THE NRAO TECHNOLOGY CENTER (NTC)

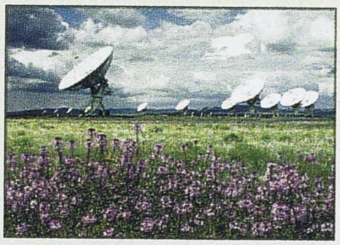
The NRAO Technology Center (NTC) is the home of NRAO's Central Development Laboratory (CDL) and the ALMA Electronics Division.

The NTC is located at 1180 Boxwood Estate Road, Charlottesville, VA

The **Central Development Laboratory (CDL)** is the world leader in research and development of radio astronomy instrumentation technology. As the Observatory's instrumentation R&D facility, the CDL designs, develops, and fabricates key components not only for our telescopes, e.g., The Very Large Array (VLA), Very Long Baseline Array (VLBA), Green Bank Telescope (GBT), and Expanded Very Large Array (EVLA), but also for other collaborative projects and activities such as the Frequency-Agile Solar Radiotelescope (FASR) Project, the Wilkinson Microwave Anisotropy (WMAP), the Cosmic Background Imager (CBI) and many radio telescopes around the world for the astronomy community.

The Very Large Array (VLA)

The VLA's 27 antennas.



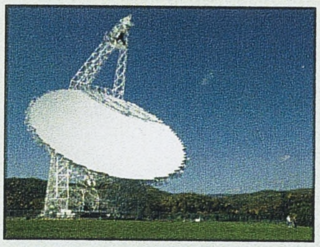
The VLA is located near Socorro, NM.

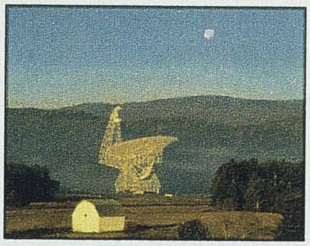
The Very Long Baseline Array (VLBA)

The VLBA's antennas are located across the U.S. From Mauna Kea, Hawaii to St. Croix, Virgin Islands.

VLBA antenna in St. Croix.

The Green Bank Telescope (GBT)

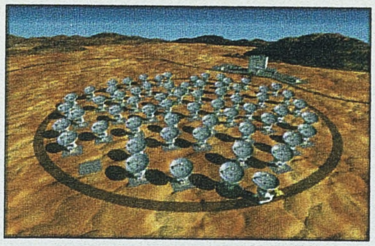




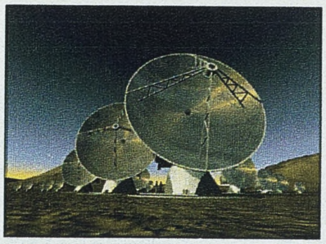
The GBT is the world's largest fully-steerable radio telescope. It is located in Green Bank, WV.

The **ALMA Electronics Division** is responsible for the design, prototyping, fabrication and integration of many of the electronic components for the ALMA receiving and signal processing systems. This includes the ALMA millimeter-wave receivers and the ALMA correlator, a special-purpose computer equal for its particular task to 500 of the world's largest supercomputers.

The Atacama Large Millimeter Array (ALMA)



The ALMA is an array of antennas.

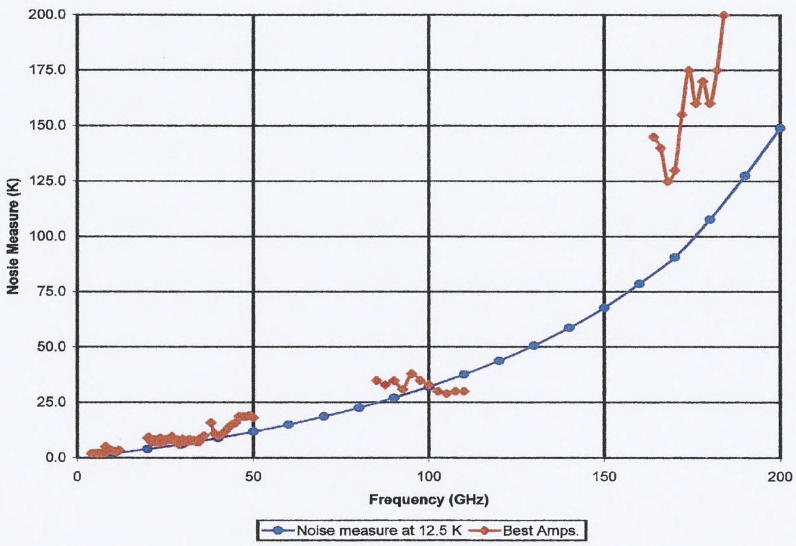


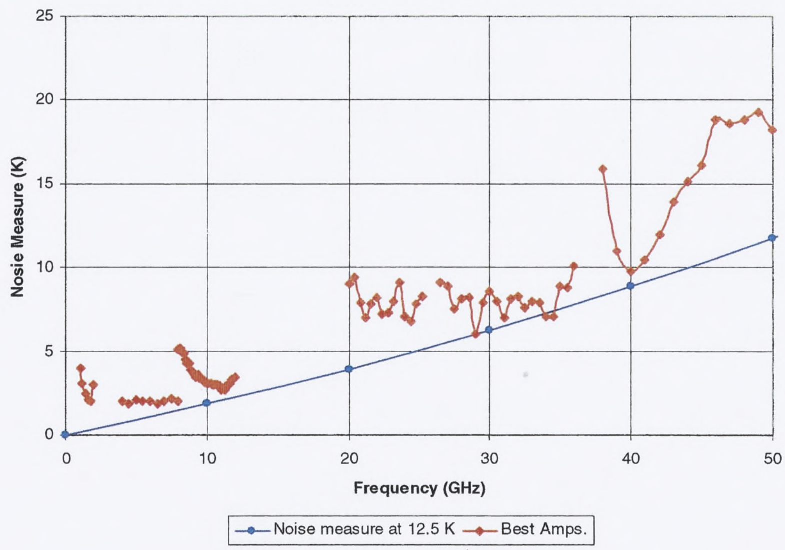
This project is an international collaboration.

The ALMA site is in the foothills of Chile's Andes Mountains.

Contact: John Webber (jwebber@nrao.edu)

CDL AMPLIFIER GROUP
State-of-the-Art Cryogenic Amplifiers in 1-118 GHz Frequency Range



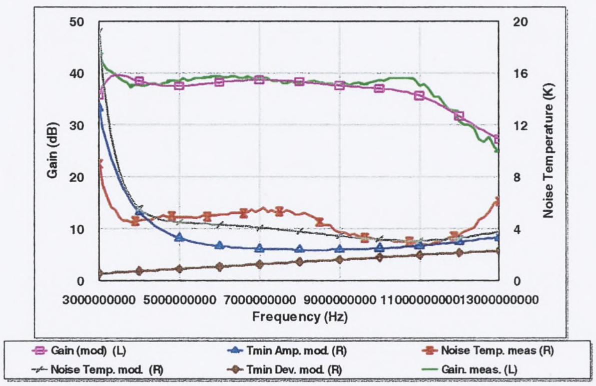


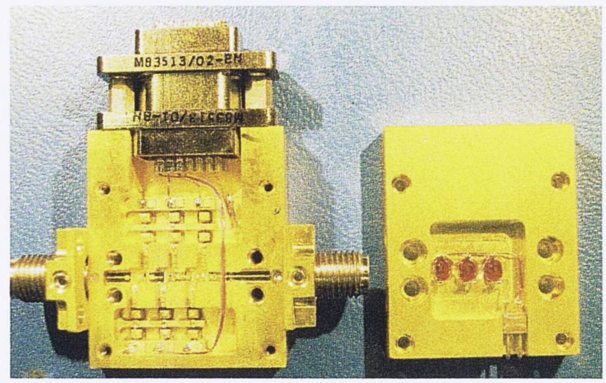
Plot of lowest possible noise temperature (minimum noise measure) at 12.5 K vs. frequency of a modern InP HFET (blue) and measured noise temperature of modern amplifiers (red).

CDL cryogenic amplifiers have not only been used in NRAO instruments (GBT, EVLA, ALMA) but also in many others, among those: Wilkinson Microwave Anisotropy Probe (WMAP) Satellite, Cosmic Background Imager (CBI), Degree Angular Scale Interferometer (DASI), Very Small Array (VSA), JPL and ESA Deep Space Networks and many others.

