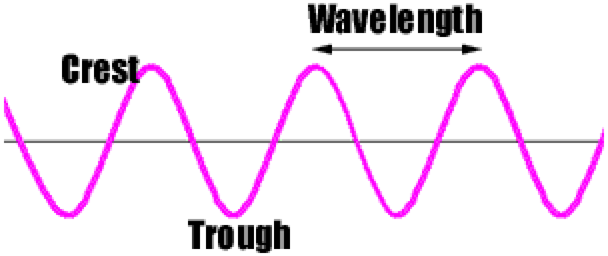
An Introduction to Radio Astronomy

Sander Weinreb

September, 2012

1. Introduce electromagnetic waves
2. Discovery of radio astronomy in 1932
3. How I got into radio astronomy – my life work
4. Most fascinating topics in radio astronomy – the cosmic background glow, pulsars, and SETI
5. Radio telescopes and instruments

We See Water Waves but Usually Do Not See Electromagnetic Waves



Water waves travel slowly but EM waves travel at the speed of light – 300,000 kilometers/second

EM waves with different wavelengths have very different applications and interact with us in very different ways

We see the EM waves that have wavelengths of around 1 micrometer.

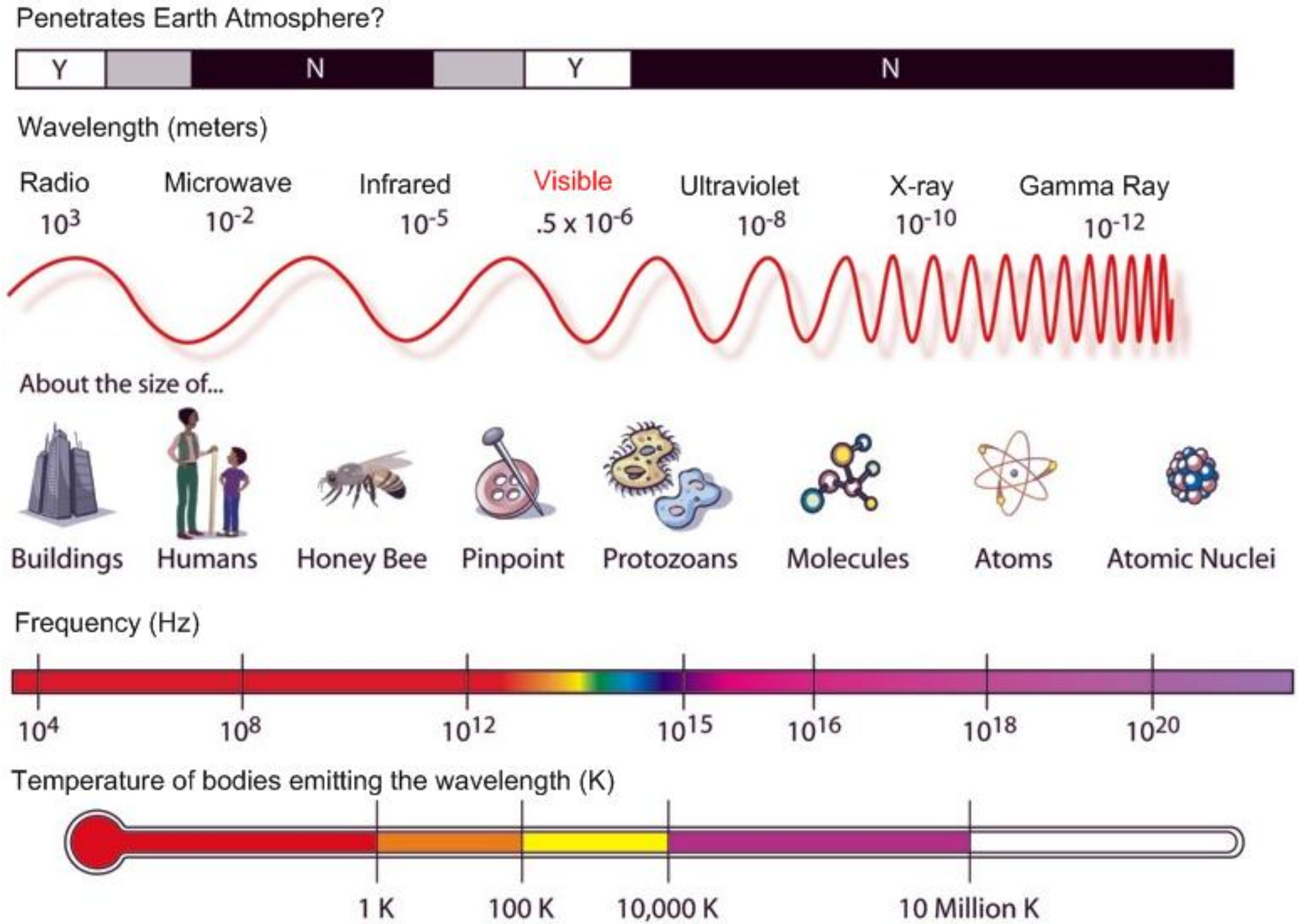
Our cell phones receive EM waves with wavelength around 30 cm.

Electromagnetic (EM) Waves

- EM waves have different wavelengths with very different properties depending upon the wavelength. Some examples are:

  - ✓ **Radio Waves** – Used by cell phones and TV – 1 meter to 1 cm wavelength
  - ✓ **Microwaves** – Used in microwave ovens – 14 cm wavelength
  - ✓ **Infrared Waves** – You feel them as heat – 10 micrometer wavelength
  - ✓ **Optical Waves** – You see them! Emitted by light bulbs and the sun – 1 micrometer wavelength
  - ✓ **X-Rays** - They go through you! - .0001 micrometer

The Electromagnetic Spectrum



Thermal Electromagnetic Waves

- EM waves are also generated by all matter with strength proportional to the temperature of the object - infrared cameras see the EM waves emitted by people – you and I are emitting EM waves!

