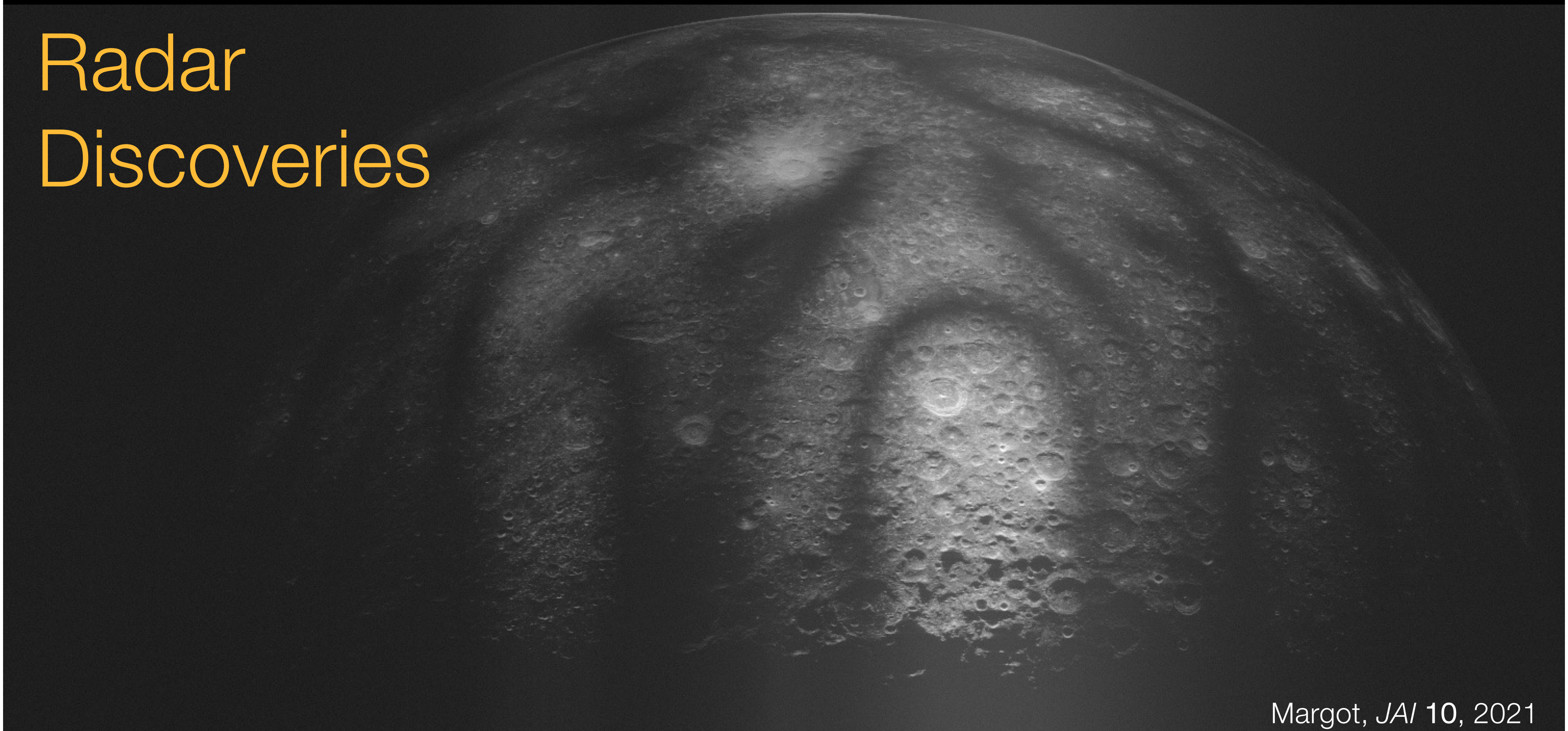
Radar Discoveries



Margot, *JAI* **10**, 2021

Acknowledgements

Colleagues were invited to submit slides for this talk. Special thanks to Patrick Taylor, Michael Busch, Lance Benner, and Flora Paganelli for their input.