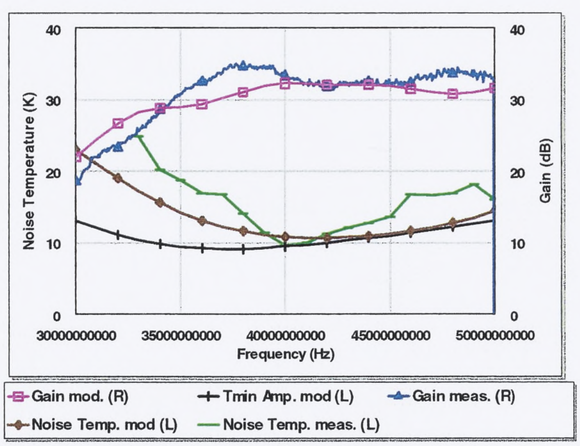
Examples:

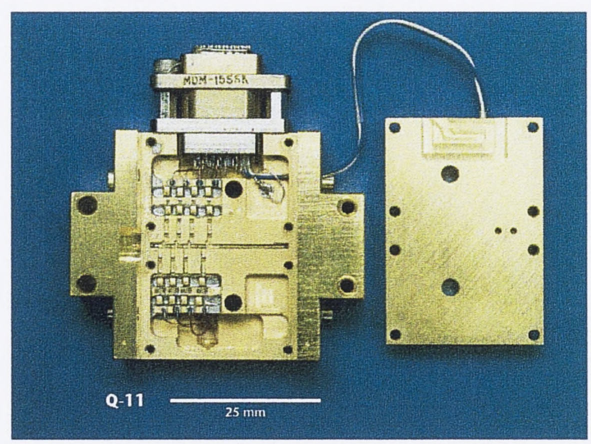
Coaxial 4-12 GHz amplifier:





Waveguide 35-50GHz amplifier:

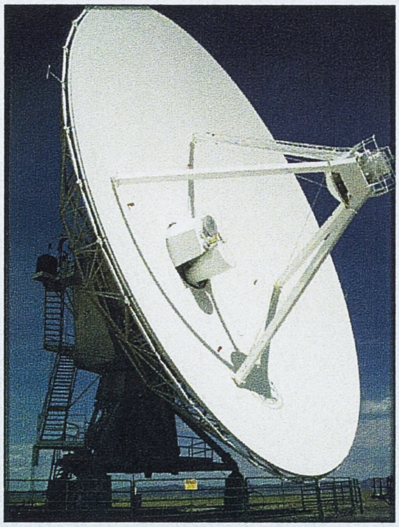




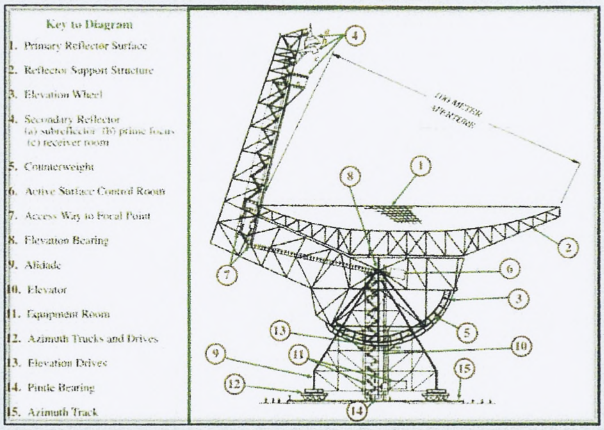
M. Pospieszalski (mpospies@nrao.edu)

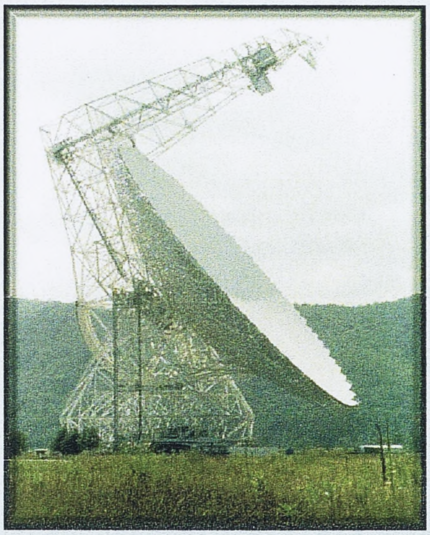
Antenna and Waveguide Components

In order to concentrate radio waves from the sky so that they can be amplified and detected, a wide variety of geometric structures is needed. Large antennas focus radio waves to a point, sometimes using a secondary reflector (as on optical telescopes). At the focal point, a special small antenna known as a feed further concentrates the sky signal into a confined space. A polarizer separates horizontal and vertical components of the signal. Finally, the energy from the sky arrives at a low-noise amplifier or mixer. Proper performance of all these mechanical structures is required in order to make the combination with electronic components sensitive and efficient. Extensive computer calculations are done in advance of construction in order to optimize the designs.



EVLA Antenna





GBT Antenna

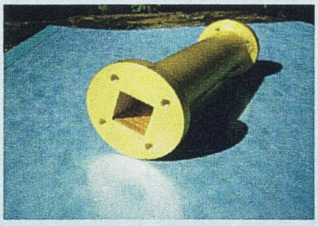
GBT – DOUBLE OFF-SET REFLECTOR GEOMETRY:

ADVANTAGES:

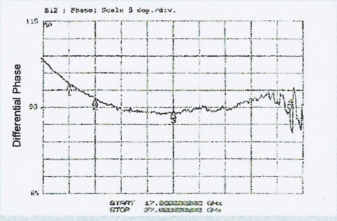
1. Blockage-free aperture leads to higher gain and lower system temperature.
2. Lower sidelobes compared to on-axis telescope (EVLA) – scattering from central blockage and feed-support legs absent leading to protection against interference.
3. Reduced standing waves – absence of multiple reflections between the feed and subreflector/main reflector leads to reduced periodic ripple in spectroscopic baselines seen in axially-symmetric telescopes.

DISADVANTAGES:

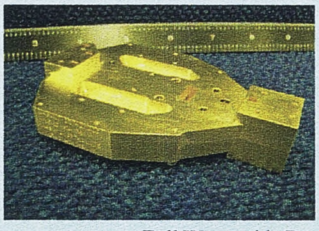
1. The complex geometry results in higher cost.
2. Poorer polarization performance from prime focus.

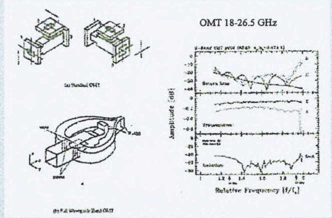


Phase Shifter



Frequency (GHz)





Full Waveguide Band Orthomode Junction

WIDE-BAND POLARIZER:

For a long time, the bandwidth of radio astronomy receivers was limited by the bandwidth of the polarizer, which separates the two linear or opposite sense circular polarizations. Quadridged-orthomode transducers, balanced orthomode junctions and broadband phase shifters developed at NRAO and elsewhere have led to wide-band receiver designs in the past decade.

Contact: (ssrikant@nrao.edu)

Dynamic Spectroscopy Laboratory

R. Bradley

rbradley@nrao.edu

The researchers of the Dynamic Spectroscopy Laboratory (DSL) are dedicated to applying a unique, synergistic approach to solving challenging problems of modern radio astronomy instrumentation. Our group includes participation by research scientists, astronomers, engineers, students, and technicians from the CDL, other NRAO sites, and universities, who work together to advance the forefront of science through the development, assimilation, and application of cutting-edge technologies. Projects have ranged from capability-enabling components to complete astronomical observing instruments coupled with clear scientific objectives. Techniques developed from these activities have directly impacted current NRAO instrument designs and will continue to influence technology pathways in the future.

The Laboratory includes a wide variety of start-of-the-art electronic test equipment, modern computer aided design software, micro-assembly workstations, and a small anechoic chamber. In addition, our Green Bank field station, located within the National Radio Quiet Zone, provides a unique opportunity for the deployment of sensitive experiments and prototype instruments.

Some examples of completed projects include:

- Pioneered the first fully-sampled, focal plane array receiver for radio astronomy.
- Pioneered the first real-time adaptive interference canceling receiver for radio astronomy.
- First to develop cryogenic, low noise HFET balanced amplifiers covering 300 – 1200 MHz for the GBT and the Axion Dark Matter eXperiment (ADMX).
- Developed the laser modulator / demodulator units for the GBT metrology system.
- Developed a consistent method for gold plating the inside of sub-millimeter waveguides enabling calibrated local oscillator power measurements for ALMA.
- Developed and maintain the world's most sensitive, high-resolution, solar radio burst spectrometer covering 20-1000 MHz. It is deployed at the NRAO in Green Bank.
- Developed and modeled an inexpensive, yet highly effective screened enclosure that was adopted by the Green Bank Interference Protection Group for site-wide instrument RFI mitigation.
- Co-discovered and modeled the Lorentz noise enhancement effect in HFETs.

