An Introduction to Radio Astronomy and Meteor forward scatter With Gnu Radio and SDR

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VE3MDL

Image appears courtesy NRAO/AUI

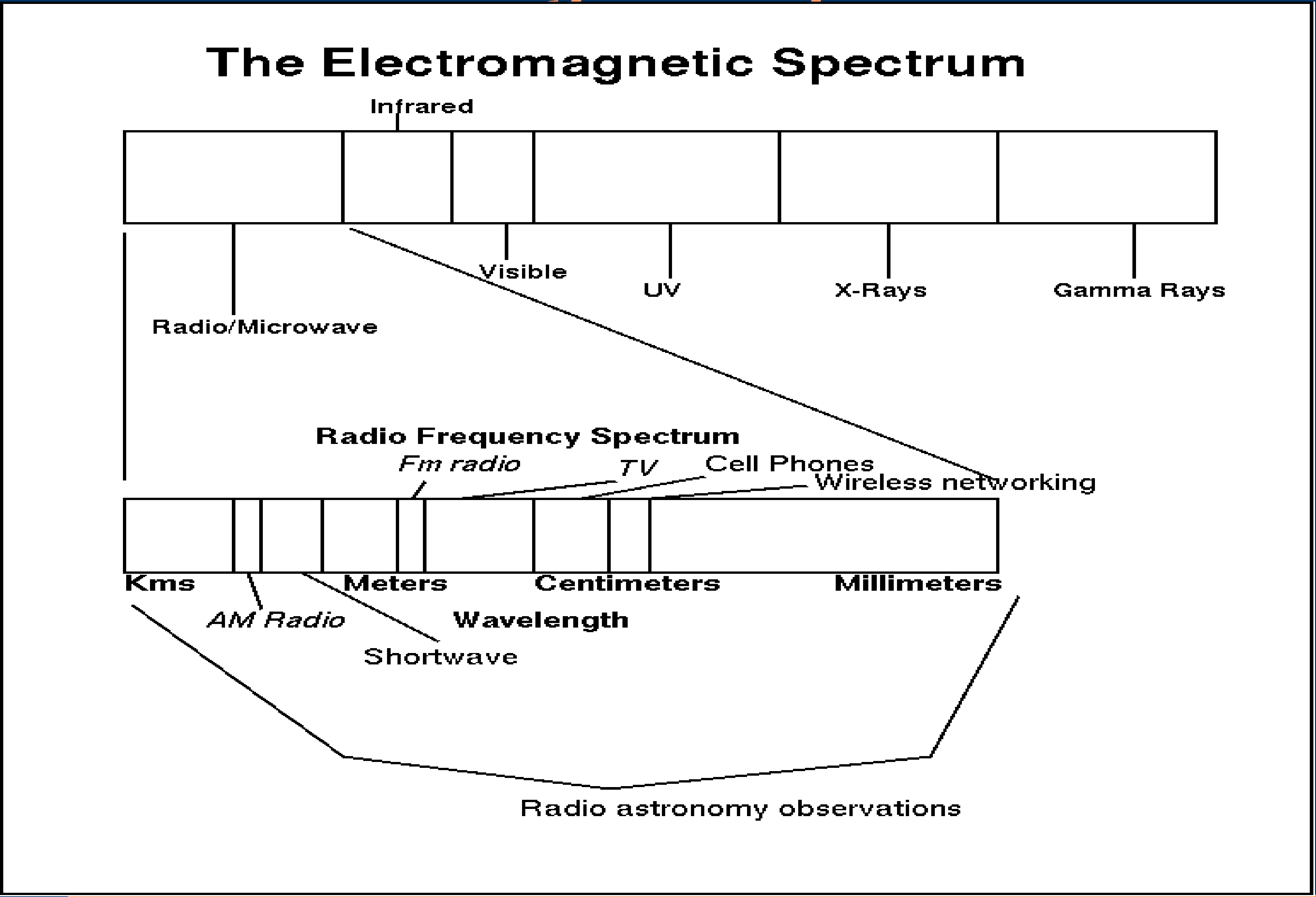
What is Radio Astronomy?

- Astronomy at wavelengths from a few mm to tens of meters
- Visible light has wavelengths in the region of 500nm, that is, 5.0×10^{-7} meters
- From a physics standpoint, there's no difference between visible light, and microwave/radio-wave “light”.
- Living things have receptors for only a tiny part of the EM spectrum

Optical vs Radio Astronomy

- Ability to resolve fine detail highly dependent on wavelength
- A 10cm optical telescope can resolve details that would require a radio telescope over 42km in diameter at 21cm wavelength!
- Sensitivity, however, is proportional to collecting area of the reflector, regardless of wavelength
  - Both use parabolic reflectors
  - Both must have a surface that is within 1/10th of a wavelength of a “perfect” parabola.

The Electromagnetic spectrum

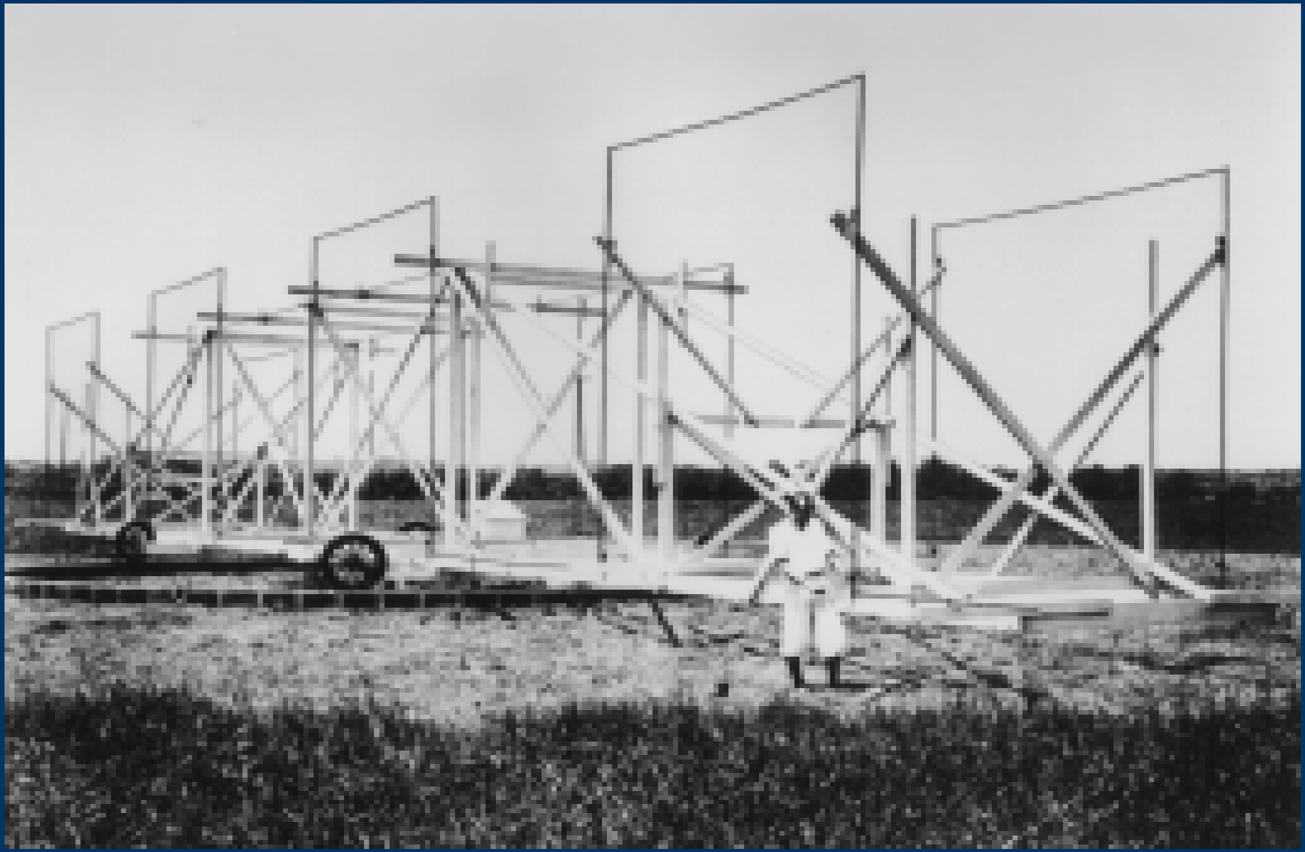


History of Radio Astronomy

- Like much in science, it was discovered accidentally
- Karl Jansky, 1933, working on sources of static on international radio-telephone circuits at wavelengths of 10-20m.
- Discovered that static rose and fell with a period of 23 hours, 56 minutes.
  - Must be of celestial origin

History, continued

- Built directional antenna
- Pinpointed source at galactic centre, in Sagittarius



The Genesis of Radio Astronomy Science

- Jansky was re-assigned to other projects after his work on radio-telephone “hiss”.
- Several years went by with nobody understanding the significance of his discovery
- Grote Reber picked up on Janskys work in 1937, building a 30ft dish in his back yard.
  - Eventually mapped entire Milky Way emission at 160MHz (1.8m wavelength)
  - Published in Astrophysical Journal in 1944
- Radio Astronomy now taken seriously

