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“Next Generation Planetary Radar” for the National Radio Astronomy Observatory

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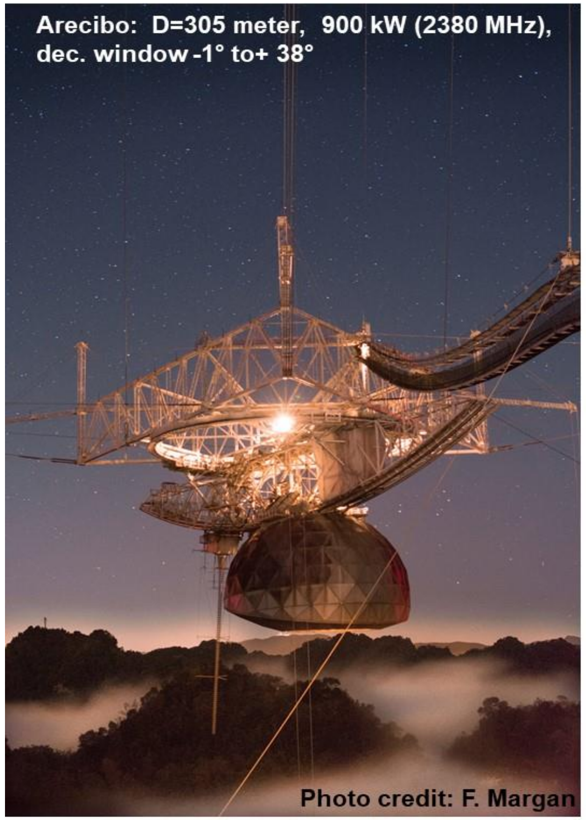
US Planetary Radar Pre 2021

Russia 2013 – Did not see it coming!!

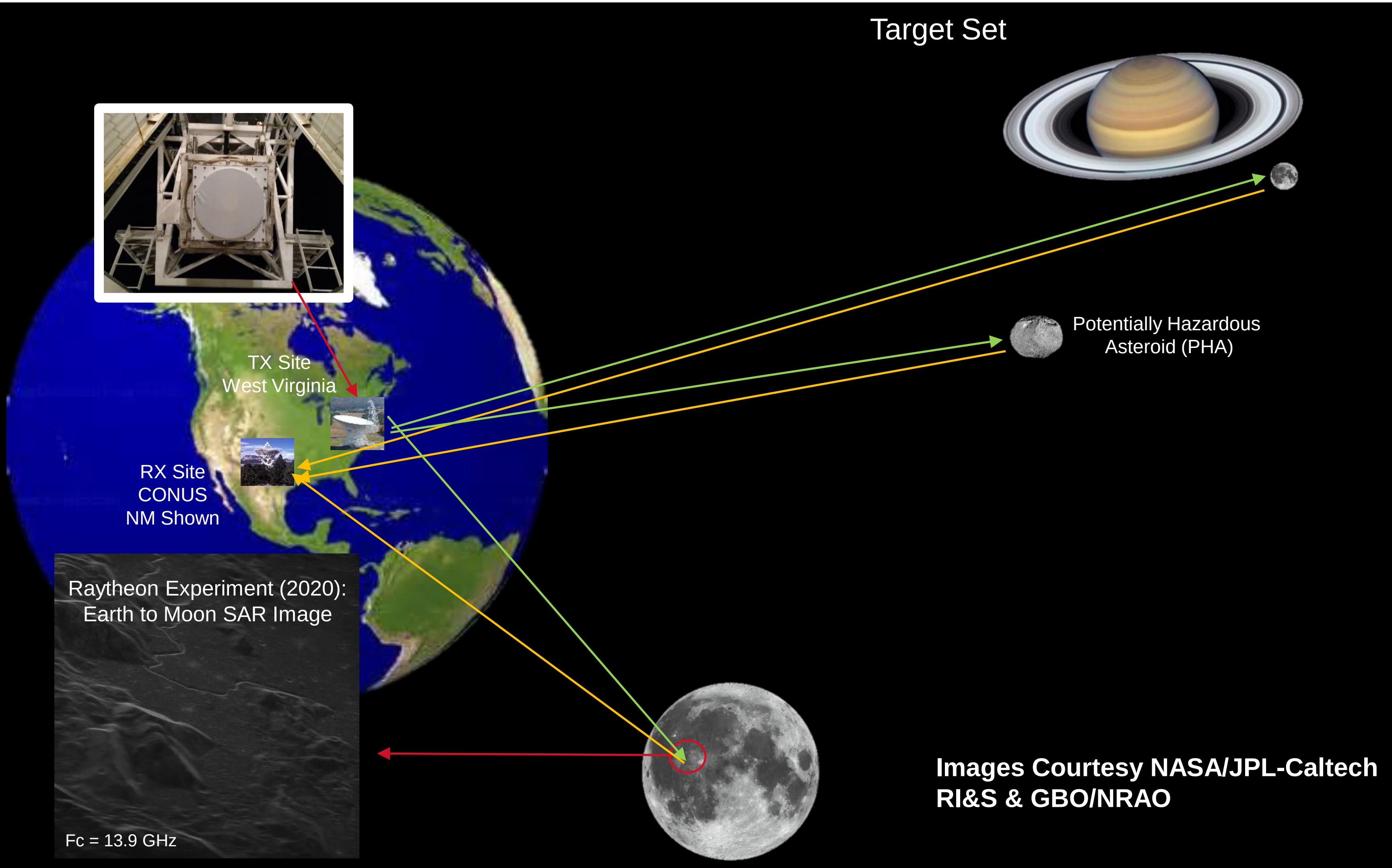
Images Courtesy NASA/JPL-Caltech & NRAO



- Started in the 1950s with a big jump in 1963 with the completion of the Arecibo Observatory
- Planetary radar is associated with transmitters and receivers located on Earth
  – Satellite based radar observations are not considered planetary radar
- After the collapse of the Arecibo Observatory the only system is Goldstone, and it is limited
- It is an early warning and a scientific system

Planetary Radar System –
Scientific Measurement and Planetary Defense to Identify Potentially Hazardous Asteroids/Objects

- Green Bank Transmitter
- VLBA/VLA and ngVLA receive
- See smaller NEOs at a longer range
- Goal: Access outer solar system objects, beyond Saturn's rings



Images Courtesy NASA/JPL-Caltech
RI&S & GBO/NRAO

Plot of many Catalogued Near Earth Asteroids - JPL

- This is a plot of a vast majority the NEAs that are in the JPL/Horizons database
- It was presented at the Next Generation Planetary Radar workshop hosted by NASA/JPL/Cal Tech
- It says something about all the objects that are in our local area
- We will get hit
- ***Apophis*** will pass Earth on 4/13/29 by less that 20,000 [mi]
  - – Inside the orbit of GPS satellites
  - – 370 [m] diameter 30 km/s

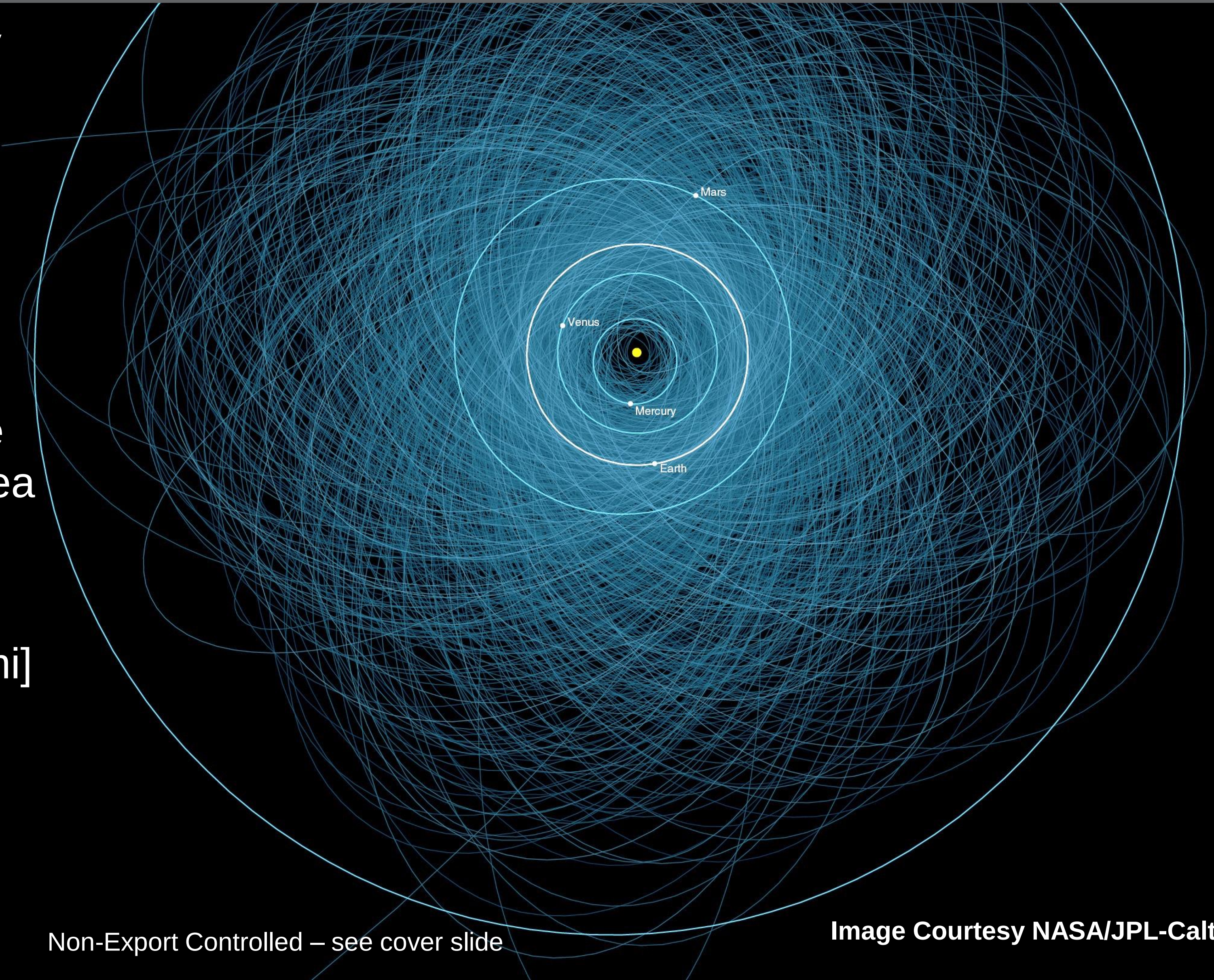
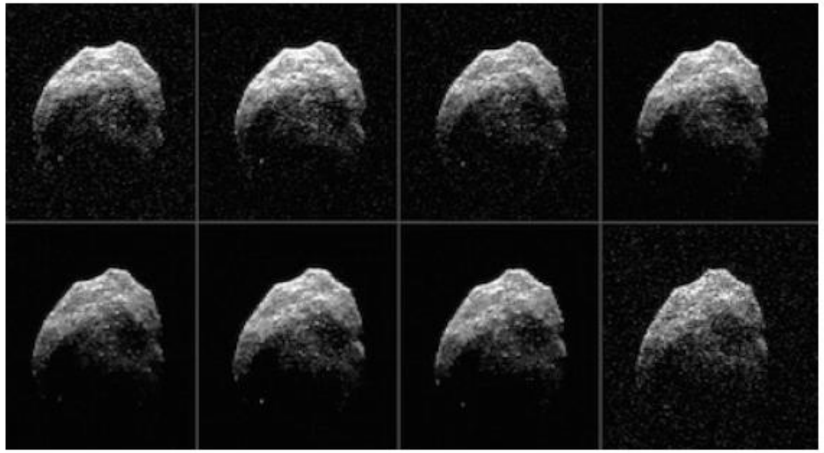