Current research and development activities by the group include:

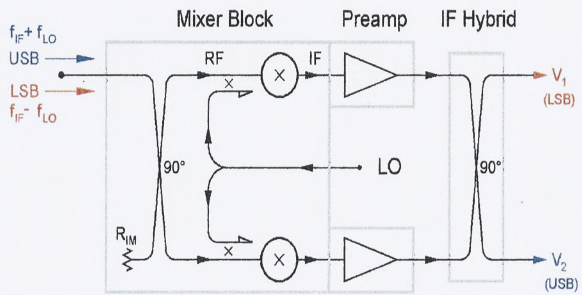
- A unique, wide-bandwidth (10:1), sinuous feed for use in the Frequency Agile Solar Radiotelescope (FASR) and as an upgrade to the Green Bank solar burst spectrometer.
- A complete radio telescope imaging array called PAPER – The Precision Array to Probe the Epoch of Reionization. This collaborative effort among researchers at UC. Berkeley, NRAO, and UVa involves the development of specialized antennas, rugged high-dynamic range amplifiers, low cost receivers, and a suitable correlator together with deployments in both Green Bank and Western Australia.
- A system to measure the power pattern of antennas using signals from a constellation of low earth orbiting satellites.
- Investigating precision calibration techniques for low frequency arrays.
- Create a network-based, mutual coupling model for close-packed array antennas.
- Integration of cryogenic amplifiers with cooled feeds for compact, low noise front-end applications such as future beam-forming arrays.

A. R. Kerr, S.-K. Pan, E. F. Lauria, A. W. Lichtenberger, J. Zhang, M. W. Pospieszalski, N. Horner, G. A. Ediss, J. E. Effland, R. L. Groves,
International Symposium on Space THz Technology, Northampton, MA, April 2004. ALMA Memo 498, http://www.alma.nrao.edu/memos/

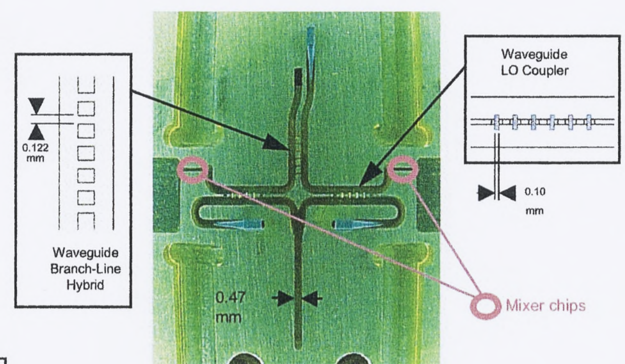
The ALMA Band 6 (211-275 GHz) Sideband-Separating SIS Mixer-Preamp

National Radio Astronomy Observatory and the University of Virginia

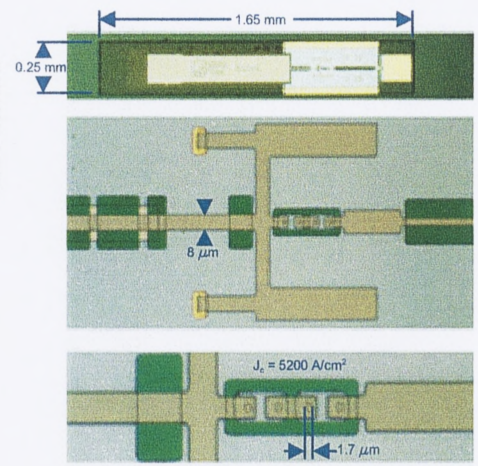
Waveguide Sideband Separating Mixer



Mixer Block Details



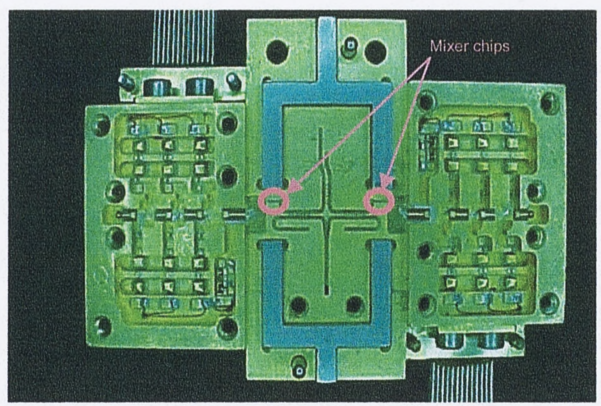
SIS375 Mixer Substrate



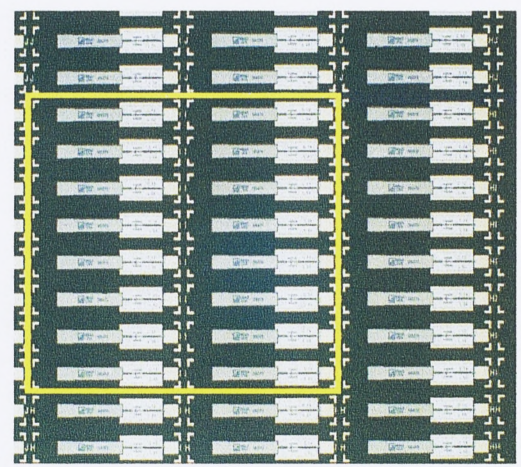
Split-Block Waveguide Mixer Design

Elements for split-block waveguide design:

- RF quadrature Hybrid [3]
- LO power splitter [4]
- LO couplers with matched terminations [5] [6]
- H-plane bends in split-block waveguide [4]
- Waveguide-to-suspended stripline transition [4]



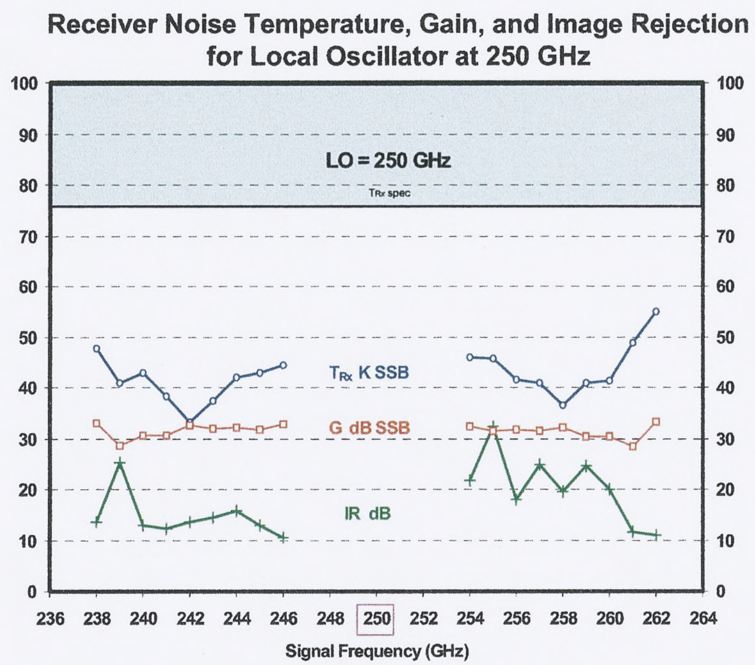
Mixer block with preamps attached either side – lids removed

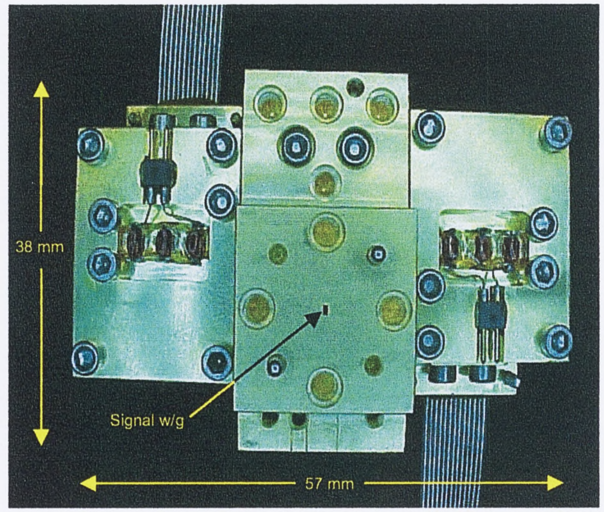


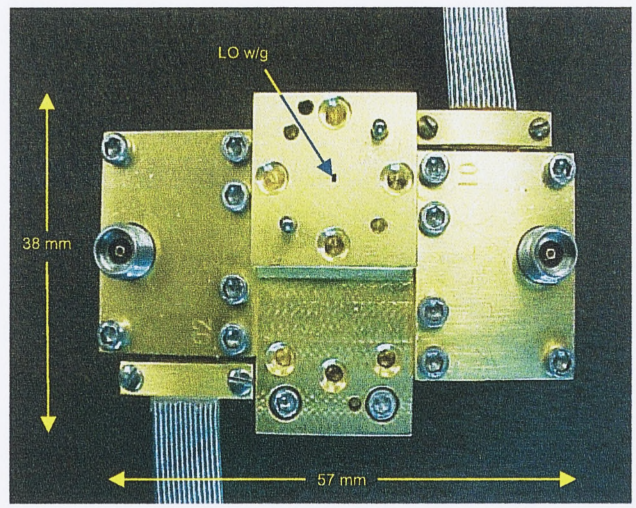
Section of a wafer showing unit cell (yellow)