Grote Rebers Dish

- Now preserved as historical artefact at NRAO, Green Bank, West Virginia

Rebers observations

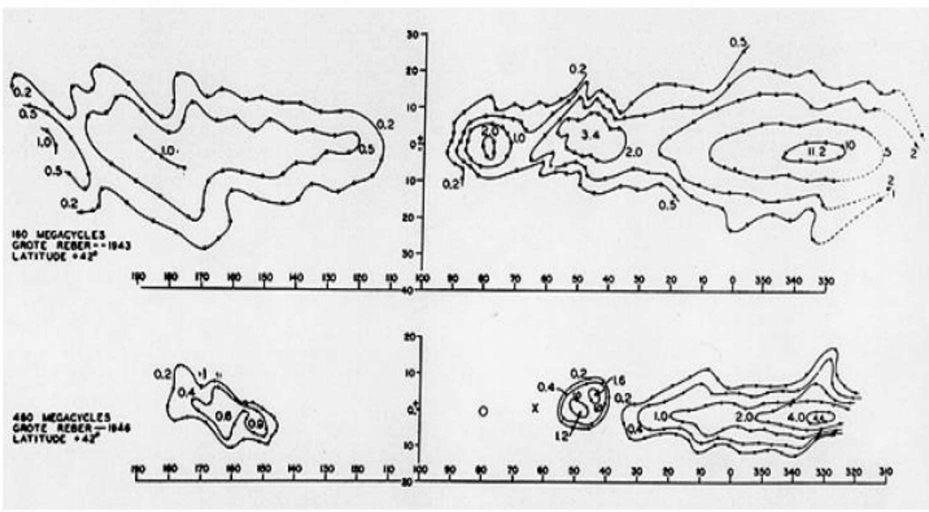
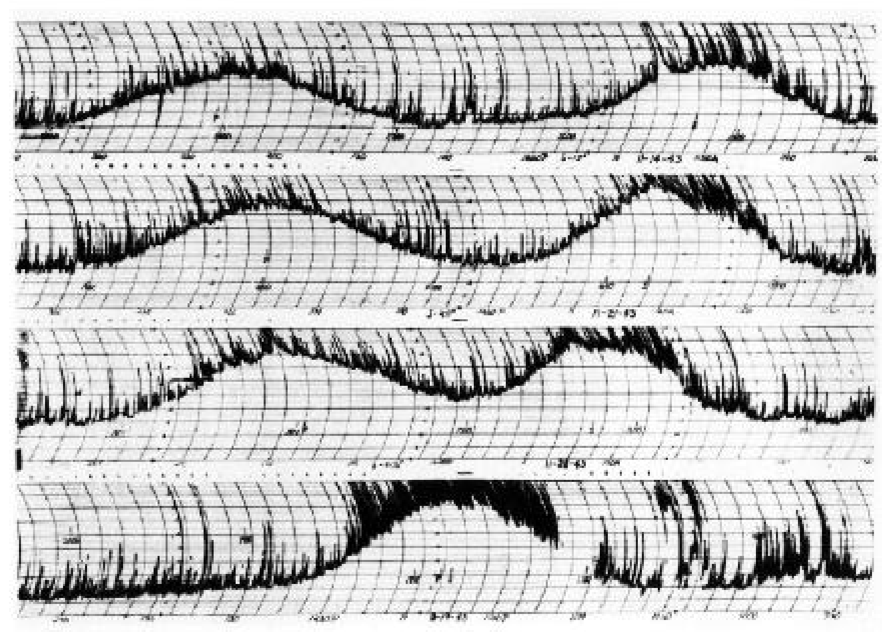


Figure 8. Contours of constant radio intensity on the sky at 160 MHz (top panel) and 480 MHz (bottom) taken by Reber from Wheaton, Illinois, in 1943 and 1946 respectively.

- 160 and 480MHz Skymap
- Made by hand from dozens of chart recordings

Figure 7. Some sample chart recorder output from Reber's early experiments.



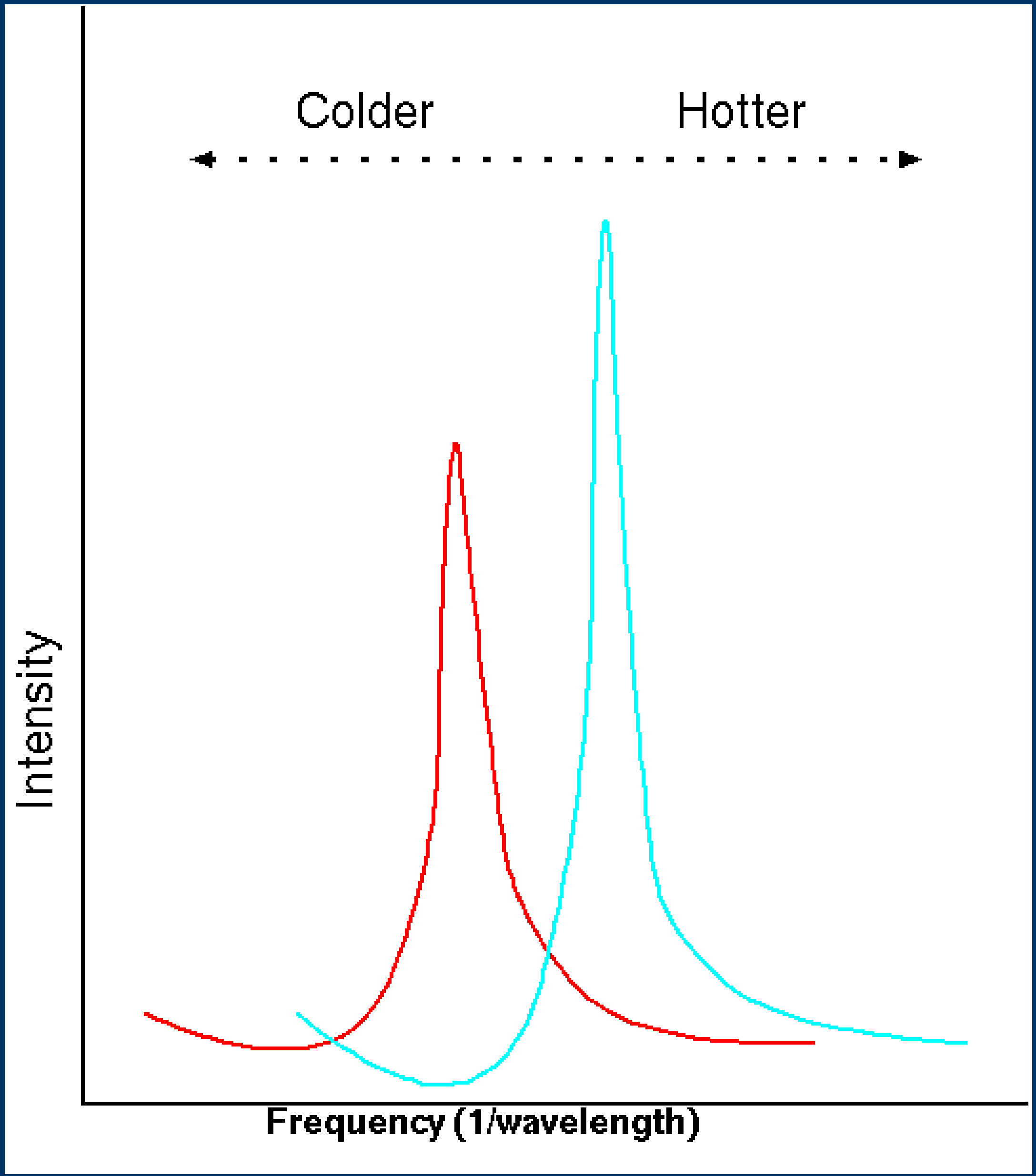
Radio Astronomy Today

- Radio Astronomy at the cutting-edge of astrophysical research
  - Roughly 70% of what we know today about the universe and its dynamics is due to radio astronomy observations, rather than optical observations
- Big projects all over the world
  - VLA, New Mexico
  - Arecibo, Puerto Rico
  - GBT, Green Bank, West Virginia
  - Westerbork, Jodrell Bank, ALMA, Hat Creek, SKA, etc
- Scientists named the basic flux unit after Karl Jansky
  - 1 Jansky == 10^{-26} watts/hz/meter^2

How does the cosmos broadcast?

- Multiple mechanisms for emissions
  - Blackbody radiation
  - Synchrotron radiation
  - Spectral lines from molecular and atomic gas clouds
    - Universe is more of a chemical “soup” than you'd guess from optical observations alone. RA lets you “see” the invisible.
  - Pulsar emissions
  - Maser emissions
    - Special case of molecular line emissions
  - **C**osmic **M**icrowave **B**ackground

Blackbody radiation



- All objects that are warmer than 0K emit EM radiation over a wide spectrum
- Warmer objects have higher peaks, at higher frequencies (shorter wavelengths)

Synchrotron radiation

- Charged particles (e.g. electrons) accelerating through a magnetic field
- Intensity higher at lower frequencies
- Above 1GHz, synchrotron radiation very weak

Spectral Line Emissions

- Many atomic and molecular species undergo emissions due to quantum phenomenon
- Emission is spectrally pure: emitted at discrete frequencies, rather than a range of frequencies
- Lots of **really big** gas clouds in interstellar space, and in star-forming regions within galaxies

The 21cm hydrogen line

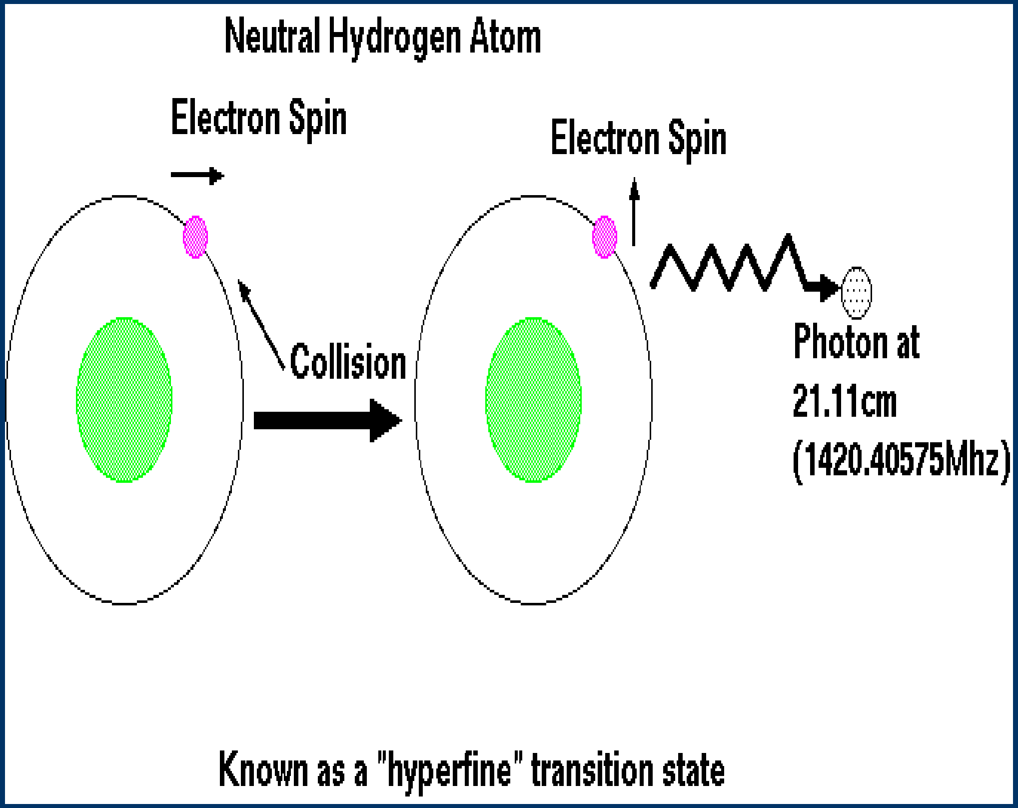
- Confirmed weeks later by team in Netherlands headed by Jan Van Oort.