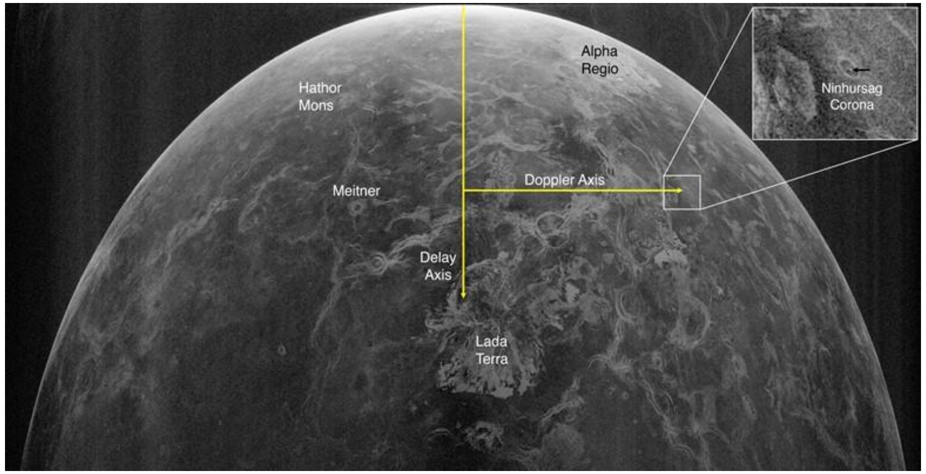
Image Courtesy NASA/JPL-Caltech

Scientific measurements using planetary radar

- Asteroid characterization
  - – Size, shape, and rotational properties
  - – Precision orbital ephemeris
    - Must be revisited since these orbits are not stable
  - – Surface & interior composition
- Planet and small body (dwarf planets, moons ….) characterization
  - – Similar asteroid characterization
- Solar system scale – early measurements
  - – Shapiro Delay – an effect predicted by General Relativity
  - – Refinement of the astronomical unit [AU],
    - Current value is 149,597,870.7 [km]
    - 1 AU is the mean Earth-Sun distance



2015 TB145 GSSR-GBT



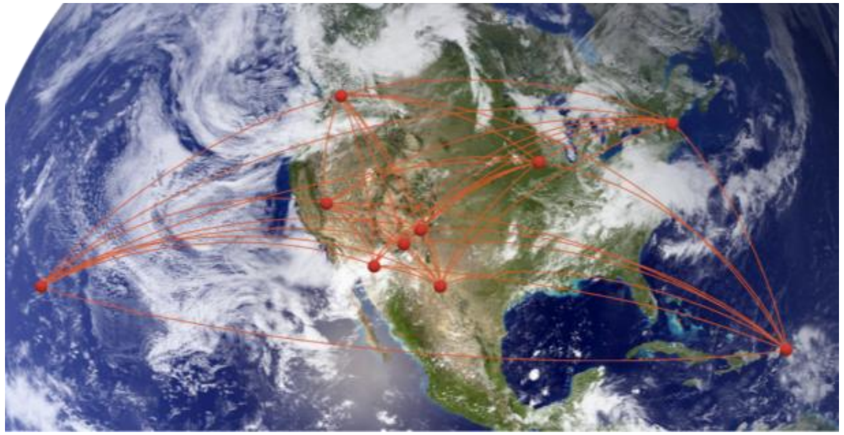
Venus

Images Courtesy NASA/JPL-Caltech NRAO/GBO

National Radio Astronomy Observatory (NRAO) - major operational facilities


Karl G. Jansky Very Large Array


Karl G. Jansky Very Large Array


Very Long Baseline Array


Atacama Large Millimeter/submillimeter Array

Images Courtesy GBO/NRAO

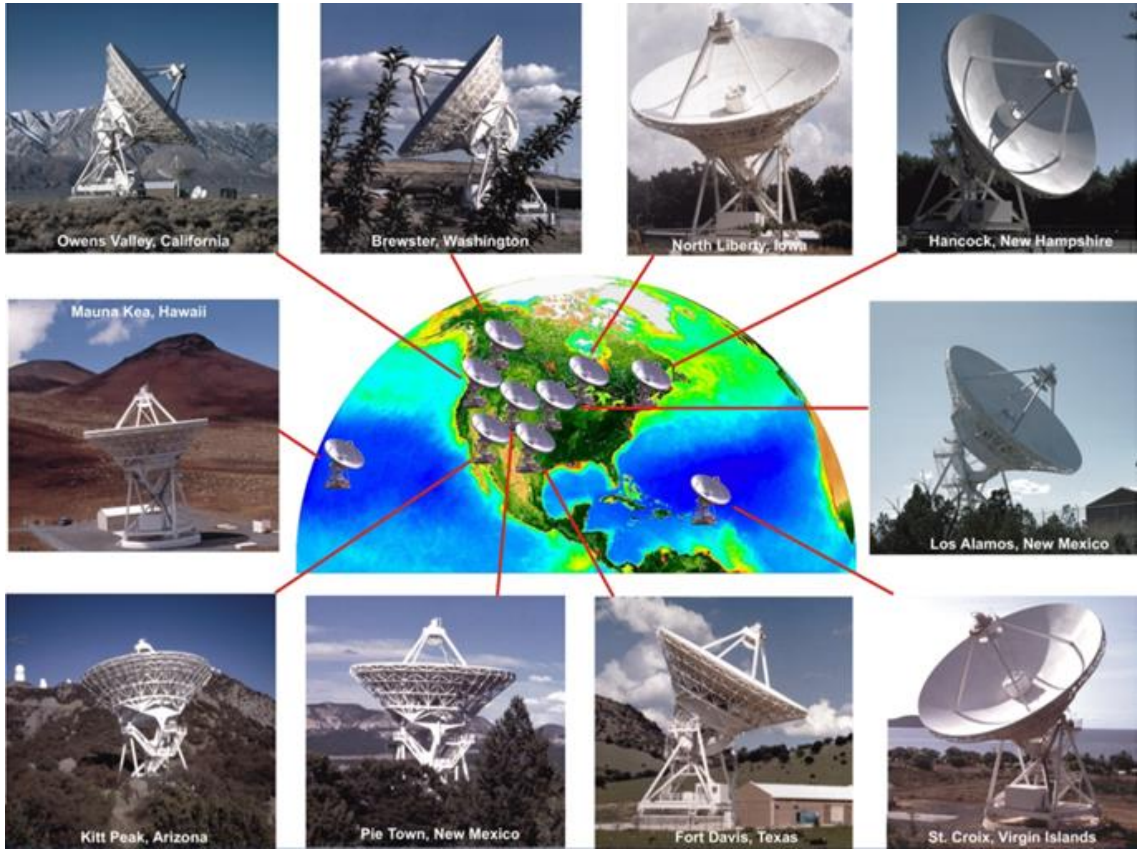

Robert C. Byrd Green Bank Telescope

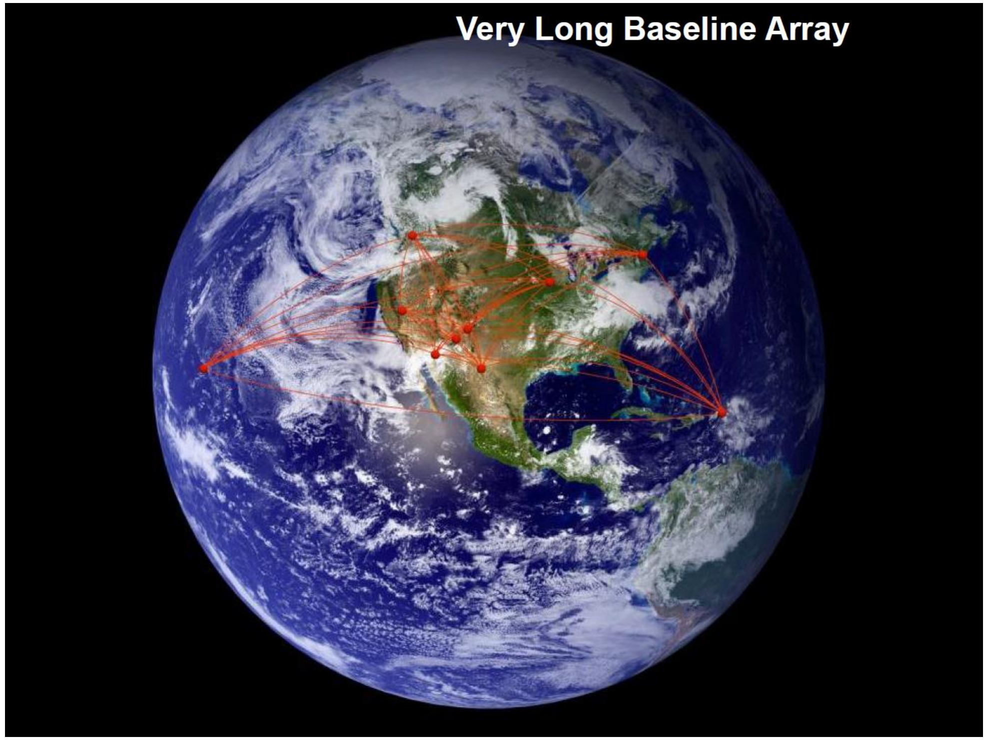
Green Bank Telescope

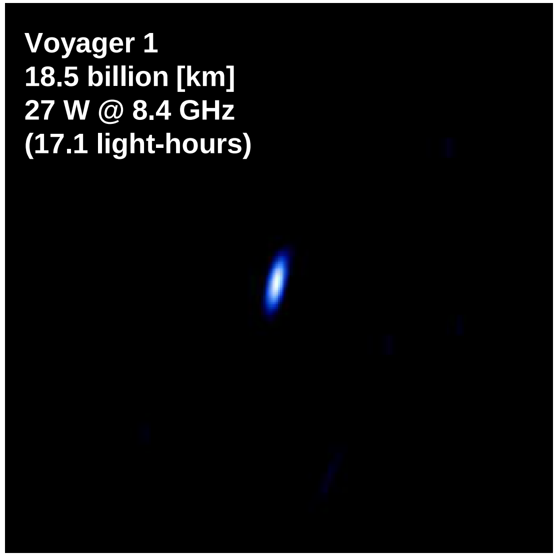
- 100 meters in diameter
- Fully-steerable, all sky
- Observational wavelengths are 4-meters to 2.5 mm
- 75 MHz – 116 GHz
- A transmitter in a Prime Focus housing was the approach for the first experiment