[1] A. R. Kerr, S.-K. Pan, and H. G. LeDuc, "An integrated sideband separating SIS mixer for 200-280 GHz," Proceedings of the Ninth International Symposium on Space Terahertz Technology, pp. 215-221, 17-19 March 1998. ALMA Memo 206, http://www.mma.nrao.edu/memos/

[2] S. M. X. Claude, C. T. Cunningham, A. R. Kerr and S.-K. Pan, "Design of a Sideband-Separating Balanced SIS Mixer Based on Waveguide Hybrids," ALMA Memo No. 316, 16 Aug 2000, http://www.alma.nrao.edu/memos/







[3] S. Srikanth and A. R. Kerr, "Waveguide Quadrature Hybrids for ALMA Receivers," ALMA Memo 343, 11 Jan 2001, http://www.alma.nrao.edu/memos/

[4] A. R. Kerr, "Elements for E-Plane Split-Block Waveguide Circuits," ALMA Memo 381, 1 July 2001.
http://www.alma.nrao.edu/memos/

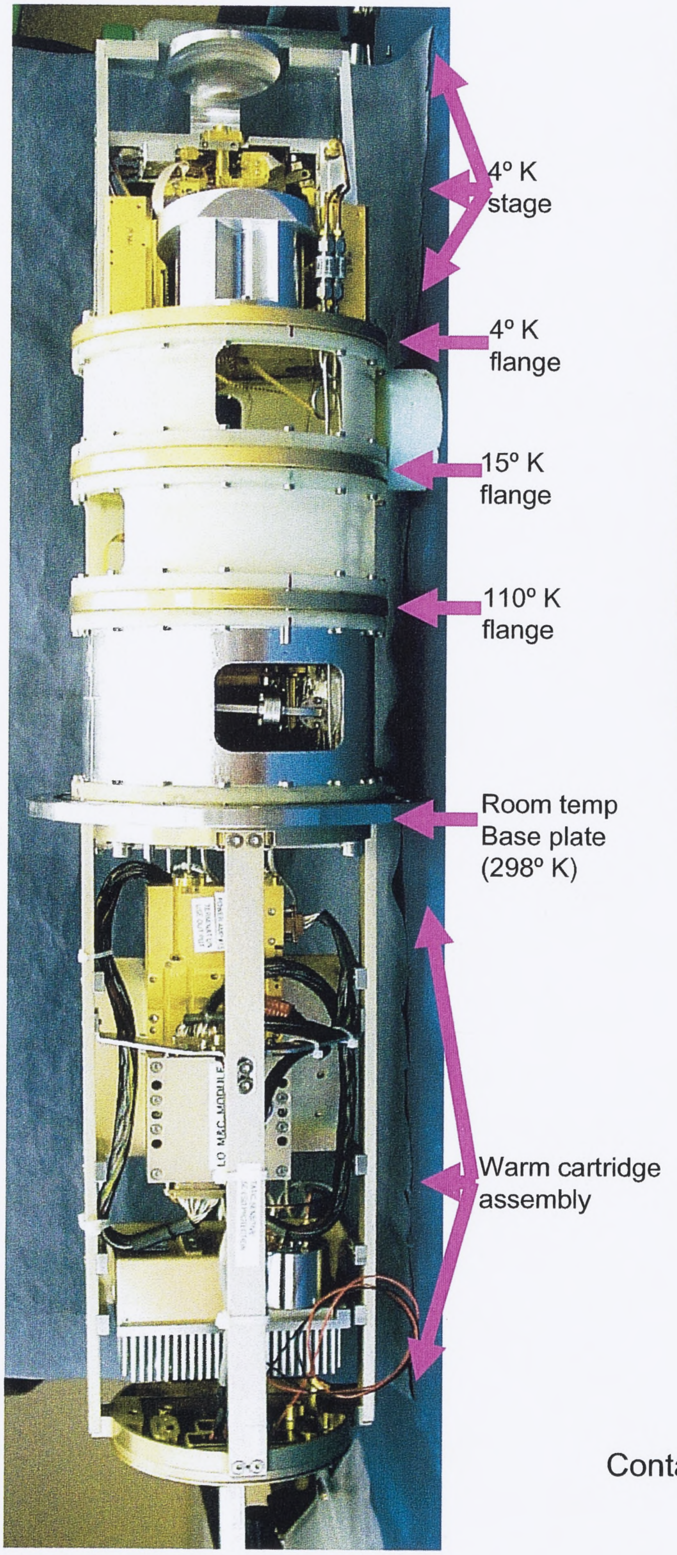
[5] A. R. Kerr and N. Horner, "A Split-Block Waveguide Directional Coupler," ALMA Memo 432, 26 Aug 2002, http://www.alma.nrao.edu/memos/

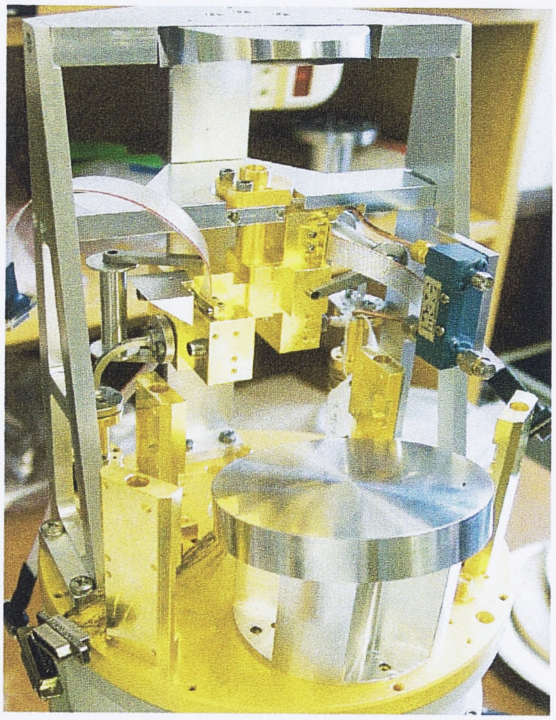
[6] A. R. Kerr, N. Horner, and V. Summers, "Fabrication of Small Metal Parts by Electroforming Through a Photomask," NRAO Electronics Division Technical Note No. 194, 21 January 2003, http://www.gb.nrao.edu/electronics/edtn/

[7] A. R. Kerr, S.-K. Pan, A. W. Lichtenberger and H. H. Huang, "A Tunerless SIS mixer for 200–280 GHz with low output capacitance and inductance," Proceedings of the Ninth International Symposium on Space Terahertz Technology, pp. 195-203, 17-19 March 1998. See ALMA Memo 205, http://www.alma.nrao.edu/memos/

[8] A. R. Kerr, S.-K. Pan, E. F. Lauria, A. W. Lichtenberger, J. Zhang, M. W. Pospieszalski, N. Horner, G. A. Ediss, J. E. Effland, R. L. Groves, "The ALMA Band 6 (211-275 GHz) Sideband-Separating SIS Mixer-Preamp," Proceedings of the 15th International Symposium on Space Terahertz Technology, April 2004. http://www.alma.nrao.edu/memos/

ALMA Band 6 Receiver Cartridge (211-275 GHz)





4 K Stage contains focusing mirrors, feed horn, polarization splitter, and sideband-separating mixer-preamps.

Contact: John Effland (jeffland@nrao.edu)

Local Oscillators for ALMA

What is a Local Oscillator?

ALMA uses heterodyne receivers to detect millimeter-wave radiation. A heterodyne receiver requires a local signal near the same frequency as the received signal to mix with (the SIS mixers for ALMA). This local signal is called the "local oscillator". The ALMA local oscillator therefore requires the generation of millimeter-wave through sub-millimeter wave radiation (almost to the far infrared part of the spectrum). This is difficult (see the Terahertz gap) below. These signals are several hundred times higher in frequency than that transmitted by a cell phone. The wavelength is very small, from 0.3-3 mm.