- Emission at 21.11cm wavelength (1420.40575MHz).
- Van De Hulst proposed existence of neutral hydrogen in interstellar space in 1944.
- Successfully detected in 1951 by Ewen and Purcell at Harvard, using very modest instrument

21cm line continued

- Density of interstellar hydrogen very low
  - Less than 1 atom per cc of interstellar space!
- Emission caused by collisional energy transfer, causing electron spin change in neutral hydrogen
- A photon gets emitted at 21.11cm
- For a given atom, “perfect” collision only happens about once every 100,000 to 1,000,000 years!
- But along any given line of sight, there's a staggering amount of neutral hydrogen

21cm emission phenomenon



- Doesn't happen to molecular hydrogen
- Ionized hydrogen gas emits so-called Hydrogen-Alpha, which is visible light

Spectral lines and doppler effect

- Existence of spectral emissions allows science to map **velocities** of gas clouds within and outside the galaxy
- Doppler shift changes the **observed** wavelength/frequency of emission.
- Just like approaching/receding train whistle
- You can compute relative velocity by using the shifted wavelength and comparing to the “at rest” wavelength.
- EXTREMELY IMPORTANT RESULT

Pulsar emissions

- Underlying physics not well understood
- It is known that pulsar emissions originate from rapidly rotating neutron stars
- Emissions arise from two or more “beams” aligned with intense magnetic field of neutron star
- First discovered by Jocelyn Bell-Burnell in 1967
- First thought to be “Little Green Men”
- Her PhD supervisor, Anthony Hewish, later won the nobel prize for this outstanding discovery.
- Many feel **Jocelyn** should have won the prize!

Pulsar emissions, contd

- Pulse rates from once every 5 seconds, to several hundred pulses per second—very short pulses
- Over 2000 pulsars have been catalogued
- Rapidly-rotating pulsars allow us to study the deep mechanisms of gravitation
- Many pulsars are very, very accurate clocks
  - Better than the best atomic clocks humans can make
  - Massive **angular momentum** means that those pulses will be arriving at nearly the same rate thousands of years from now!

Cosmic Microwave Background

- Theorized by George Gamow, in 1948
  - Would have to be present if Big Bang theory correct
- Penzias and Wilson at Bell Laboratories discovered it while calibrating sensitive satellite communications experiment in 1965.
  - Found 2.7K excess system noise--why?
  - Received Nobel Prize in Physics for this work in 1978
- In 2006, George Smoot received Nobel Prize for mapping the so-called anisotropy (tiny variations) in the CMB, using a satellite to produce map.

Solar system objects

- Sun
  - Very strong microwave emitter
  - Makes daytime observing of weaker objects impossible
  - Upper solar atmosphere strong black-body emitter
- Moon
  - Black-body radiation with surface temperature around 200K
  - NOT reflection of solar microwave radiation!
- Jupiter/Io
  - Io plasma torus interacts with Jupiters magnetic field
  - Synchrotron emission peaked at 20-30MHz

SETI observing

- Some amateur RA observers also engage in amateur SETI research
- Looking for extremely-narrow “signals” near the hydrogen line frequency
- On the hairy edge of theoretical possibility
  - ET civilization within 100ly with 300-400M dish could produce signal strong enough for detection with amateur-sized dish (3.8m approx)
  - Could get “lucky”

Radio Astronomy Instruments

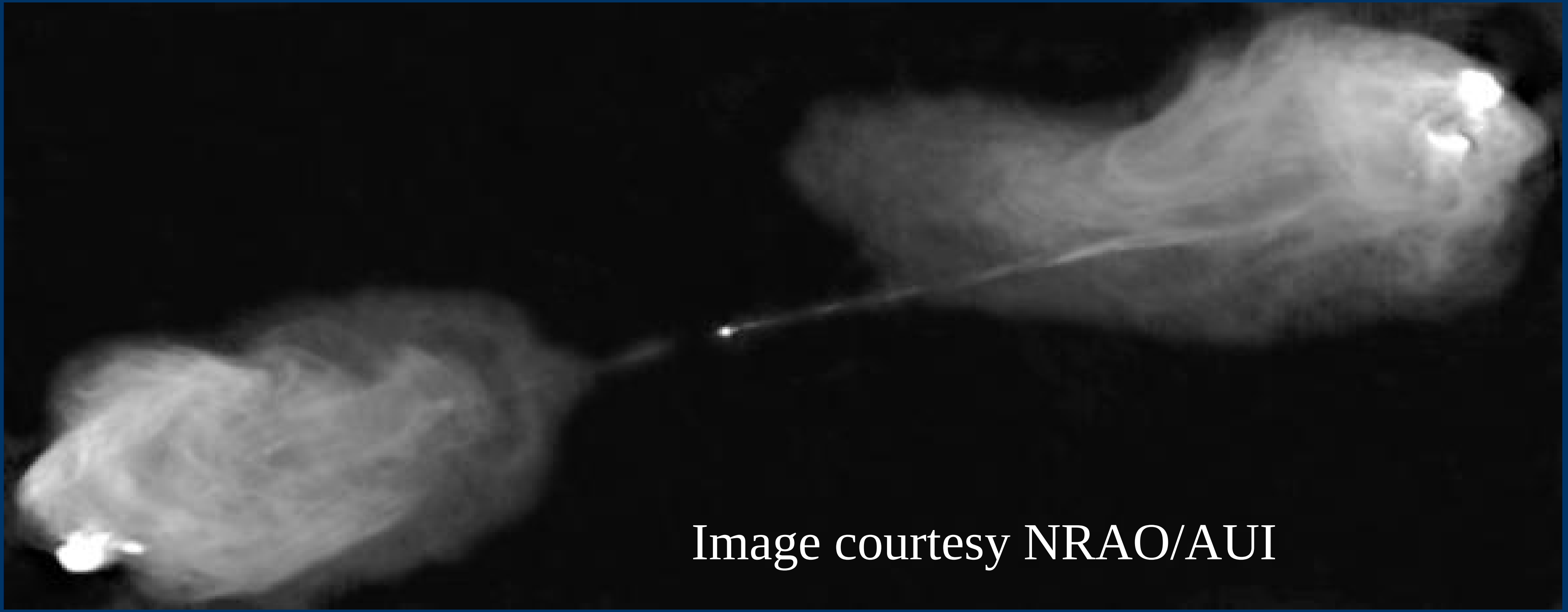
- Parabolic reflector
  - From a few meters to over 300m!
- Focal-plane antenna at focus of reflector
  - Waveguide
  - Dipole
  - Various
- One or more **L**ow **N**oise **A**mplifiers
  - Professional instruments chill the amplifiers in liquid Helium to reduce inherent electronic noise
  - Amateurs don't (usually) have that option
    - Use the best amplifiers they can afford
    - Sometimes chill with dry ice

Radio Astronomy instruments

- Receiver chain
  - Spectral
  - Total-power
  - Pulsar
- Back-end data processing
  - Pulsar processing can require enormous computer power
  - Total-power and spectral can require large amounts of storage space

Imaging with multiple dishes

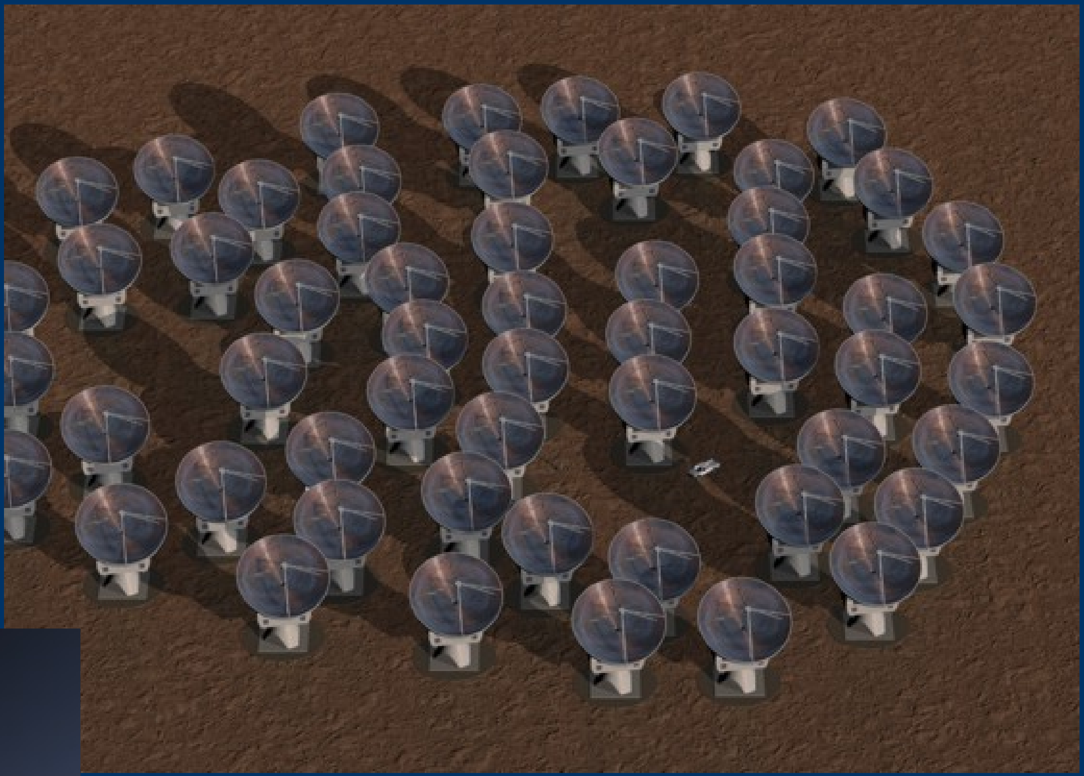
- Using multiple dishes, actual images can be formed using *interferometry*, and *image synthesis*

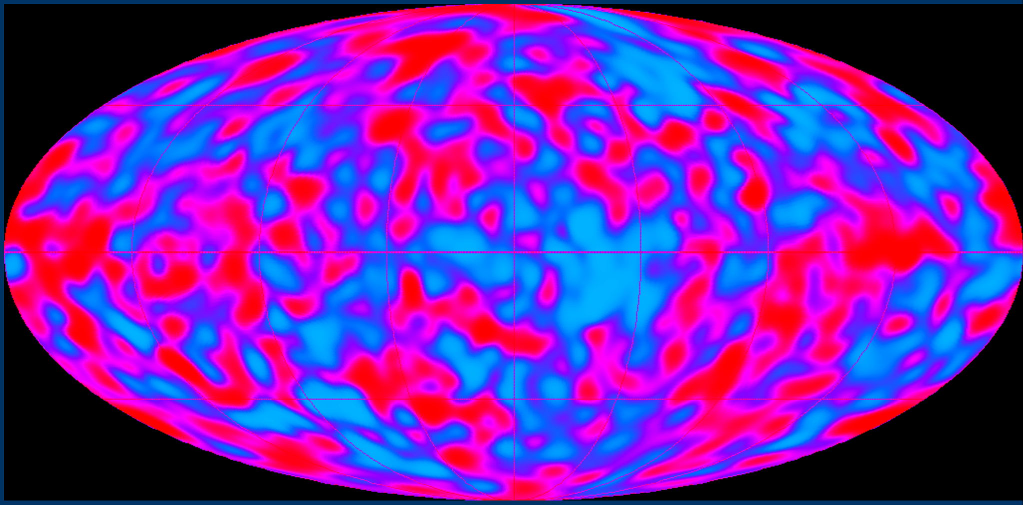


- This image was made with 27 dishes at the VLA, in New Mexico
- *Cygnus A* is 760Million light years away, with its features stretching over 400,000 light years