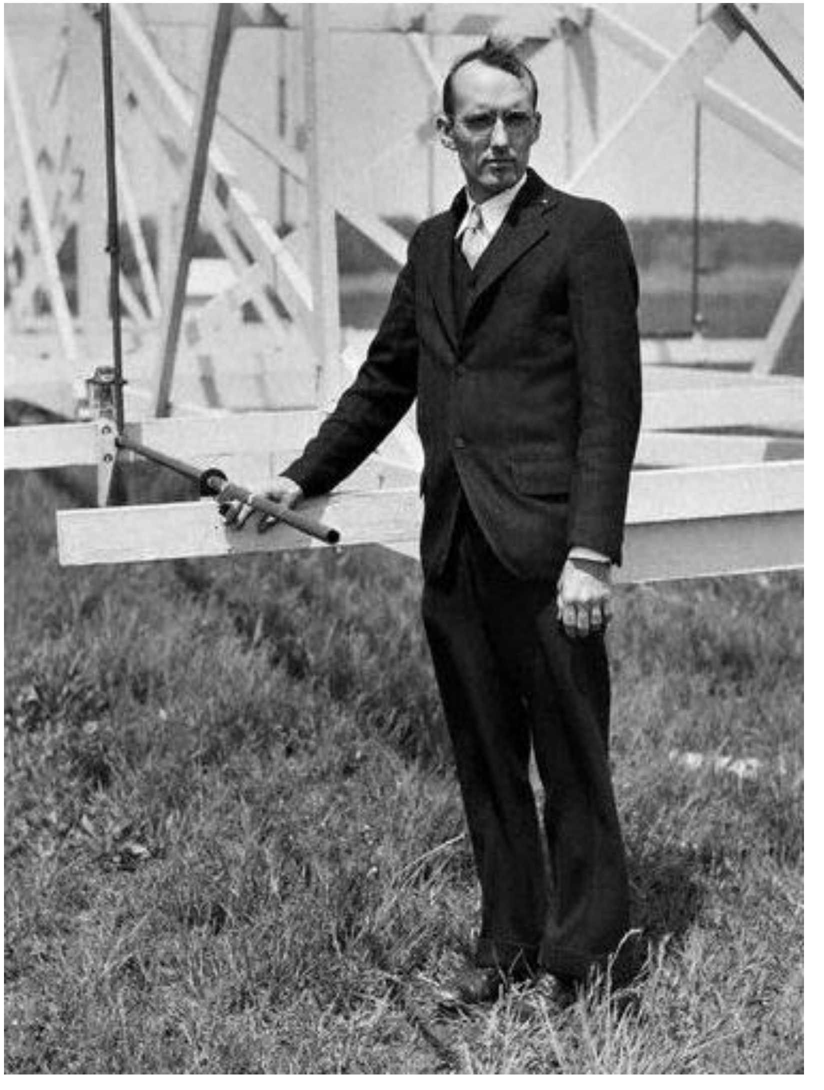
- EM waves are emitted by distant objects in the universe and are incident on the earth – we measure and study these waves in astronomy to learn about distant objects – moon, planets, sun, stars, galaxies

- The study of astronomical EM waves at radio wavelengths (mm to meter) is radio astronomy discovered by accident in 1932.

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.

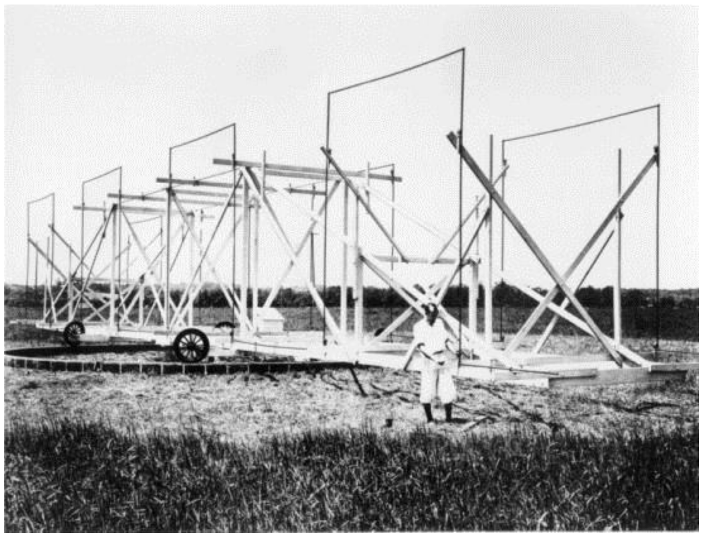
Mysterious static reported by K. G. Jansky, held to differ from cosmic ray. Direction is unchanging. Recorded and tested for more than a year to identify it as from Earth's galaxy. Its intensity is low. Only delicate receivable able to register—no evidence of interstellar signaling.

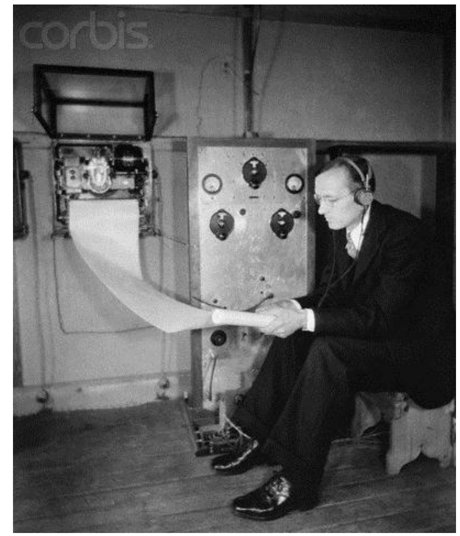


- Discovered first cosmic radio wave by accident while investigation "static" associated with trans-atlantic telephone calls.
- Wanted to build a 30m dish antenna to follow up on his discovery but was not granted the funds to do so.
- Professional astronomers ignored the discovery and an amateur, Grote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





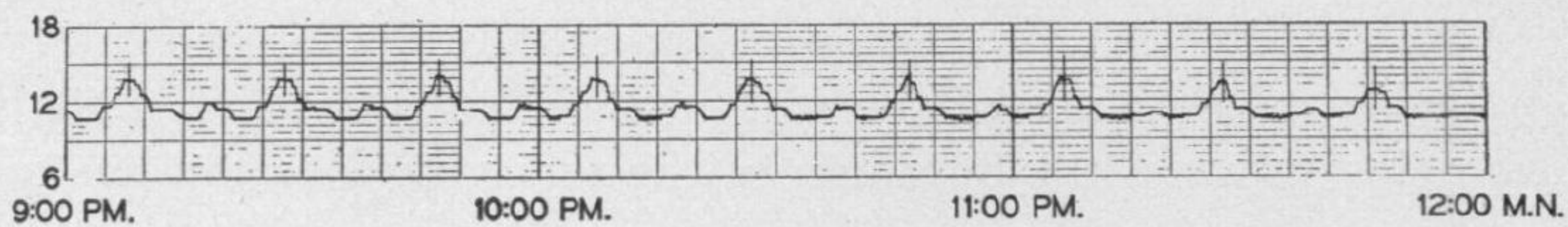
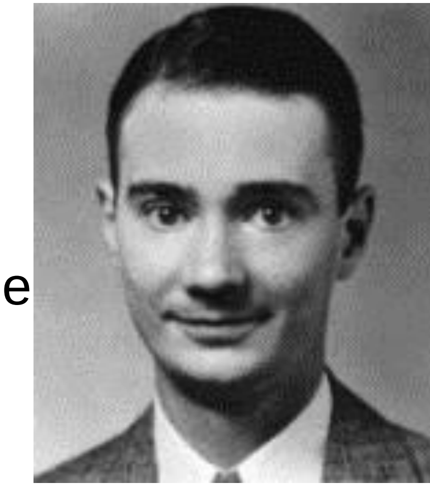


Fig. 2—Sample record of waves of interstellar origin. Record taken 12:00 noon to 12:00 midnight on September 16, 1932.

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.