More Challenges for the ALMA LO

Not only is the frequency of the signal hundreds of times higher than radio and microwave transmissions, but because it is being used to detect very faint signals, the LO itself must be very, very quiet: **SNR > 160 dB**

Also, ALMA is an interferometer, combining the outputs of up to 80 antennas 10 km apart in phase. Variations in path length (equivalent to time) mean that the array can not work together to form a coherent image: **Timing errors less than 50 femtoseconds (1 fs = 10^{-15} s), equivalent to a length accuracy of 15 microns (less than the width of a human hair) over a 10km distance (~1 part in a billion)**

Our Role in ALMA

Our customers include laboratories from all over the world, using our local oscillators to develop and build receivers for ALMA.

These customers/partners include:

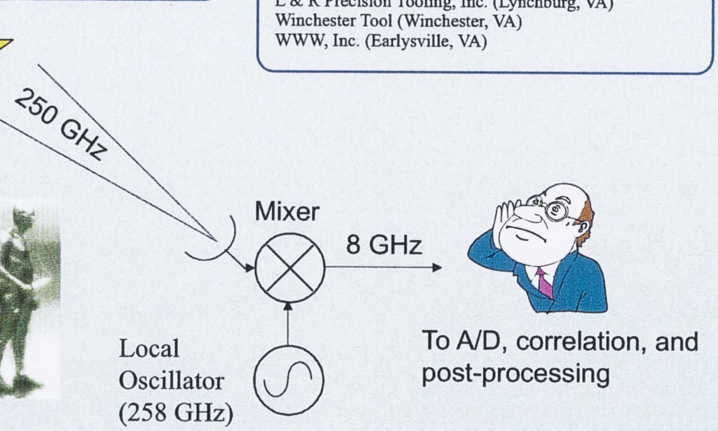
- Canada (Herzberg Institute for Astrophysics)
- France (Institut de Radioastronomie Millimetrique)
- Netherlands (Netherlands Institute for Space Research)
- Japan (National Astronomical Observatory of Japan)
- U.S. (our colleagues down the hall)
- U.K. (Rutherford Appleton Lab)
- Germany (European Southern Observatory)

Local partners and subcontractors:

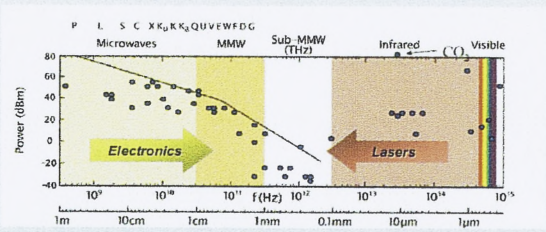
Virginia Diodes, Inc. (Charlottesville, VA)
L & R Precision Tooling, Inc. (Lynchburg, VA)
Winchester Tool (Winchester, VA)
WWW, Inc. (Earlysville, VA)

What else can millimeter-wave power sources be used for?

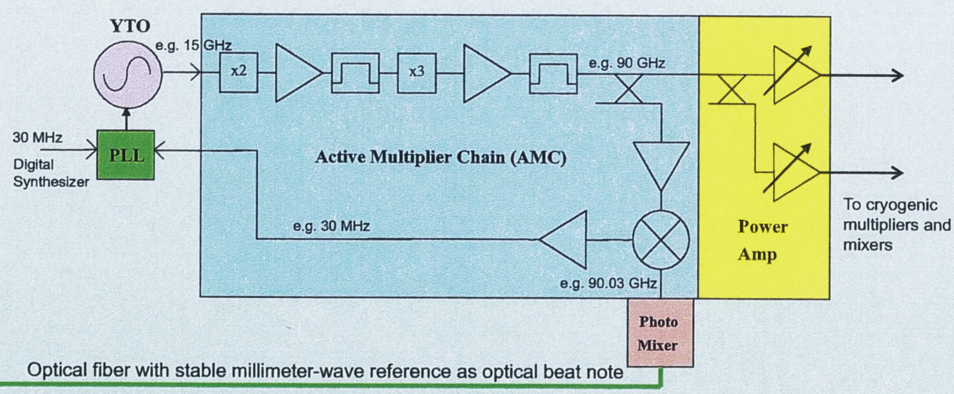
- Automotive radar (77 GHz, can see through fog)
- Medical diagnostics
- Imaging (high-resolution images without using harmful ionizing X-rays)
- Deep-space communication
- Biological identification



Lack of power sources at millimeter-waves



How do we Generate Quiet and Stable Sub-millimeter Wave Power?

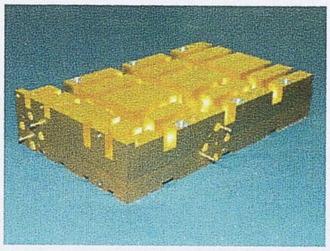


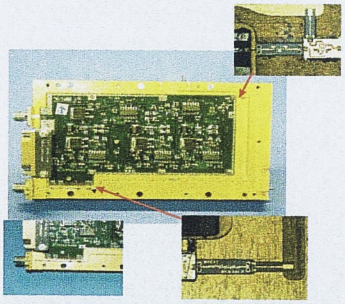
The YTO (YIG Tuned Oscillator) is the fundamental generator operating at a frequency between 12-24 GHz. From the YTO, the signal enters AMC where it is doubled in frequency, amplified, filtered, tripled in frequency, amplified and filtered again. A portion of the signal is tapped off and compared to a very phase stable millimeter-wave reference tone delivered over optical fiber (see other posters). The output of this comparison is used to stabilize the YIG tuned oscillator, such that the YTO tracks the phase of the reference tone (this is called a phase-locked loop, PLL). The other half of the signal is amplified further before entering the cryostat. Inside the cryostat, at the 80K stage, there is, for most receivers, another frequency multiplier, which brings the LO signal up to the final sub-millimeter wave frequency where it then goes to the SIS mixer to downconvert the signals from the sky.

Contact: D. L. "Skip" Thacker (sthacker@nrao.edu)

ALMA Local Oscillator Components

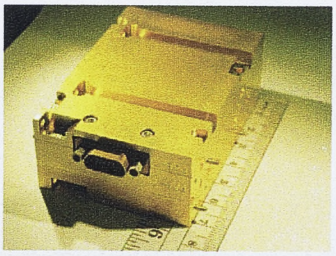
Active Multiplier Chains (AMCs)



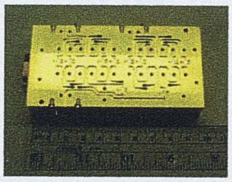


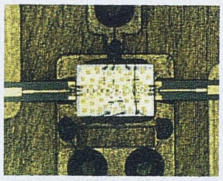
The AMC multiplies, amplifies, and filters the output of the oscillator using a combination of commercial and custom-designed MMICs (Monolithic Microwave Integrated Circuits)

Power Amplifiers

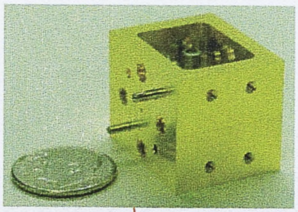


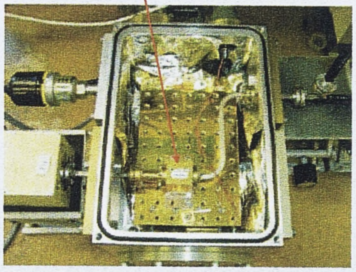
The power amplifiers boost the signal strength from the AMC to a sufficient level to properly drive the cryogenic frequency multipliers. They use 0.002" thick GaAs or InP HEMT MMIC amplifiers custom designed by NRAO and JPL.





Cryogenic Frequency Multipliers

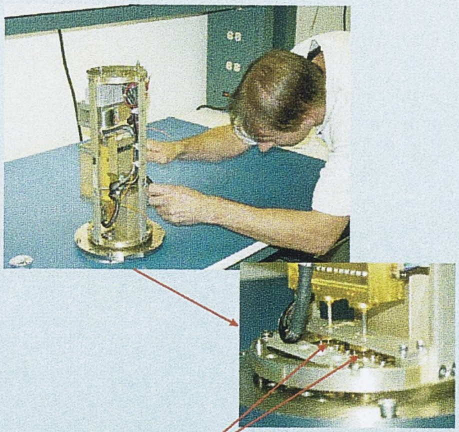




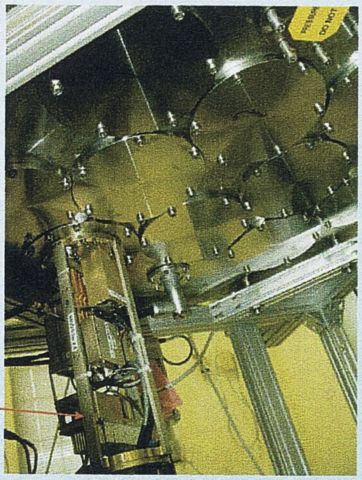
These Schottky diode multipliers operate at cryogenic temperatures (~80K) and perform the final frequency multiplication up to the sky frequency. These are designed and produced by Virginia Diodes, Inc., a Charlottesville based company that specialized in millimeter and THz components and systems

Connecting the Local Oscillator to the Receiver

The room temperature components of the local oscillator are housed in a single assembly (shown below) which mates with the receiver cartridge on a flange on the bottom of the cryostat. Guide pins are used to obtain the critical alignment of the high-frequency connections. The waveguide flanges must be aligned within 0.003" of each other to ensure that the signal passes into the receiver unimpeded. Due to there being 10 cartridges in close proximity, this alignment is done blind using accurately machined dowel pins and guide holes.