New RA science

- Many “big science” RA projects underway
  - SKA Square Kilometer Array
    - Goal is to build a multi-dish telescope with an effective collecting area of $1km^2$ or more!
  - ALMA Atacama Large Millimeter Array
    - 80 dish array, movable dishes
    - Located 5km up on the Atacama plain, Chile
    - Allows observing millimeter and submillimeter wavelengths
  - New CMB satellites: WMAP, PLANCK
    - More detailed maps of the CMB anisotropy



An amateur RA observatory

- Here's my (very modest!) dish

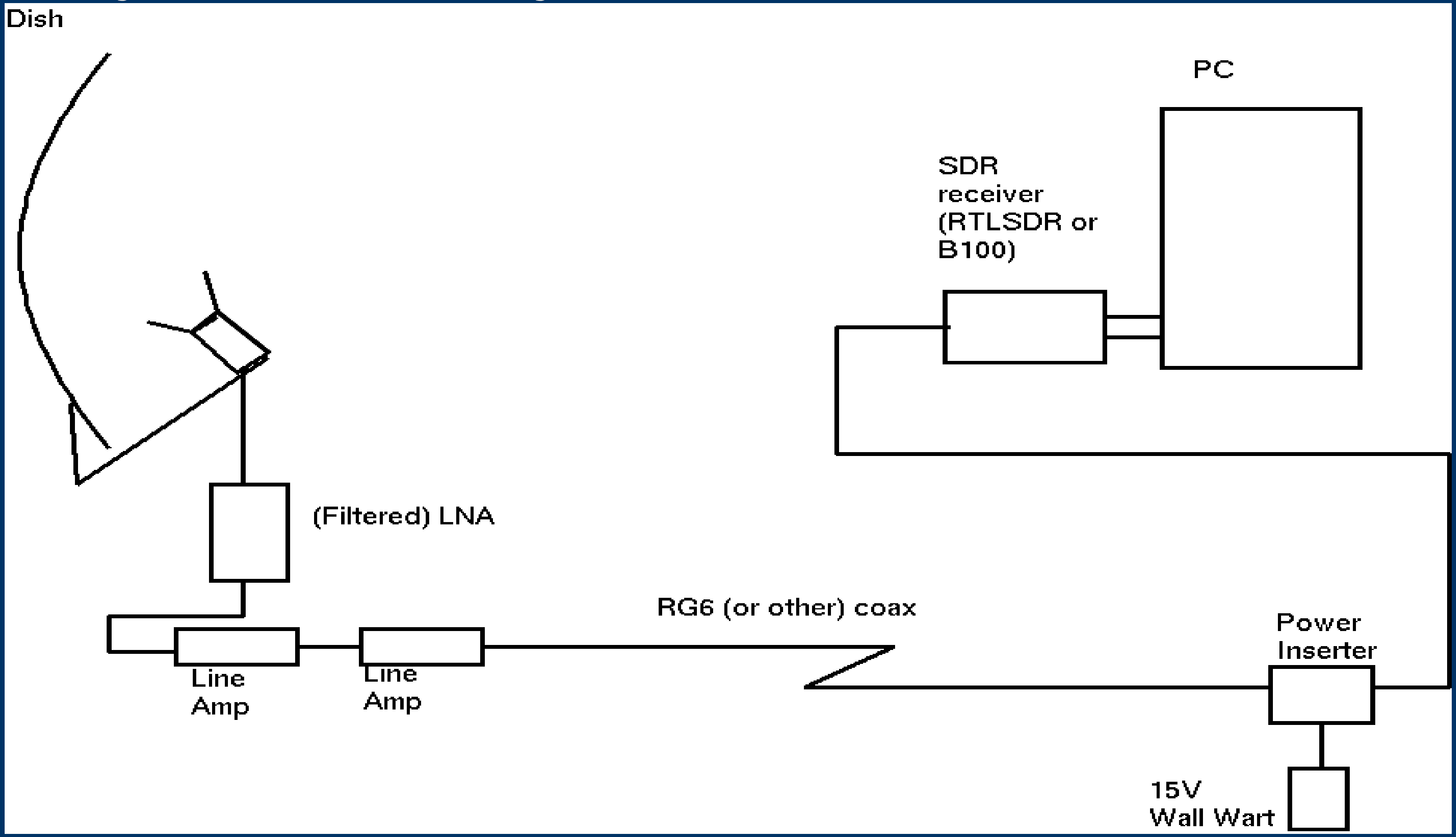
..and my not so modest one

Meridian Transit Dish Arrangement

- Easiest for amateur to use
  - Dish is aligned on the north-south **meridian**
    - **Use the pole star (polaris) as a guide for alignment**
  - Driven in elevation only
  - Wait for earths rotation to bring objects into view
- The original 300ft dish at Green Bank was a meridian-transit setup

SDR-based receiver for amateurs

- System I currently use



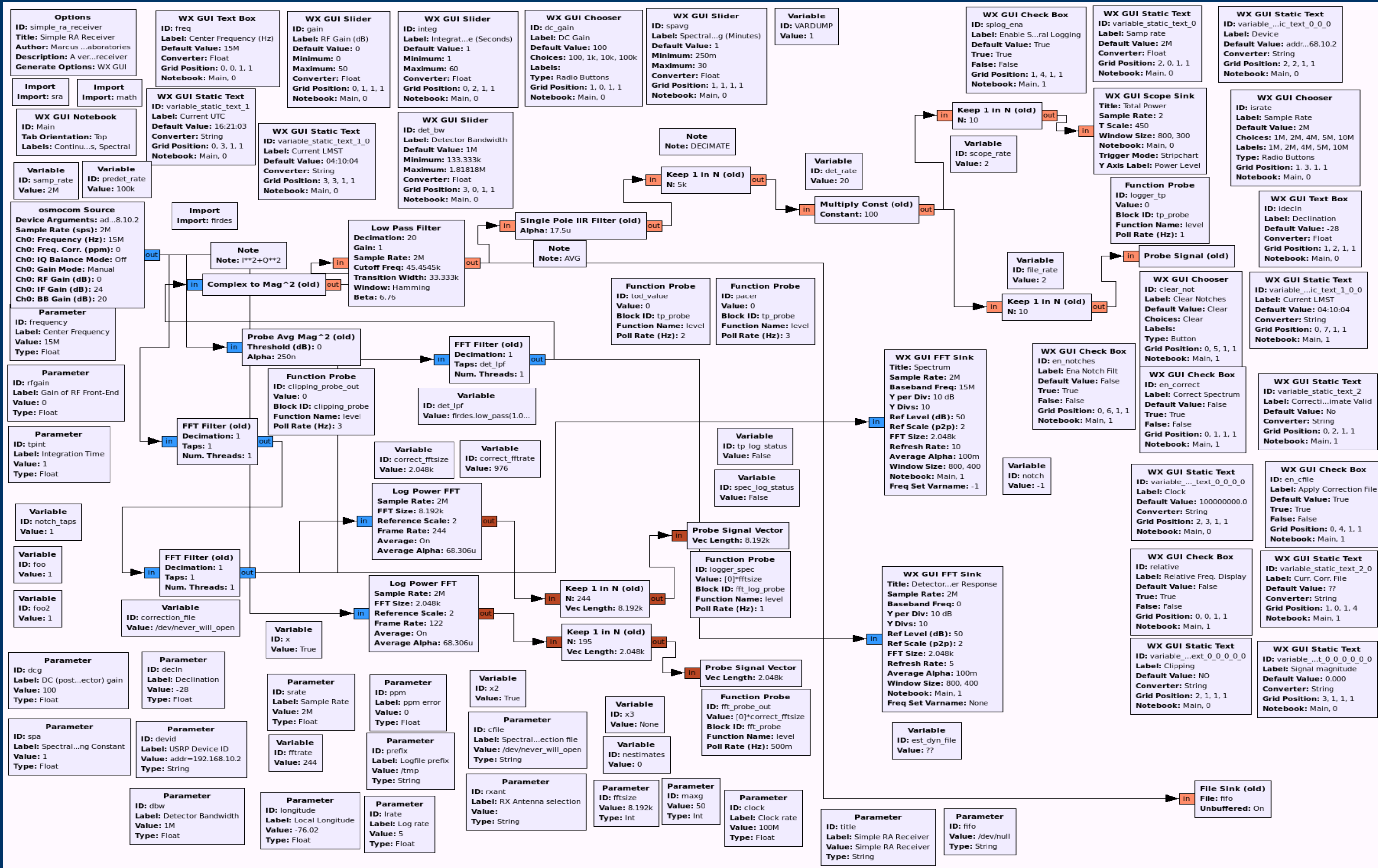
Processing signals

- Complex digitized signal:
  - 'I' component (real)
  - 'Q' component (imaginary)
  - Total power:
    - T.P. = average $(I^2 + Q^2)$
  - Spectrum:
    - average(FFT (I,Q))