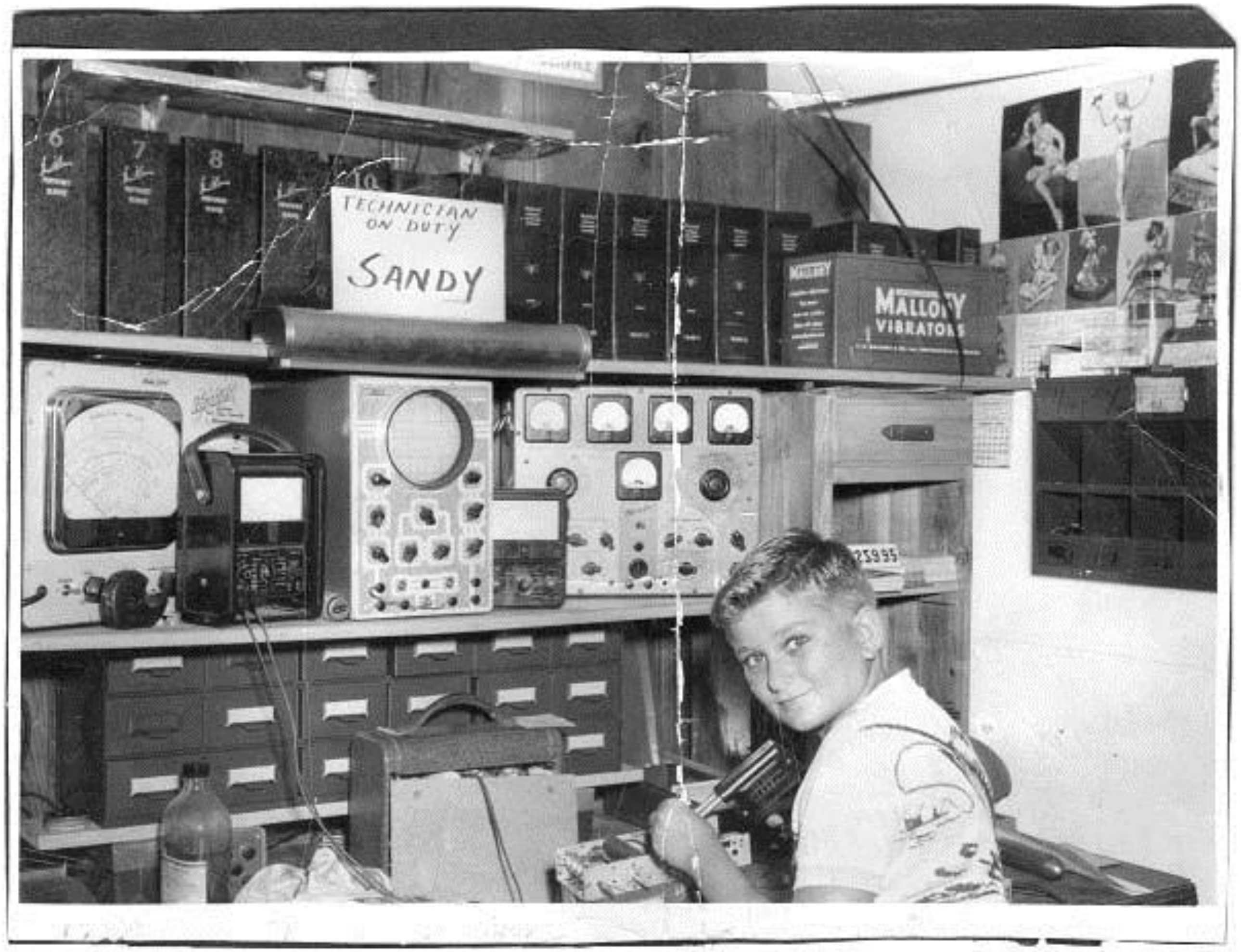
Following in Reber's Footsteps

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

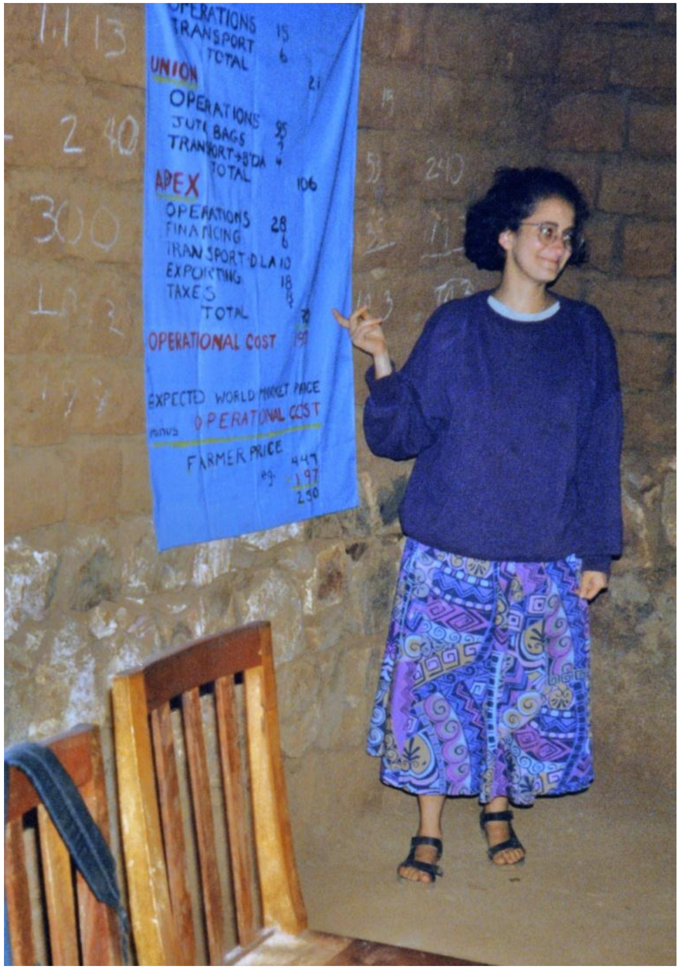
- Gave him birthday present of Heathkit Microprocessor Trainer Kit, $200, best investment I ever made!

- 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!