Alignment of the waveguide pins



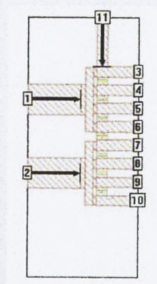
Local Oscillator

Contact: D. L. "Skip" Thacker (sthacker@nrao.edu)

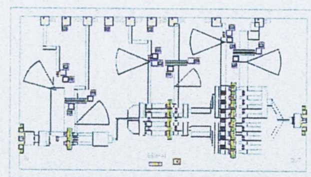
How are the MMICs Designed?
(or, what does a microwave engineer do?)

First, we design the circuit using simple circuit elements (resistors, capacitors, transmission lines, transistors, etc.) using microwave circuit simulator software (Microwave Office)

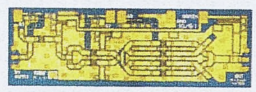
Then, we translate this circuit model to a layout that can be fabricated using photolithography at a foundry. We draw several layers of metal and insulator. The foundry creates a mask for each layer. Electromagnetic modeling software (such as Sonnet and Microwave Studio) is used to match the metal or insulator geometry to circuit element values



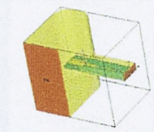
Drawing software such as AutoCAD is used to draw all the metal and insulator layers according to foundry processing rules.

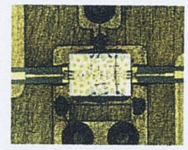


The foundry fabricates the integrated circuit using the masks produced from our drawings to determine where metal is deposited or etched away



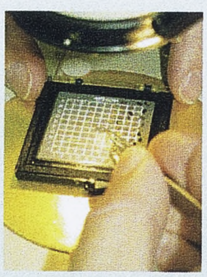
Finally, the MMIC has to be packaged and tested. The block which it is mounted in is also carefully designed using 3D electromagnetic modeling software to model, for example, the transitions between metal stripline and waveguide.

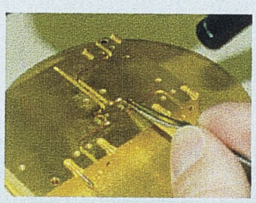




How are the MMICs packaged into an amplifier?

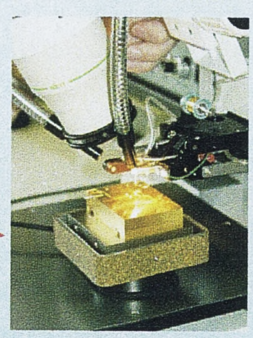
Chips are diced at the foundry and delivered in Gel-paks. We first carefully remove the chips.

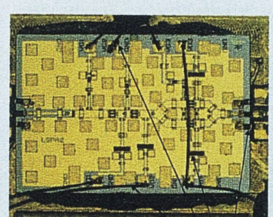




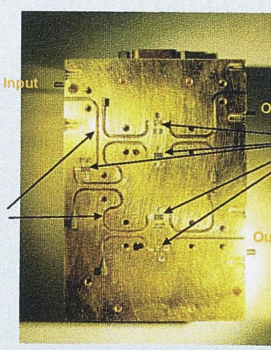
The MMICs are placed in pockets in the brass blocks. They are glued to the housing using a thin layer of conducting silver epoxy.

Wires connecting the MMICs to each other are installed using a wire bonder. Wires can be used only over very short distances (the distance must be small compared to the wavelength) and must be placed using a wire bonder (see photo), which connects 0.001" diameter gold wire to pads 0.002" square.





MMIC amplifier with wire bonds



MMIC amplifiers

Waveguides

Completed amplifier assembly

Contact: D. L. "Skip" Thacker (sthacker@nrao.edu)

National Radio AstronomyObservatory
Charlottesville NTC Photonic LO Group

Juanita Banda, Rodrigo Brito, Jason Castro, Wes Grammer, Chris Jacques, Yoshihiro Masui, Bill Shillue (bshillue@nrao.edu)

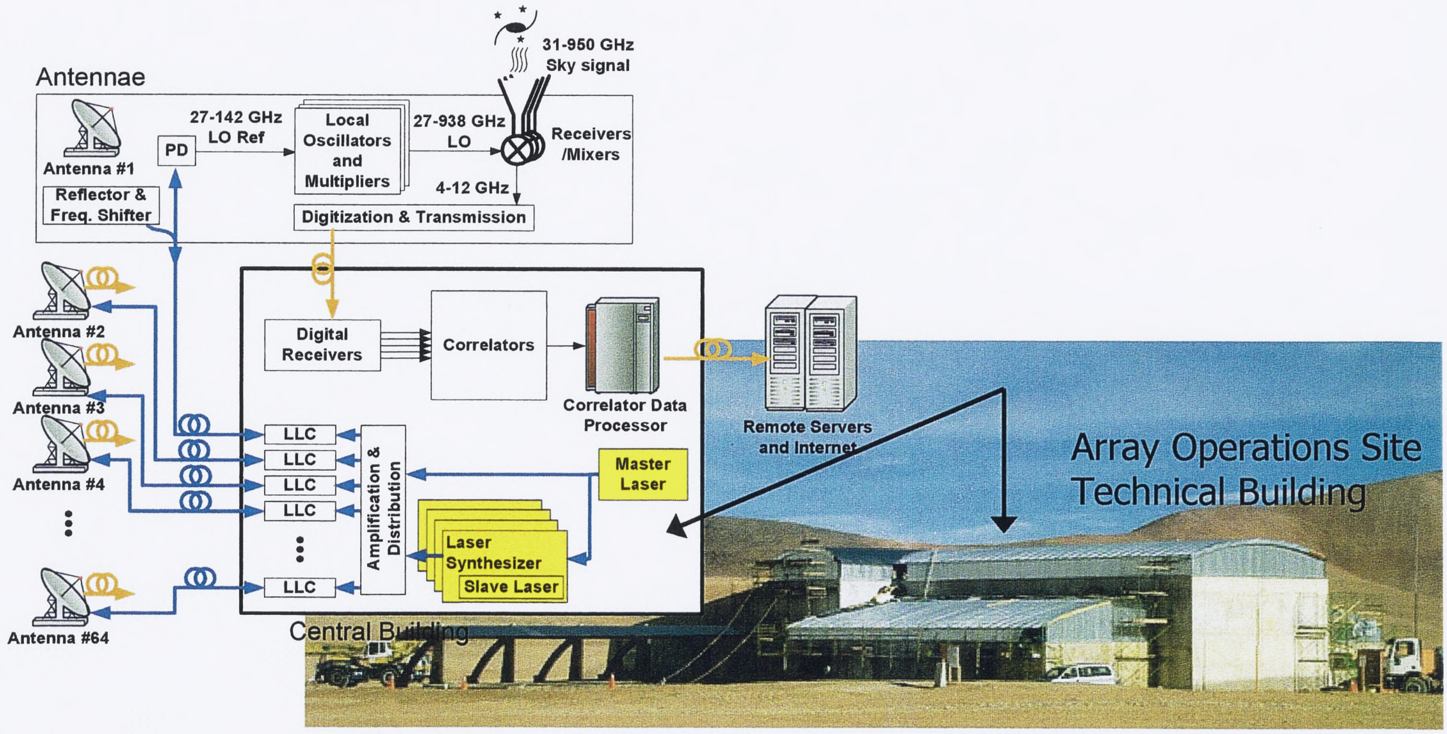
Other Contributors to the Photonic LO Group have included:
John Payne, Larry D'Addario, Sarmad AlBanna, Jack Meadows – NRAO
Pengbo Shen, Nathan Gomes – University of Kent
Peter Huggard – Rutherford Appleton Labs

Summary of the Mission of the Photonic LO Group

ALMA requires very high performance antennas, low-noise receivers, and powerful correlators for high dynamic range imaging of the millimeter and submillimeter wavelengths. Additionally, ALMA needs very precise, low drift local oscillator references to maintain the high degree of coherence necessary for imaging. At the maximum frequency of ALMA (950 GHz) and maximum baselines (15-20 km), this represents one of the most precise timing requirements ever attempted on a scientific instrument. The Photonic LO Lab at the NTC in Charlottesville is responsible for the design, construction, and delivery of the LO System that will meet this requirement.