Data-Taking Hardware & Software

720 MHz to 30 MHz downconverter

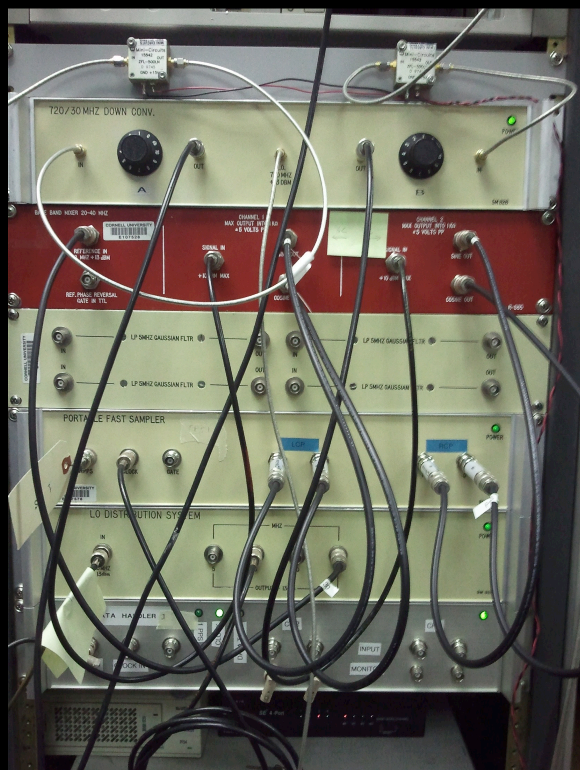
Baseband mixer

Low-pass filters

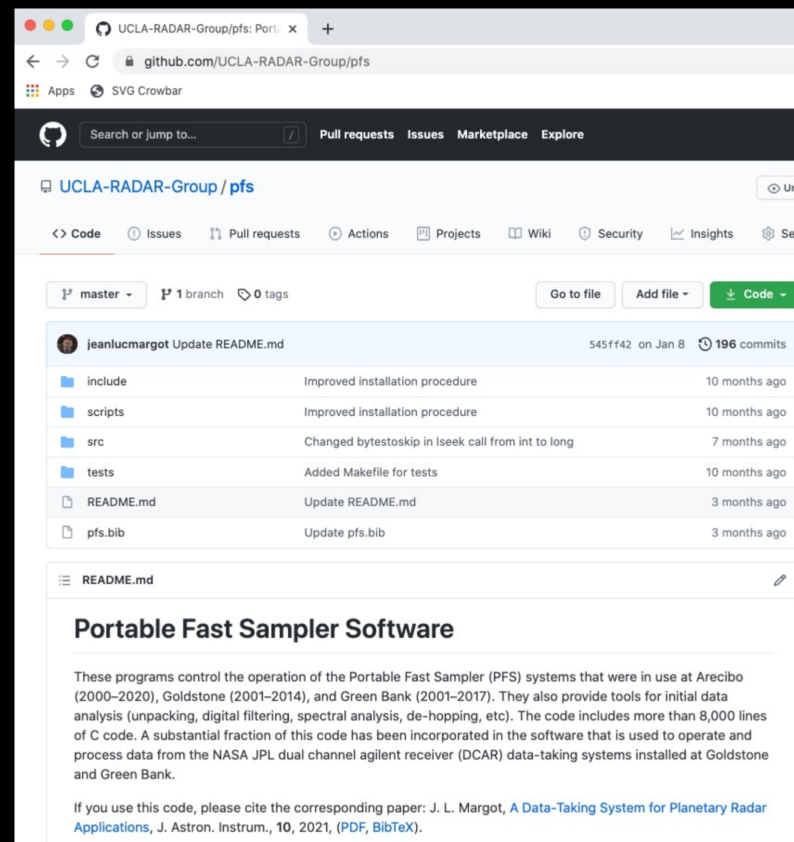
Data-taking unit

5, 10, 20 MHz clock distribution

JPL clone



The portable fast sampler
2 units at Arecibo, 4 units at Goldstone, 2 units at Green Bank



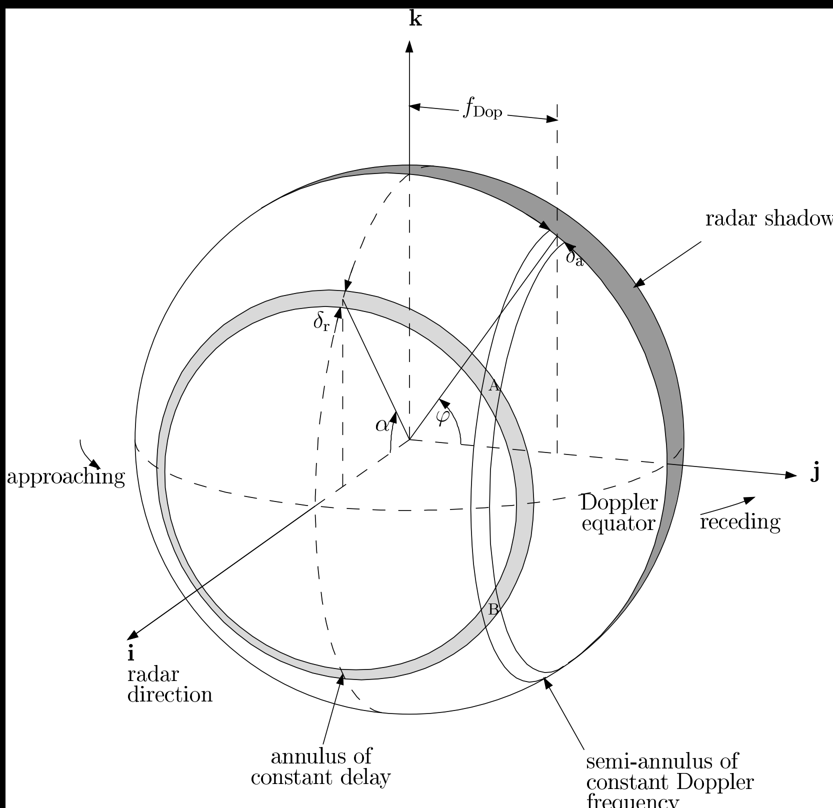
Radar Observables

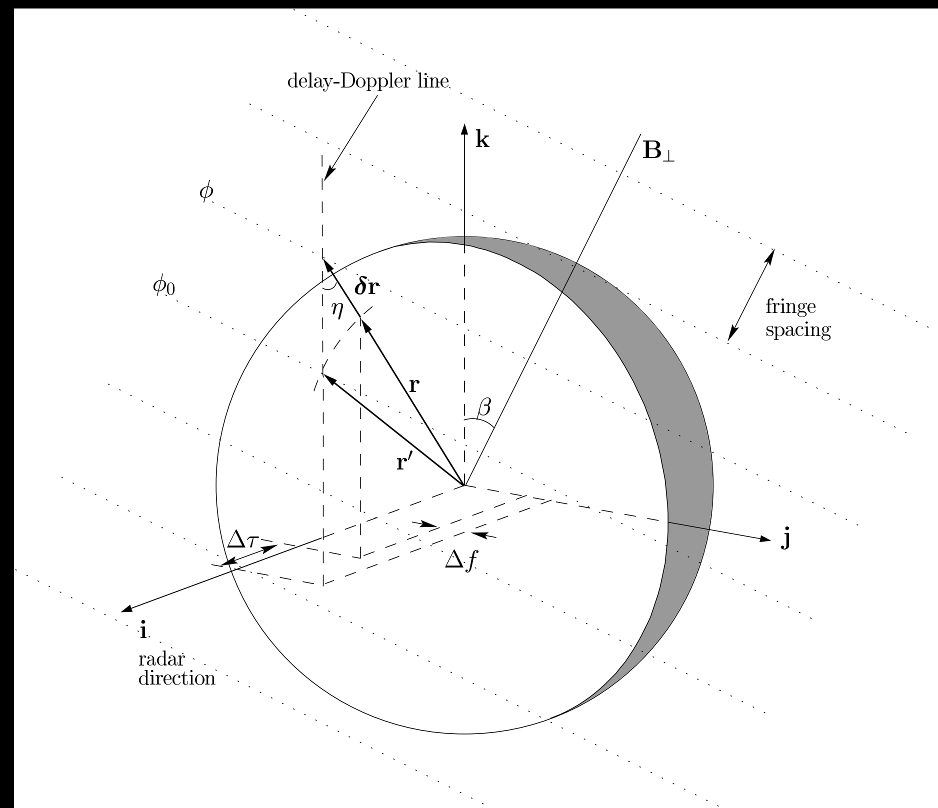
- Time delay τ
- Doppler shift f
- Received power P_r
- Polarization properties S_i
- Interferometric phase ϕ
- Space-time correlation function χ

Radar Measurements

- Velocities
- Distances
- Orbits
- Spin orientation
- Spin rate
- Mass
- Bulk density
- Moments of inertia
- Images
- Surface change
- Topographic maps
- 3D shape
- Roughness
- Dielectric constant
- Near-surface density
- Composition