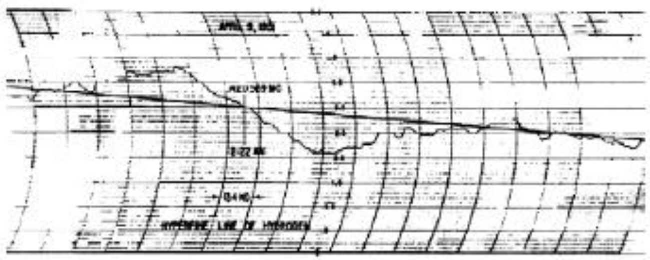
Last Name Weinreb First Sandy Middle Semester Ending 6/4/54

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	Colley J
Social Studies	SP	B	B	B	1/2	Kieffer J
Science Chem.	2	B	B	B	1/2	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	J
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

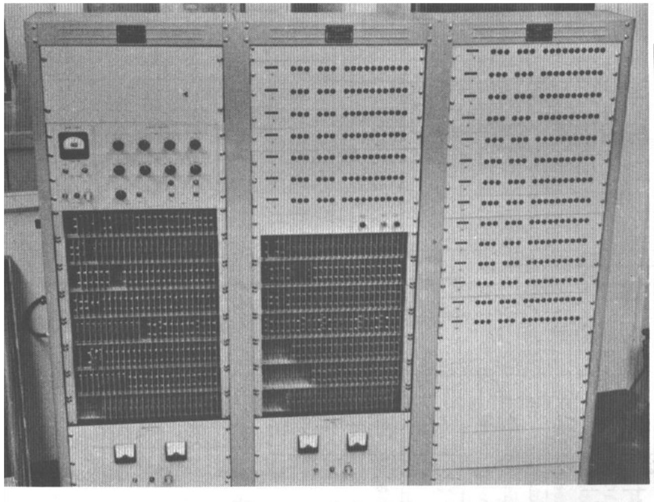
Harlow Shapley)

January 1949

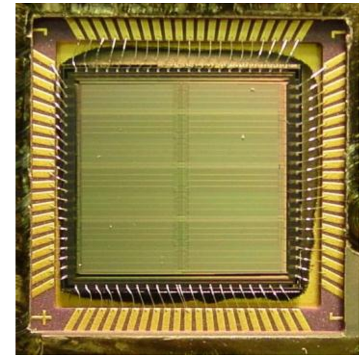
Itemized List includes:

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

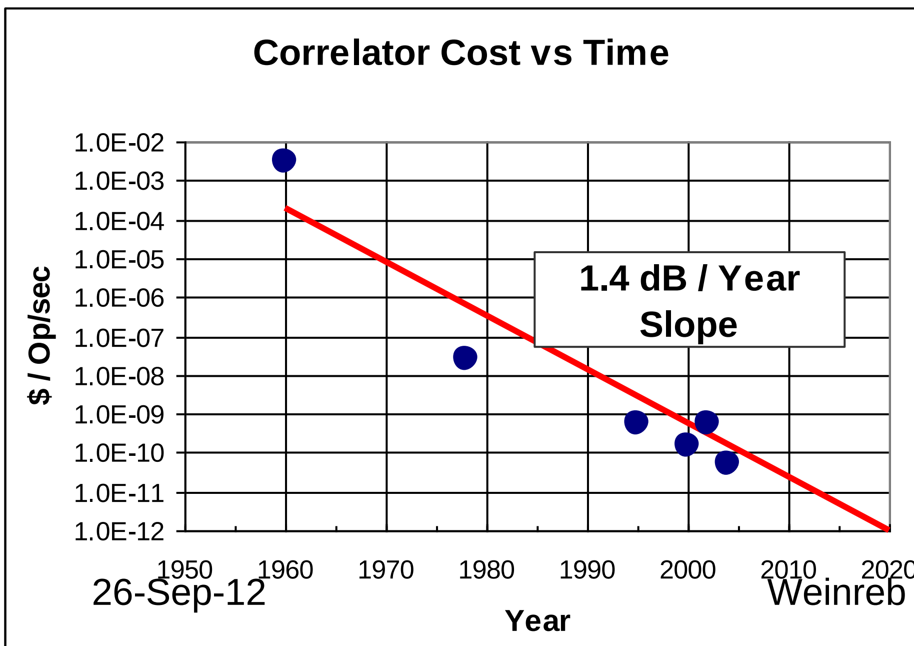
The Development of Correlators in Radio Astronomy



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

From One Radio Molecular Line in 1963 to Thousands in 1987

- Enables Chemical Studies of Star Formation Regions

Terahertz Spectroscopy 233

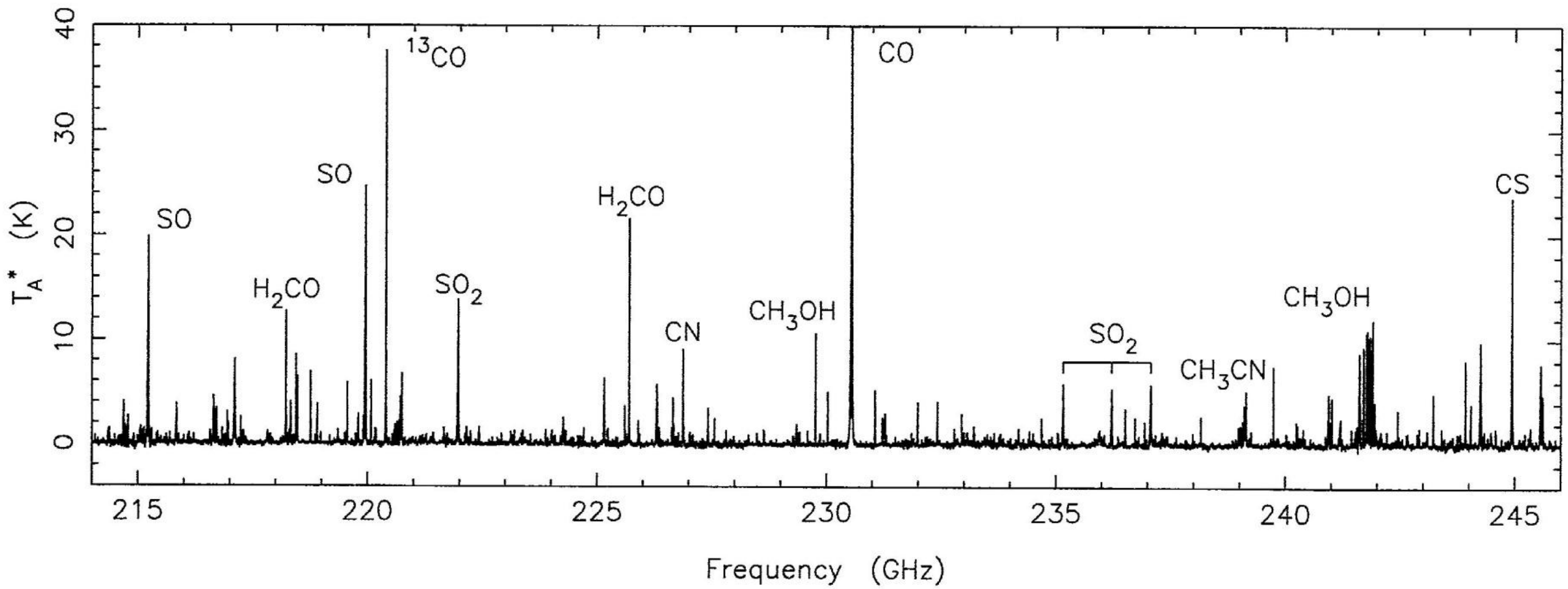


Figure 1. The OVRO 1.3 mm spectral line survey of Orion KL (adapted from Blake et al. 1987). A survey RMS of ~0.2 K was achieved after 20+ nights of integration.

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.

