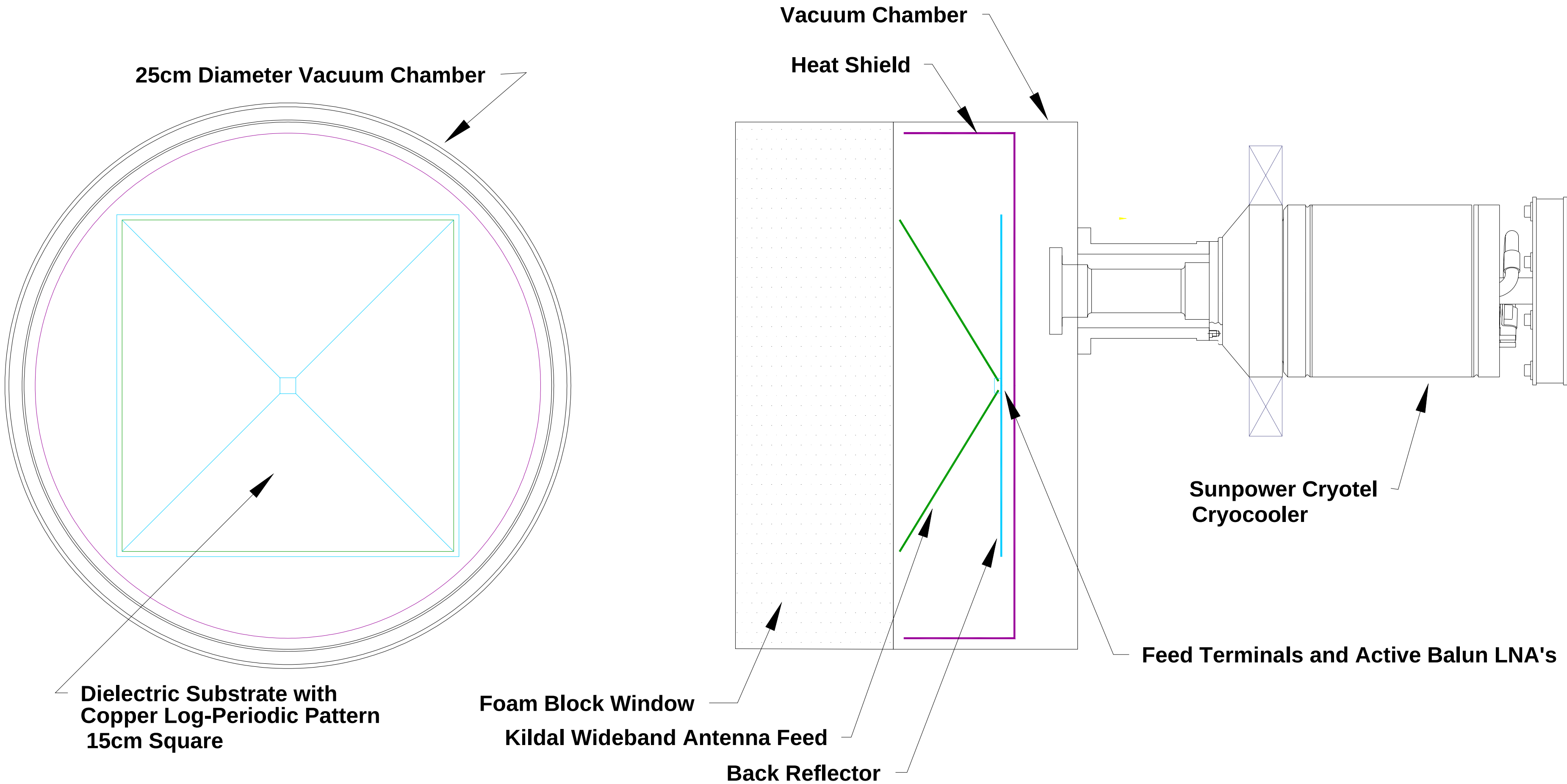


Cryocooler Development

- SunPower Inc Cryotel cooler provides 12W of cooling at 77K with a claimed life of >50,000 hours and cost under $6K
- Recent development is a modification which provides 0.5W at 25K.
- Further studies of LNA noise vs temperature and heat loading in cryogenic system including cooled feeds for above 1.2 GHz is needed to optimize cooler selection.

