Radio Astronomy from Jansky to the Future – An Engineer's Point of View

1. Historical highlights including my history
2. Most fascinating science topics
3. Most important technology advances
4. Future recommendations

Sander Weinreb

Jansky Lecture

September, 2011

Discovery of Radio Astronomy
Holmdel, NJ, 1932

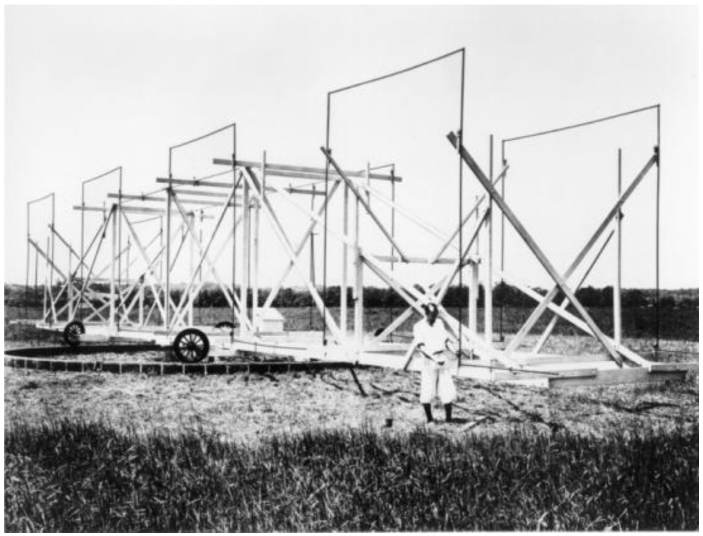
"NEW RADIO WAVES TRACED TO CENTRE OF THE MILKY WAY"—So announced *The New York Times* on May 5, 1933.

> Mysterious static reported by K. G. Jansky, held to differ from cosmic ray. Direction is unchanging. Recorded and tested for more than a year to identify it as from Earth's galaxy. Its intensity is low. Only delicate receivable able to register—no evidence of interstellar signaling.

- Discovered first cosmic radio wave by accident while investigation "static" associated with trans-atlantic telephone calls.
- Wanted to build a 30m dish antenna to follow up on his discovery but was not granted the funds to do so.
- Professional astronomers ignored the discovery and an amateur, Grote Reber, took up the work

Jansky's Detection of Galactic Radio Waves

The antenna was rotated once every 20 minutes and produced a peak signal which was fixed in space in the direction of the center of our Milky Way galaxy



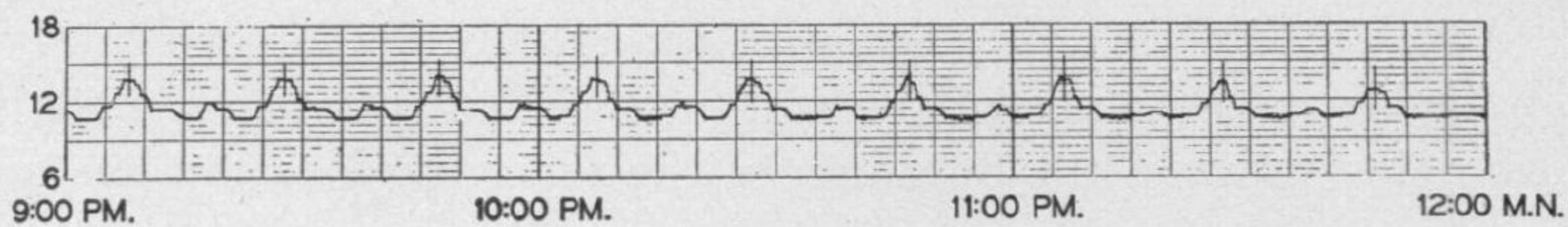


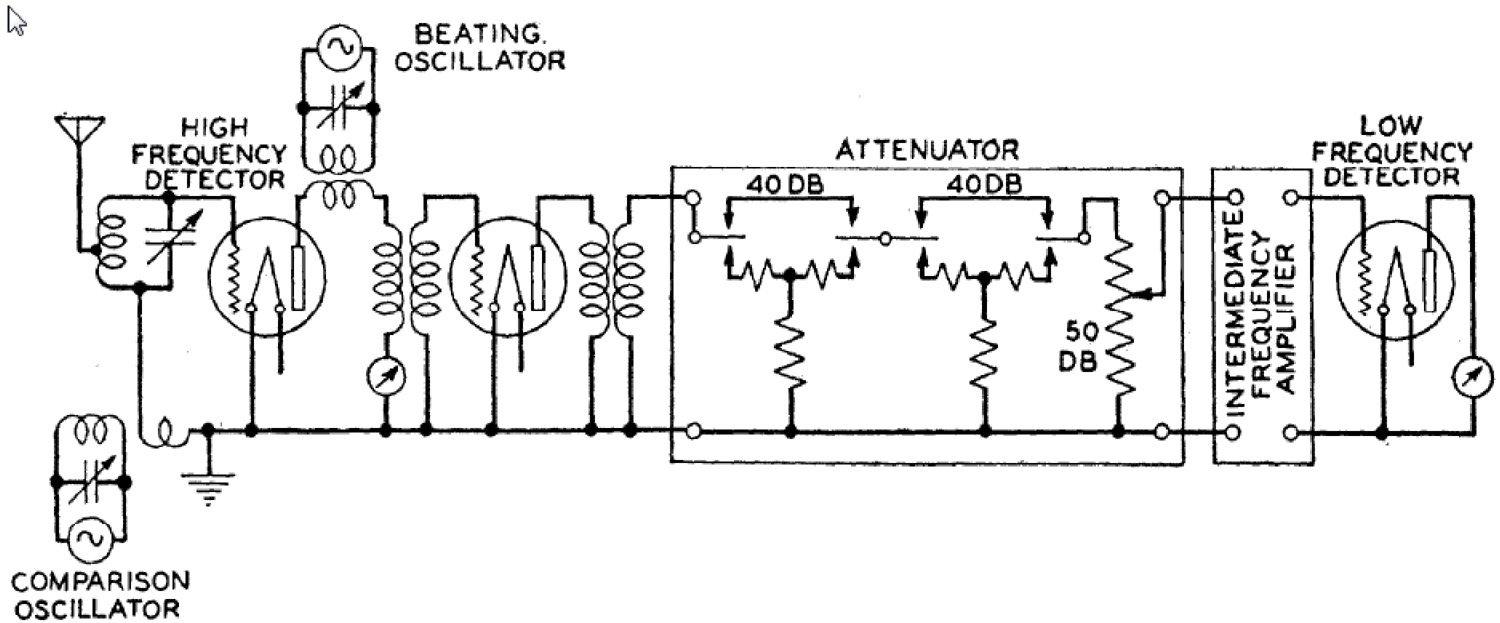
Fig. 2—Sample record of waves of interstellar origin. Record taken 12:00 noon to 12:00 midnight on September 16, 1932.

Jansky's Receiver

• Receiver noise was not a problem given the strength of 20 MHz RFI and radio astronomy signals and the performnace of available vacuum triodes

• Receiver challenge was dynamic range, linearity, and calibration

• Innovative receiver developed by Friis and others was a feedback automatic level control design utilizing a motor-driven IF rotary attenuator to maintain a constant receiver output. The position of the attenuator was proportional to input signal level.



Jansky's Receiver

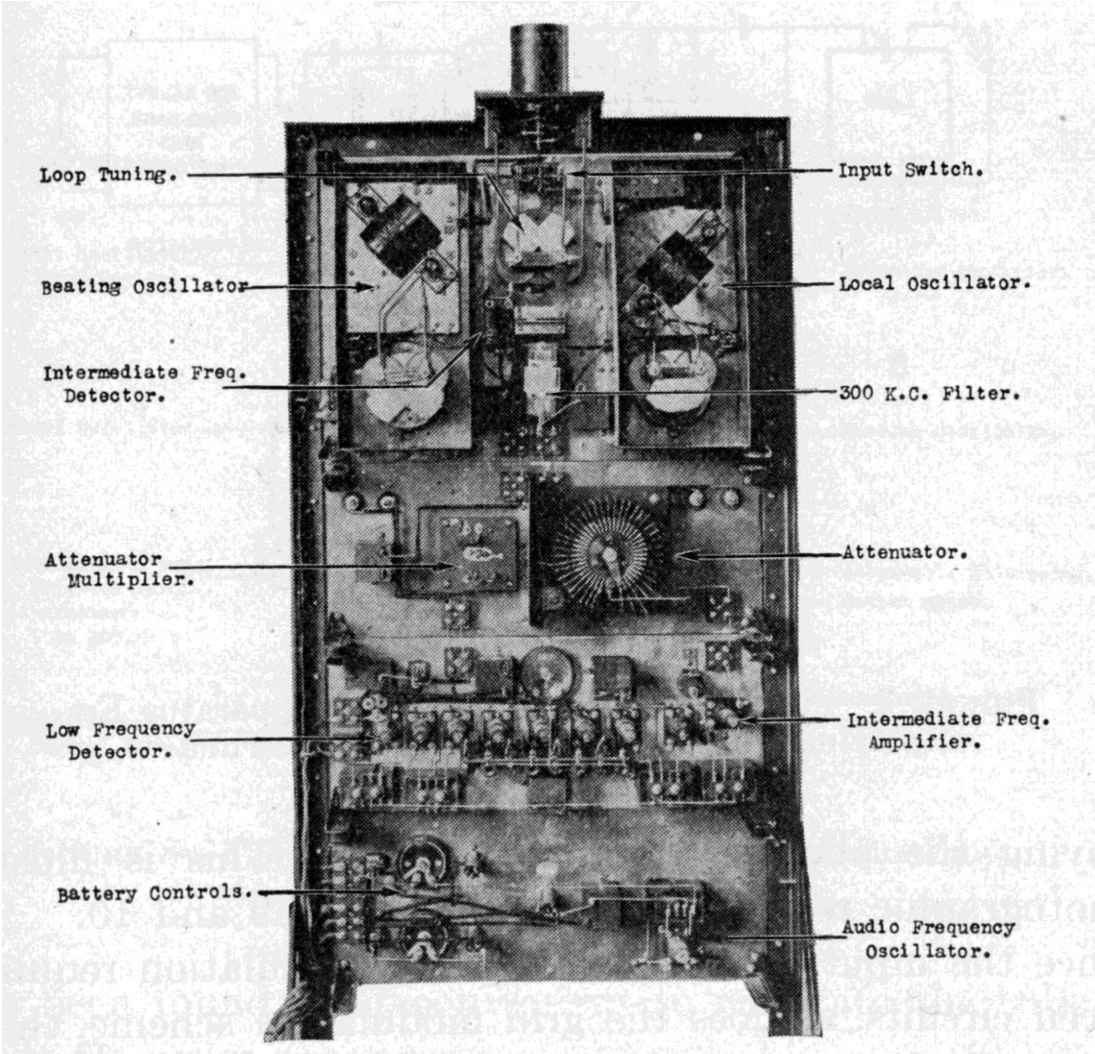


FIGURE 6—Same as Figure 5, with Copper Shielding Boxes Removed

A Previous Attempt to Detect Cosmic Waves Was Not Succesful

In 1920, Millener and Gaimer used a wire antenna 30 miles long to attempt to detect Mars in the 1 to 6 kHz range

Mars Refuses To Answer

A Wave Length of 300,000 Meters Tried to no Avail

Narry a sound from neighbor Mars came over what was probably one of the most sensitive and long range receiving sets ever constructed to reward an all night listening-in vigil by two enthusiastic experimenters of Omaha, Nebraska.