Image Courtesy GBO/NRAO

Very long baseline array (VLBA)-Receiver





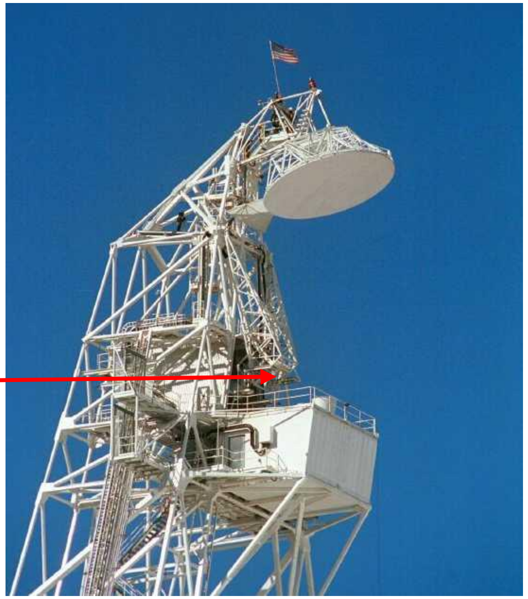


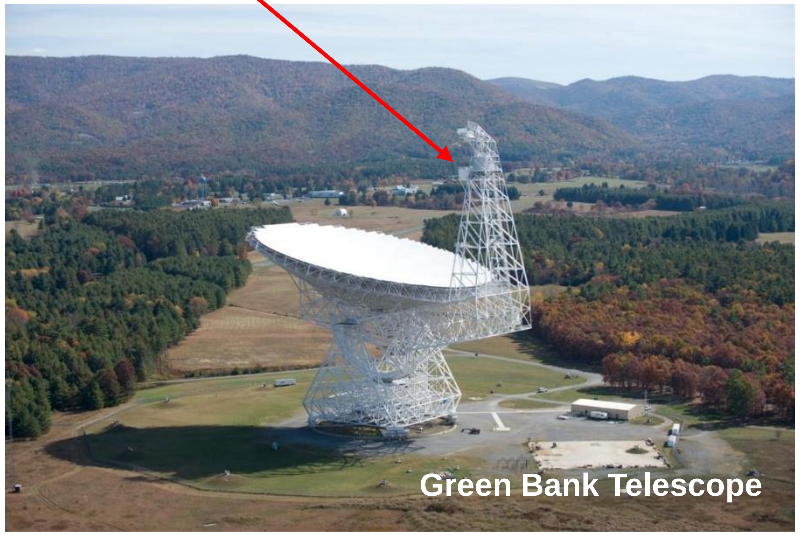
- VLBA is a long baseline radio interferometer
- It collects high resolution imagery of astronomical objects

Images Courtesy NRAO/GBO

Transmitter parameters and placement on GBT

GBT prime focus transmitter





Images Courtesy GBO/NRAO

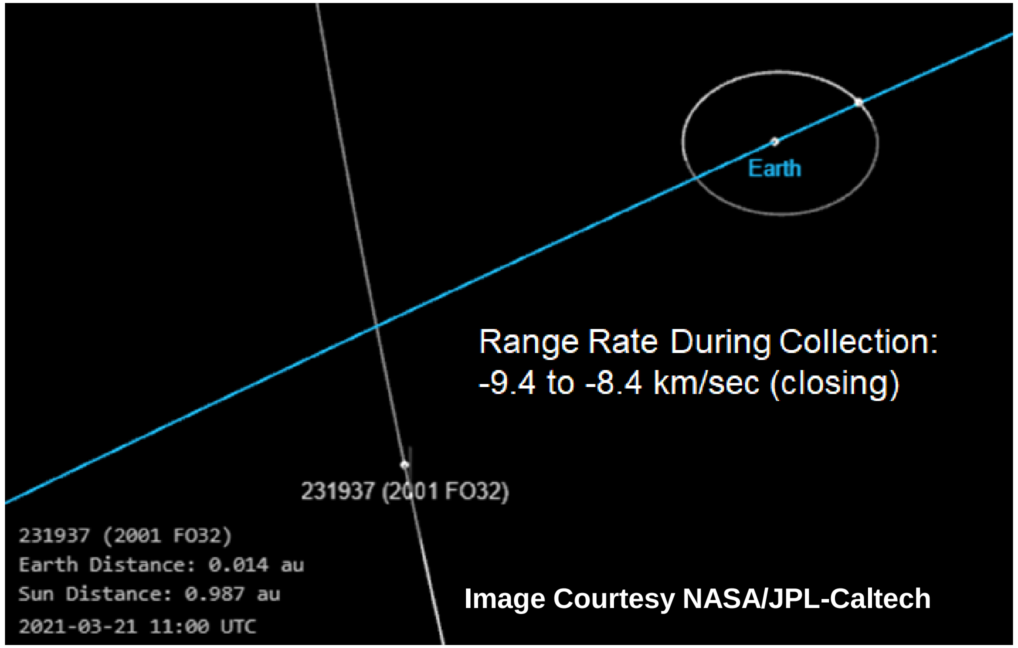
- Center frequency: 13.9 GHz
- Bandwidth: 200 MHz, (±100 MHz)
- Output power: 700 W CW
- EIRP = 109.5 dBW
  - Gain = 81.7 dBi, Power = 27.8 dBW
- Waveform: LFM 100% duty
- Solid State HPA
- AWG/LO is referenced to the GBT Hydrogen Maser for frequency stability
- Simple control interface
- Monitored voltages, temperature at various location and humidity in the housing

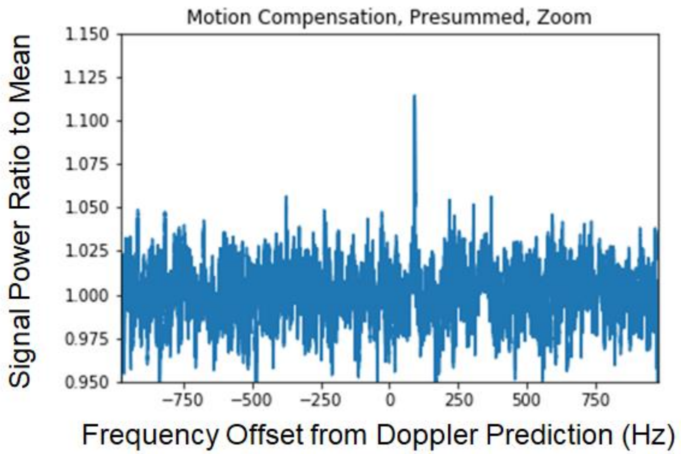
Transmitter on Green Bank Telescope November 10, 2020

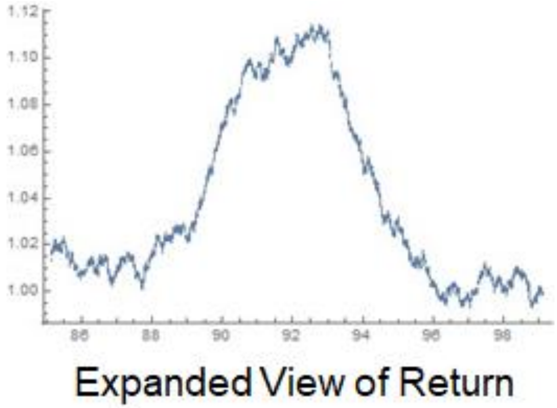
Image Courtesy GBO/NRAO

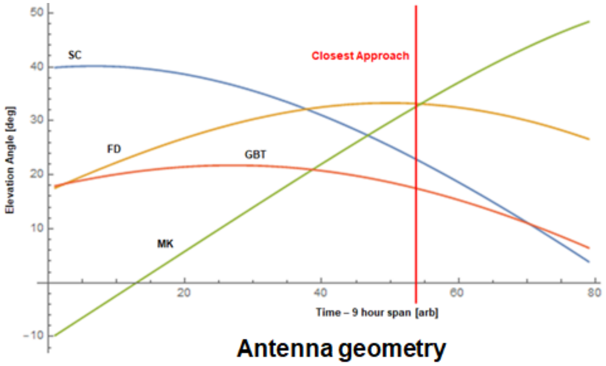
- System was controlled over the internet
- A beautiful blue sky on the 10th
- Was raining during the experiment but only the GBT team can comment
- Transmitter control – California
- VLBA – New Mexico
- GBT – West Virginia
- NRAO– Virginia

