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

Radio Astronomy -
Galaxies, quasars, pulsars

Space Communications

SETI, Other Civilizations
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

SKA Cost Breakdown by Subsystem vs Antenna Diameter
Aeff/Tsys = 20,000, Aeff=360,000, Tsys=18K, BW=4GHz, 15K Cryogenics
Antenna Cost = 0.1D^3 K$, 2001 Electronics Cost = $54K per Element
### Comparison of Existing Large Antennas and Future Arrays

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

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

OPERATIONAL

RADIO ASTRONOMY

SPEAKER ORDER

VLA 27X25m

UNDER CONSTRUCTION

ATA 350X6m

XNTD 20X15m

EMBRACE 50,000X0.1m

ALMA 64X12m

SKA 4550X12m

SPACE COMMUNICATIONS

OPERATIONAL UNDER CONSTRUCTION FUTURE

DSN 70m, 34m

B'BOARD 2X6m+ 12m

PROTO 12 X 12m

DSAN 3X400X12m
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.
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

APERTURE PLANE ARRAY OR PHASED ARRAY

FOCAL-PLANE ARRAY

ARRAY BEAM

ELEMENT BEAM

OFFSET ANTENNA BEAMS

SUB-REFLECTOR

OFFSET FEEDS IN FOCAL-PLANE

PARABOLIC REFLECTOR OR LENS

N ELEMENTS COMBINING ELECTRONICS

N^2 PIXEL IMAGE OR SINGLE BEAMS

N RECEIVERS

N PIXEL IMAGE
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

Mesh Antenna – India, Australia

Cylindrical Paraboloid - 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.

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

Noise Figure ($F$) and Noise Temperature for Various Devices and Natural Limits 1996

- Galactic Noise
- 300 K Mixer
- 300 K Bipolar
- Earth
- 300 K HEMT
- 4K SIS MXR
- 20K Schottky Mixer
- 20K HEMT
- Atmosphere
- Photon Noise
- 2.7K Cosmic Background

Frequency (MHz) vs. Frequency (GHz)
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

- 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

- Input Resonator - High Impedance Line
- Two mHEMT’s in parallel
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
Thermoelectric 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

- 25cm Diameter Vacuum Chamber
- Dielectric Substrate with Copper Log-Periodic Pattern 15cm Square
- Foam Block Window
- Kildal Wideband Antenna Feed
- Back Reflector
- Heat Shield
- Vacuum Chamber
- Sunpower Cryotel Cryocooler
- Feed Terminals and Active Balun LNA's
Active Balun Function - Needed for Wideband Feeds

A Microwave Low-Noise Cryogenic Differential Amplifier

Wideband Feed with Output Balanced with Respect to Ground

Active Balun

• 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