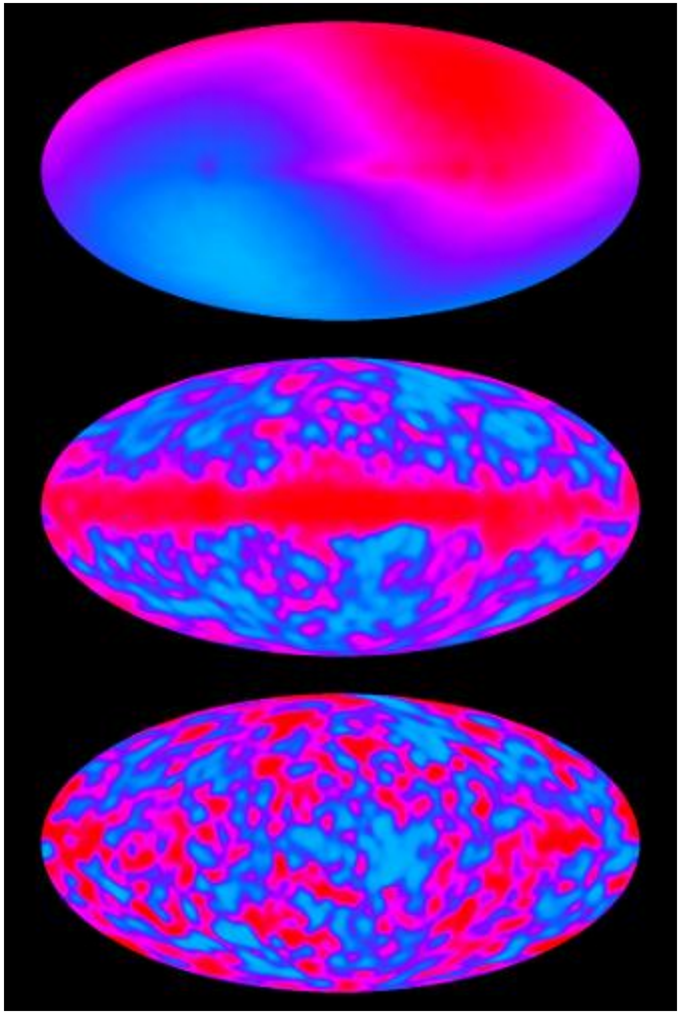
Microwave Sky Background Radiation

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.

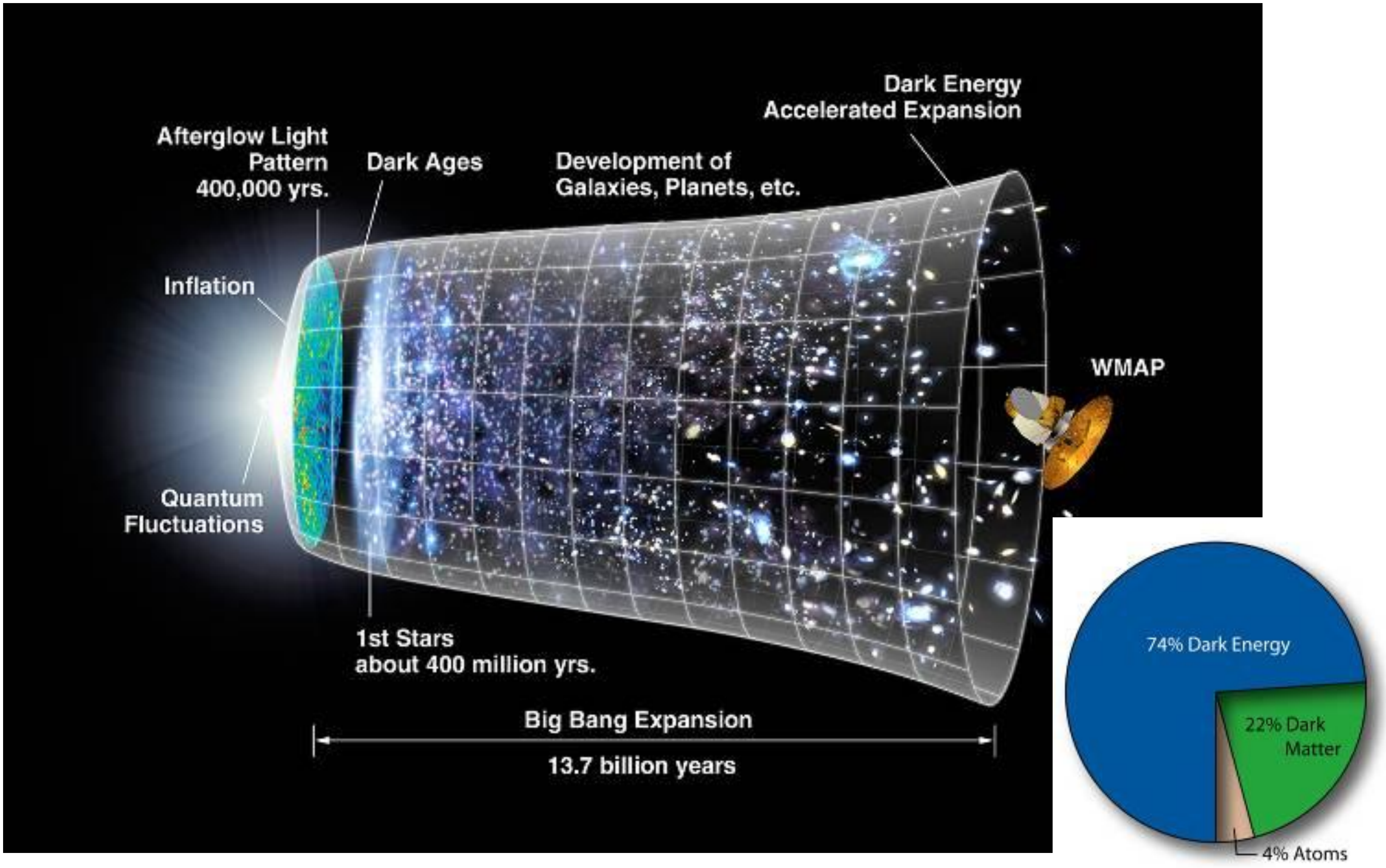


After subtraction of the 2.725K mean to reveal the mK dipole due to motion of our galaxy

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.