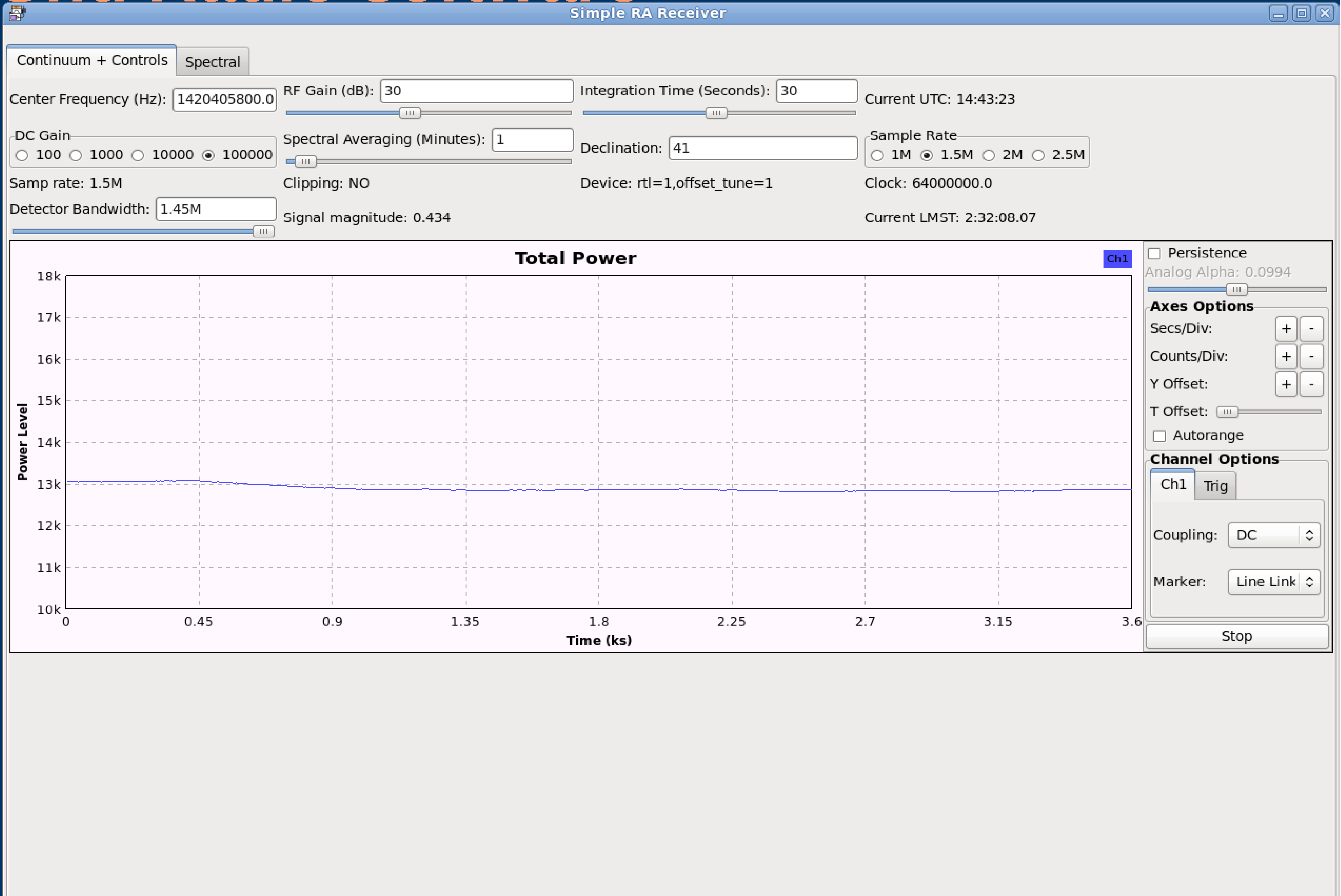
Simple averaging using IIR filter

- Let α be the averaging factor
  - Chosen to produce the best “smoothing”
- Let S be the current sample
- Let X be the previous output value
- Then:
  - $X = (S * \alpha) + ((1-\alpha) * X)$

simple_ra: flow Graph in GRC



Gnu Radio software



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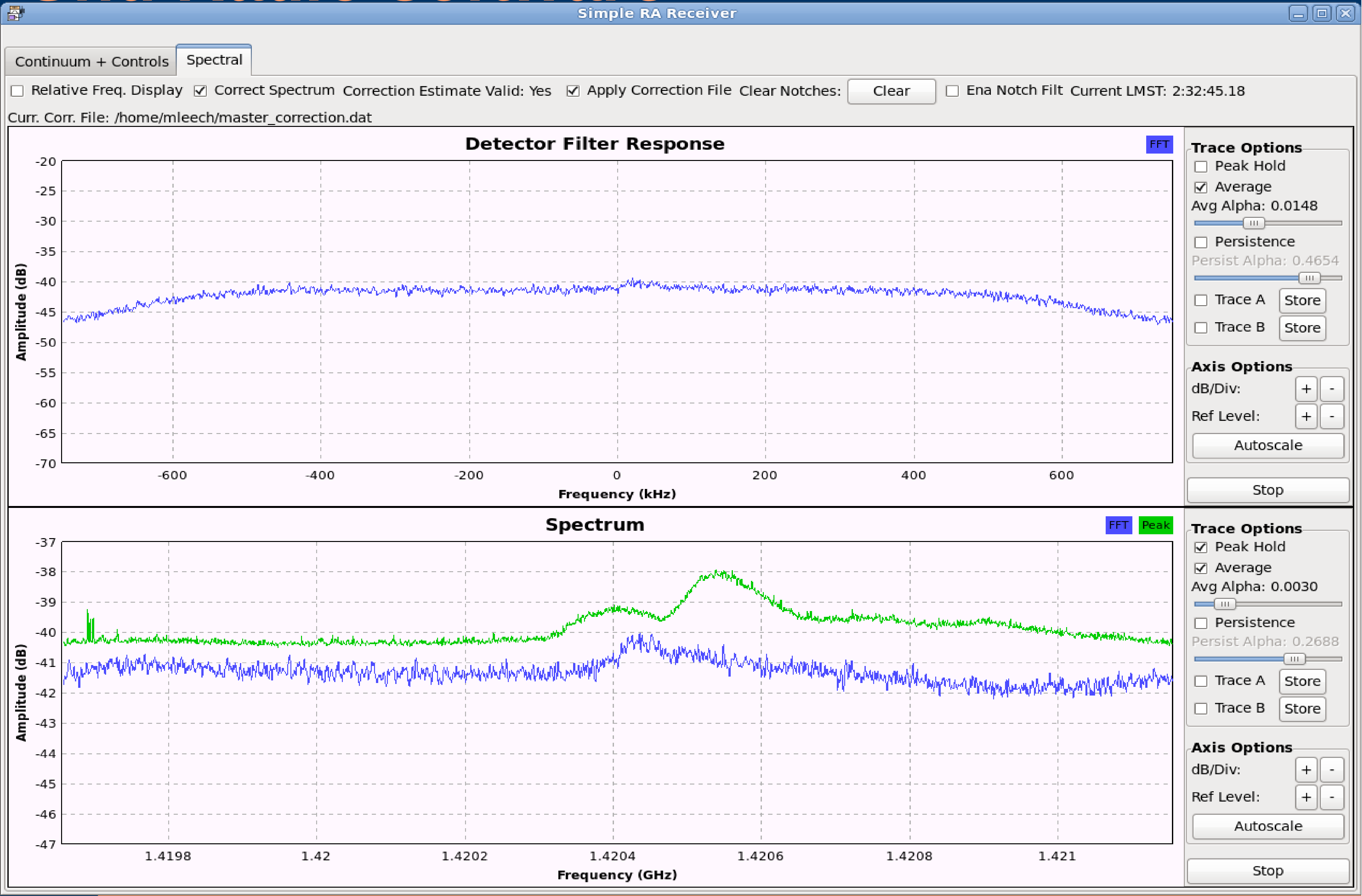
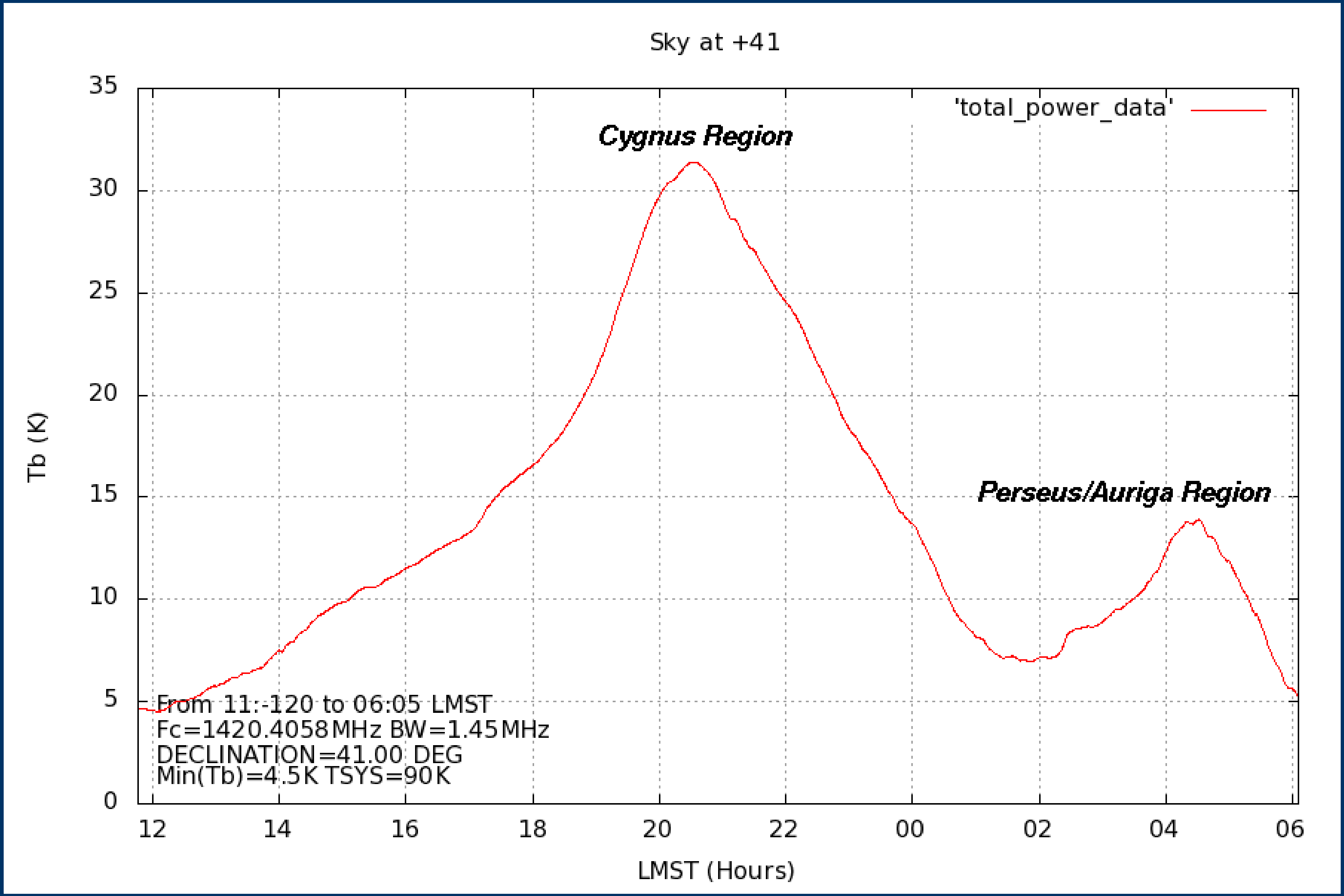