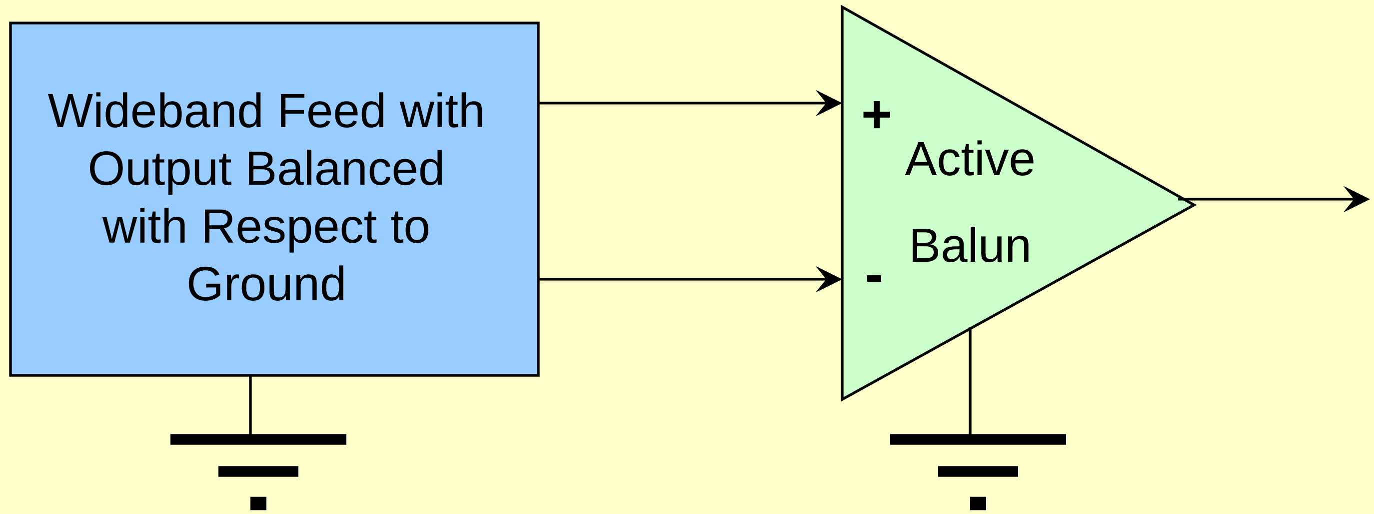
Cryogenic Wideband Receiver, 1.2 to 11 GHz

In Development at Caltech, May, 2005



Active Balun Function - Needed for Wideband Feeds

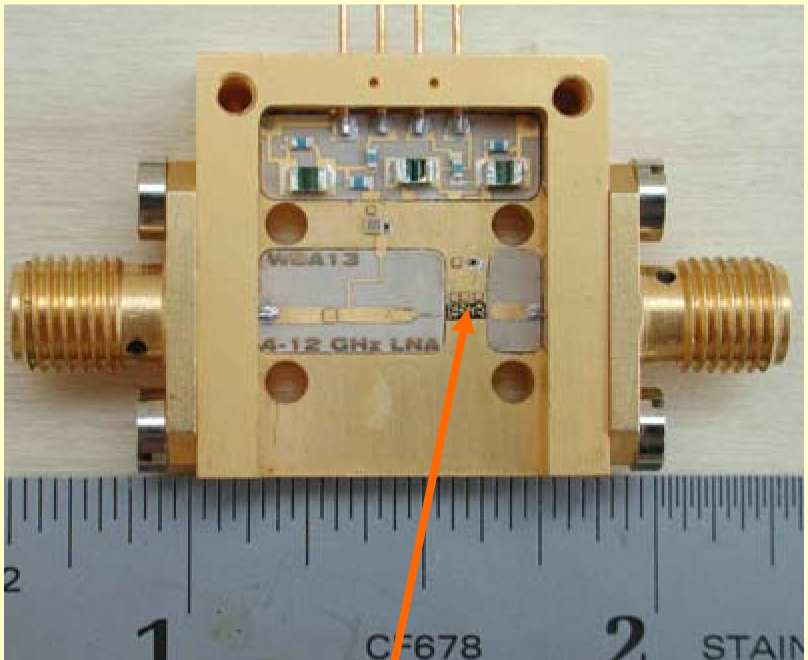
A Microwave Low-Noise Cryogenic Differential Amplifier