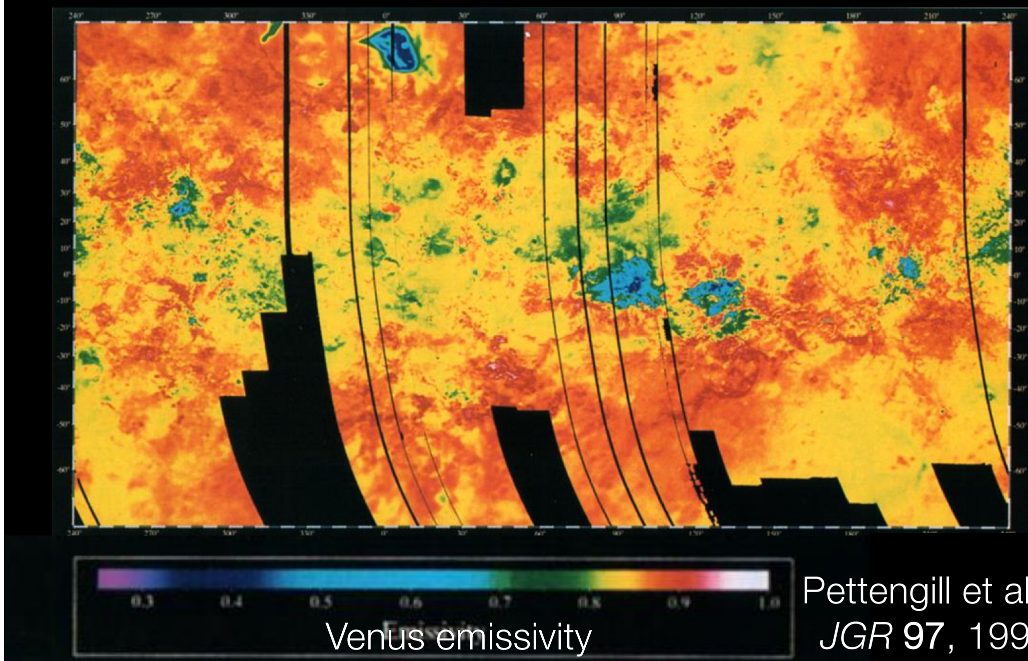
Range-Doppler Imaging and InSAR





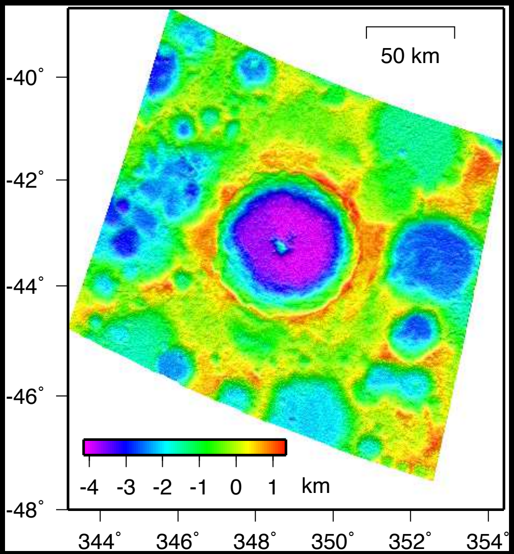
Margot et al., *IEEE TGRS* **38**, 2000

First Science Observations at GBT: Venus



Venus emissivity

Pettengill et al., *JGR* **97**, 1992



Lunar topography
Margot et al., *JGR* **104**, 1999

Goal: measure the topography of several high-reflectivity, low-emissivity mountains to explain the relationship between surface emissivity, reflectivity, and altitude on Venus (PI: Don Campbell)

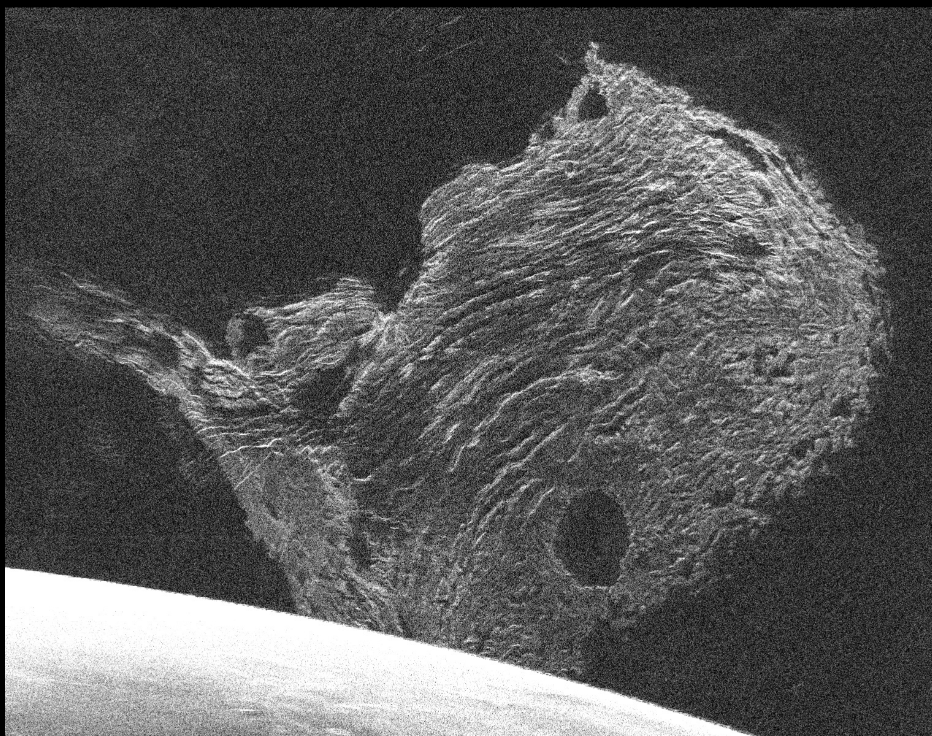
An Auspicious Start

Venus 24 Mar 2001

GB windy
& no internet

Arecibo-GBT Radar Image of Venus

Maxwell Montes



National Radio Astronomy Observatory
520 Edgemont Road
Charlottesville, VA 22903
http://www.nrao.edu

May 10, 2001

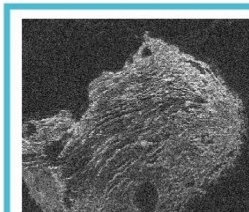
Contact:

Dave Finley, Public Information Officer
(505) 835-7302
dfinley@nrao.edu

New Radio Telescope Makes First Scientific Observations

The world's two largest radio telescopes have combined to make detailed radar images of the cloud-shrouded surface of Venus and of a tiny asteroid that passed near the Earth. The images mark the first scientific contributions from the National Science Foundation's (NSF) new Robert C. Byrd Green Bank Telescope in West Virginia, which worked with the NSF's recently-upgraded Arecibo telescope in Puerto Rico. The project used the radar transmitter on the Arecibo telescope and the huge collecting areas of both telescopes to receive the echoes.