With an instrument so senstive that without any antenna whatever it copied a message from Arlington, and with thirty miles of wire hooked up to it and a wave length of 50,000 meters, Dr. Frederick H. Millener of Omaha and Harvey Gaimer, electrical expert, listened for hours for anything that might be construed as a signal from the planet, but heard nothing. April 22 was chosen for the experiment, because Mars was closer to the earth than it will approach again in several years. The listening will be continued for some time however.

Reber Followed Up on Jansky's Work

- Built a 10m parabolic reflector, probably the largest in the world, in his yard in Wheaton, Illinois.
- Did most of the construction of the antenna and electronics himself on his own nickel.
- Reasoned that higher frequencies, i.e. 3300 MHz, would produce much stronger signals than Jansky received at 20 MHz if they came from unresolved disks of constant brightness temperature. Receiver was crystal detector coupled to audio amplifier. Detected nothing.
- In 1938 changed frequency to 910 MHz and detected nothing.
- In 1939 changed to 160 MHz with a TRF receiver and detected the Milky Way in spite of much RFI from automobiles. Results were published in 1944 as "Cosmic Static".
- Reber moved to Tasmania to do radio astronomy under 50 MHz and wrote many articles about his equipment and observations.

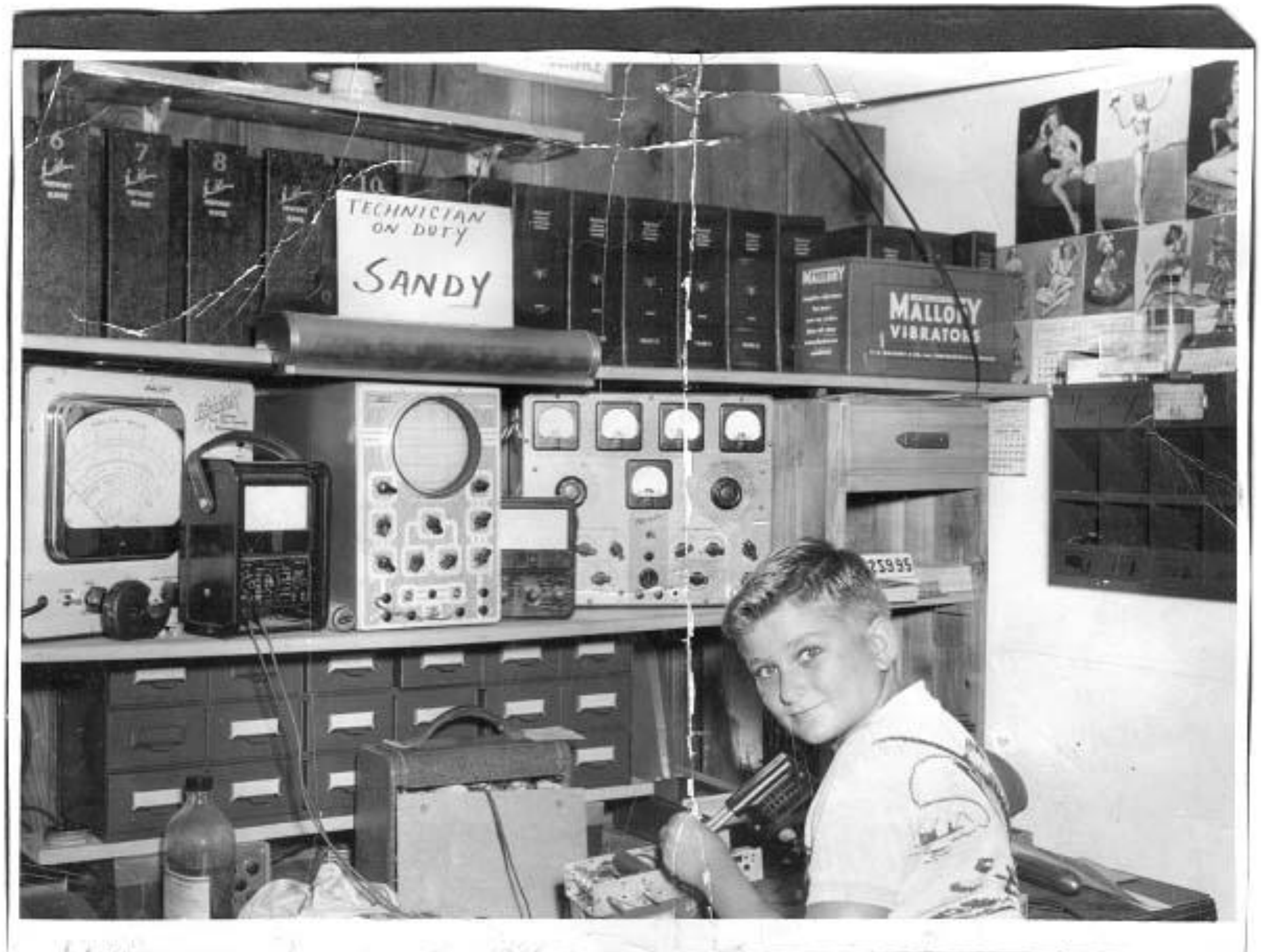
Following in Reber's Footsteps

Hamdi Mani, an amateur radio astronomer from Tunisia who worked with me at Caltech for 5 years, 2005-2010

Highlights of My Career

When	Where	Highlights
1936	NYC	Born
1945-1949	Miami	Built and fixed radios
1949-1954	Atlanta	Fixed TV's, cars, plucked chickens
1954-1958	Cambridge	MIT, Outstanding EE Student Award
1957-	Newton, MA	Married, two children
1958-1963	Cambridge	Ph.D. work, correlator, OH line
1965-1968	Green Bank	NRAO, 140' telescope receivers
1968-1988	Charlottesville	NRAO, 36'telescope, VLA design
1989-1996	Columbia, MD	Martin Marietta, learned MMIC design
1996-1999	Amherst, MA	Umass, Teaching, MMIC design
1999-	Pasadena, CA	JPL , DSN Array, LNA's, Mentoring

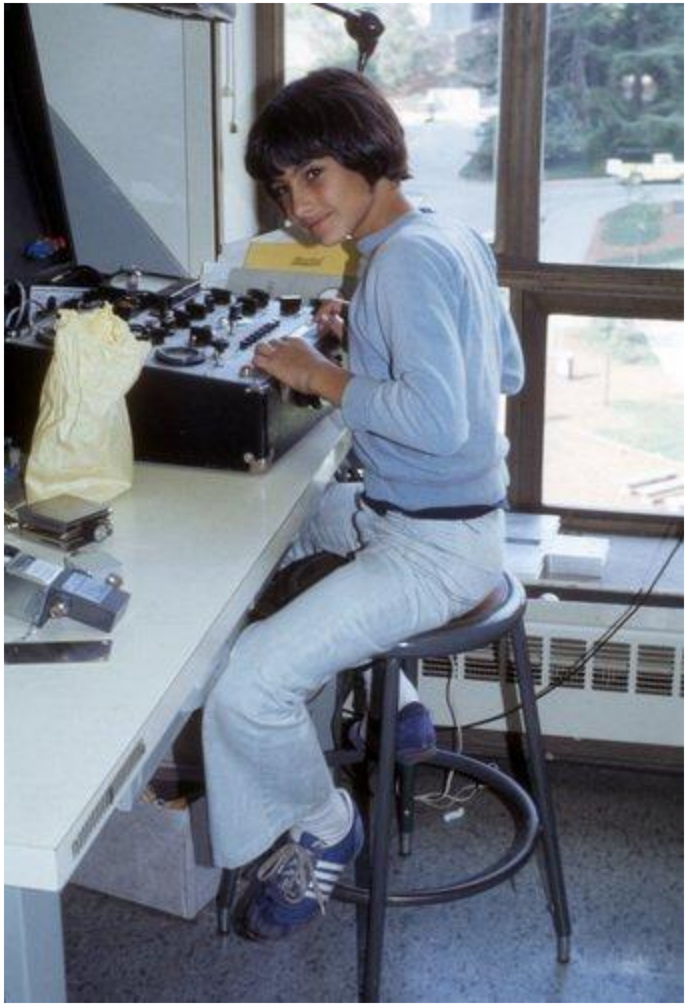
Enter Sandy Weinreb, age 13 at a radio shop in Miami, Florida, 1949



Son, Glenn, Age 12, Helping Dad in Berkeley Lab, 1976

- Gave him birthday present of Heathkit Microprocessor Trainer Kit, $200, best investment I ever made!

- Eventually started and still runs GW Instruments, a company selling data acquistion equipment,
- www.gwinst.com



Daughter, Ellen, in Peace Corp in Cameroon, Teaching Coffee Economics to Coffee Farmers, 1991

• Now runs a recruiting company for jobs in the social responsibility area – www.weinrebgroup.com

• Married with two children living in Berkeley, CA

High School Final Report Card, 1954

I Do Not Know How I Got Into MIT as I was a solid B student!

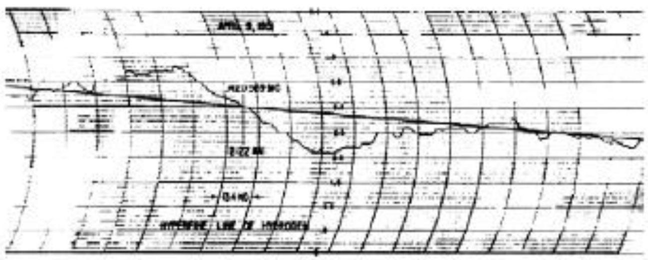
Last Name Weinreb First Sandy Middle Semester Ending 6/4/54

SUBJECTS	Course No.	1st Qr.	2nd Qr.	Sem. Avg.	Units Cr.	Teacher's Signature
English	10	B	B	B	1/2	M.B. J
Mathematics alg	5	B	B	B	1/2	J. Colley
Social Studies	SP	B	B	B	1/2	Kieffer J
Science Chem.	2	B	B	B	1/2	[illegible] J
Commercial						
Foreign Language						
Industrial Arts						

SUBJECTS	Course No.	1st Qr.	2nd Qr.	Sem. Avg.	Units Cr.	Teacher's Signature
Home Making						
Art						
Music (U. C.)						
Music (A. C.)						
Military (U. C.)						
Military (A. C.)		A	B	a	1/4	[illegible]
Spelling						
City-Wide Spelling Test Percent						
Physical Training						
Conduct		a	a	a		J
Absences		0	—			J
Tardies		0	—			
Amount Fees Paid	2.50					