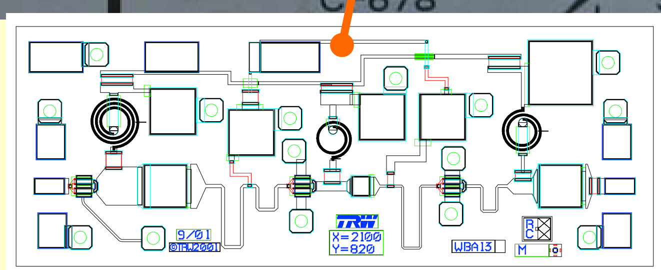


- Wideband antenna feeds have balanced output which cannot connect to a low-noise amplifier without a passive balun
- Passive baluns are large, lossy, and add noise to the system

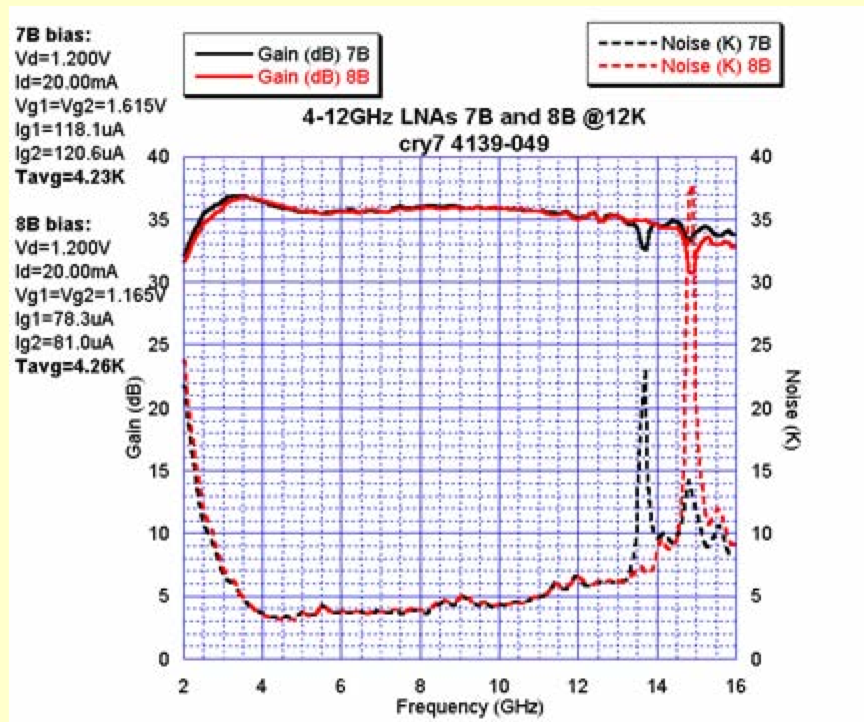
MMIC Wideband Low Noise Amplifiers

Low-cost assembly MMIC package





Amplifier provides 5K noise from 4 to 12 GHz when cooled to 12K



Three-stage LNA in 2mm chip