Amateur RA observations

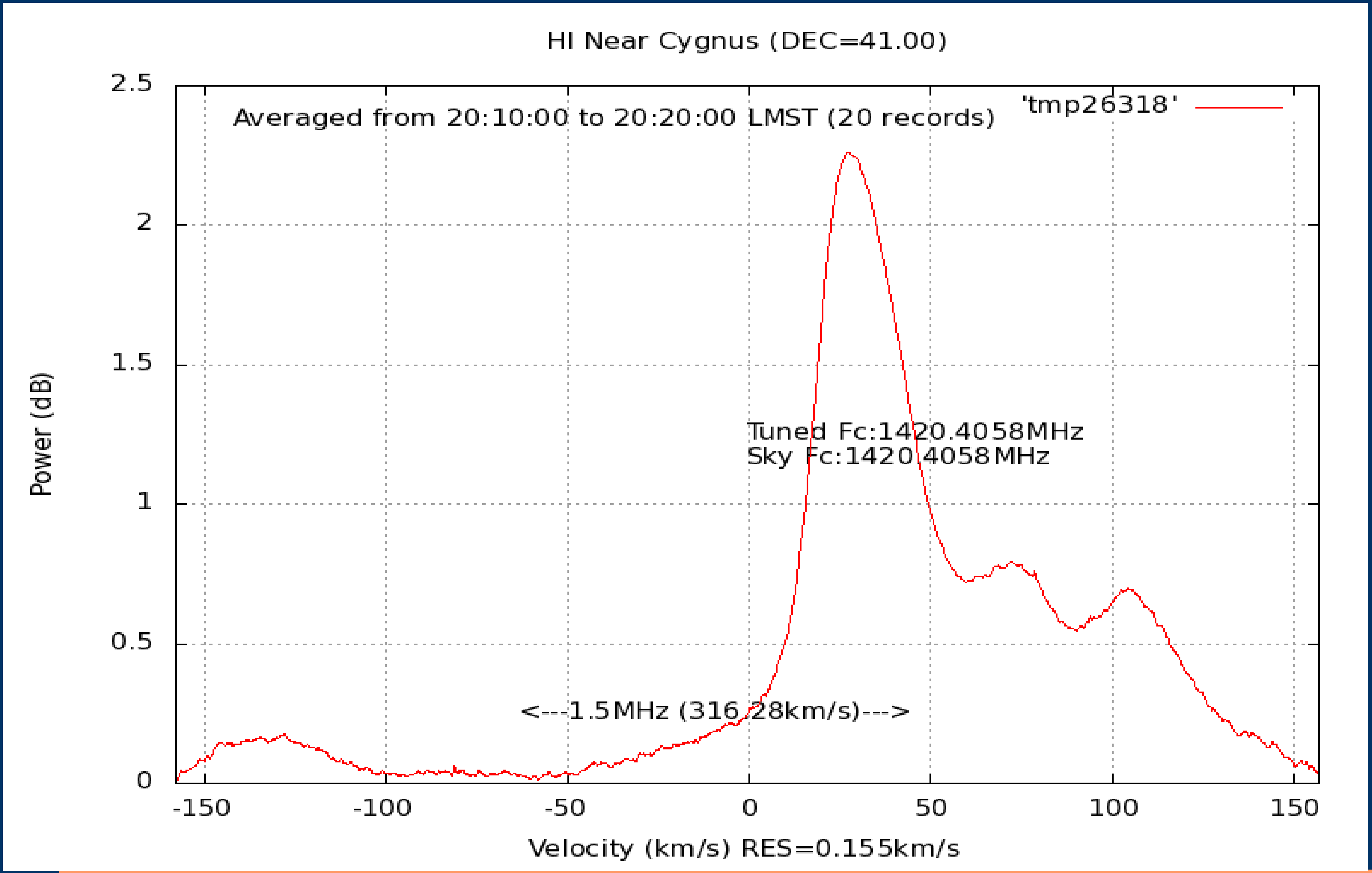
- Typically single-dish instrument
  - Total-power observations
  - Spectral observations
  - Stability issues due to tiny amplification changes caused by temperature cycling
- Some use two-element fixed interferometer
  - Higher spatial resolution than single dish
  - Can't do image synthesis
  - Much more stable than single-dish—gain changes factored out due to mathematics of correlation
  - Higher cost

Typical Total-Power observation



Typical Spectral Observations

- HI (Neutral hydrogen) spectrum near Cygnus A



Amateur Observations Continued

- With patience, can do quite sophisticated projects
- Total-power mapping of galaxy, for example

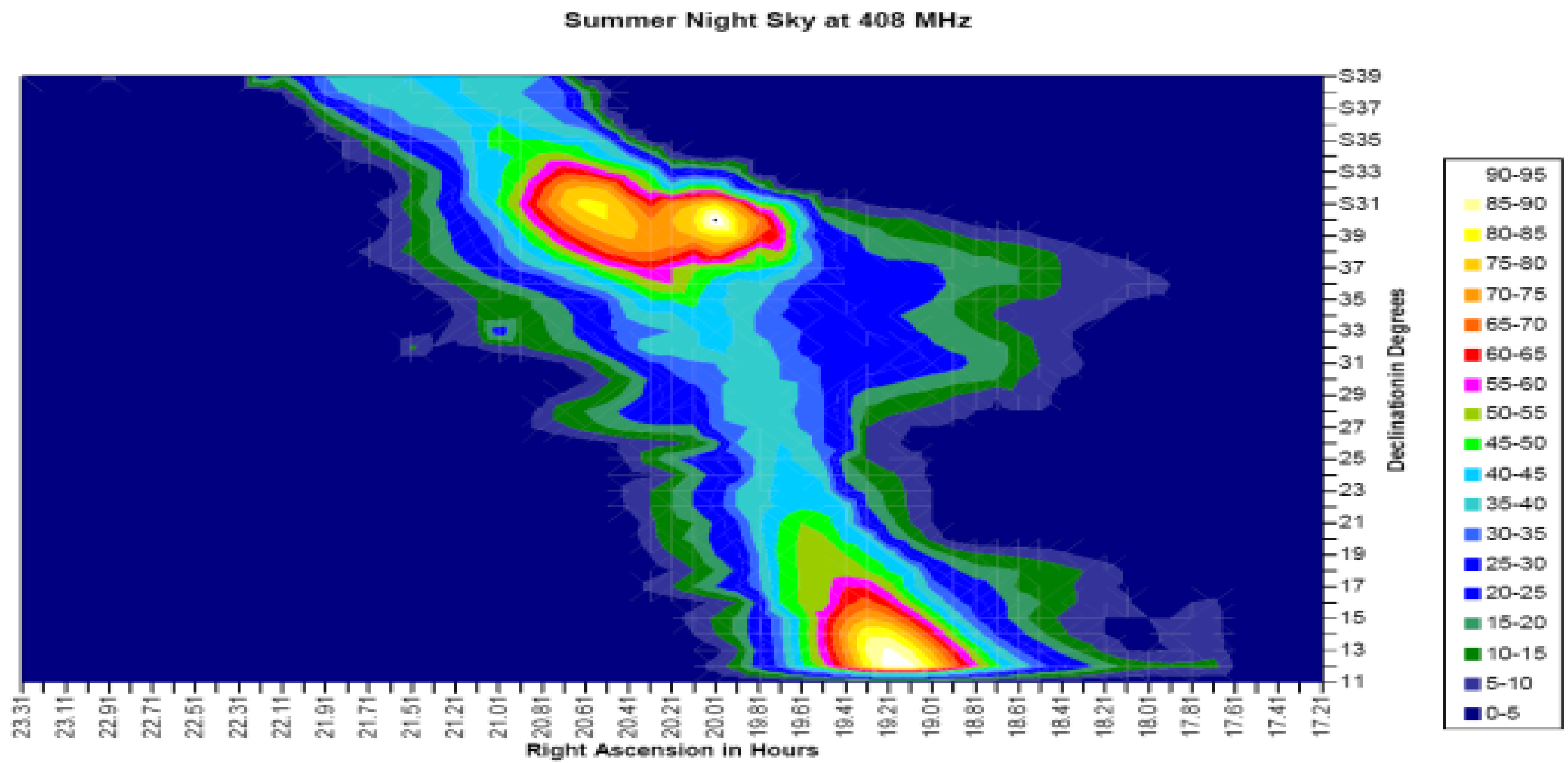
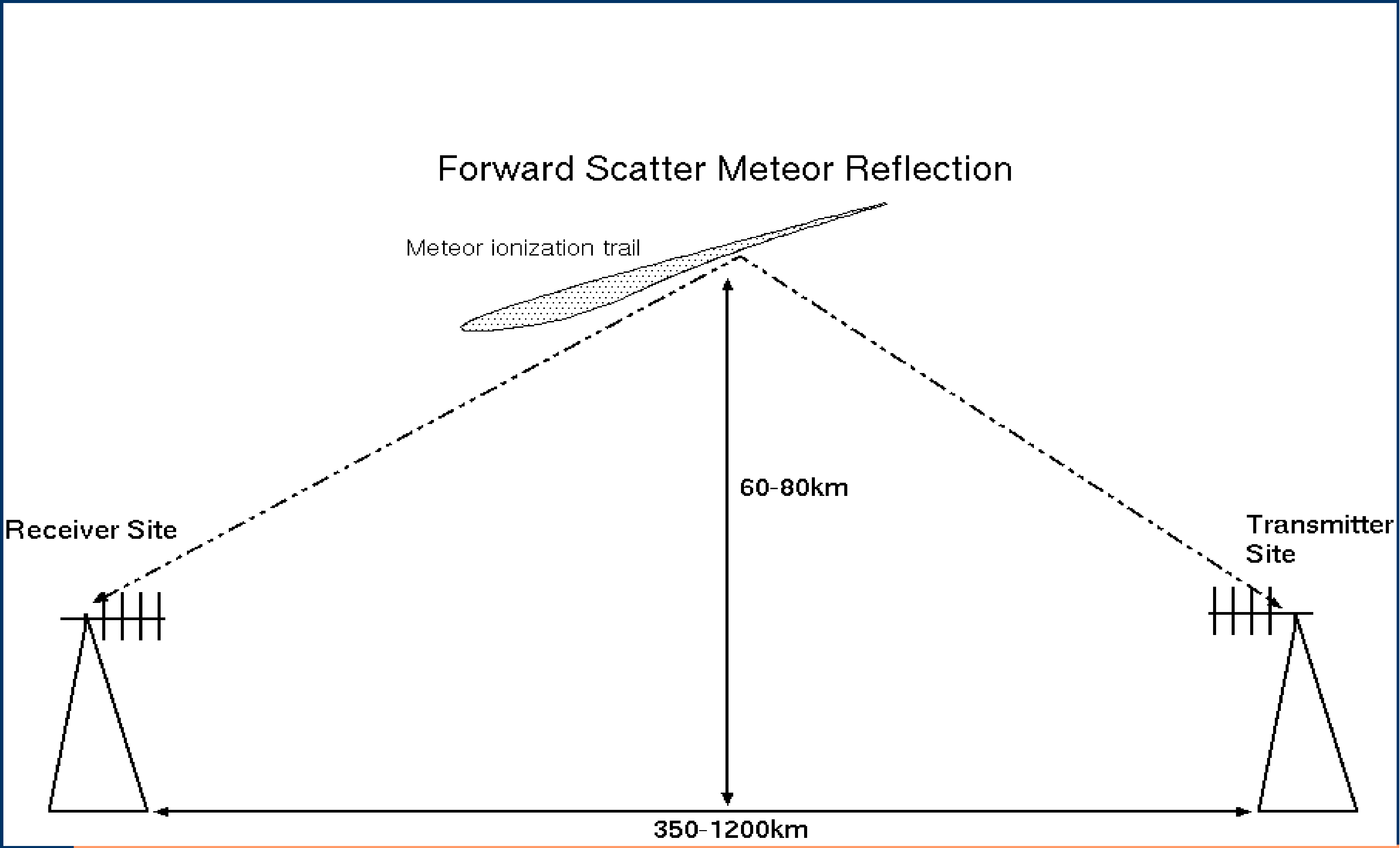


Figure 1: The Summer Night Milky Way at 408 MHz. The two bright patches towards the top of the map are due to the radio sources Cygnus A (right) and Cygnus X (left). The units are antenna temperature in Kelvins.