Sandy and High School Pals – 20 Years Later 1974

Inspired in 1957 by "Doc" Ewen, Discoverer of the 21cm Hydrogen Line in 1951



Frequency scan through line

Ewen and his receiver

Funding Proposal

(page 2 of Purcell's letter to

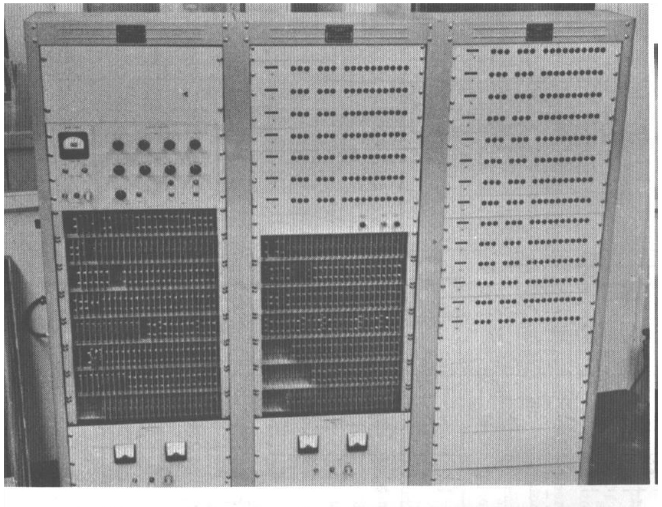
Harlow Shapley)

January 1949

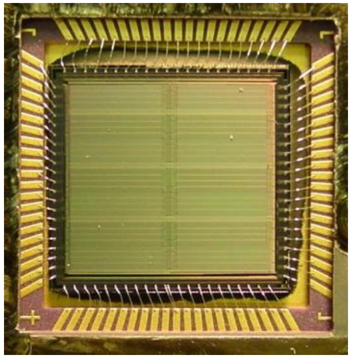
Itemized List includes:

antenna	*$150*
APT-5 xmtr	*$100*
power supply	*$ 75*
mixer parts	*$100*
waveguide	*$ 75*
TOTAL	*$500*

The Development of Correlators in Radio Astronomy

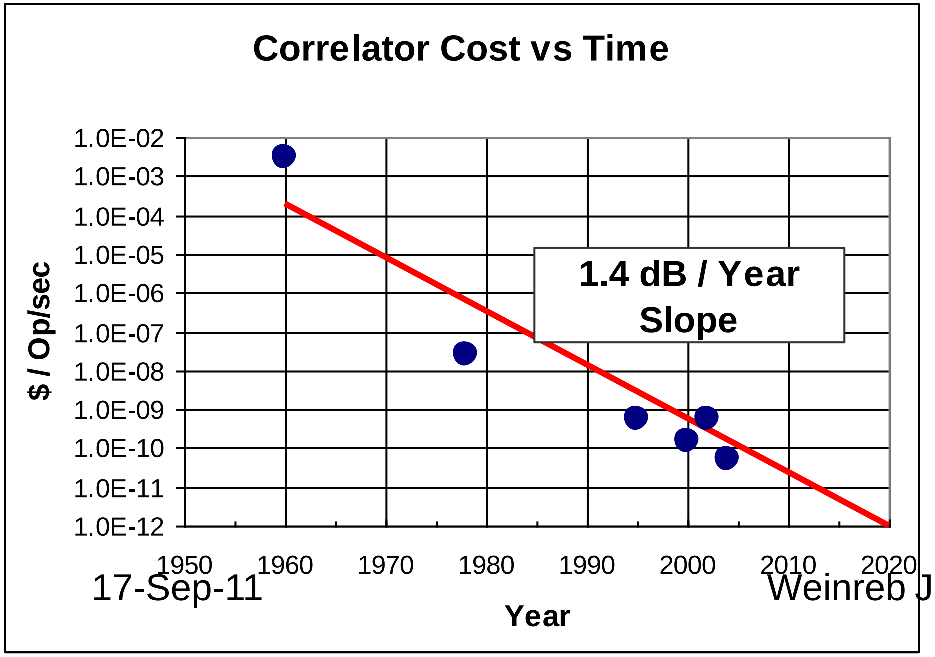


1960 – First Radio Astronomy Digital Correlator, 21 Lags, 300kHz Clock, $19,000



1995 – GBT Spectrometer Chip, 1024 Lags, 125 MHz Clock, $200

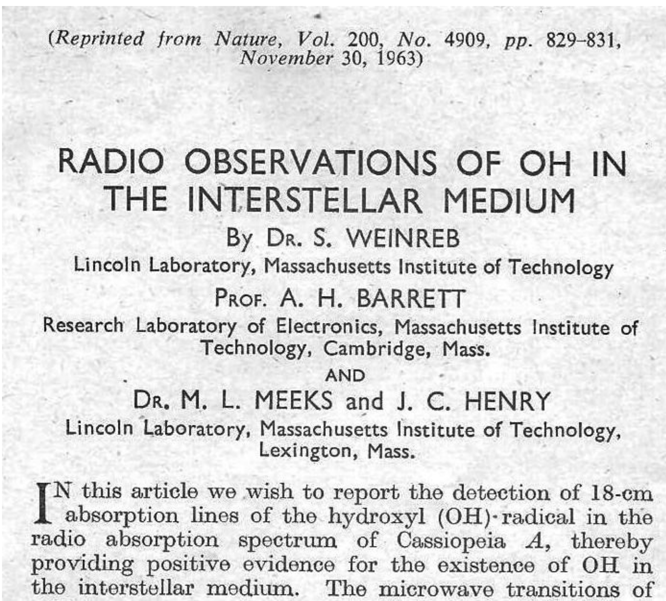
2005 – Proposed SKA Chip, 100 x 100 x 1 lag, 400 MHz Clock, $500



Billionaire Bose Founder Gives Majority Of Company To MIT

Discovery of OH, the First Molecular Line in Radio Astronomy

After several months of searching for the deuterium line at 327 MHz it was a pleasure to detect OH at 1667 MHz in the first 20 minutes.



(*Reprinted from Nature, Vol.* 200, *No.* 4909, *pp.* 829–831, *November* 30, 1963)

RADIO OBSERVATIONS OF OH IN THE INTERSTELLAR MEDIUM

By Dr. S. WEINREB
Lincoln Laboratory, Massachusetts Institute of Technology
Prof. A. H. BARRETT
Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Mass.
AND
Dr. M. L. MEEKS and J. C. HENRY
Lincoln Laboratory, Massachusetts Institute of Technology, Lexington, Mass.

IN this article we wish to report the detection of 18-cm absorption lines of the hydroxyl (OH) radical in the radio absorption spectrum of Cassiopeia *A*, thereby providing positive evidence for the existence of OH in the interstellar medium. The microwave transitions of

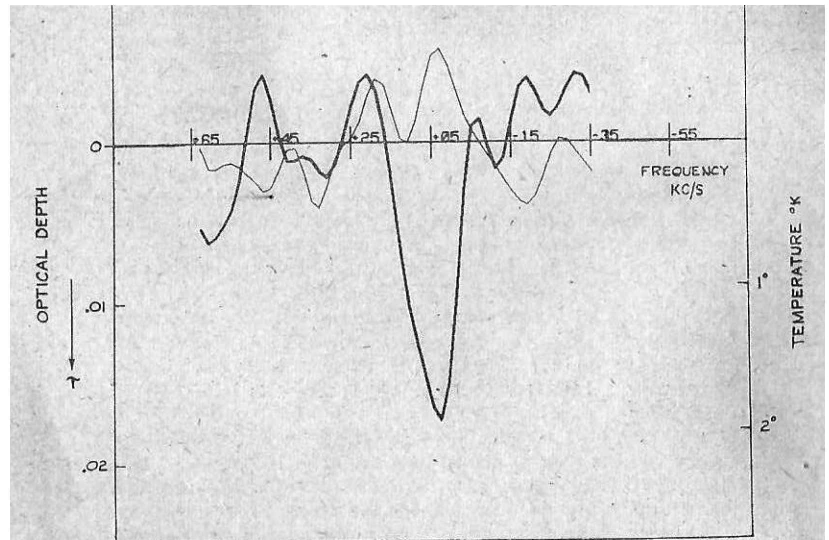


Fig. 1. Observed 1,667 Mc/s OH absorption spectrum in Cassiopeia *A*. The heavy line shows 8,000 sec of data taken with the antenna beam directed at Cassiopeia *A*, and the light line shows 6,000 sec of data taken with the beam displaced slightly from Cassiopeia *A*. The frequency scale is specified in kc/s with respect to the local standard of rest assuming the line rest frequency to be 1,667,357 kc/s

From One Radio Molecular Line in 1963 to Thousands in 1987

- Enables Chemical Studies of Star Formation Regions

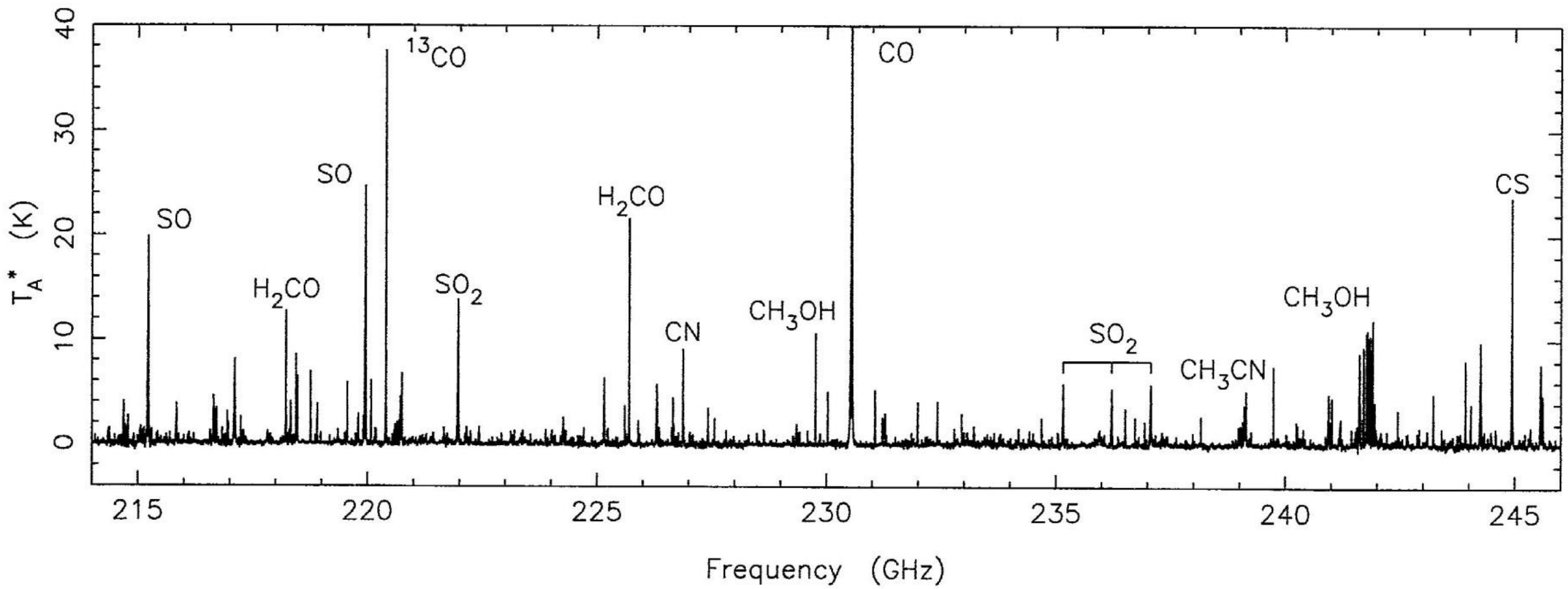


Figure 1. The OVRO 1.3 mm spectral line survey of Orion KL (adapted from Blake et al. 1987). A survey RMS of ~0.2 K was achieved after 20+ nights of integration.