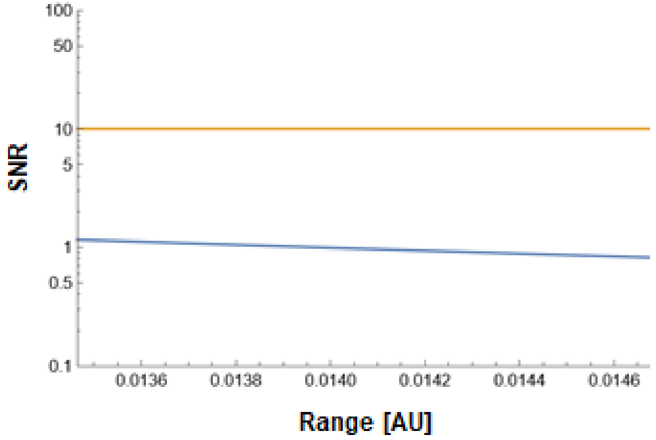
Detection of Asteroid 2001 FO32











- Single tone provided detection since it had the best SNR
- Took over 1000 seconds of coherent integration
- Measured the rotation rate to be 45.3 hours (low SNR)
  - JPL measurement 39.86 hours
- Antenna geometry a factor in SNR (atmospheric loss)
  - SC data was the best – highest in the sky

Target: Asteroid 2001 FO32, Range: 2.088 billion meters, relative velocity: ~ 34 km/s

Five Meter Resolution

Radar Image collected 12 November 2020 1517Z

Green Bank WV to Hancock NH

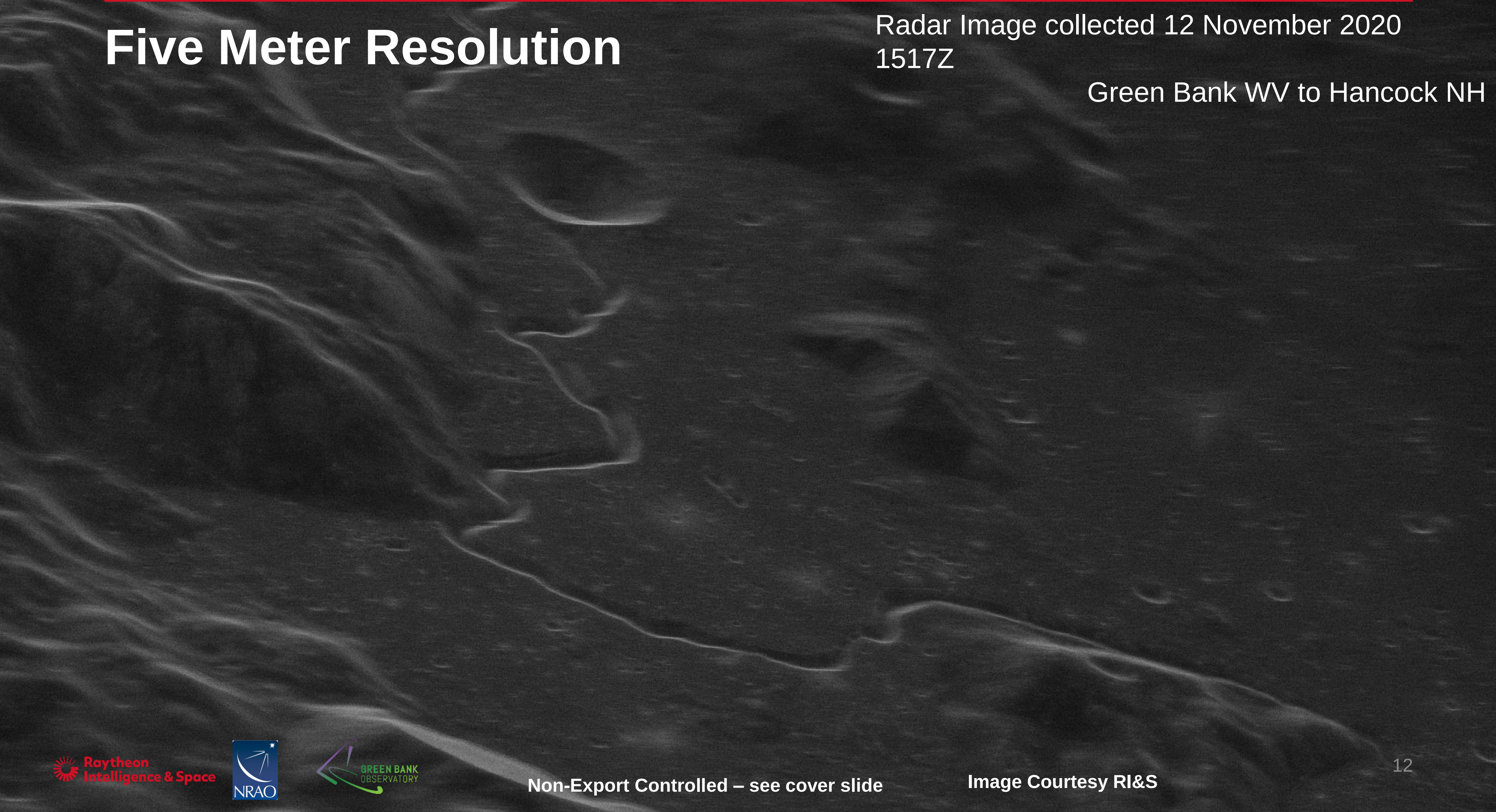


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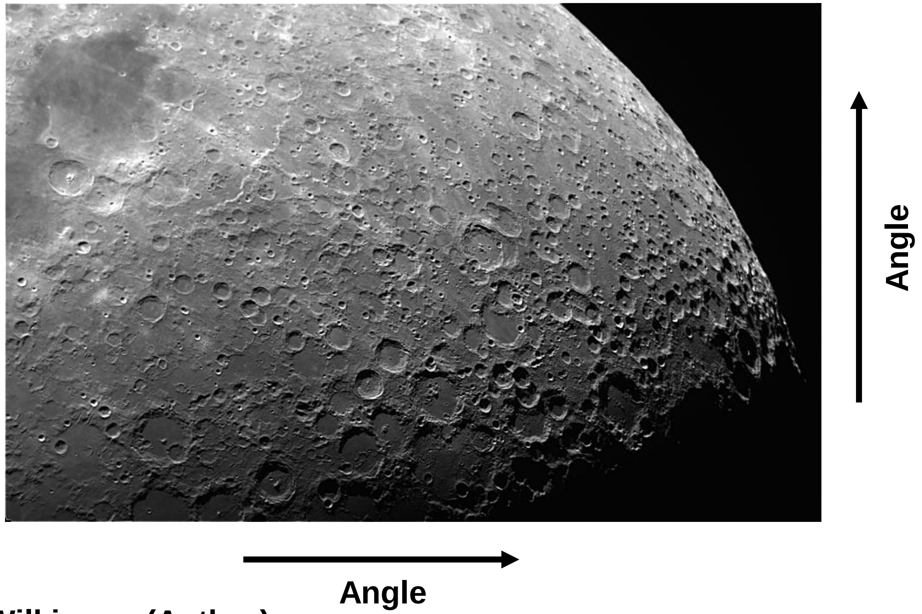
Image Courtesy RI&S

Optical Telescopes- The primary instrument for Amateur Astronomy

D = 9.25”

$$Angular\ Resolution \approx \left(1.22\frac{\lambda}{D}\right)$$

(For λ = 550 [nm] we get) $= 2.85 * 10^{-6}[radians]$



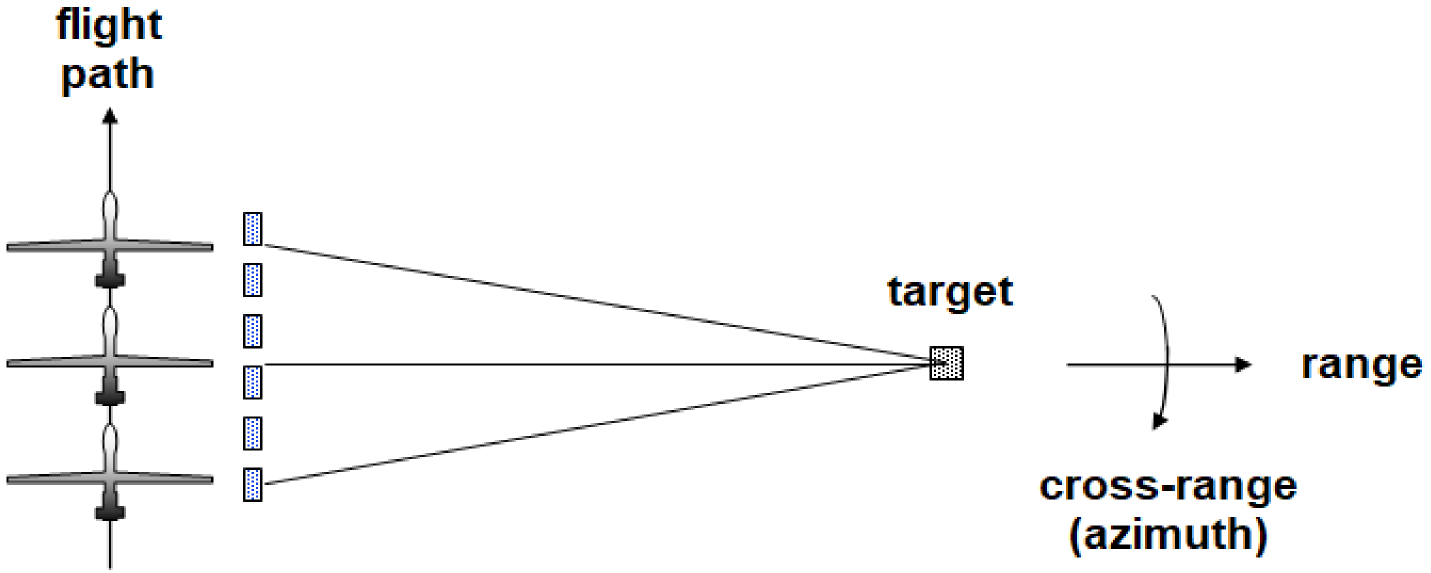
Images Courtesy SR Wilkinson (Author)

- Optical wavelengths are less than a millionth of a meter
- A small optical telescope can have less than 1 arcsecond of resolution
- Radar wavelengths are much longer
- To have similar angular resolution the aperture must be larger by a factor of >10,000

Using the initial radar wavelength for the GBT observations requires an antenna 5.7 miles in diameter to obtain the same angular resolution

Synthetic Aperture Radar (SAR) – The Basics

- As the name indicates, SAR "synthesizes" a large aperture to effectively achieve finer azimuth (angle) resolution.
- This is accomplished by moving the radar (in a straight line) to create a large aperture to achieve fine azimuth resolution (angle)
- A SAR image in not angle-angle as an optical image. It is an angle-range image.
- To achieve comparable range-resolution we use "short pulses" that equal the azimuth resolution
- Requires mathematical algorithms to construct the image.
- From an optical perspective the camera would be directly overhead of the scene looking down.