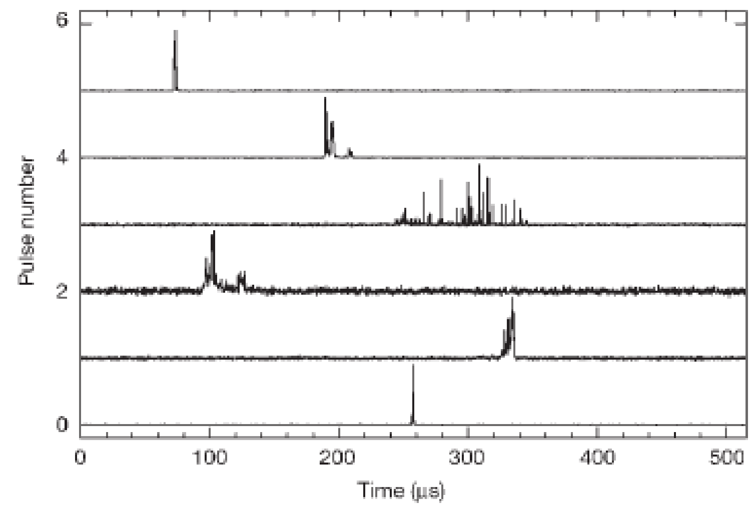


Figure 1 A sequence of dedispersed Crab giant pulses. The arrival time jitter and varied shapes of the total intensity are shown. The time axis origin is modulo one pulsar rotation period. Each pulse has been plotted with a time resolution of 250 ns and is normalized to the same maximum amplitude. The 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. What is the next step?
- 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 0 1 1 0 0 0 0 1 1 0 1 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 1 0 1 1 0 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 0 1 0 0 0 1 0 0 1 1 1 1 1 0 0 0

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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

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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

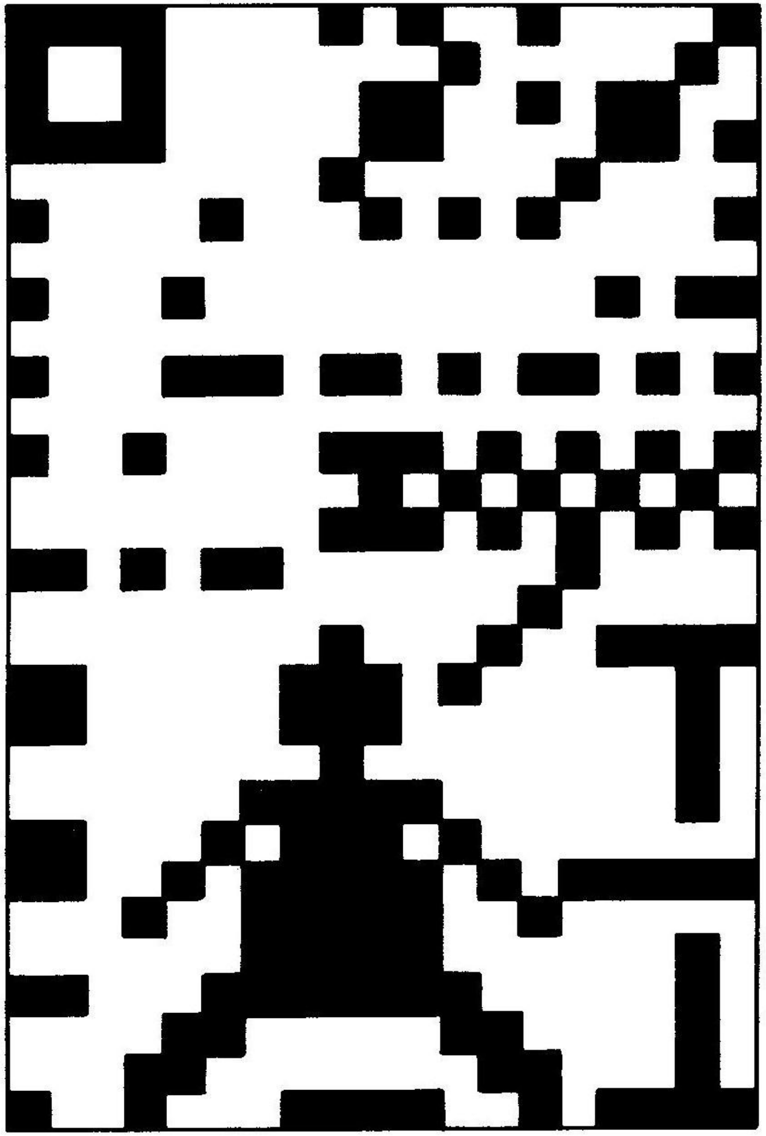
0 0 1 0 0 0 1 1 1 1 0 0 1 0 1 1 1 1

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

What I Do – Instruments for Radio Astronomy

1) Radio telescopes – parabolic reflectors – show principal and examples of large reflectors

2) Arrays of reflectors – show VLA, ALMA, SKA

3) Low noise amplifiers

Caltech EE Radio Astronomy Group, May, 2010

Ahmed Akgiray – Ph.D. student SKA feed design and integration

Hamdi Mani – Research technician worked on everything

Glenn Jones - Ph.D. graduate 2009 works on wide bandwidth processing

Zan Zhang – MSEE graduate 2010 SKA feed design and tests

Damon Russell – Ph.D. student LNA design and testing

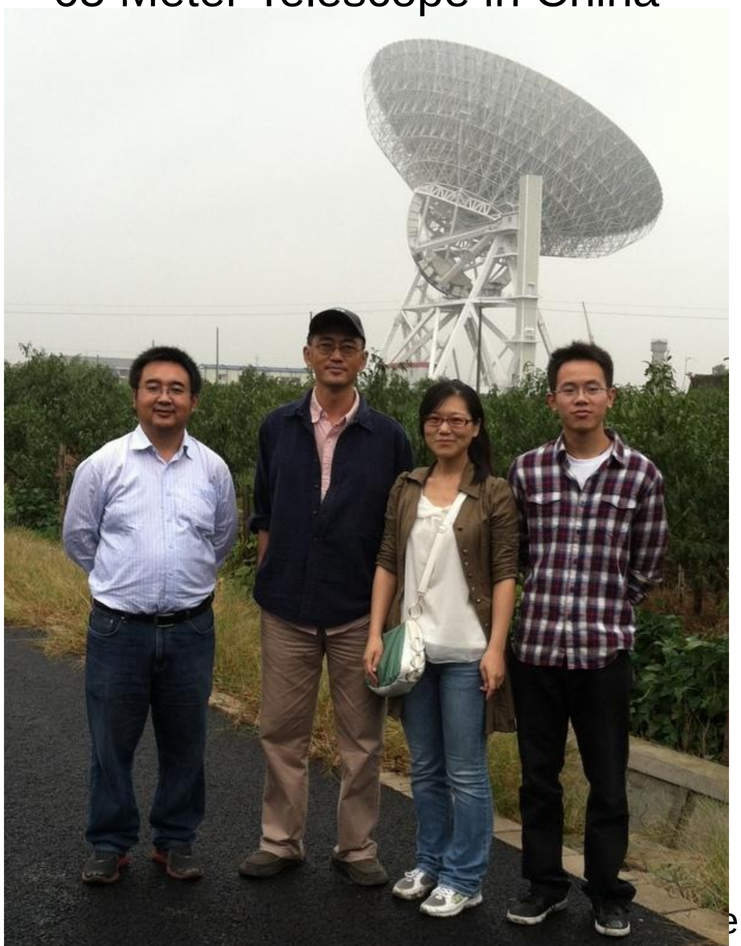
Steve Smith – Research engineer, LNA's, systems