Key NRAO Engineering Decisions, 1970’s

Move Antennas on Rails (rather than rubber tires)

Connect VLA Antennas with Waveguide (rather than coaxial cable)

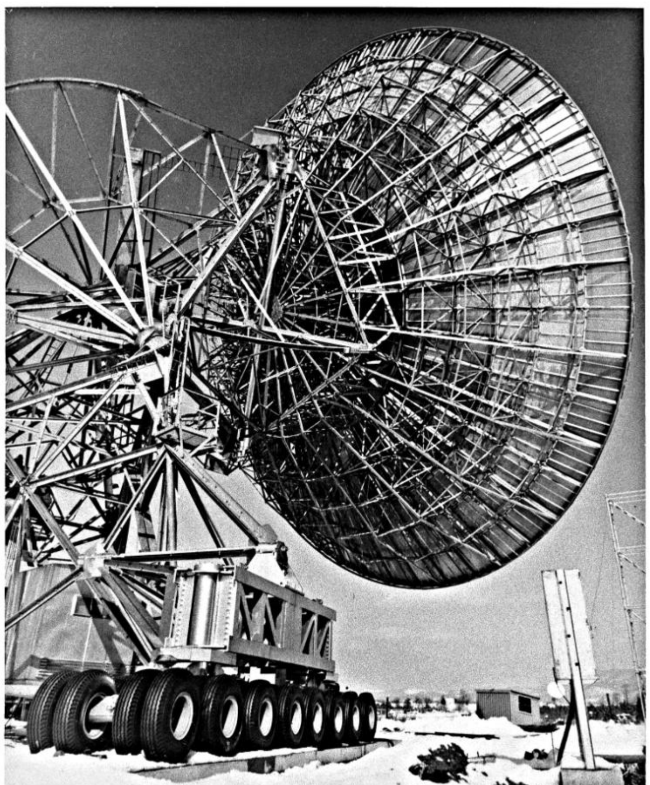
Add VLA Front Ends (L, C, X, U, and K)

Change VLA Front-Ends to Cooled Transistors (in place of cooled paramps)

Use Digital Delays on VLA (rather than cable delays)

Move VLA Antennas on Rubber Tires or Railroad?

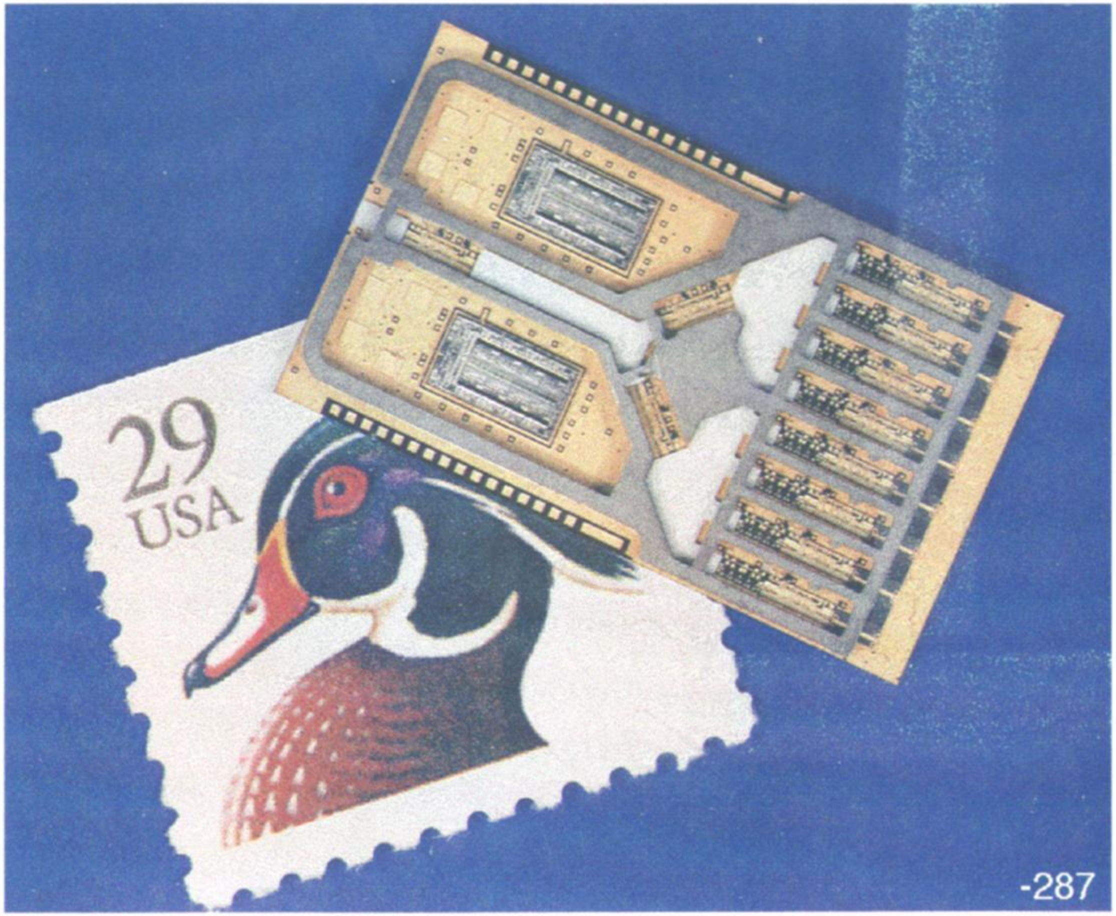
Major decision which cost the VLA several million dollars but,
I believe was correct.



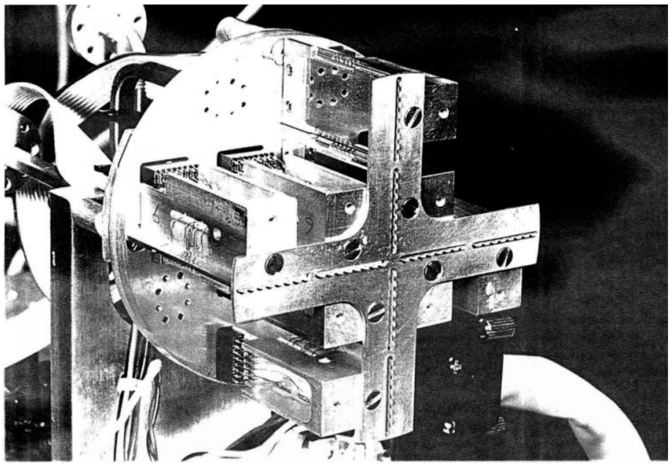
My Seven Year Vacation from Radio Astronomy

At Martin Marietta Central Research Laboratory

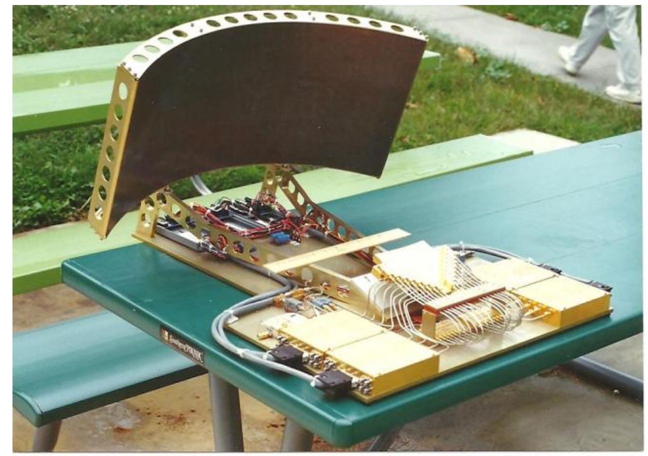
Use VLA Techniques to Build an Array on a Postage Stamp! Very Small Array!



My Seven Year Hiatus from Radio Astronomy
At Martin Marietta Laboratories

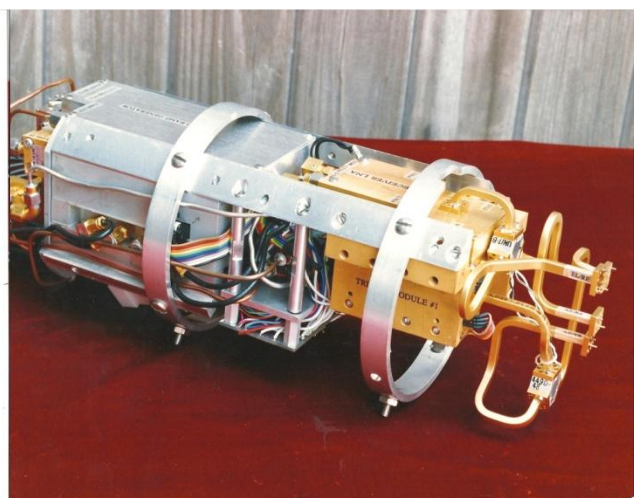


64 Element 94 GHz Phased Array



Cylindrical Paraboloid with 32 Element Feed

LOCAAS – Low Cost Anti-Armor Submunition – A 94 GHz radar transceiver within 10cm diameter



My Day at the Army Science Board!

Most Interesting Science Topics in Radio Astronomy

1) Cosmic background
2) Pulsars
3) SETI

Discovery of the Microwave Cosmic Background

Holmdel, NJ, site of Jansky Discovery

“A Measurement of Excess Antenna Temperature at 4080 Megacycles per Second”

A. Penzias and R. Wilson, Astrophysical Journal Letters, 1965

John Bahcall, a leading astrophysicist , said,

"The discovery of the cosmic microwave background radiation changed forever the nature of cosmology, from a subject that had many elements in common with theology to a fantastically exciting empirical study of the origins and evolution of the things that populate the physical universe.“

He called it the most important achievement in astronomy since Hubble's discovery of the expansion of the universe.