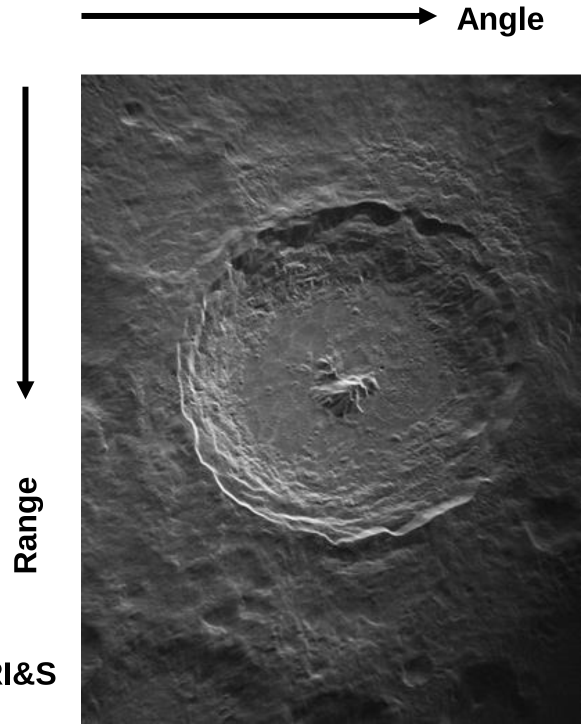
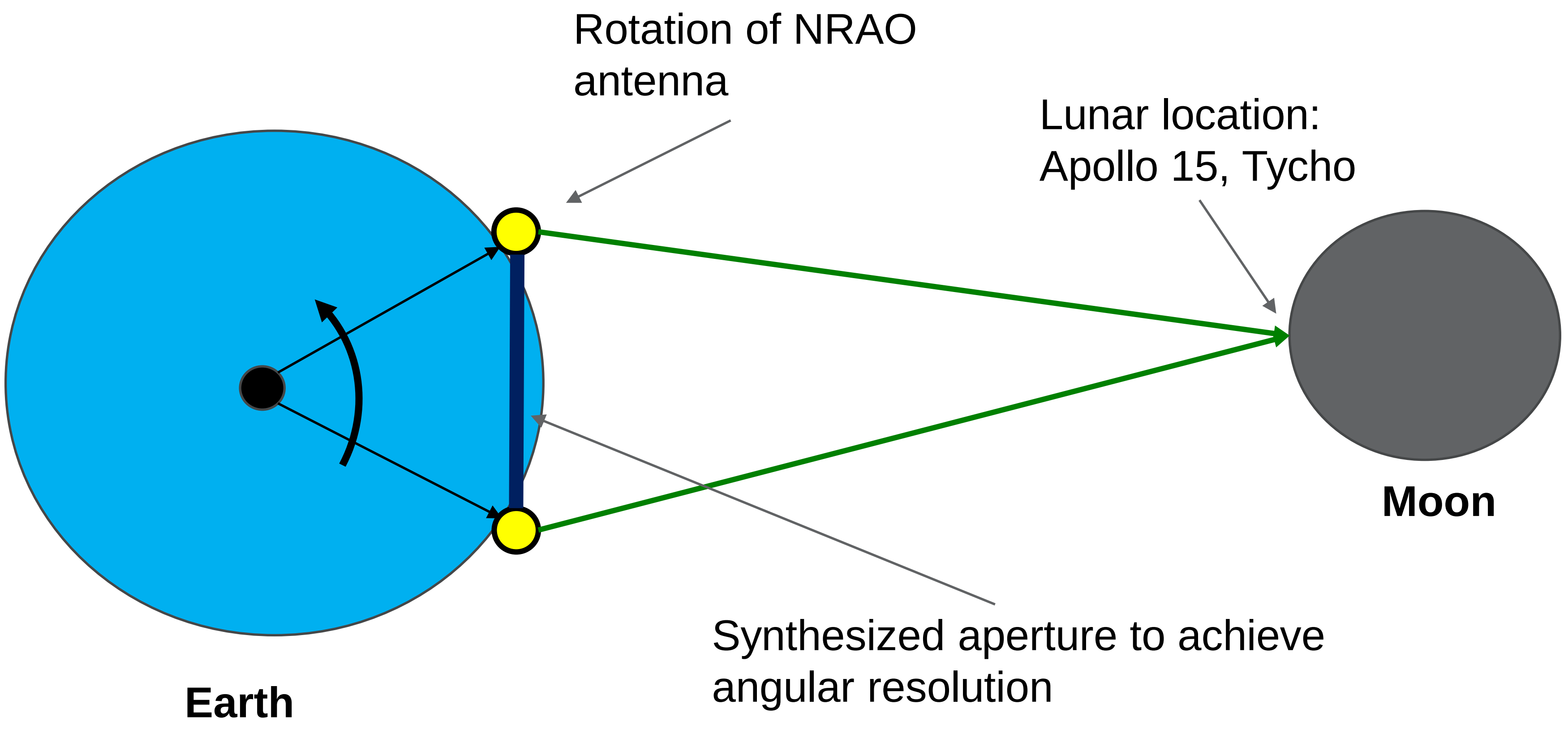


Image Courtesy RI&S

SAR Earth-Moon Geometry



Synthesized aperture to achieve angular resolution

Time it takes is range-dependent

We must remove all motion or image will be smeared

- We synthesize a large aperture using the rotation of Earth
- We have produced the finest resolution radar images from Earth – 1.25 meters
- That requires a ground based optical telescope over 200 meters in diameter!
- The problem: it takes hours to synthesize the aperture, and everything is moving

Planetary Radar Geometry – Long Distant Spherical Object – radar coordinates

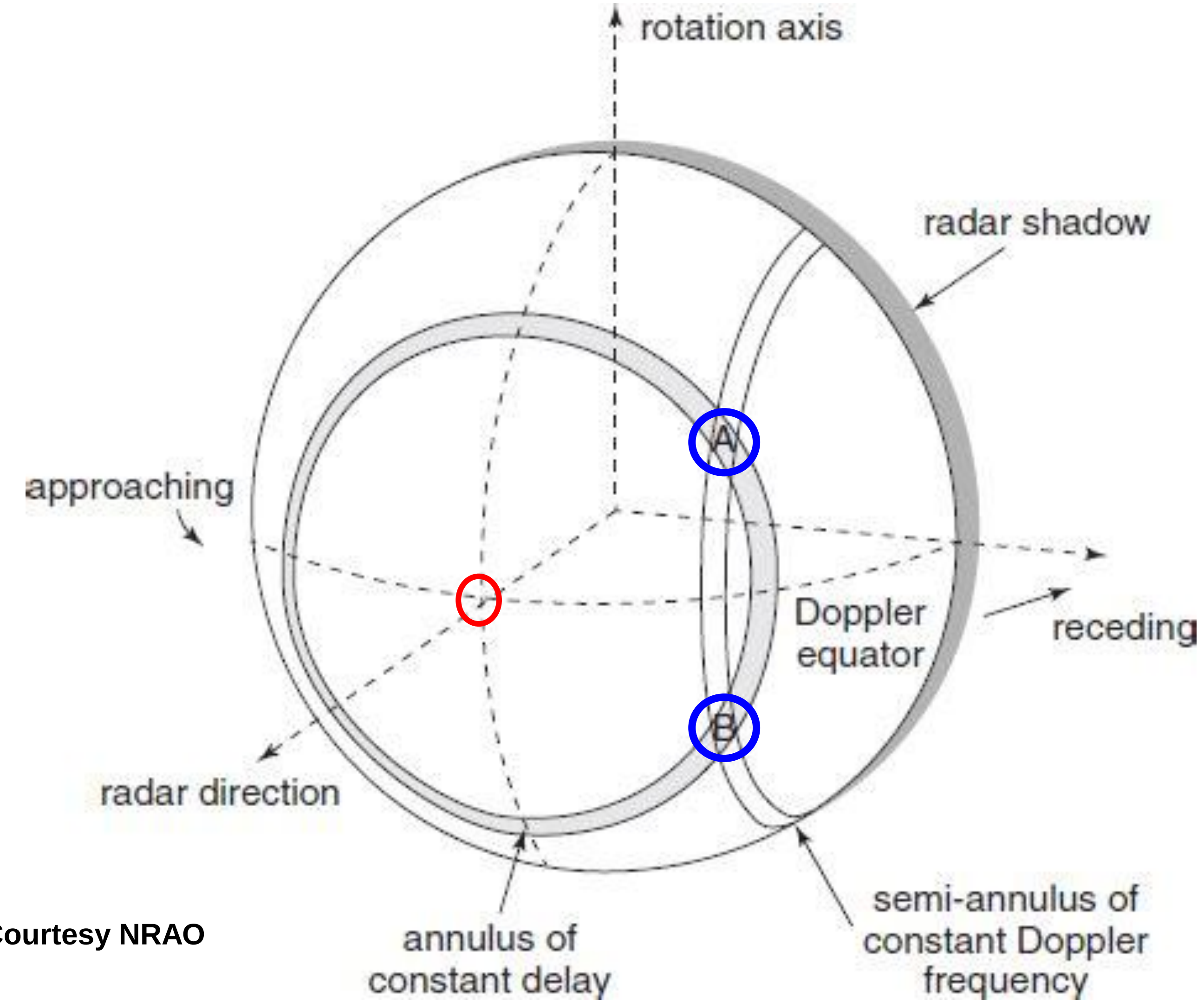
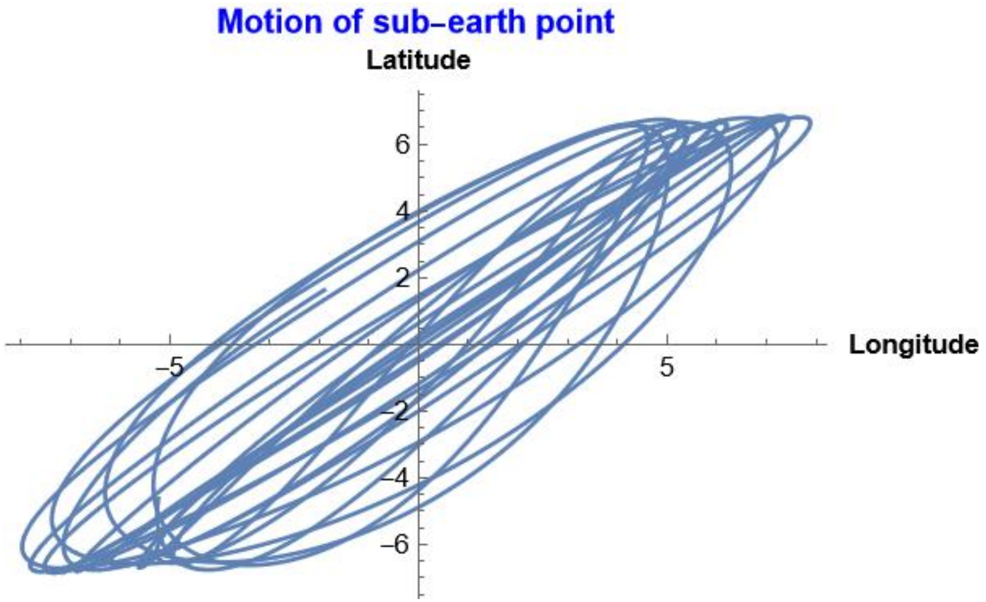


Image Courtesy NRAO

- Applies for all objects in solar system, big and small
- Closest point on the object defines the sub-radar point (red circle)
  - Has geometric meaning for range/delay-Doppler contours
- Range/delay-Doppler was used in the early radar mapping of the moon
  - Finer resolution than optical from earth
- Points A & B call the north-south ambiguity because they fall into the same range/delay-Doppler bin (if beam covers above/below Doppler equator)
- Not required for image formation!