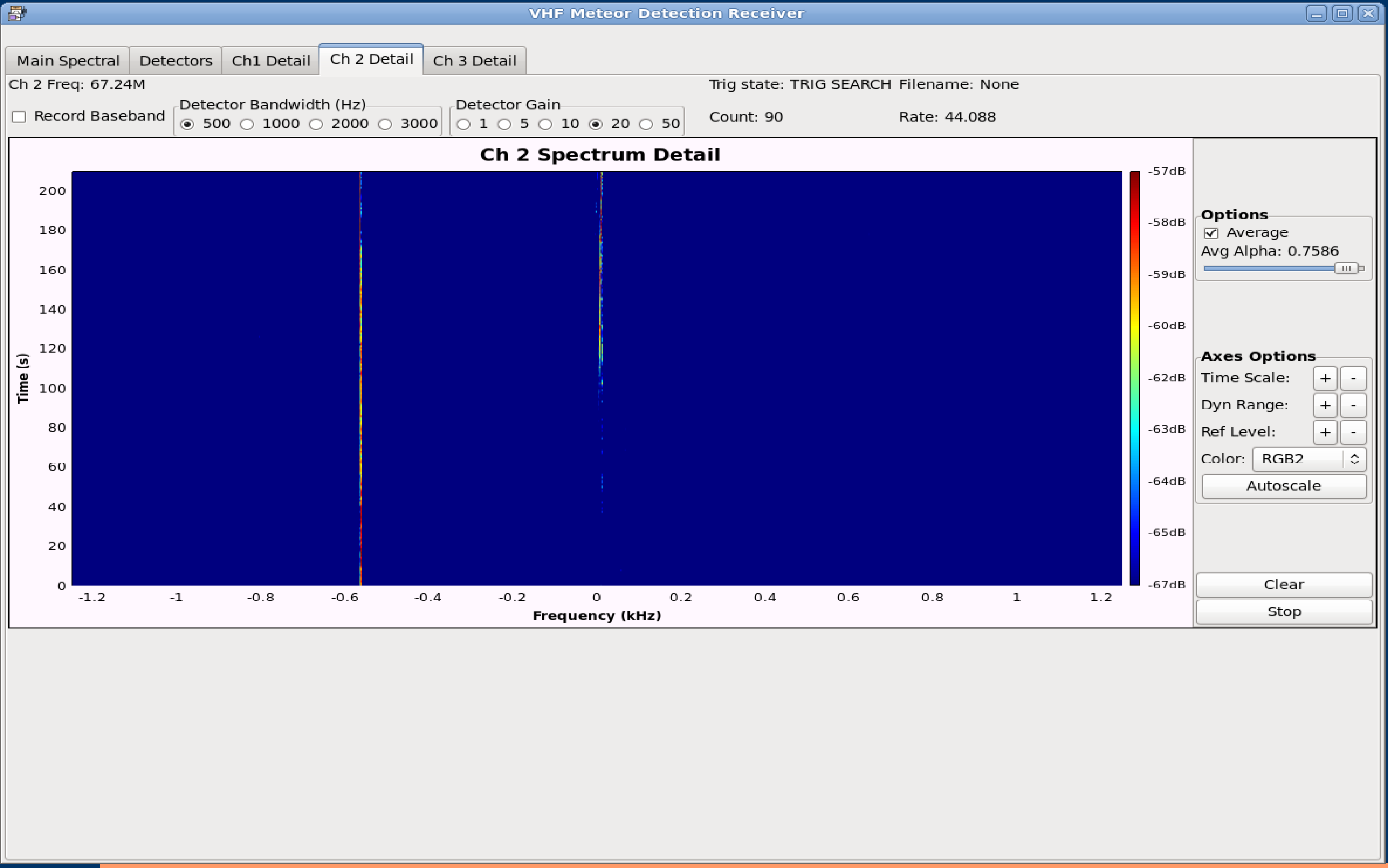
Meteor Forward Scatter

- Use remote VHF stations to detect meteor inflow
- Pick a TX that's below the radio horizon
- Broadcast FM, and VHF NTSC stations popular
  - Fewer (almost none!) VHF NTSC stations left
  - Might be able to use pilot tone of ATSC
  - FM in many markets is saturated—there are no empty channels

Meteor Forward Scatter



meteor_detector Gnu Radio app



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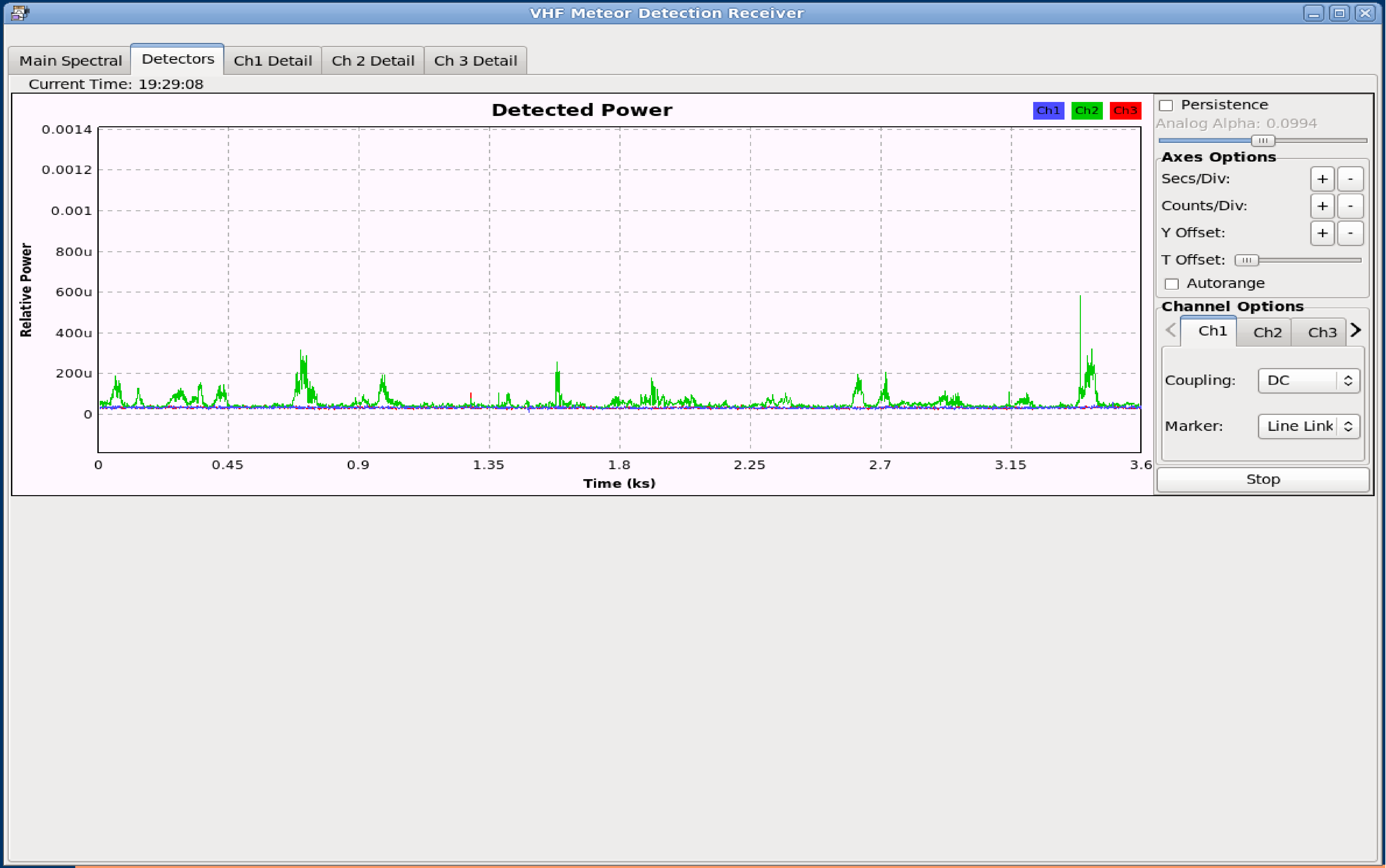