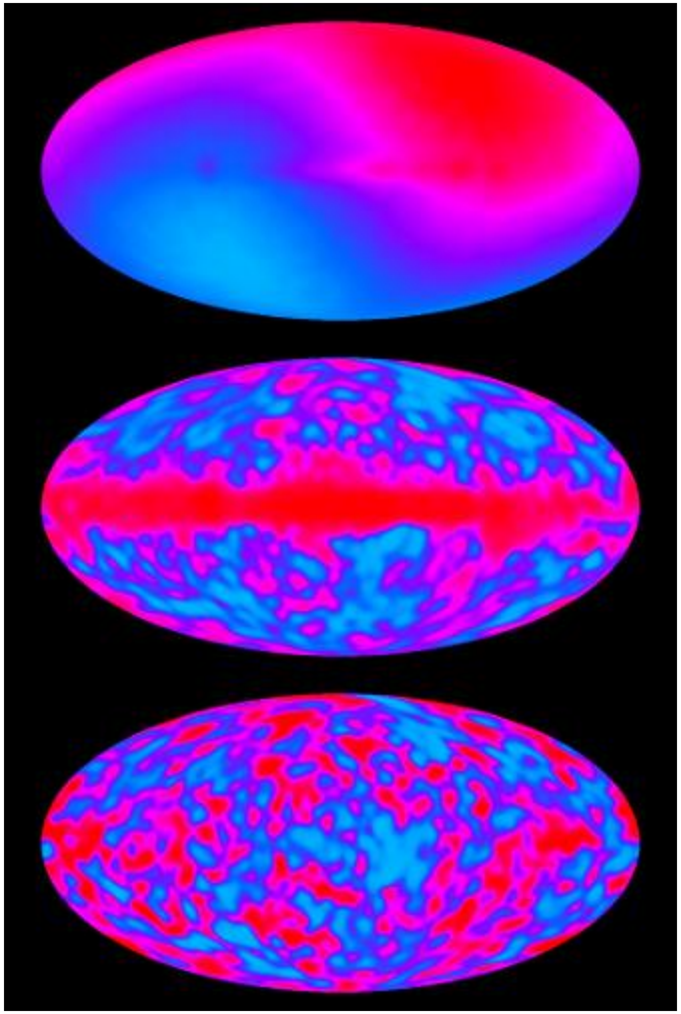
Microwave Sky Background Radiation

Sky Maps of Deviations from 2.725K

Data from the 31, 53, and 90 GHz radiometers on the COBE spacecraft

The 2006 Nobel Prize in Physics was awarded to Mather and Smoot for this measurement.

COBE was launched in 1989 and many other cosmic background instruments, space and ground based, have added much more information about the cosmic background.

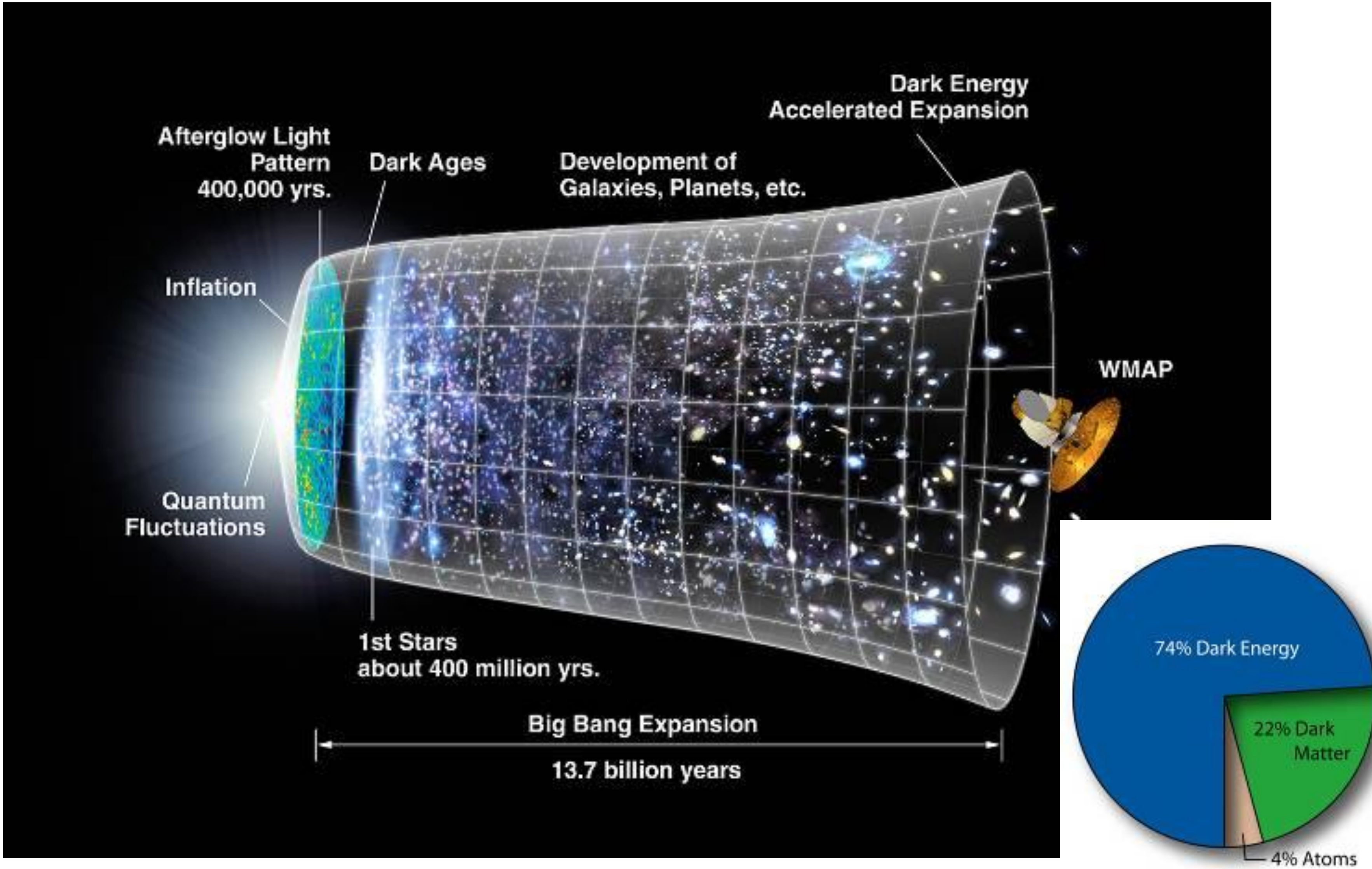


After subtraction of the 2.725K mean to reveal the mK dipole due to motion of our galaxy

After subtraction of the dipole moment to show radiation of our local galaxy.

After subtraction of both the dipole and galactic emission to show the 100uK variations due to emission variations in the early universe

Detailed Observations of the Cosmic Background Have Led to Revised Concepts of the Age and Composition of the Universe



Interesting New Topic in Radio Astronomy

Pulses from a neutron star in a supernova which exploded 6000 years ago.

Nanosecond radio bursts from strong plasma turbulence in the Crab pulsar

T. H. Hankins*, J. S. Kern*†, J. C. Weatherall* & J. A. Eilek*

* *Physics Department, New Mexico Tech, and † National Radio Astronomy Observatory, Socorro, New Mexico 87801, USA*

The Crab pulsar was discovered[1] by the occasional exceptionally bright radio pulses it emits, subsequently dubbed 'giant' pulses. Only two other pulsars are known to emit giant pulses[2,3]. There is no satisfactory explanation for the occurrence of giant pulses, nor is there a complete theory of the pulsar emission mechanism in general. Competing models for the radio emission mechanism can be distinguished by the temporal structure of their coherent emission. Here we report the discovery of isolated, highly polarized, two-nanosecond subpulses within the giant radio pulses from the Crab pulsar. The plasma structures responsible for these emissions must be smaller than one metre in size, making them by far the smallest objects ever detected and resolved outside the Solar System, and the brightest transient radio sources in the sky. Only one of the current models—the collapse of plasma-turbulent wave packets in the pulsar magnetosphere—can account for the nanopulses we observe.

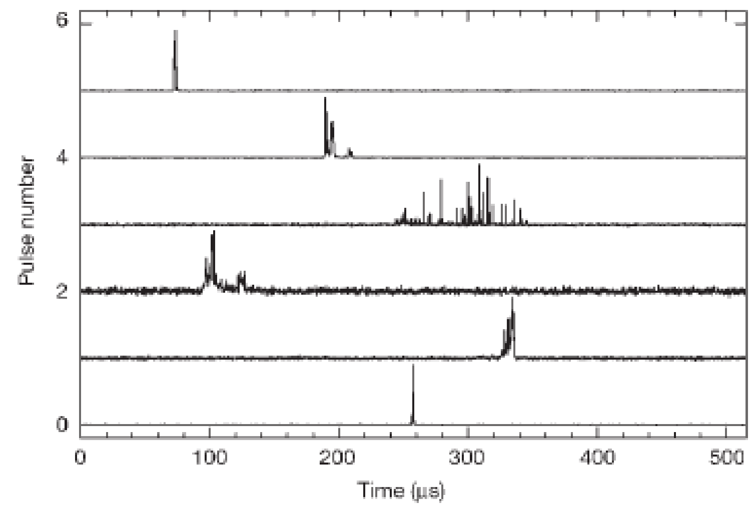


Figure 1 A sequence of dedispersed Crab giant pulses. The arrival time jitter and varied shapes of the total intensity are shown. The time axis origin is modulo one pulsar rotation period. Each pulse has been plotted with a time resolution of 250 ns and is normalized to the same maximum amplitude. The centre frequency is 5.5 GHz and the sampled bandwidth is 0.5 GHz. A square-law power detector with a 200-μs time constant was used to detect the presence of a giant pulse in the receiver pass band. A 2-ms time window, synchronous with the Doppler-shifted main pulse arrival times, was obtained from our separate pulsar timing system. When the detected intensity exceeded a preset threshold of eight times the r.m.s. off-pulse noise during the main pulse 2-ms window, a giant pulse was captured by digitally sampling the voltage of both orthogonal polarizations at 1 or 2 $\times 10^9$ samples per second using a LeCroy 9354L or LC584L digital oscilloscope.

Chronology of the Crab Pulsar

5750 BC A star in the Crab Nebula collapses to form the bright flash of a supernova

1054 AD The flash is observed for days by Chinese and Arabian astronomers

1758 Messier discovers the supernova remnant, the Crab Nebula

1934 The existence of neutron stars is predicted by Zwicky

1967 The first pulsed radio waves from an astronomical object are detected by Anthony Hewish and Jocelyn Bell who suggest the pulses are from a rotating neutron star.

1968 Staelin and Reiffenstein discover the Crab pulsar

1974 Hewish receives the Nobel Prize in Physics for the pulsar discovery

2003 Hankins discovers pulses of < 1 ns duration from the Crab pulsar. These pulses left the neutron star in 4800 BC and have a dispersion of the order of 1ms between 8 and 9 GHz – about 2 x 10^{-15} of the transmission time. This is due to an electron content of .03 per cm^3 in the interstellar medium

When Will Earth Communicate with Extraterrestrial LIfe? - SETI Chronology

- In the first 5 billion years the technology to communicate at stellar distances did not exist on earth
- We have only had radio technology for ~100 years
- It is only in the past several years that we have detected planets around other stars
- The Kepler spacecraft mission has the goal of detecting 50 earth-like planets by 2012. <u>What is the next step</u>?
- An SKA size array could increase the volume of space with detectable radio emission by a factor of ~350

Kepler mission, shown at right, will examine 100,000 stars looking for fluctuations due to planet occultation's

Number of Detectable Extraterrestrial Transmitters vs Antenna Area on Earth

	Number of Stars at Detectable Distance and (Distance, Light Years)		
Extraterrestrial Transmitter⟶	**1MW Isotropic Leakage Signal**	**Beacon, 1KW**	**Beacon, 1MW**
2011 Technology A= 2 x 10^4 m^2	0 (2.7 LY)	7 (19 LY)	216,000 (600 LY)
SKA Technology A = 10^6 m^2	7 (19 LY)	2500 (135 LY)	74,000,000 (4200 LY)

Assumptions: 20K Receiver Noise, Arecibo type Beacon, 21cm Wavelength, 0 dB S/N at Detection in 1Hz Bandwidth

Suppose we receive this sequence of 551 one's and zero's from space. What are they trying to tell us?