"These images are the first of many scientific contributions to come from the Robert C. Byrd Green Bank Telescope, and a great way for it to begin its scientific career," said Paul Vanden Bout, director of the National Radio Astronomy Observatory (NRAO). "Our congratulations go to the scientists involved in this project as well as to the hard-working staffs at Green Bank and Arecibo who made this accomplishment possible," Vanden Bout added.



A portion of Maxwell Montes on Venus, imaged with the Arecibo-GBT radar system. This image shows detail as small as 1.2 kilometers. Courtesy Campbell et al., NRAO, NAIC, NSF.

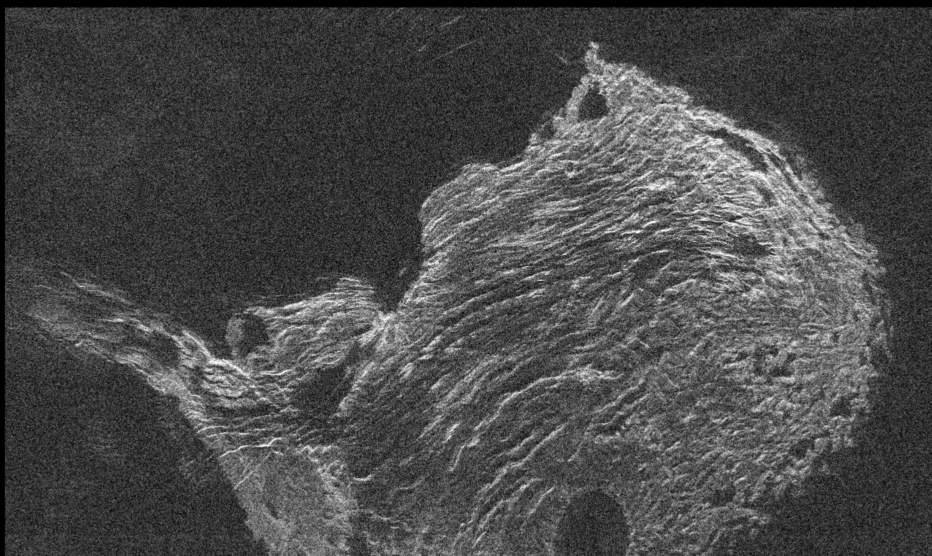
To the eye, Venus hides behind a veil of brilliant white clouds, but these clouds can be penetrated by radar waves, revealing the planet's surface. The combination of the Green Bank Telescope (GBT), the world's largest fully-steerable radio telescope, and the Arecibo telescope, the world's most powerful radar, makes an unmatched tool for studying Venus and other solar-system bodies.

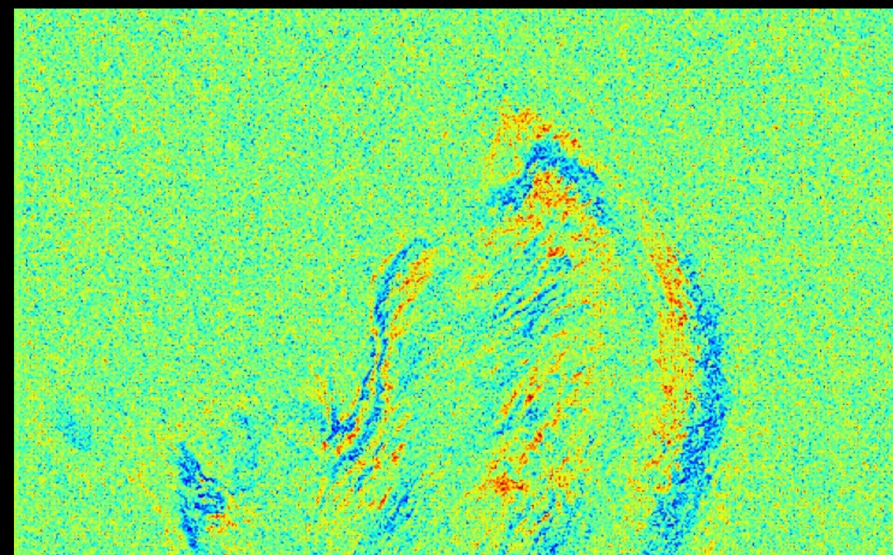
"Having a really big telescope like the new Green Bank Telescope to receive the radar echoes from small asteroids that are really close to the Earth and from very distant objects like Titan, the large moon of Saturn, will be a real boon to radar studies of the solar system." said Cornell University professor Donald Campbell, leader of the research team.

Ten years ago, the radar system on NASA's Magellan spacecraft probed though the clouds of Venus to reveal in amazing detail the surface of the Earth's twin planet. These new studies using the GBT and Arecibo, the first since Magellan to cover large areas of the planet's surface, will provide images showing surface features as small as about 1 km (3,000 ft), only three times the size of the Arecibo telescope itself.

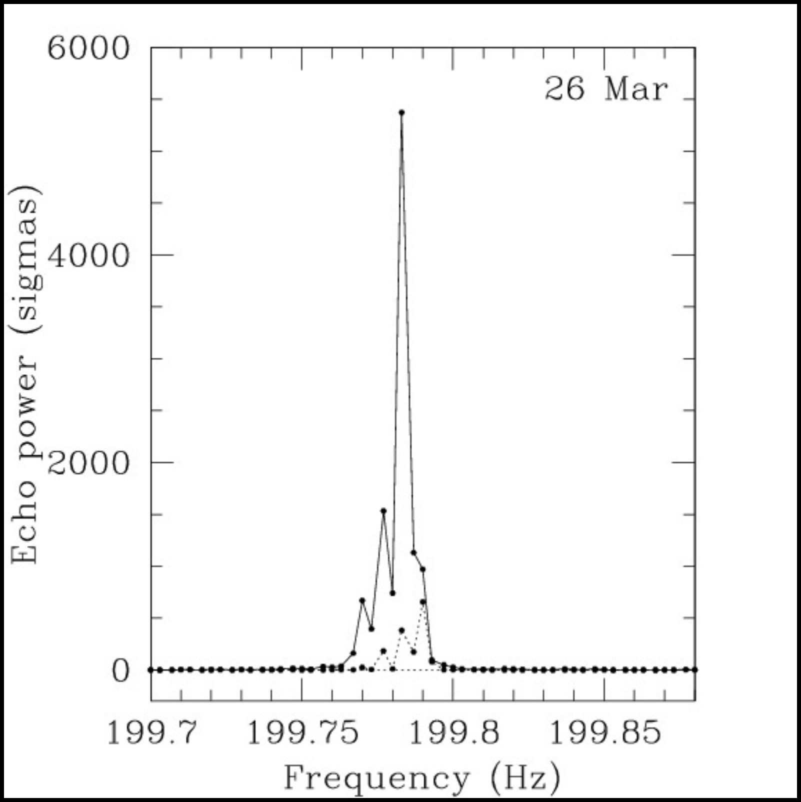
Venus may be a geologically active planet similar to the Earth, and the new images will be used to look for changes on Venus due to volcanic activity, landslides and other processes that may have modified the surface since the Magellan mission. The radar echoes received by both telescopes also can be combined to form a radar interferometer capable of measuring altitudes over some of the planet's mountainous regions with considerably better detail than was achieved by Magellan.