The system is based on two innovative approaches:

1. To maintain the long term phase accuracy, optical fiber connects the central equipment to each antenna in a spoke and wheel arrangement. Each "spoke" has a precise real-time phase correction applied by use of a ultra-stable master laser, and piezo-electric fiber length adjustment.
2. To meet short term phase jitter requirements, the LO reference frequency is sent to all of the antennas in the array by sending the outputs of two lasers, locked in phase and separated by the desired reference frequency.



ALMA

Atacama
Large
Millimeter /
submillimeter
Array

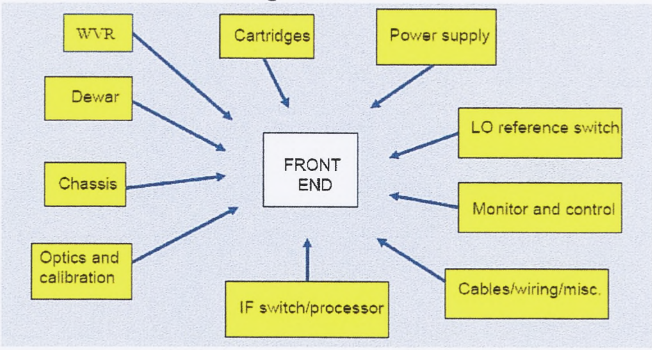
The North American Front End Integration Center
At the NRAO Technology Center

The ALMA Front End Assembly (FE) involves the integration of a large number of subsystems. The subsystems are produced by many institutes around the world and shipped to the Front End Integration Center. At the FEIC, the subsystems are integrated in the FE assembly and thoroughly tested for compliance with ALMA specifications. The tests are documented and the FE is shipped to the OSF site in Chile as a completed, functioning and tested unit ready to be installed on an antenna.

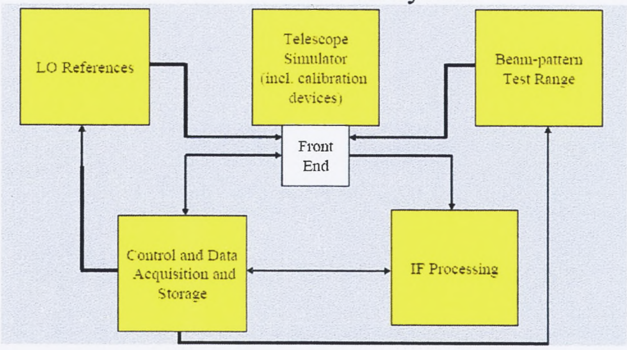
Main tasks performed at the integration center:

- Acceptance testing at module level
- The assembly of a Front End from modules and parts that are supplied by partners, procured or fabricated in-house
- Thorough tests of the Front End prior to delivery
- Documentation
- Support of the Front Ends during integration
- Training of ALMA operations staff
- Shipment of completed and tested FE Assembly to Chile

FE Integration Process



FE Test System



NA FEIC Contact Information:

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The ALMA 64-Antenna Correlator

Interesting information about the ALMA Correlator…

Its **basic function** is to turn data from 64 separate antennas into data from one telescope.
Each telescope produces eight 2-GHz bandwidth signals and a data rate of 96 Giga-bits/sec

Computation rate:
64 Antennas * 64 Antennas * 256 Lags * 32 planes * 4 quadrants * 125 MHz clock rate = $1.7 * 10^{16}$ calculations/sec
Equivalent to about 500 super computers.

Cost:
$3M in labor
$8M in parts
When designed, had the equivalent computing power of $1B worth of personal computers

Complexity:
5200 Signal cables
20 million solder joints
20,000 via holes per correlator card
170 KW power dissipation

Contact Information:
Correlator IPT Leader: John Webber, jwebber@nrao.edu
Correlator Group lead engineer: Rich Lacasse, rlacasse@nrao.edu

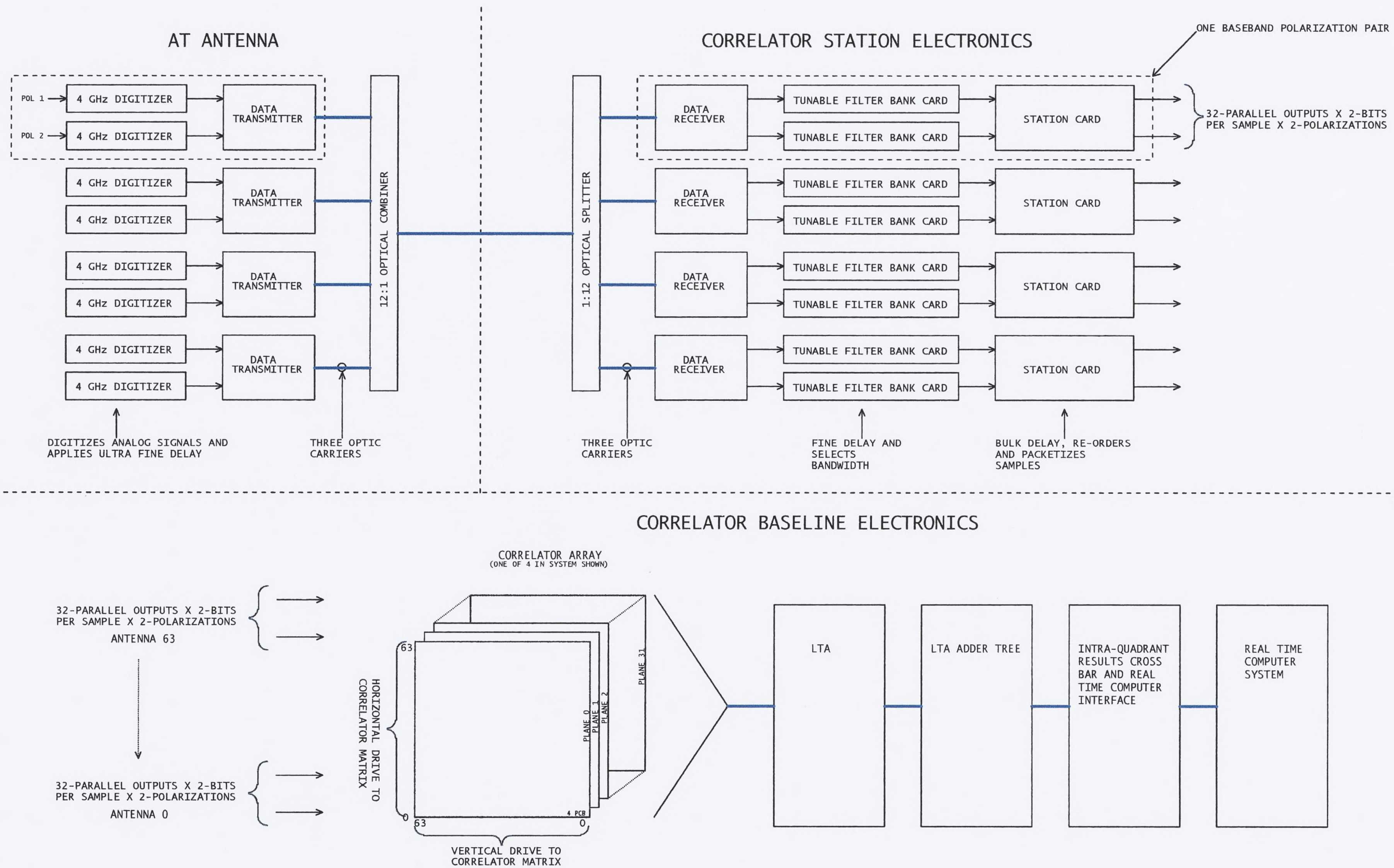


Figure 1 Correlator Block Diagram

ALMA Correlator Software

1. What does the ALMA correlator software do?

There are many functions the software performs:

- It programs the correlator hardware for an observation
- It monitors the correlator hardware voltages, temperatures, etc.
- It collects the raw correlator output and processes it into spectral data as the basis of the observational data.
- It provides an interface to the 'bigger' ALMA software infrastructure, e.g., observatory operator software, real-time calibration and data processing software, and ALMA observatory control software.