1 1 1 1 0 0 0 0 1 0 1 0 0 1 0 0 0 0 1 1 0 0 1 0 0 0 0 0 0 0 1 0 0 0 0 0 1 0 1 0 0

1 0 0 0 0 0 1 1 0 0 1 0 1 1 0 0 1 1 1 1 0 0 0 0 1 1 0 0 0 0 1 1 0 1 0 0 0 0 0 0 0

0 0 1 0 0 0 0 0 1 0 0 0 0 1 0 0 0 0 1 0 0 0 1 0 1 0 1 0 0 0 0 1 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 1 0 0 0 1 0 0 0 0 0 0 0 0 0 0 1 0 1 1 0 0 0 0 0 0 0 0 0 0 0 0

0 0 0 0 0 0 0 1 0 0 0 1 1 1 0 1 1 0 1 0 1 1 0 1 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

0 0 0 0 1 0 0 1 0 0 0 0 1 1 1 0 1 0 1 0 1 0 1 0 0 0 0 0 0 0 0 0 1 0 1 0 1 0 1 0 1

0 0 0 0 0 0 0 0 0 1 1 1 0 1 0 1 0 1 0 1 1 1 0 1 0 1 1 0 0 0 0 0 0 0 1 0 0 0 0 0 0

0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 1 0 0 0 1 0 0 1 1 1 1 1 1 0 0 0

0 0 1 1 1 0 1 0 0 0 0 0 1 0 1 1 0 0 0 0 0 1 1 1 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0

1 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 1 1 1 1 1 0 0 0 0 0 0 1 0 1 1 0 0 0 1 0 1 1 1 0

1 0 0 0 0 0 0 0 1 1 0 0 1 0 1 1 1 1 1 0 1 0 1 1 1 1 1 0 0 0 1 0 0 1 1 1 1 1 0 0 1

0 0 0 0 0 0 0 0 0 0 0 1 1 1 1 1 0 0 0 0 0 0 1 0 1 1 0 0 0 1 1 1 1 1 1 1 0 0 0 0 0

1 0 0 0 0 0 1 1 0 0 0 0 0 1 1 0 0 0 0 1 0 0 0 0 1 1 0 0 0 0 0 0 0 1 1 0 0 0 1 0 1

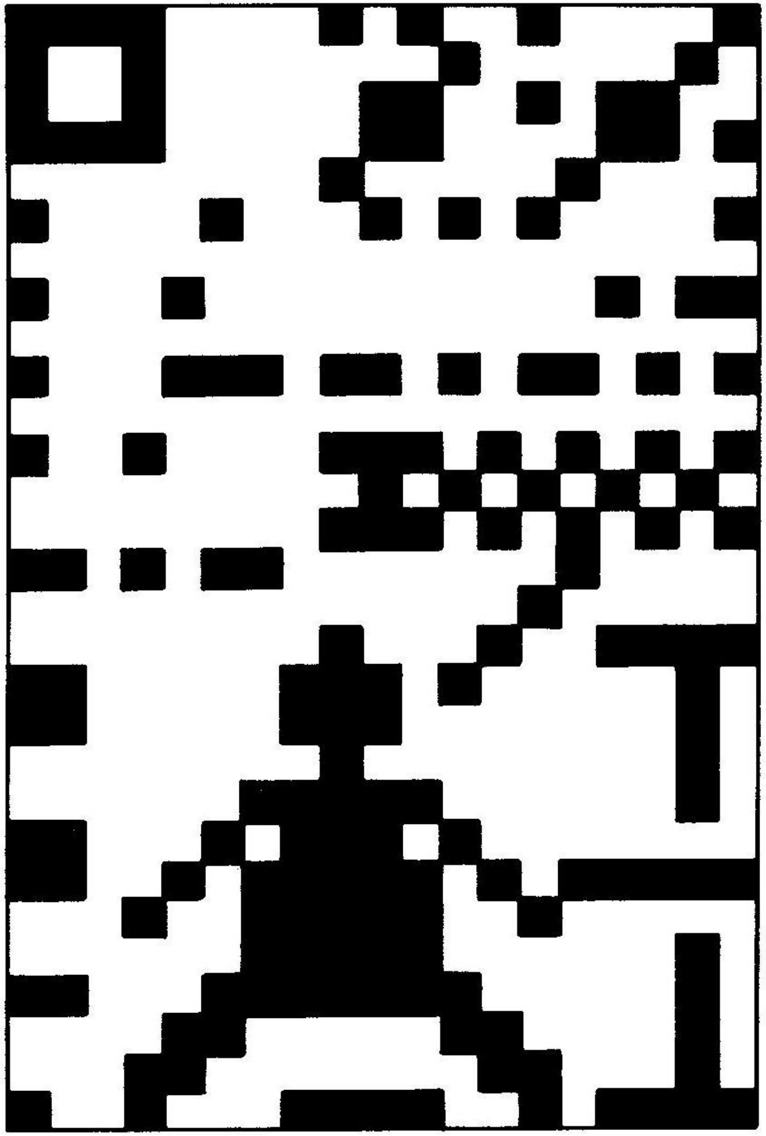
0 0 1 0 0 0 1 1 1 1 0 0 1 0 1 1 1 1

Reprinted from *Murmurs of Earth*, by Carl Sagan, p. 50

Answer:

551 is the product of two prime numbers, 29 x 19

Arrange the 551 as 29 rows of 19 characters with each one drawn in black



Reprinted from *Murmurs of Earth*, by Carl Sagan, p. 51

Most Important Engineering Developments Applied to Radio Astronomy in Past 50 Years

1) Digital correlators

2) LNA’s from paramps to transistors

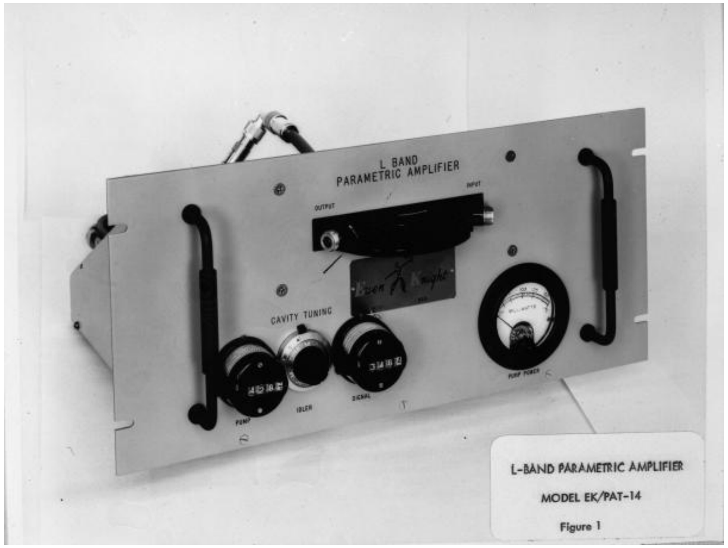
3) Optical fiber connections of arrays of antennas

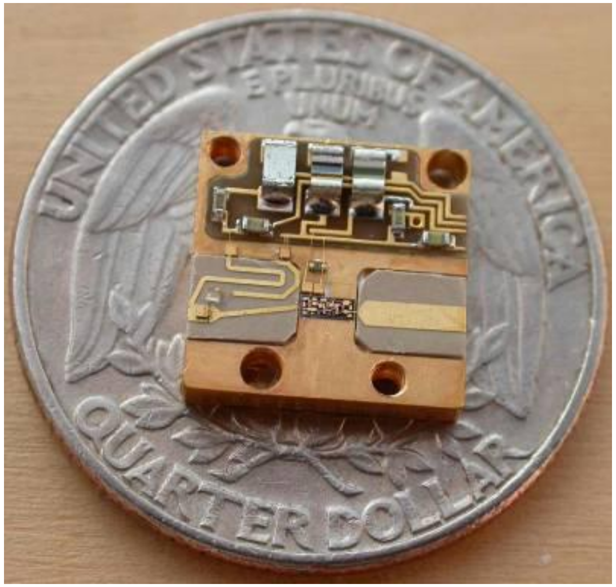
4) Chip integration of receivers

VLA Prototyped with Paramps, Built with Transistor LNA's

Paramps
Bulky, expensive, unstable, unreliable

Transistor Low Noise Amplifiers
Small, less expensive, stable, reliable, more sensitive than paramps