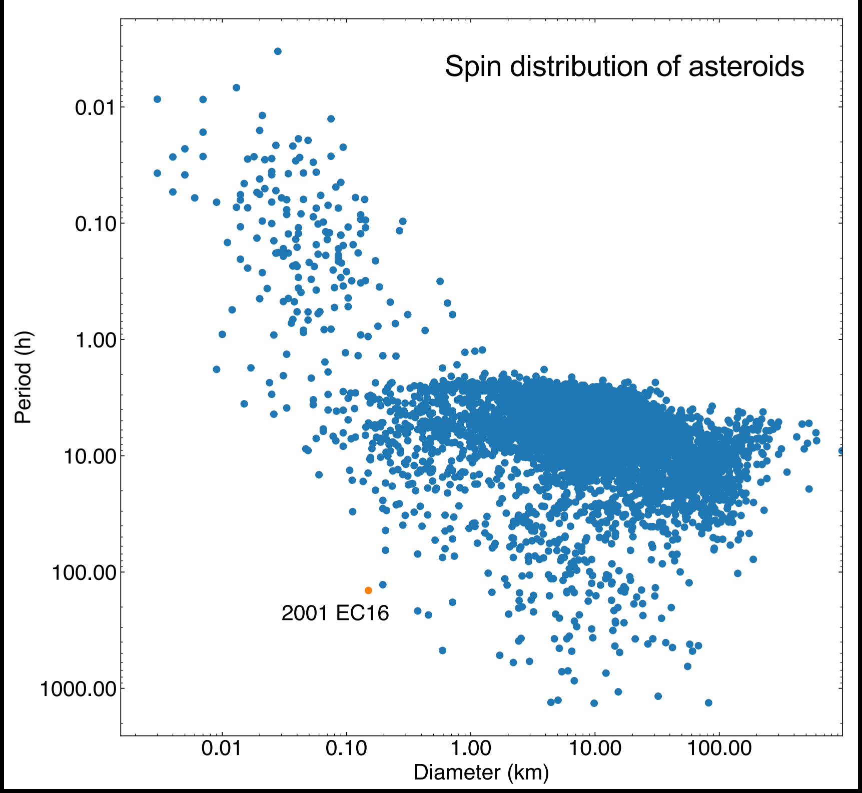
Interferometric Fringes





Second Science Observations: 2001 EC16





Equal-Mass Binary Near-Earth Asteroid

Other Near-Earth Asteroid Results

2001 FO32

https://echo.jpl.nasa.gov/asteroids/2001FO32/2001FO32.2021.goldstone.planning.html

2017 VR12

https://echo.jpl.nasa.gov/asteroids/2017VR12/2017VR12_planning.2018.html

Apophis in 2021

https://www.jpl.nasa.gov/news/nasa-analysis-earth-is-safe-from-asteroid-apophis-for-100-plus-years

2011 UW158 and 1999 JD6

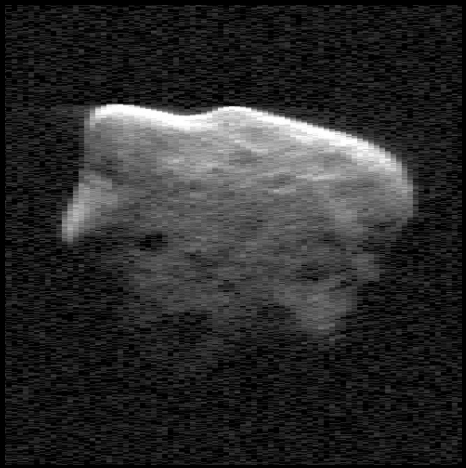
https://echo.jpl.nasa.gov/asteroids/2011UW158/2011UW158_planning.html