Hector Navarette – Research technician, LNA's construction

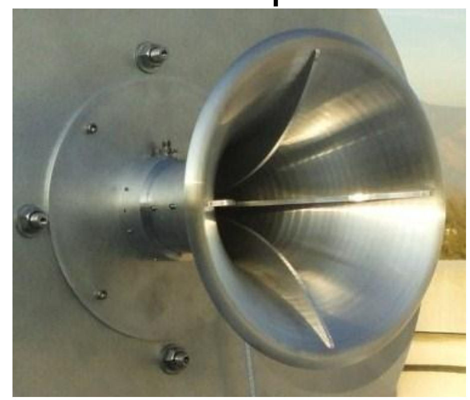
Joe Bardin – Ph.D. graduate SiGe Cryogenic LNA's

Radio Telescopes

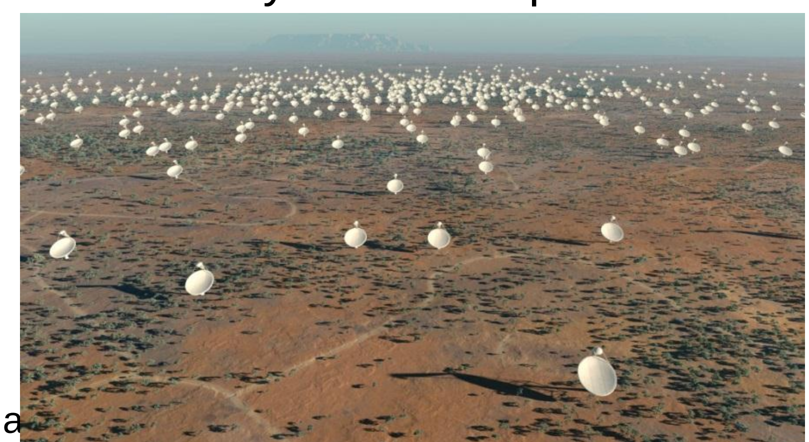
65 Meter Telescope in China



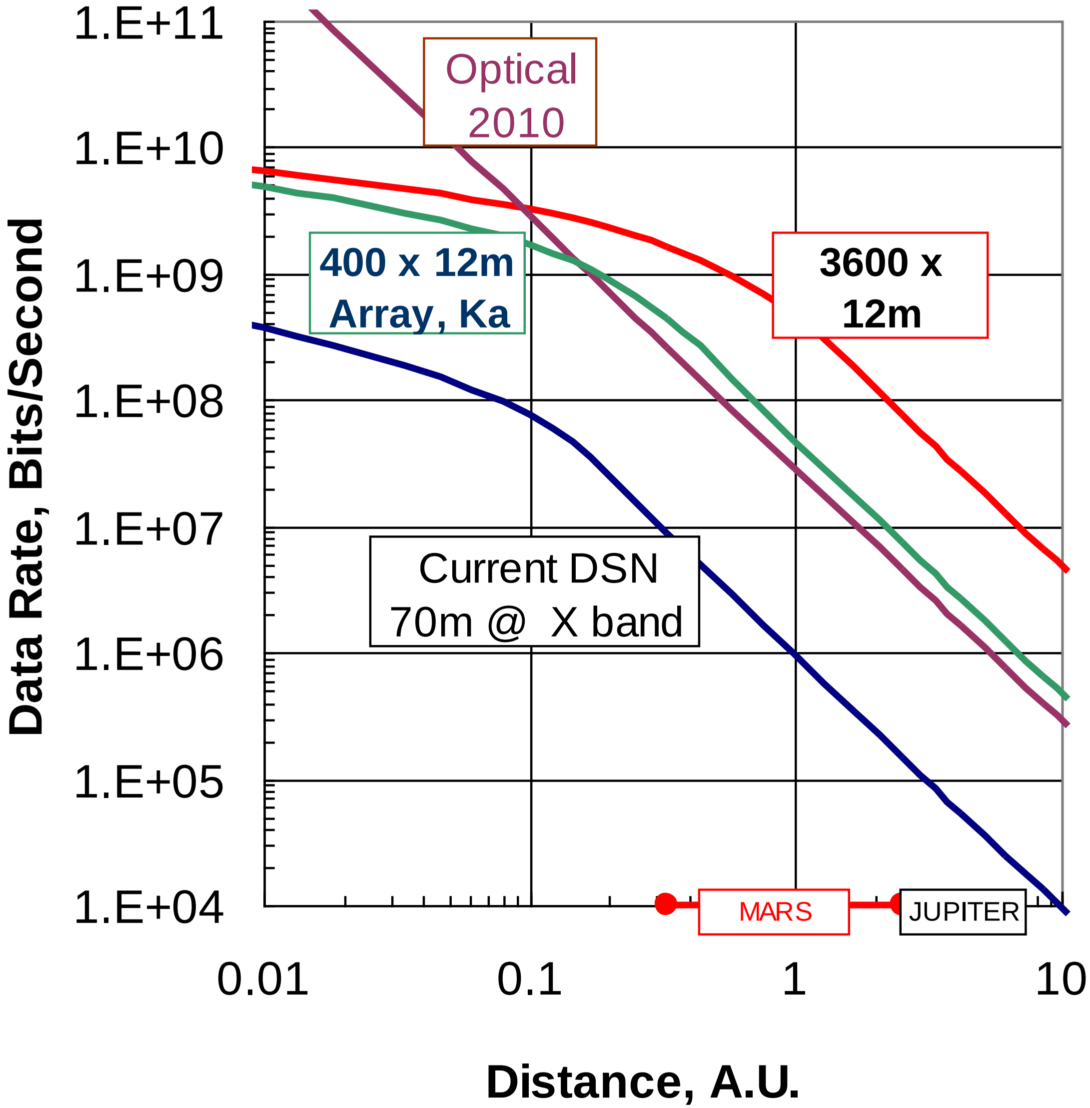
Feed Collects Waves Reflected by Telescope