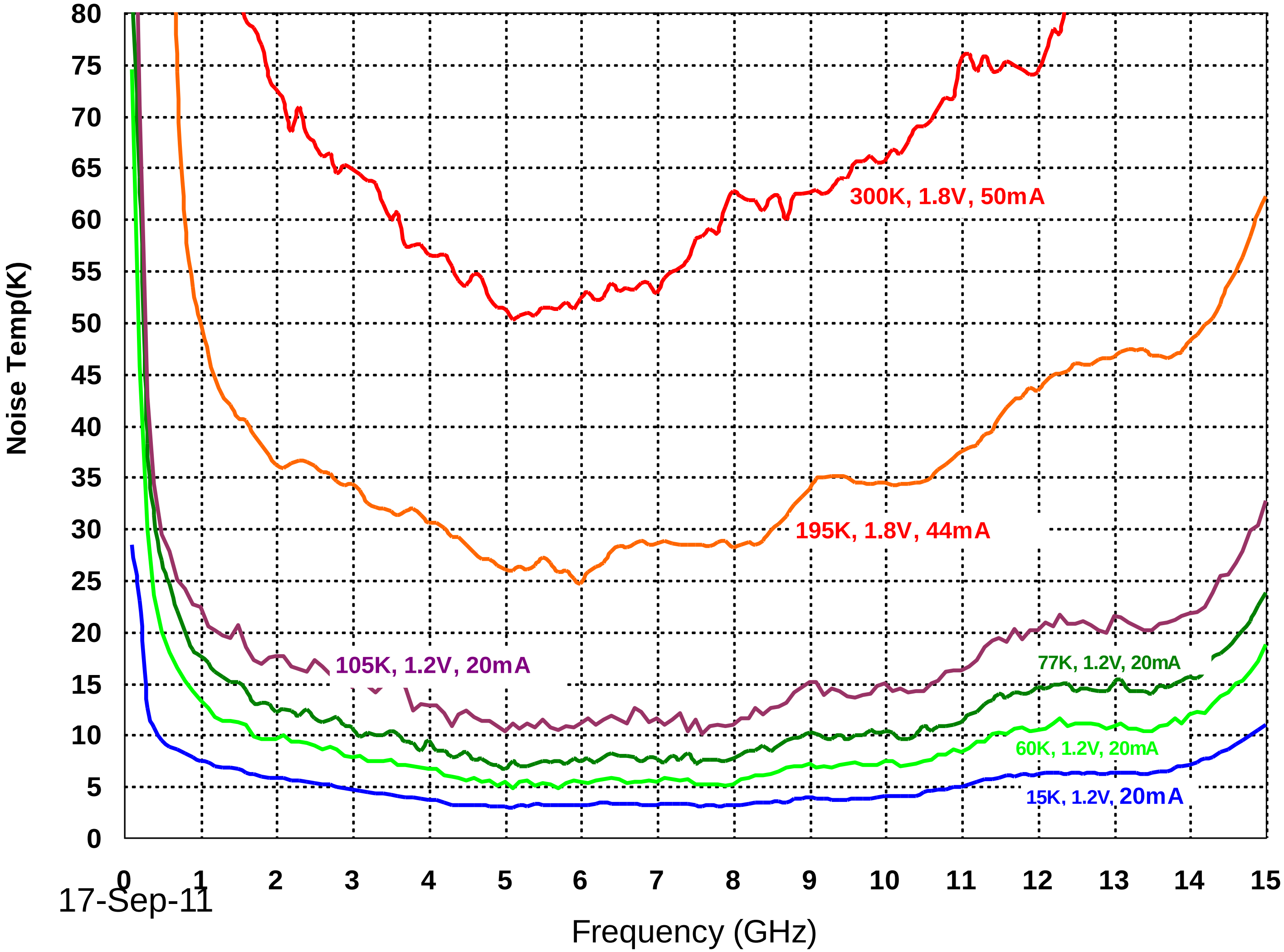


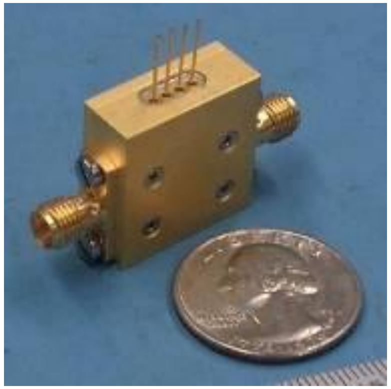


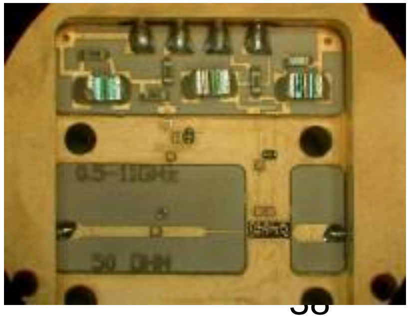
Noise Temperature vs Frequency at 300K, 195K, 105K, 77K, 60K, and 15K

InP HEMT MMIC, WBA13, Tested at Caltech May, 2007

Over 300 of these modules in use in radio astronomy and physics research.

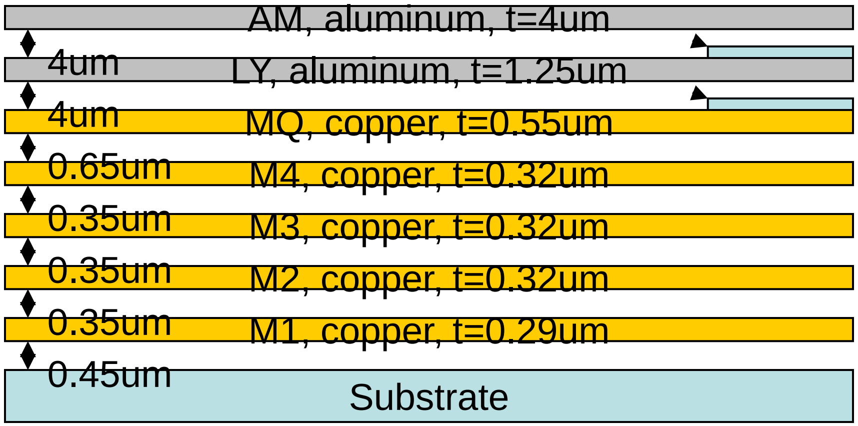


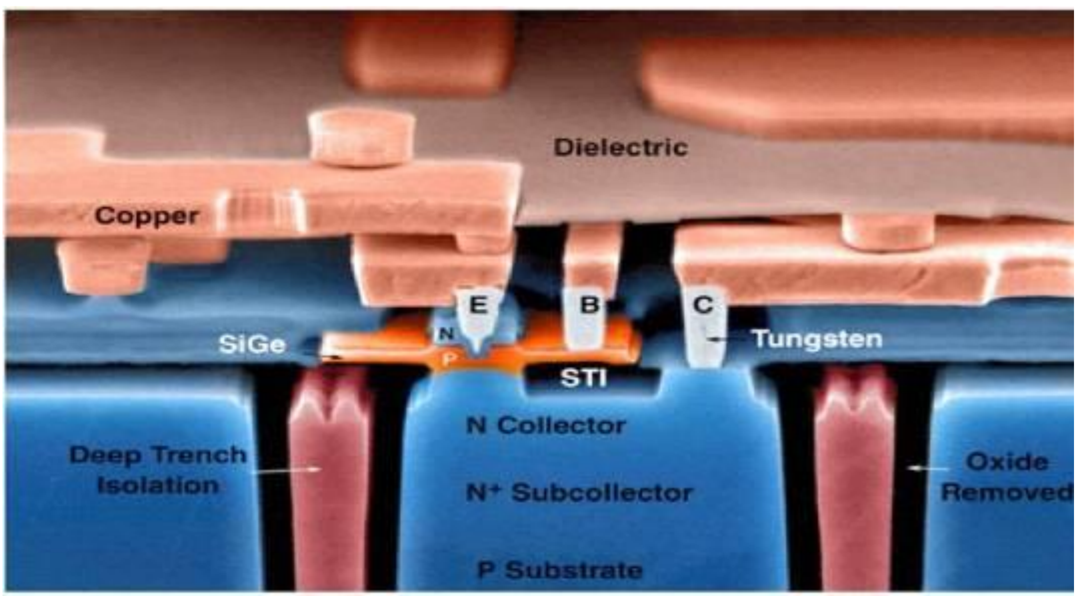




SiGe Integrated Circuit Cross-Section

- Many interconnect layers allow complex functions on one chip
- Precise lithography developed for high-density digital IC, i.e. 32nm features





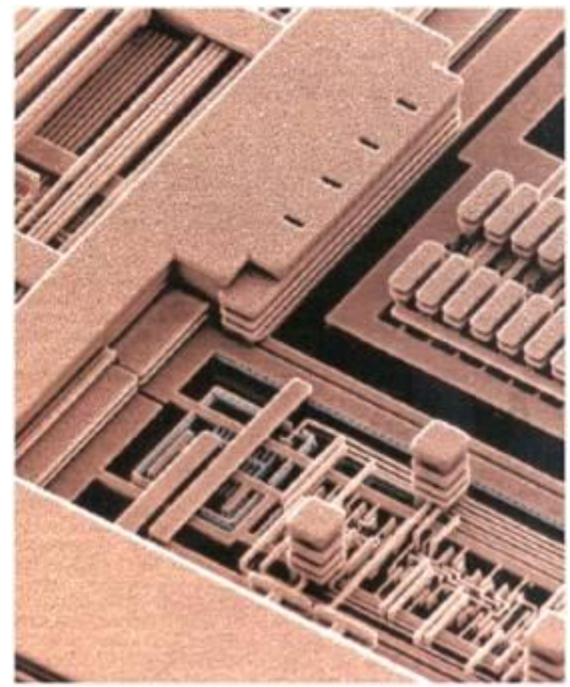
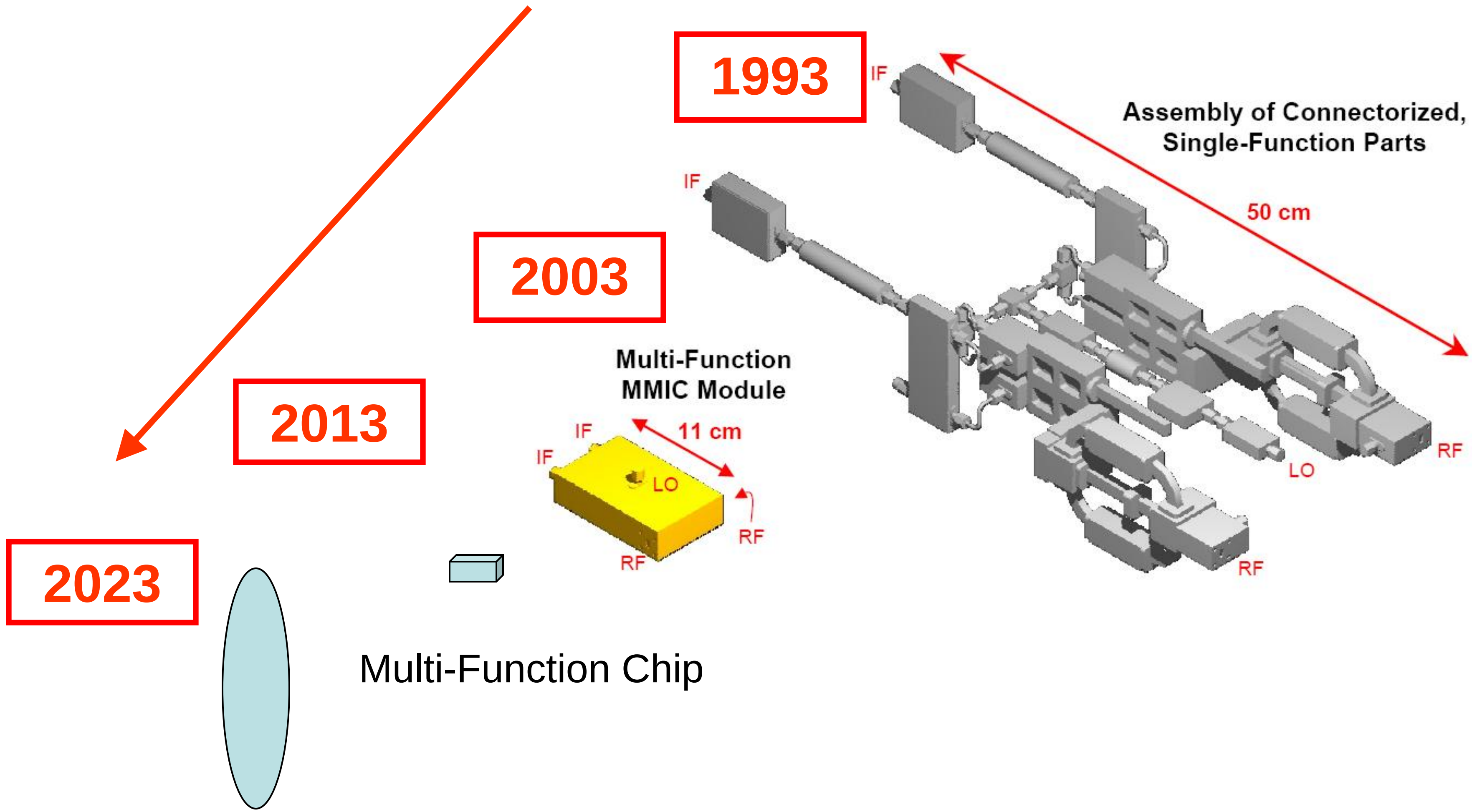


Photo reproduced from: http://users.ece.gatech.edu/~cressler/

Packaging Technology of Modern Electronics

- Electronic functions are orders of magnitude smaller and less expensive
- How can we use this technology for radio astronomy.