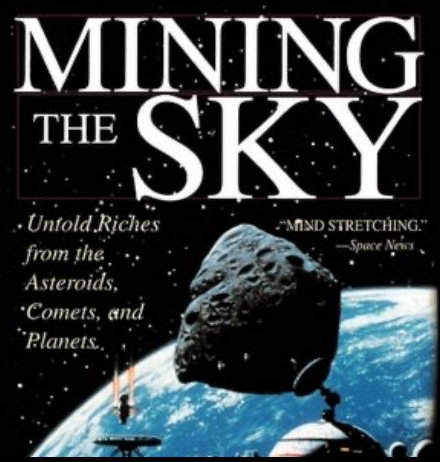
2004 BL86

https://www.youtube.com/watch?v=ef2kkhY0teM

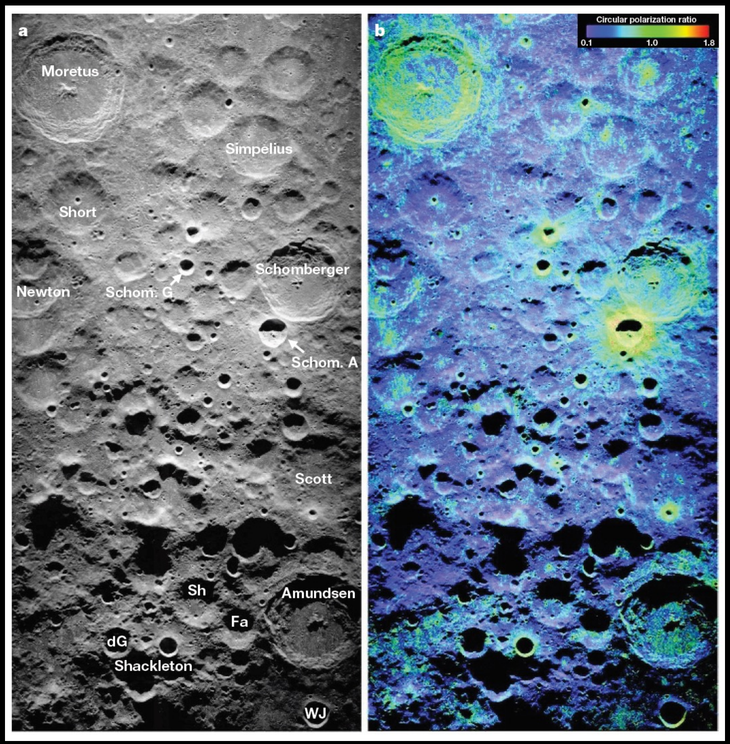
Courtesy Lance Benner

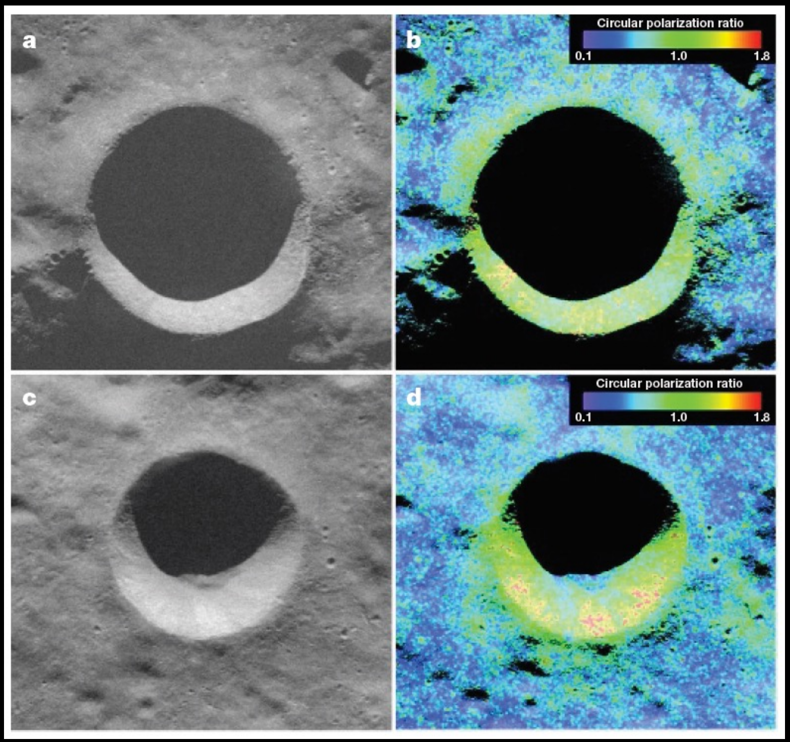
Importance of Near-Earth Asteroids





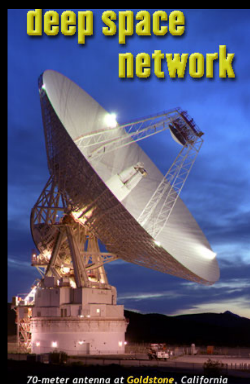
No Evidence for Thick Deposits of (Clean) Ice at the Lunar South Pole