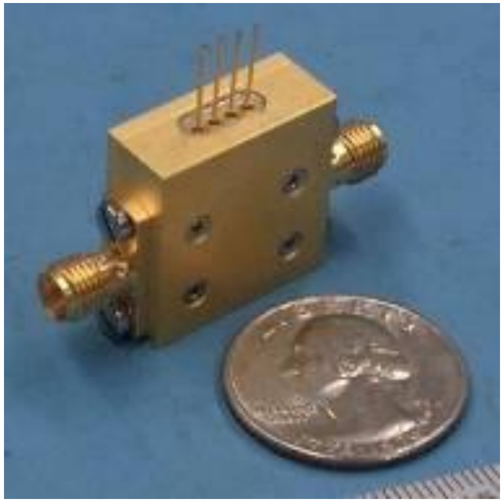
Array of Telescopes

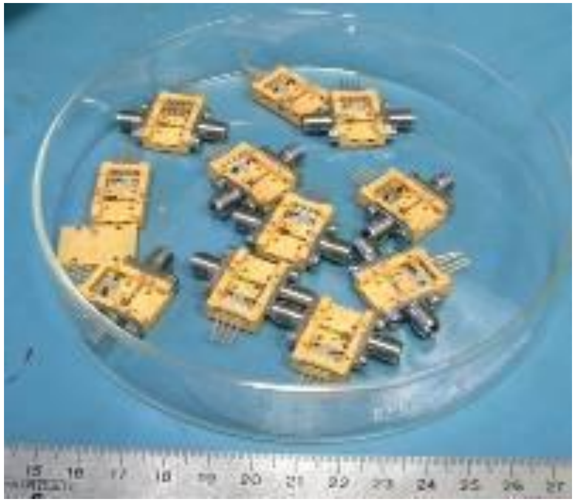


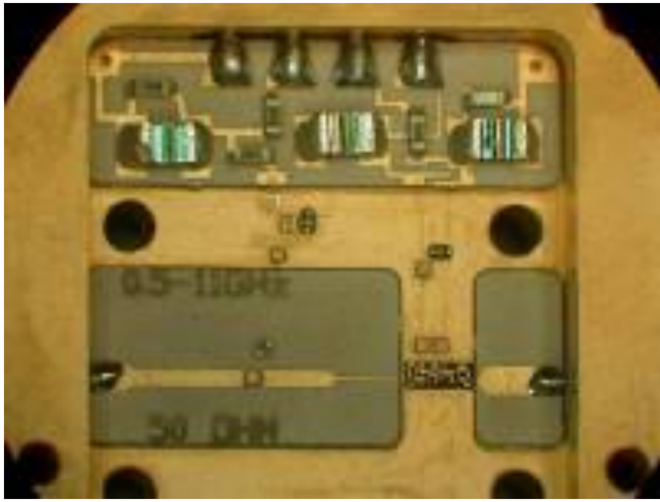
Large Arrays Can Greatly Expand the Data Rate from Distant Spacecraft



My Group at Caltech Develops Ultra-Sensitive Amplifiers Used to Receive Radio Astronomy EM Waves at Many Observatories World-Wide

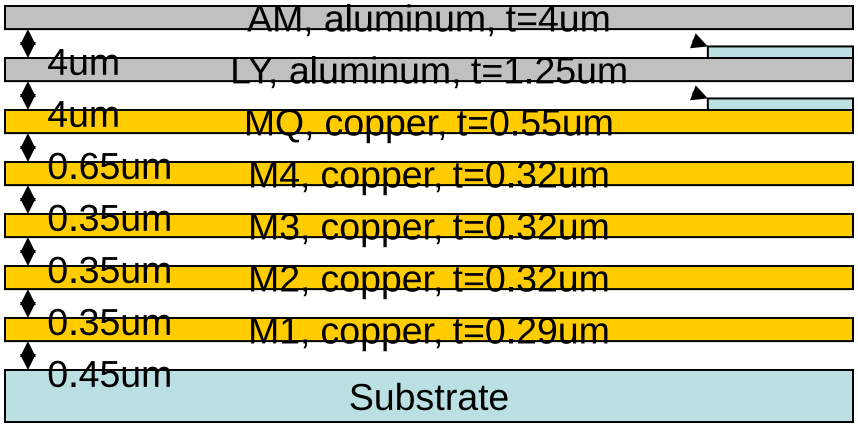


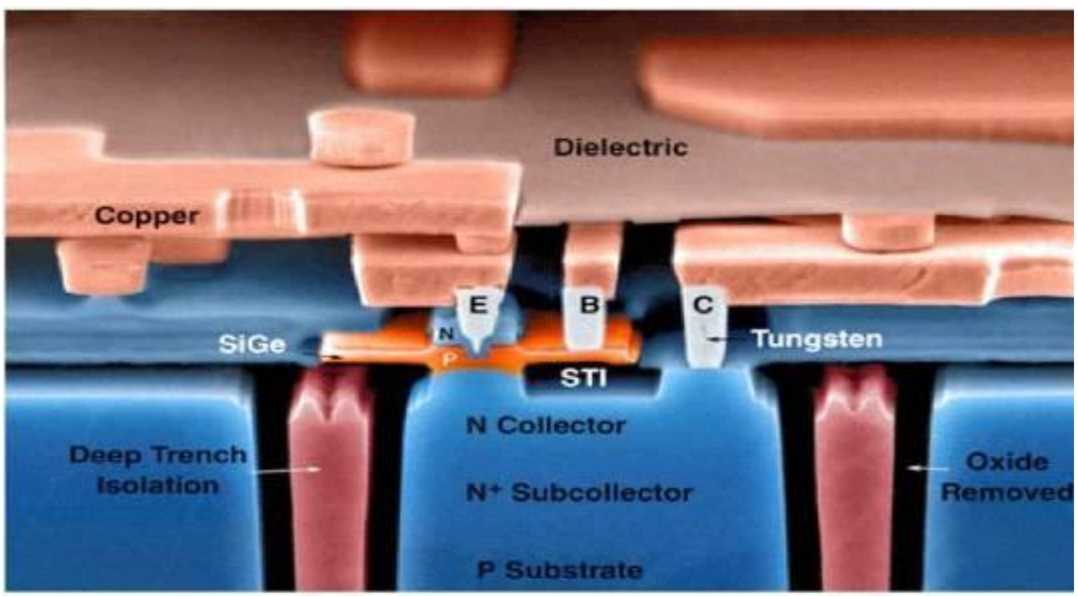




SiGe Integrated Circuit Cross-Section

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





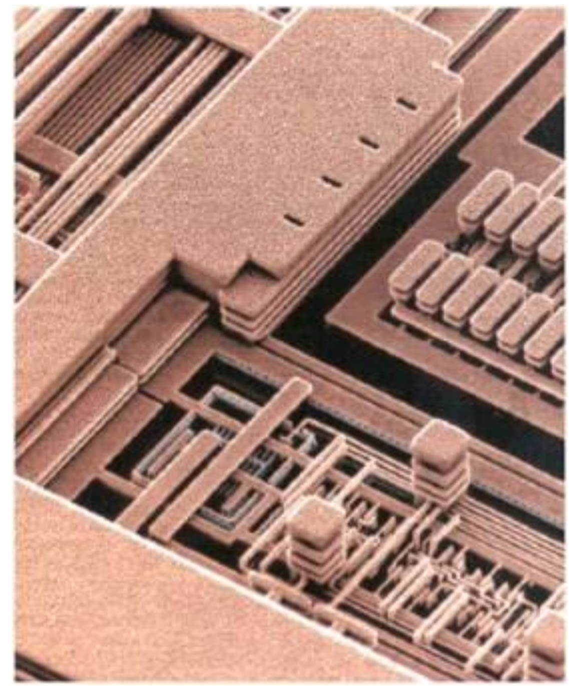


Photo reproduced from: http://users.ece.gatech.edu/~cressler/

Recommended Reading

Asimov on Astronomy [ペーパーバック]
Isaac Asimov (著)
1975, Doubleday, ISBN 0385068816

Asimov is a great science fiction writer but the above book is not fiction! He starts with the earth and then expands out to planets, the sun, stars, and galaxies – all written in an easily understood style with no equations.