Multi-Pixel Array Wafer

Evolution of the VLA

	Prototype (GB Interf.)	VLA	EVLA	SKA Hi
Reflectors	3 x 25m	27 x 25m	27 x 25m	400 x 15M
Era	1965-1975	1980-2011	2011-2025	2025-2040
Frequency GHz	2.7/8.1	1.4, 4.7, 15, 23	1 to 50	8 to 50
Receivers	2	4	8	1
Bandwidth, GHz	.01	.05	8	42
Effective Area/VLA	0.11	1	1	5.3
Rel Survey Speed	-	.006	1	410
Cost, $M	3	70	70	300

Major Assumptions: 1) By 2025, EVLA is obsolete compared to SKA mid. 2) SKA site is not suitable for SKA Hi

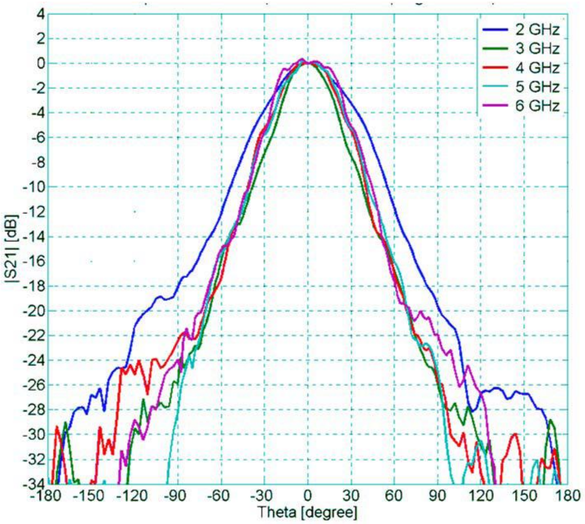
Feasibility of 8 to 50 GHz Feed

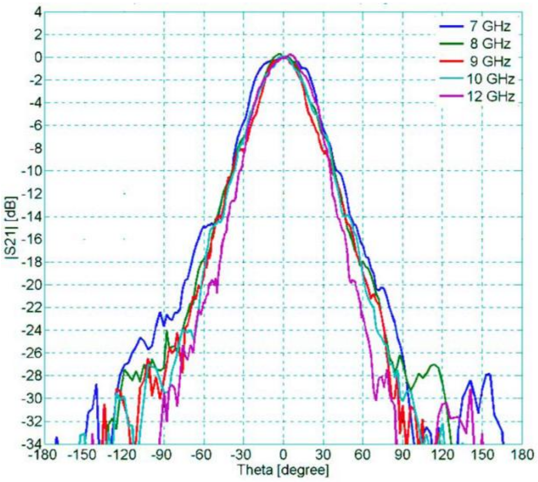
• A 2 to 12 GHz feed has been designed, tested, and installed on a 12m antenna giving 60% efficiency

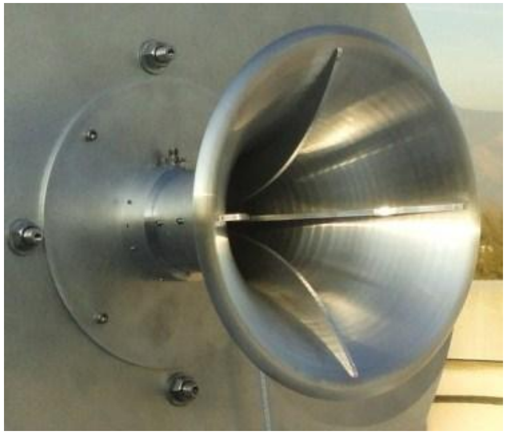
• Making this feed 4 times smaller, ~5cm diameter, would cover 8 to 48 GHz.

• Patterns are fairly constant from 8 to 50 GHz as required for an efficient feed for a parabolic reflector.

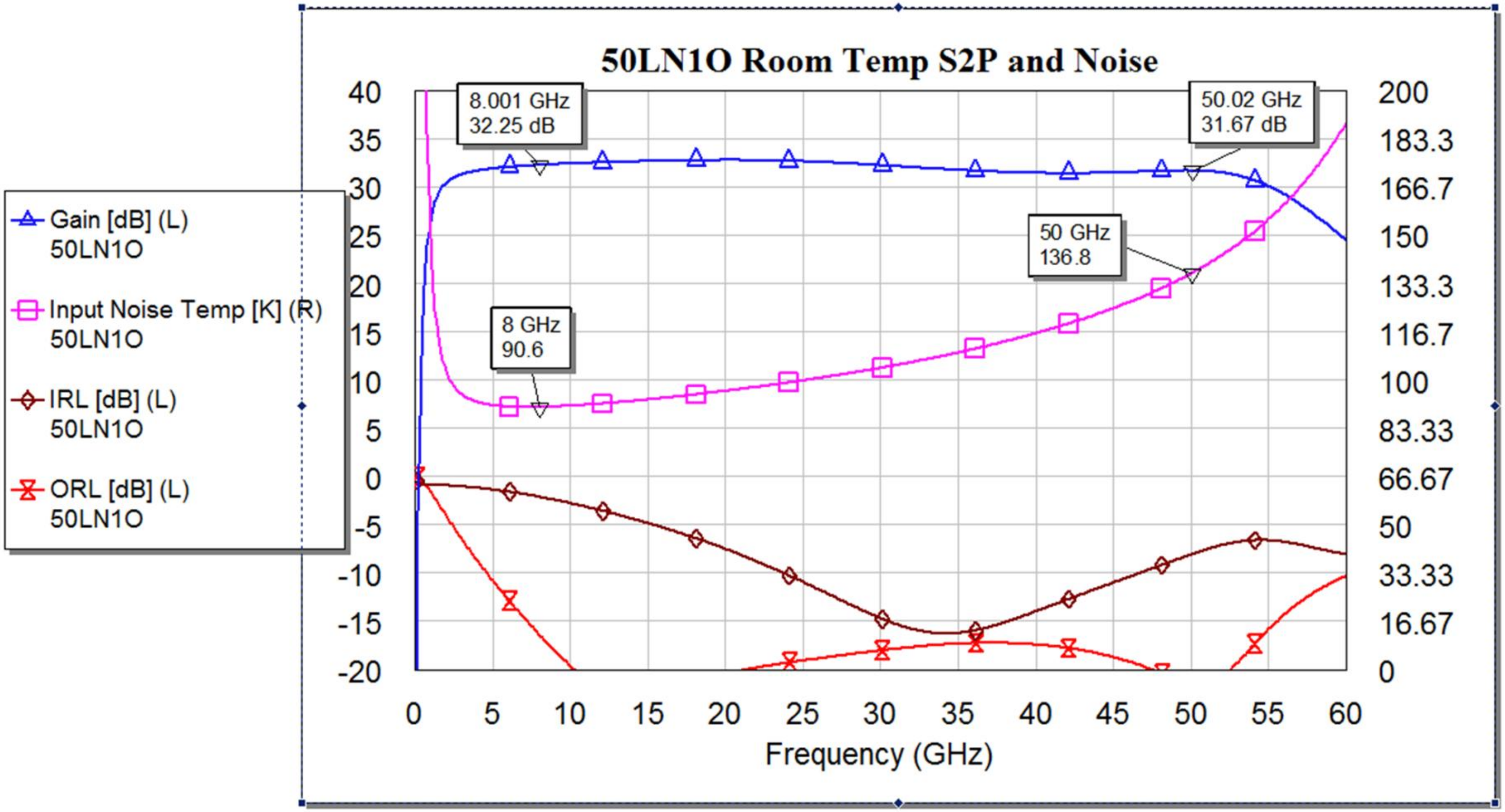
• Return loss is >15 dB over most of the frequency range.







Feasibility of 8 to 50 GHz Cryogenic Low Noise Amplifier

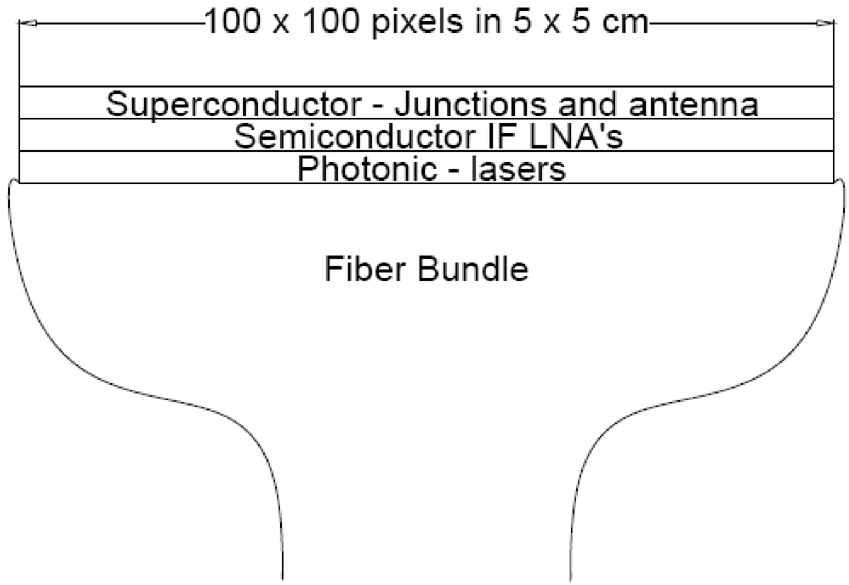


Future Dream – The Radio Photographic Plate!

A Millimeter Wave, 10,000 Pixel, Camera

Wafer Scale Integration of SIS/LNA/Photonic 300 GHz Spectrometer Array

1) Hot via interconnections
2) Needs feasibility study leading to 5 year plan
3) Alternative to photonics is miniature flexible printed-circuit ribbons



Recommendations for US cm-Wave Radio Astronomy in the 2010-2030 Era

International Mid Frequency SKA - Support the international SKA with technology development where needed.

US High Frequency Array - Construct an array in the US with 4 times the EVLA area for the 8 to 50 GHz range in the 2018-2025 interval at a cost capped at $300M..

Technology Development Plan - Between now and 2018 develop the array technology to support the above instrument at a cost cap of $20M.

Combined Array for Radio Astronomy and Space Communication – Share costs for construction and operation of the US 50 GHz array with NASA. A receiving array as large as SKA would be of great value to NASA for critical events and emergencies

Large Arrays Can Greatly Expand the Data Rate from Distant Spacecraft