How does the moon move with respect to Earth?

The moon has the most complex motion of any celestial body with respect to Earth



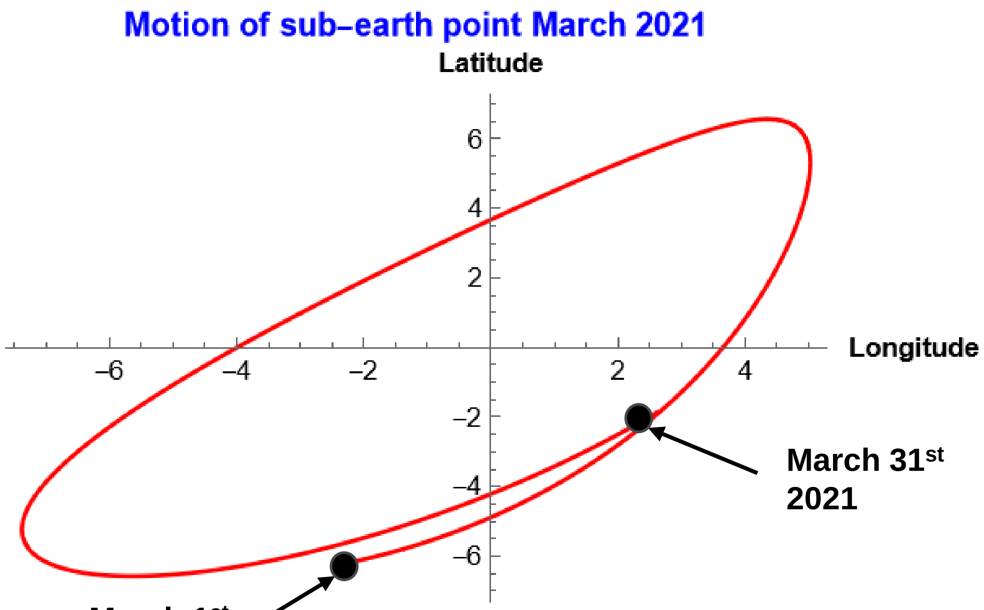
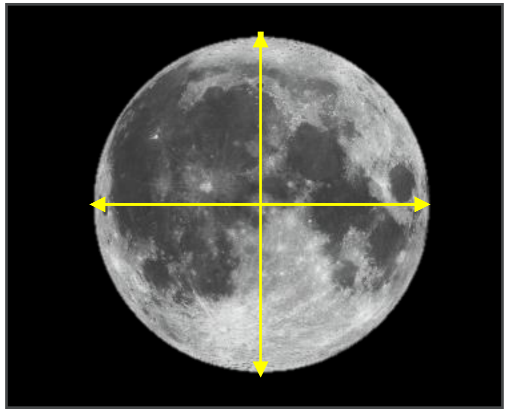
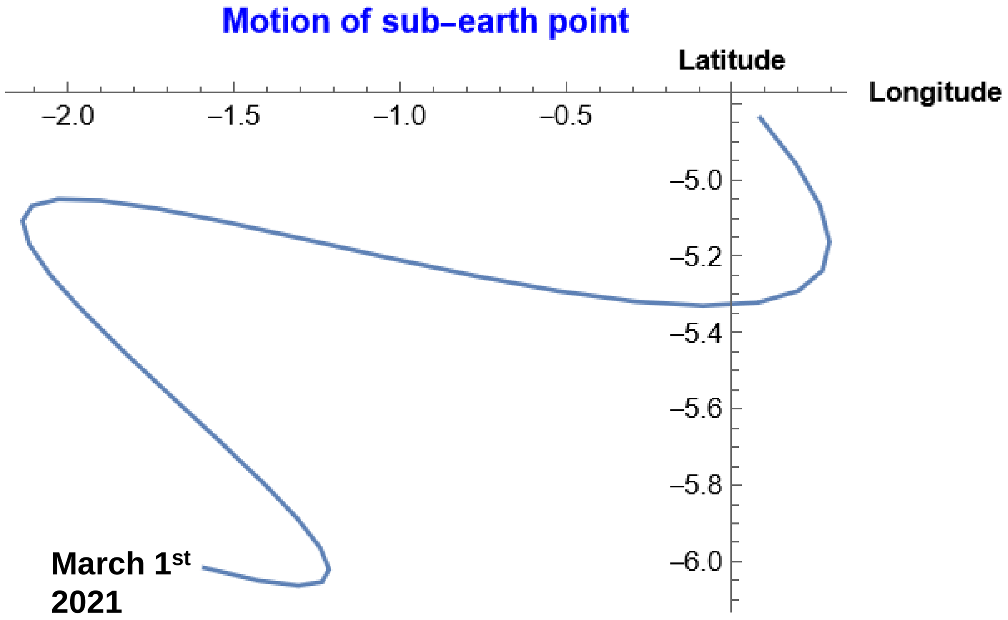


Image Courtesy
NASA/JPL-Caltech



- The lunar sub-earth-point is the closest point on the moon to the earth.
- The path on the lunar surface is due to the ellipticity of the lunar orbit, the tilt of the orbital plane, and one side always faces earth

How does the Earth observer move as viewed on the moon?



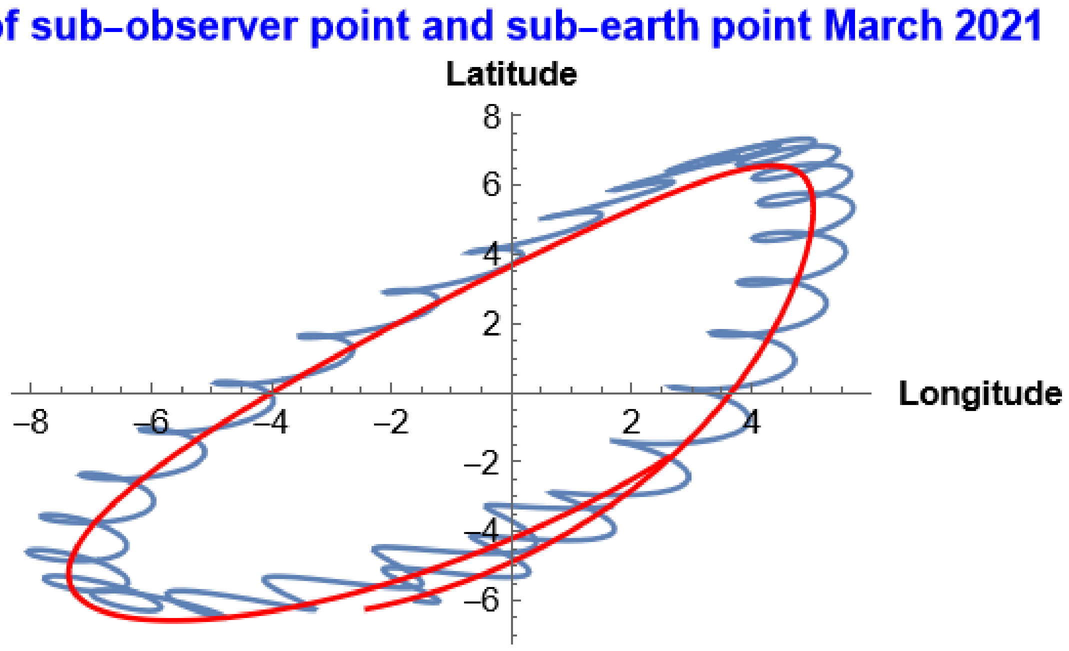
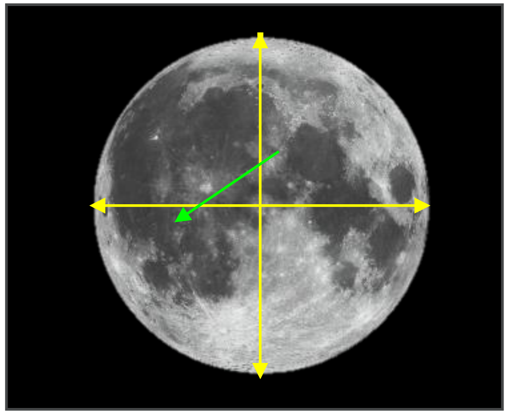


Image Courtesy NASA/JPL-Caltech



- The path of the sub-observer point from the start of the radar observation to the end defines the Doppler equator
- The cross-product of the start/stop vectors define the apparent rotation angle
- The angle between the start/stop vectors divided by the collection time define the apparent rotation rate seen by the radar

How Does a Radar View the Moon? March 2021 lunar radar coordinates for 1.25-m data

Red lines are the Doppler equator and the apparent rotation axis. Apparent rotation rate: 1.123×10^{-6} rad/s

Doppler equator is defined as the surface motion of the sub-radar point across the lunar surface

Yellow circles are the range contours, center on the point where the Doppler equator intersects with the apparent rotation

Green lines parallel with the apparent rotation axis are the Doppler frequencies seen by the radar