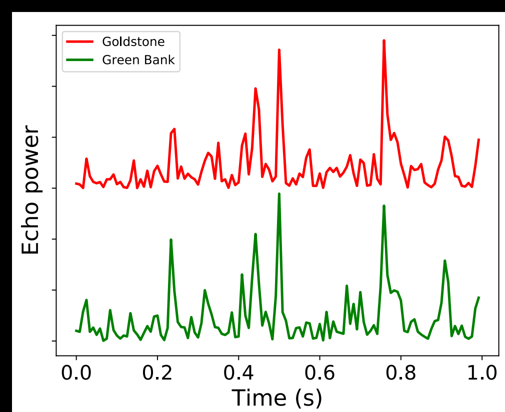
Campbell et al., *Nature* **443**, 2006

Radar Speckle Tracking



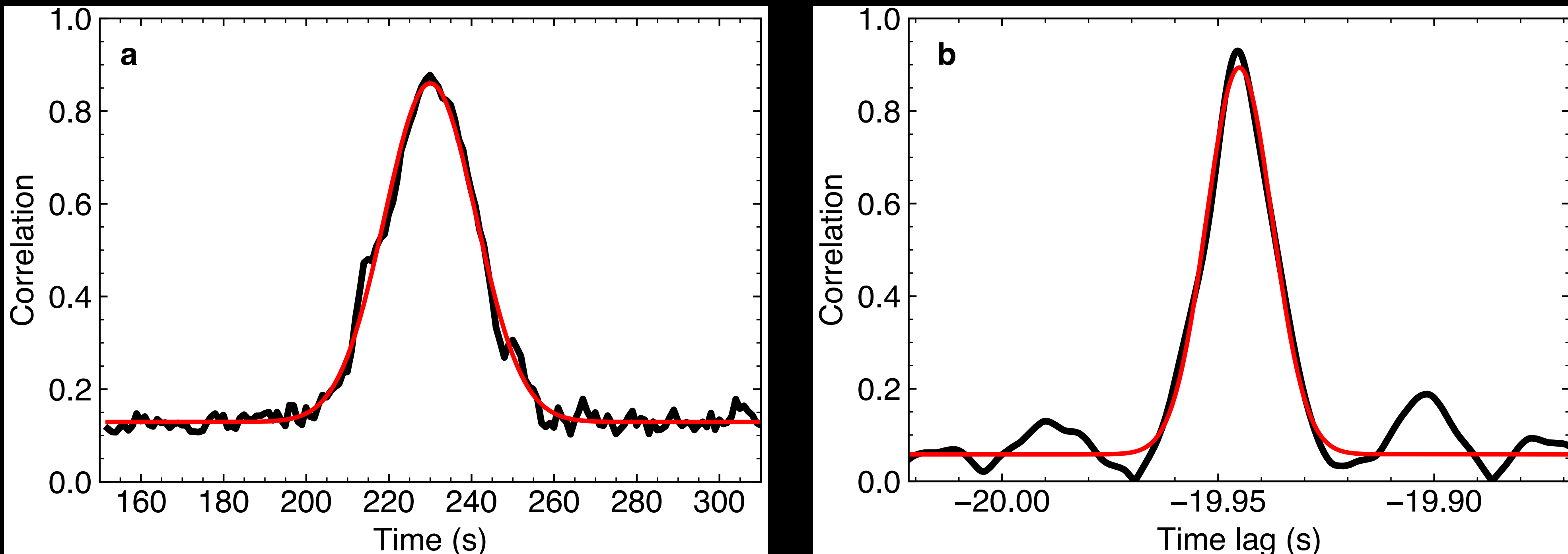
Goldstone, CA

Green Bank, WV

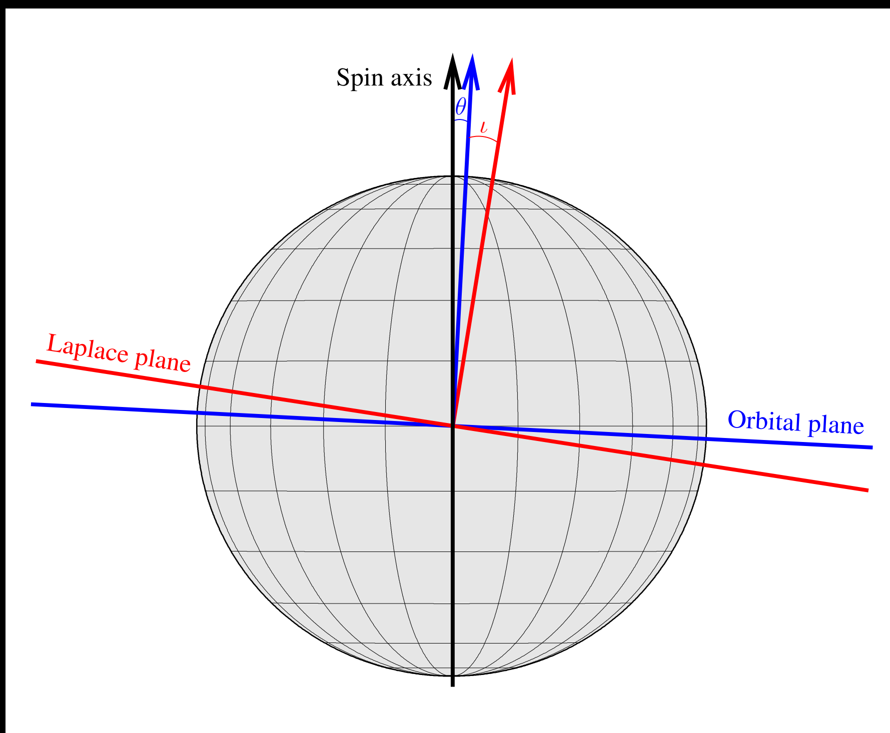


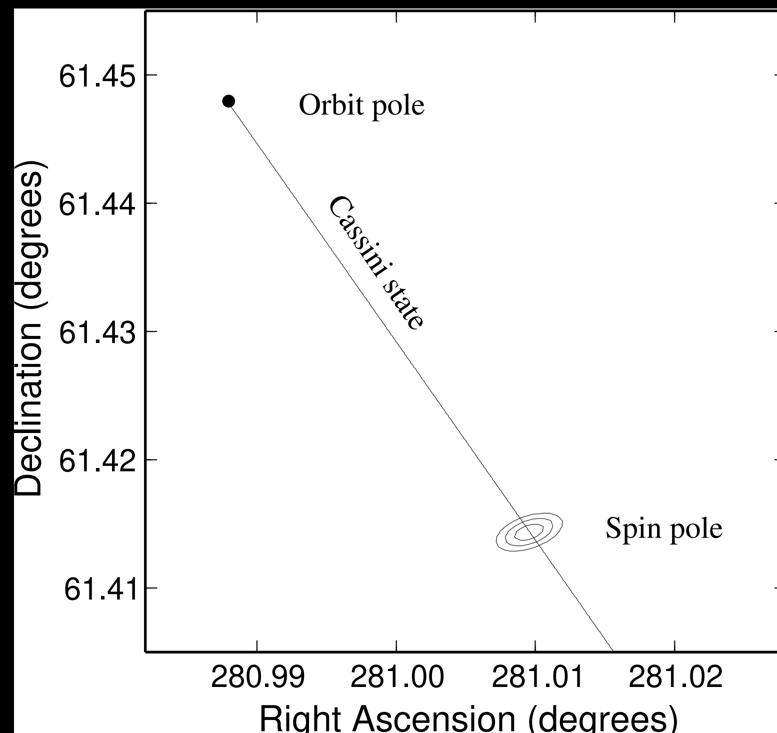
Green 1962, 1968
Holin 1988, 1992
Margot 2007, 2012