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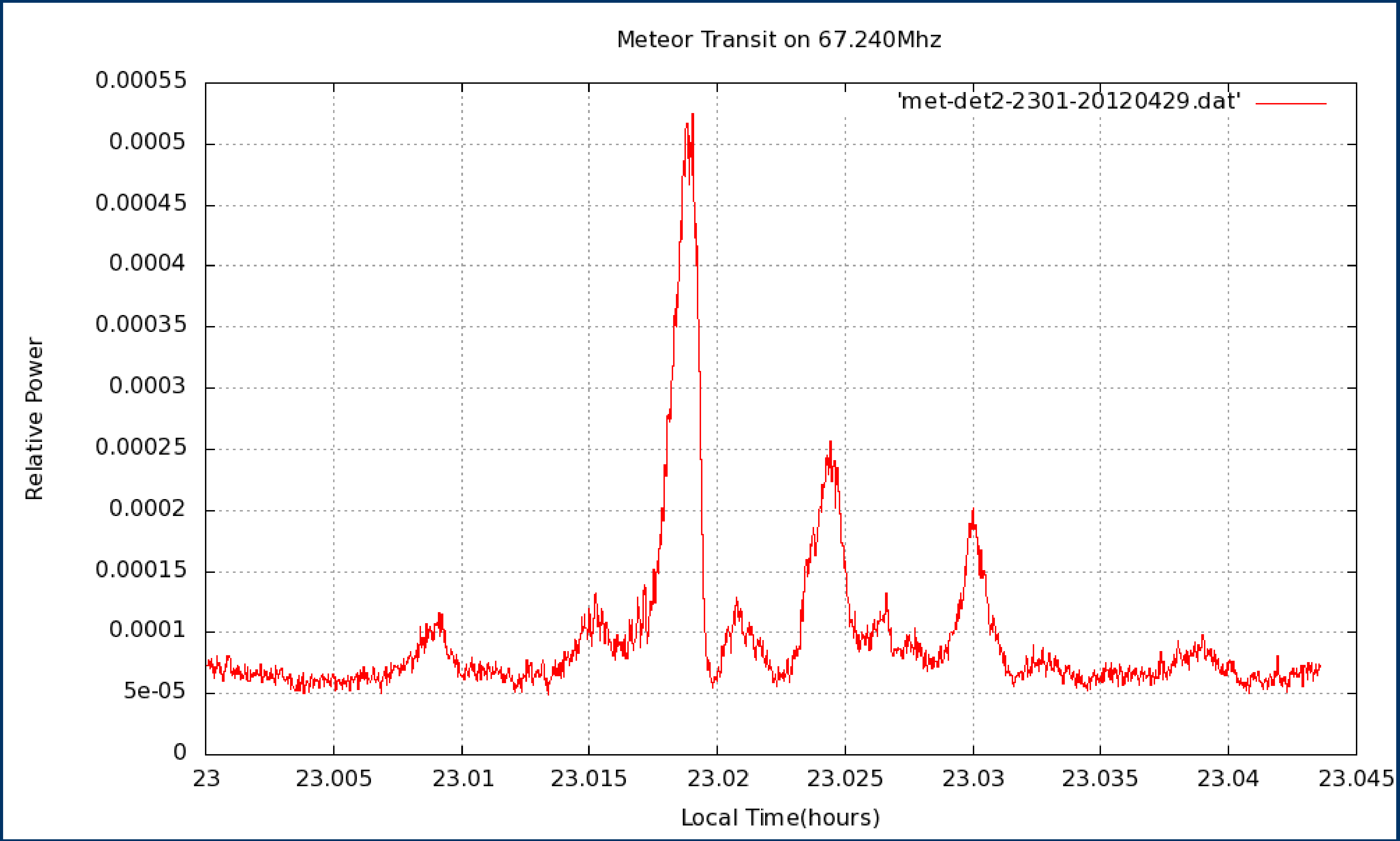

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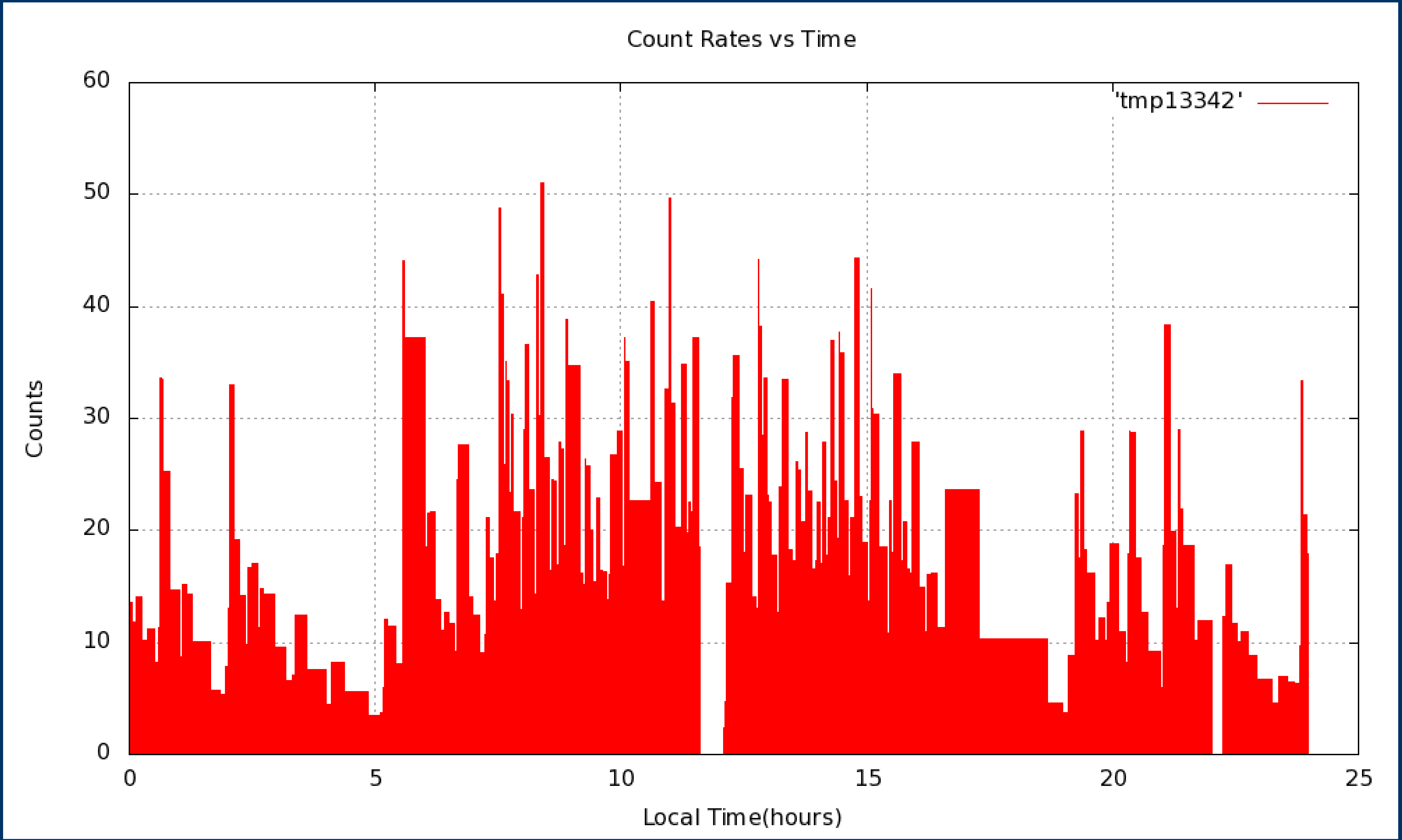

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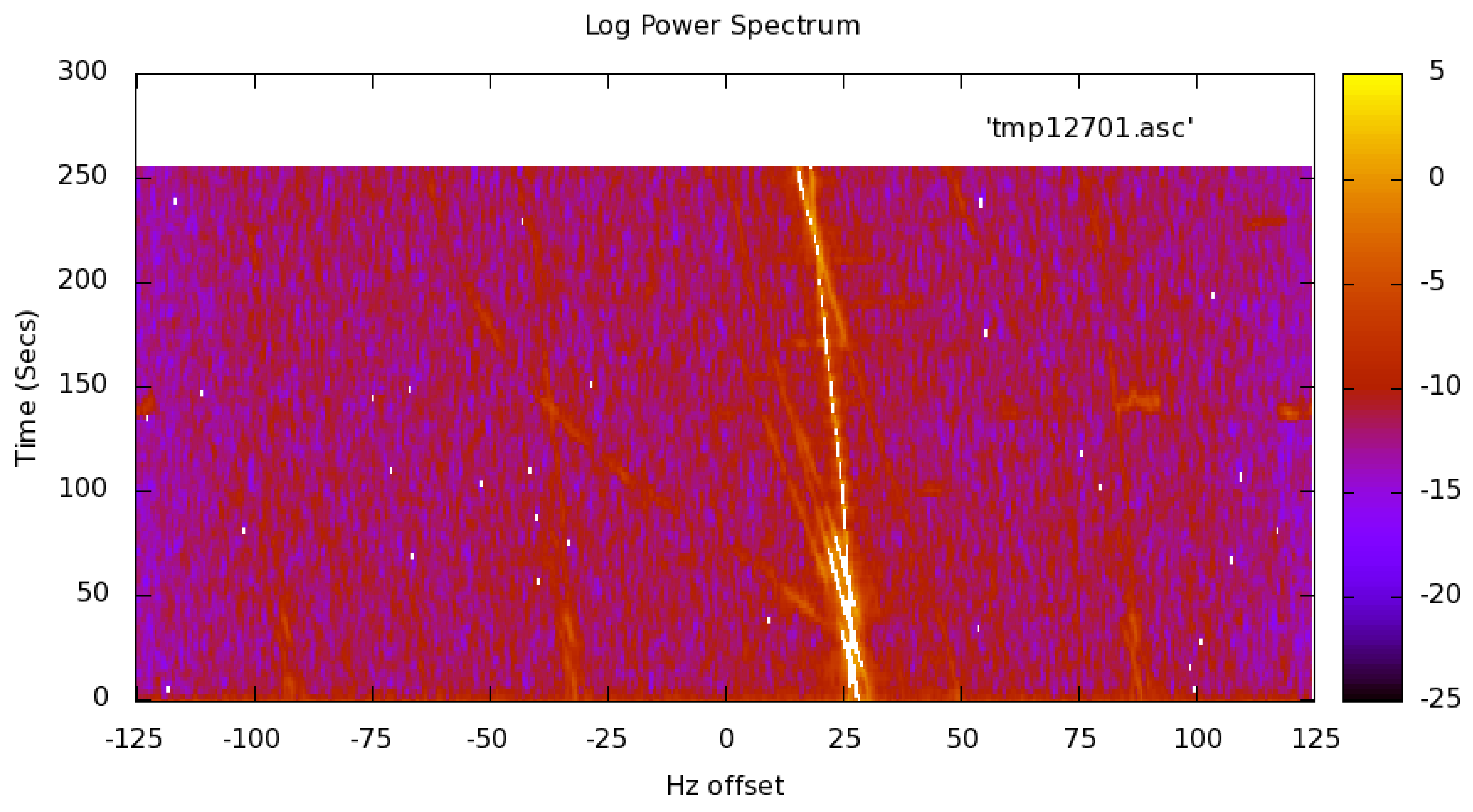

Closing remarks

- Fewer students are entering post-secondary astronomy programs
- Even fewer are pursuing careers in radio astronomy
- The existing scientists in RA are getting old :-)
- If science is your “thing”, consider astronomy

Further reading: Science

- Society of Amateur Radio Astronomers
  - http://www.radio-astronomy.org
- “Radio Astronomy Projects, 3rd ed”, William Lonc
  - http://www.radiosky.com
- National Radio Astronomy Observatory
  - http://www.nrao.edu
  - http://www.cv.nrao.edu/course/astr534/ERA.shtml

Further reading: Tools

- Gnu Radio
  - http:www/gnuradio.org
- Ettus SDR radios
  - See http://www.ettus.com
- RTL-SDR radios
  - See http://www.rtlsdr.org
- simple_ra
  - See https://www.cgran.org/svn/projects/simple_ra