2. What is special about the ALMA correlator software?

The correlator produces a prodigious amount of data, up to 1 GB per second. This requires much processing to convert the data from the time domain to frequency domain, correct for data delays among distant antennas in the array, correct atmospheric fluctuations, and flag faulty data. This processing must be done within a small time window often within 10's to 100's of milliseconds. This puts a huge demand on the software to keep up with the high input data rate. Special attention is given to the processing routines to ensure that all data sets are processed before a new set arrives to avoid data corruption. Specialized hardware components between the correlator and other hardware and the computers require customized software modules.

Also, the ALMA observatory is a huge synchronous machine where all of the antennas, receivers, correlator, local oscillator equipment and corresponding computer systems must be tightly synchronized to within nanoseconds, using 48 millisecond spacing timing pulses. If the correlator software loses its synchronization, data are corrupted.

3. How does the ALMA correlator software accomplish its goals?

We use a two-tiered approach. First, there is a network of high performance computers allowing us to distribute the work load. Second, we use a real-time operating system which enables the software to react immediately to external inputs and execute required actions with minimal delay.

There are 16 data processing computers, each with 4 microprocessors (CPUs) which effectively distribute the computational load among 64 CPUs. The processed data from the 16 computers channel their results to a 17-th computer which transmits the data over a high-speed optical fiber network to a database archive at the Operations Support Facility (OSF) for further processing. Each of the 16 computers runs a specialized set of tasks that break up the computations into many small, sequential steps. This processing pipeline allows the software developers to identify data flow bottlenecks and to optimize the processing routines.

4. Special considerations

Because this computer system is planned to run at an altitude of over 16,500 feet (5,000 meters), special care is required to ensure proper operation. For example, these computers will not have hard disks as standard hard disks will not operate in such low air densities. Cooling is another factor with low-density air. Multiple fans in the chassis and on the CPUs ensure that sufficient airflow extracts excess heat.

5. Who develops the ALMA correlator software?

A group of 4 software engineers work full time on this software within a larger group of 50 or so developers in North America, Europe, and Japan. We have been working for over 5 years on this effort and continue to develop software while the correlator hardware is being built.

6. Status

Our software is deployed at a test facility at the VLA site in New Mexico which utilizes 2 antennas plus correlator. Initial deployment in Chile is planned for the coming year and will continues as the correlator hardware is deployed to Chile in stages.

For more information, please contact Jim Pisano at jpisano@nrao.edu.

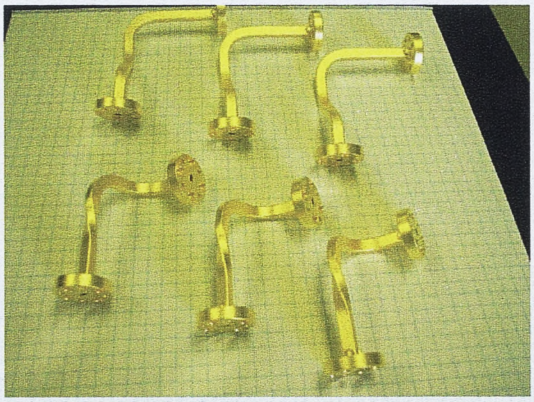
NRAO – Central Development Laboratory

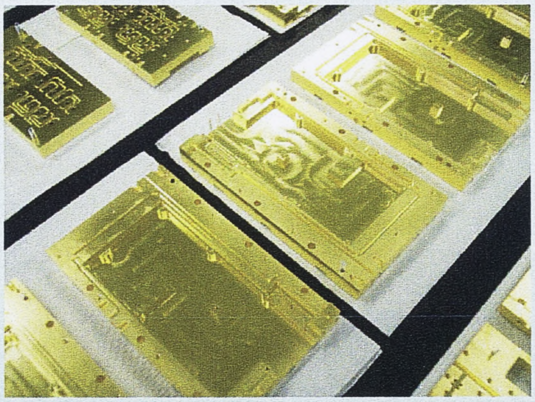
CHEMISTRY LAB

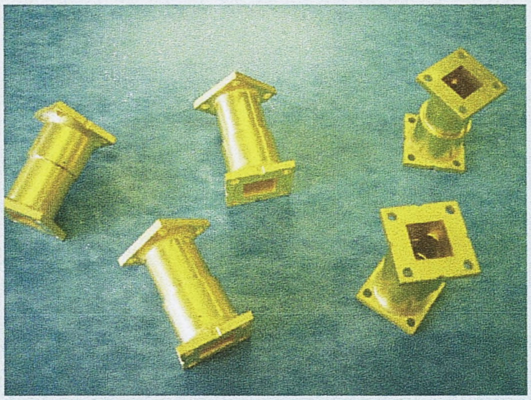
The Chemistry Lab at NRAO is primarily engaged in precision metal finishing, employing two gold electroplating processes and various other chemistries for plating zinc, nickel, and copper. Being a development laboratory, in house plating capability can save weeks in the test and development cycle of new components, with a typical cost reduction of 70-80 percent as compared to commercial plating.

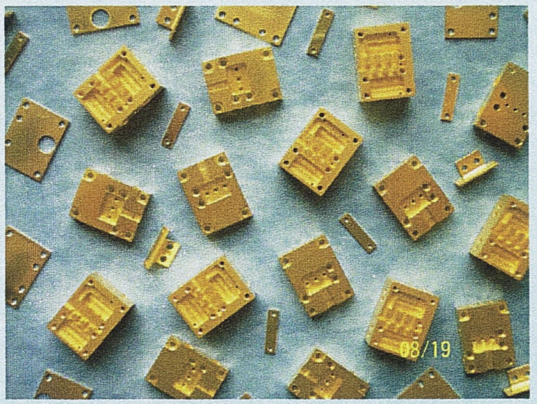
Capabilities include:

- copper plating
- nickel plating
- gold plating
- electroforming
- electropolishing
- chemical etching
- zinc plating









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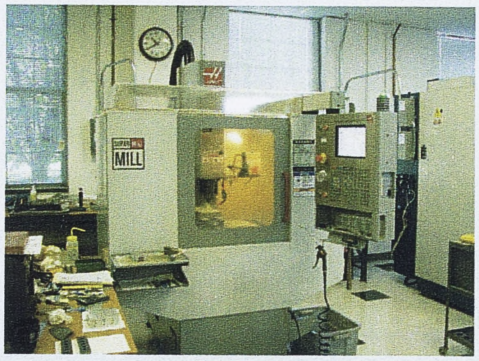
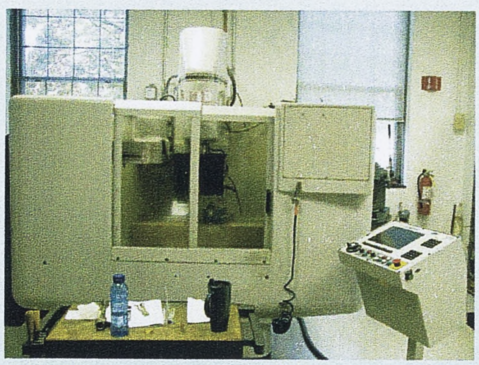
NRAO – CENTRAL DEVELOPMENT LABORATORY MACHINE SHOP

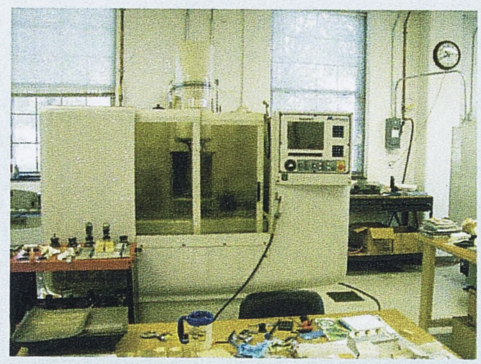
The Machine Shop supports Research and Development at the NRAO. The shop provides a quick turn-around for prototyping parts and producing small production runs. The Machine Shop Staff are accustomed to working within the tight tolerances required for the Lab's critical components. NRAO's Machine Shop uses CNC milling machines and computers with Mastercam software.

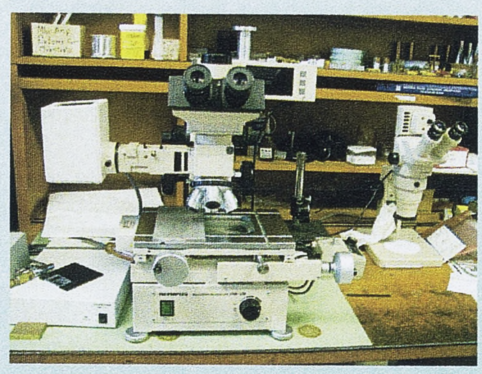
CAPABILITIES INCLUDE:

- HIGH PRECISION MILLING
- HIGH PRECISION TURNING
- DRILLING
- REAMING
- GRINDING
- BRAZING
- MEASURING









Contact: Greg Morris (gmorris@nrao.edu)