The small elliptical is an estimate of the surface illumination from GBT

Light grey lines are the selenographic coordinate system

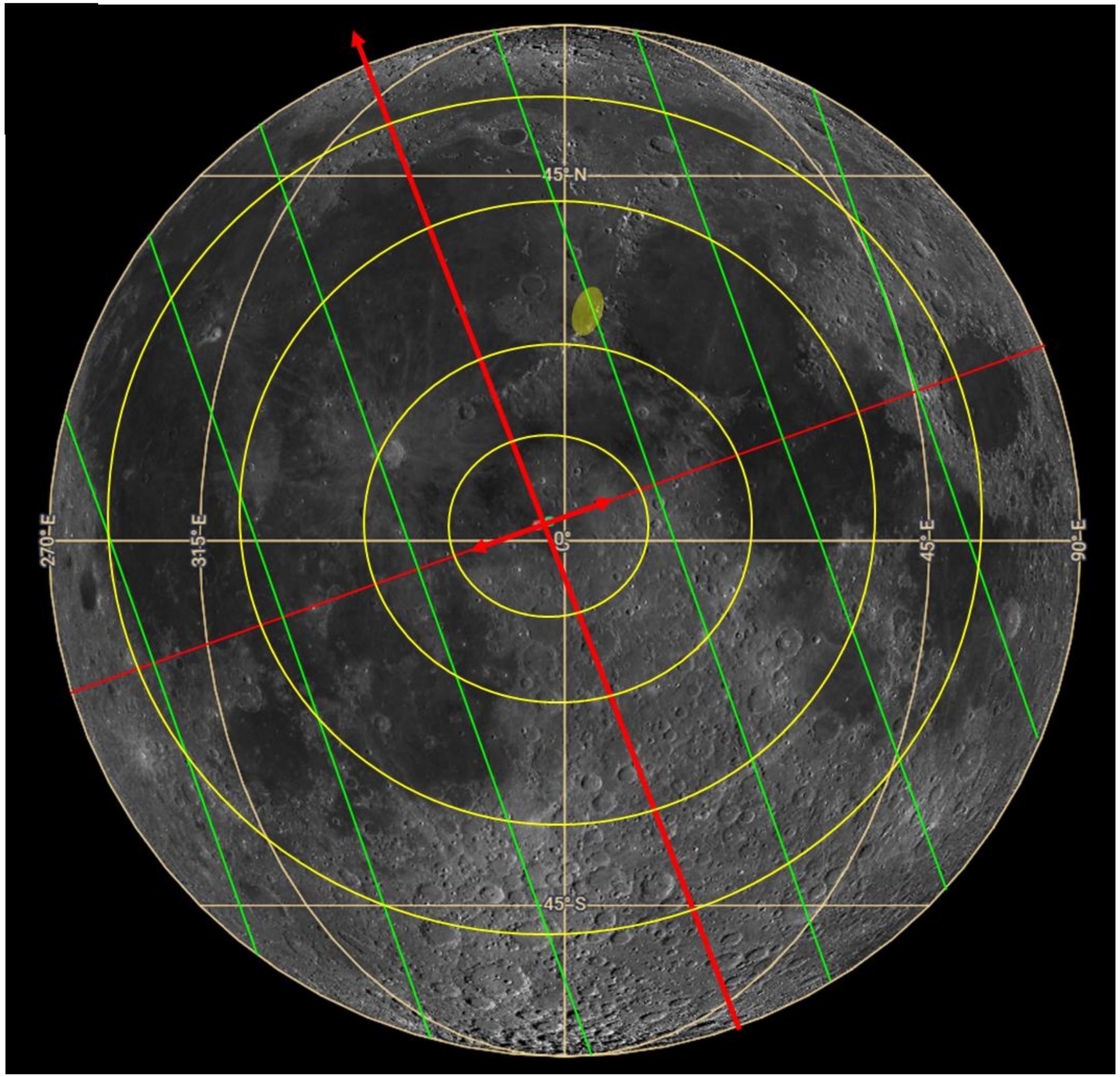
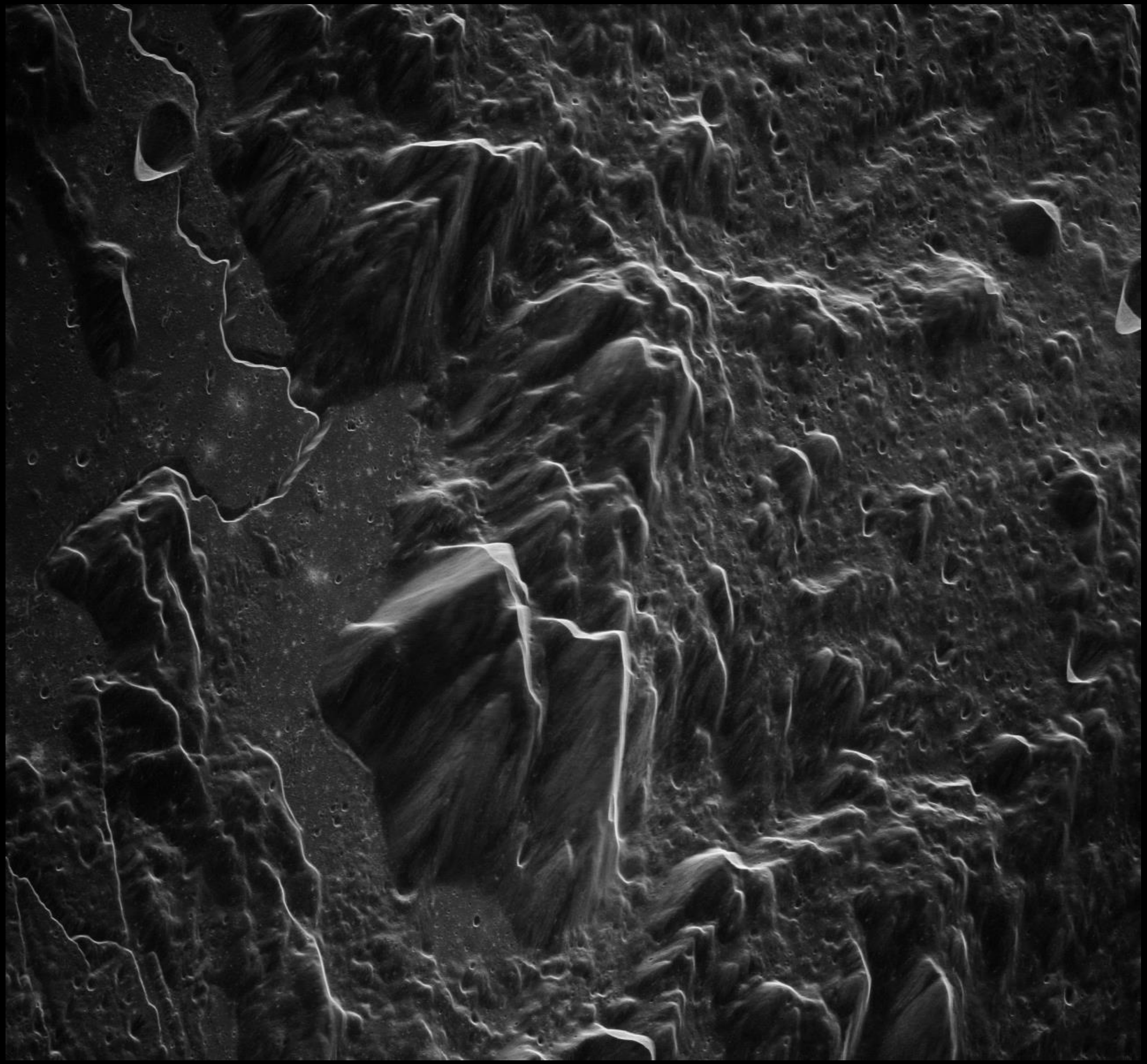


Image Courtesy NASA/JPL-Caltech

Initial & latest Apollo 15 SAR images



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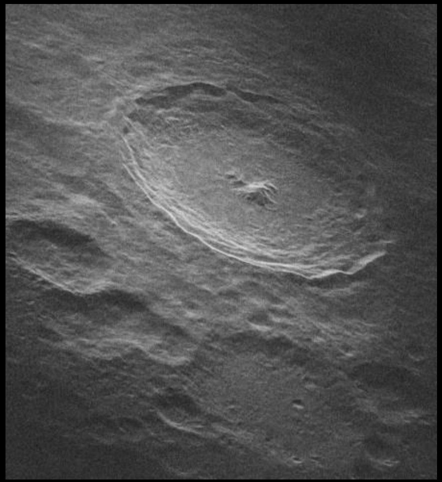
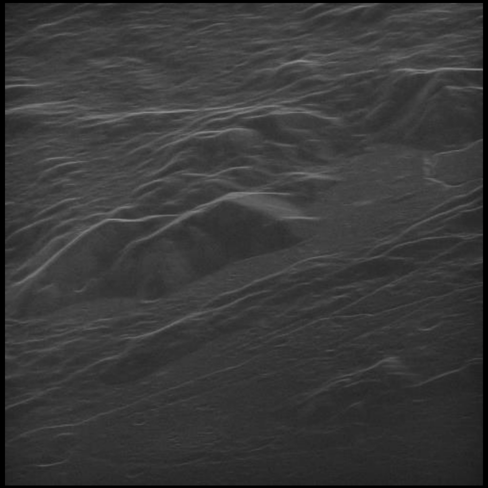
Images Courtesy RI&S

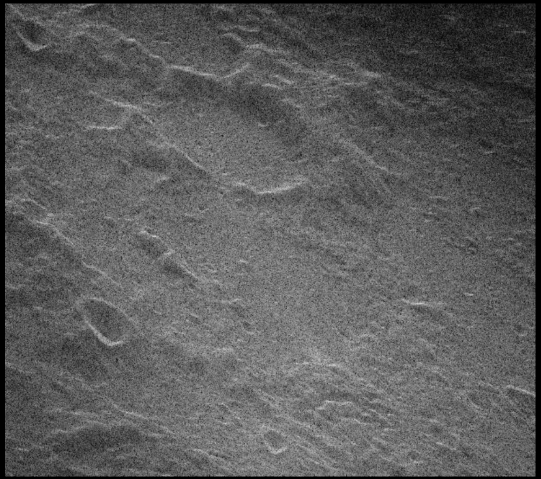
Imagery from March 2021 Experiment

Tycho



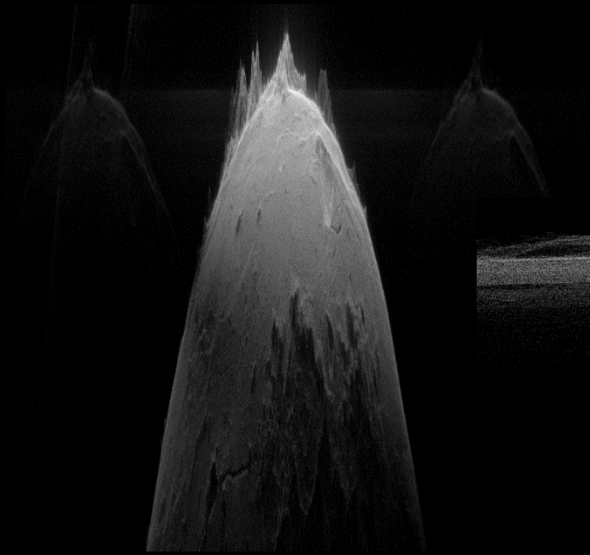


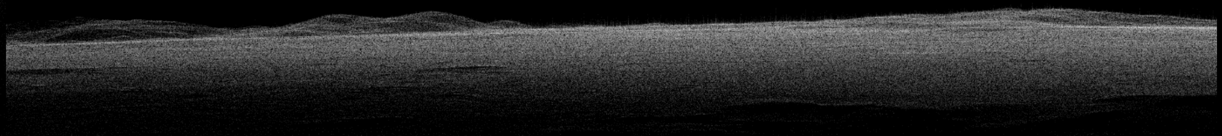
1.25 m quick look

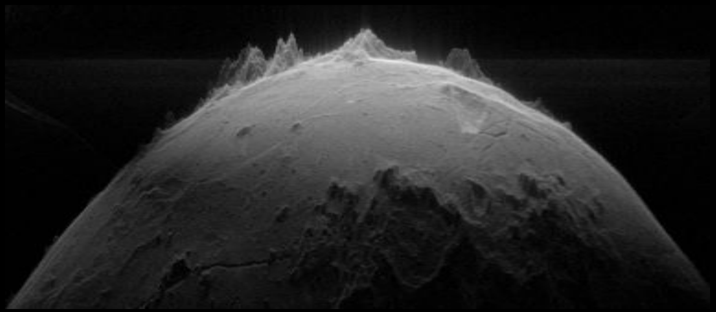


Apollo 16 50-meter

Sub-radar point: Range Range-Rate images



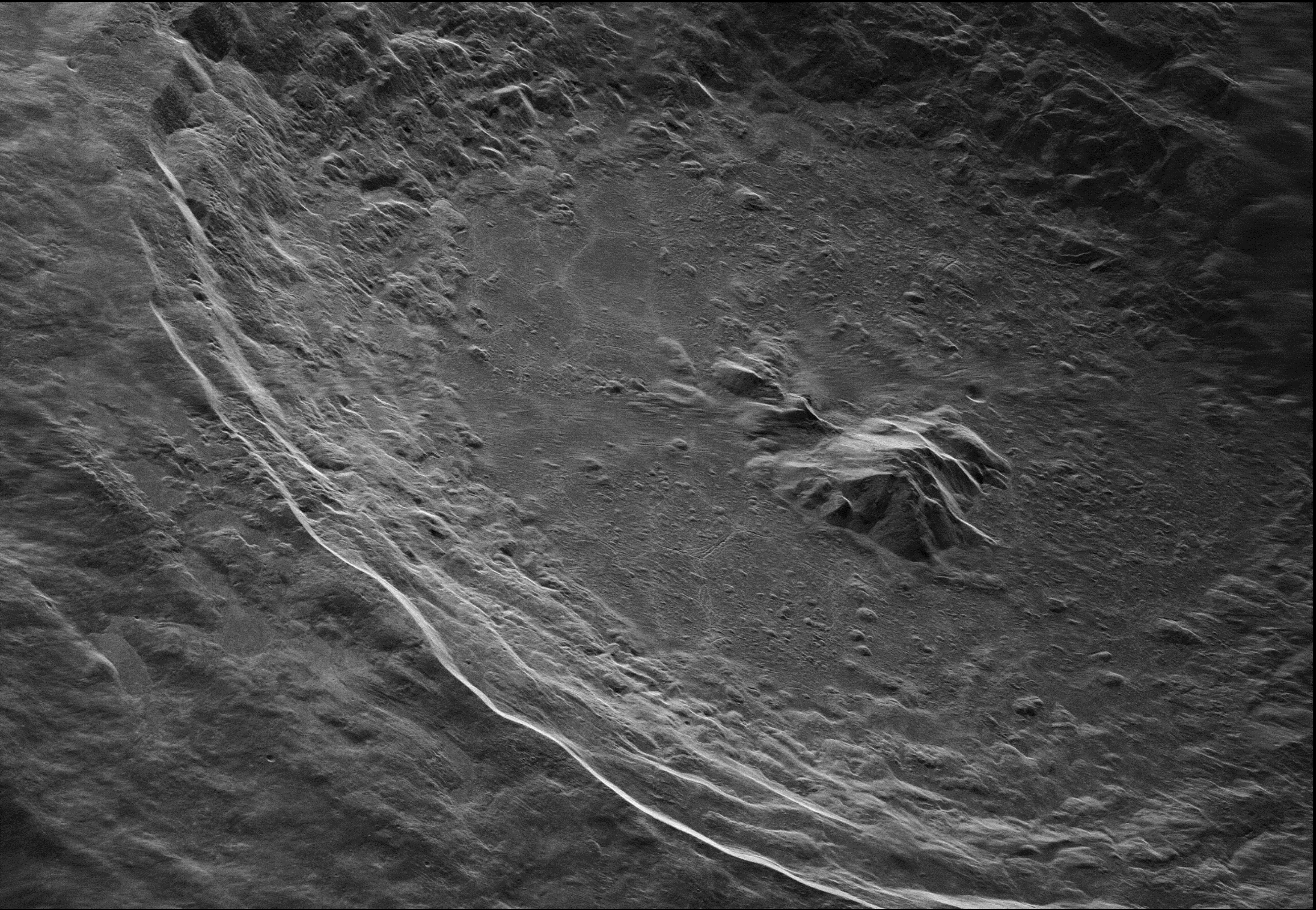




Images Courtesy RI&S

Tycho Crater & Improved Focus

Images Courtesy RI&S



Tycho Crater
Improved Focus

Image Courtesy RI&S

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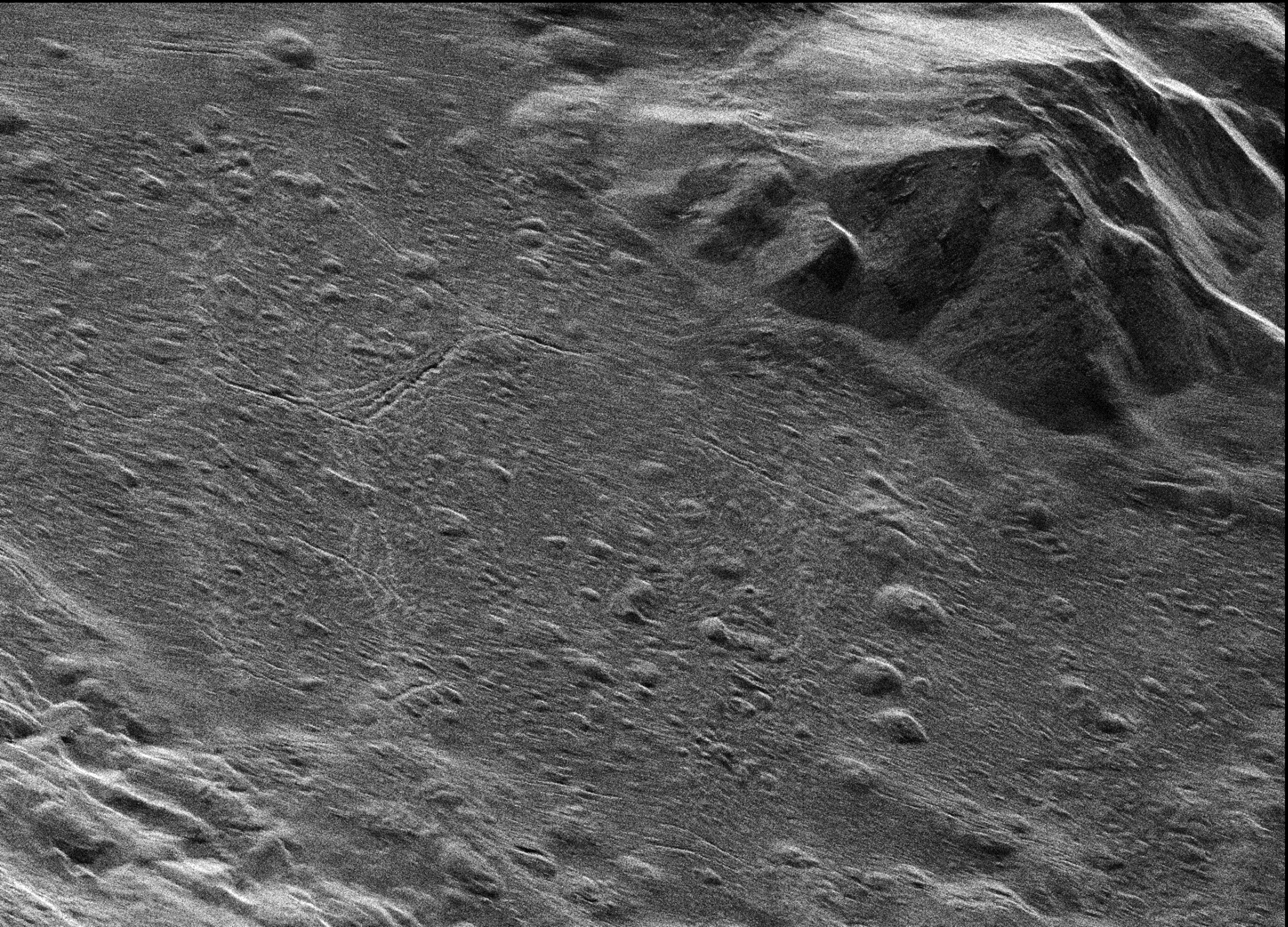

Tycho Crater
Improved Focus

Image Courtesy RI&S

Tycho Crater

with recent improvements

Approaching optical quality

Image Courtesy RI&S

Thank you!