Space-Time Correlations



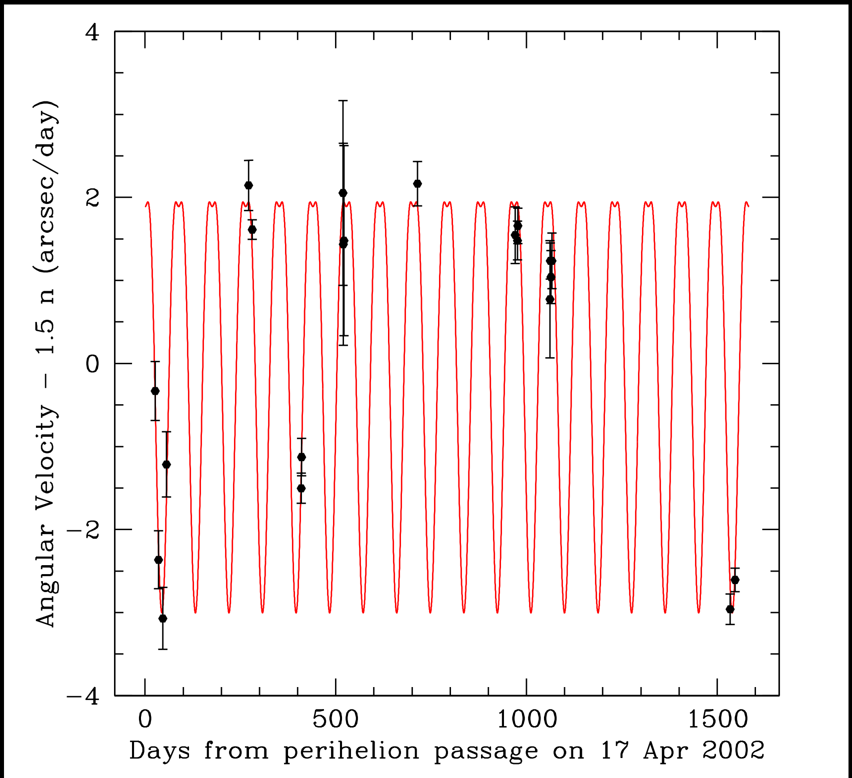
Mercury is in Cassini State 1

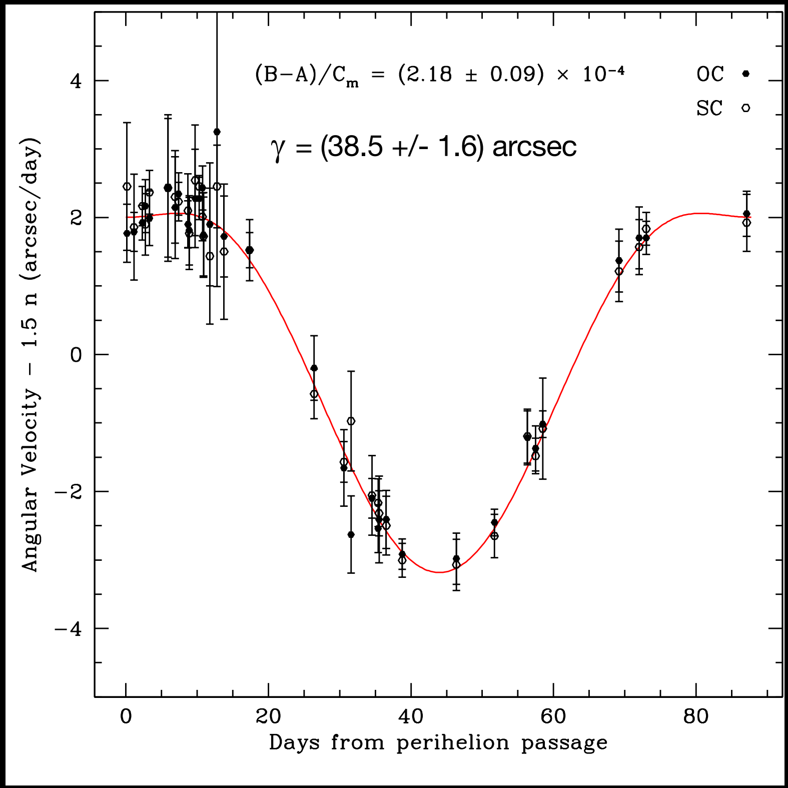




Margot et al., *Science* **316**, 2007

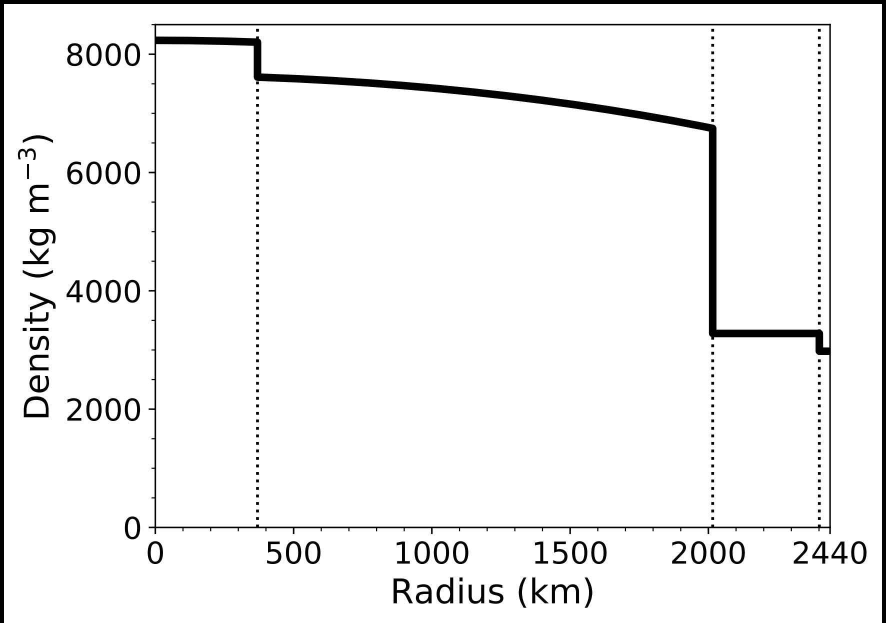
Mercury's Core is Molten

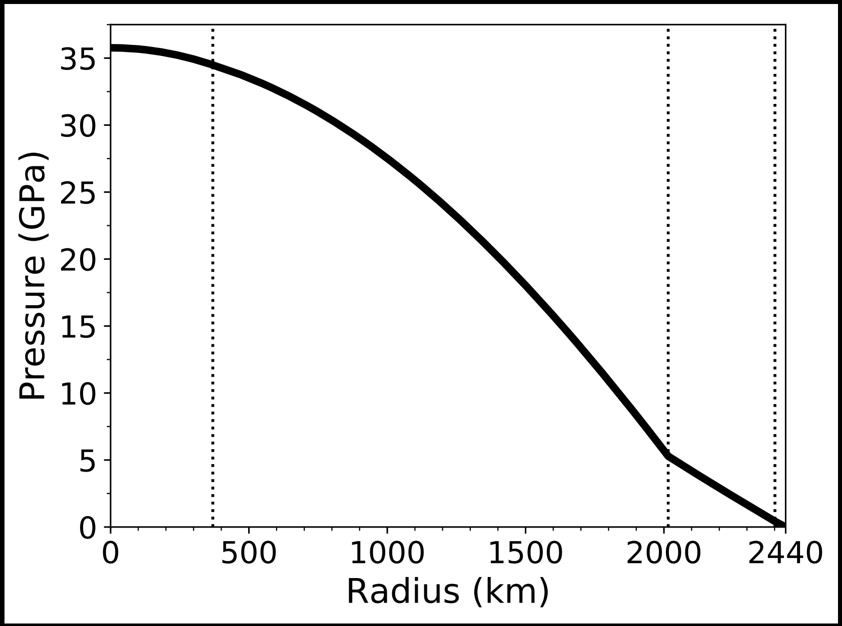




Margot et al., *Science* **316**, 2007

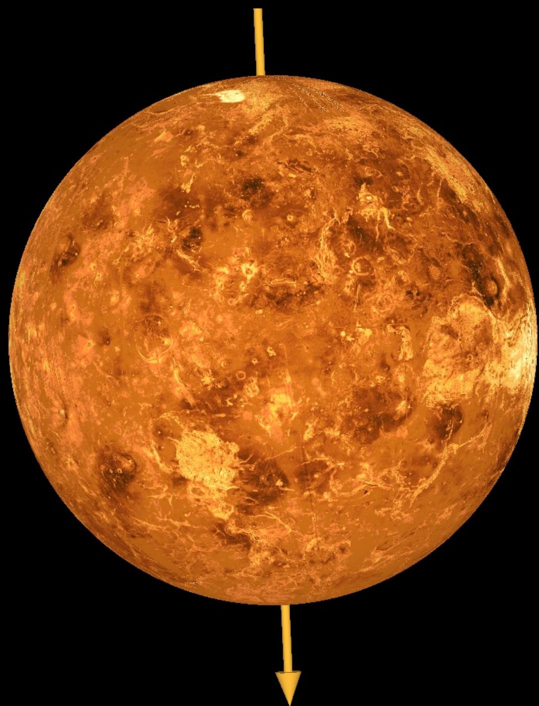
Measurement of Mercury’s Core Size

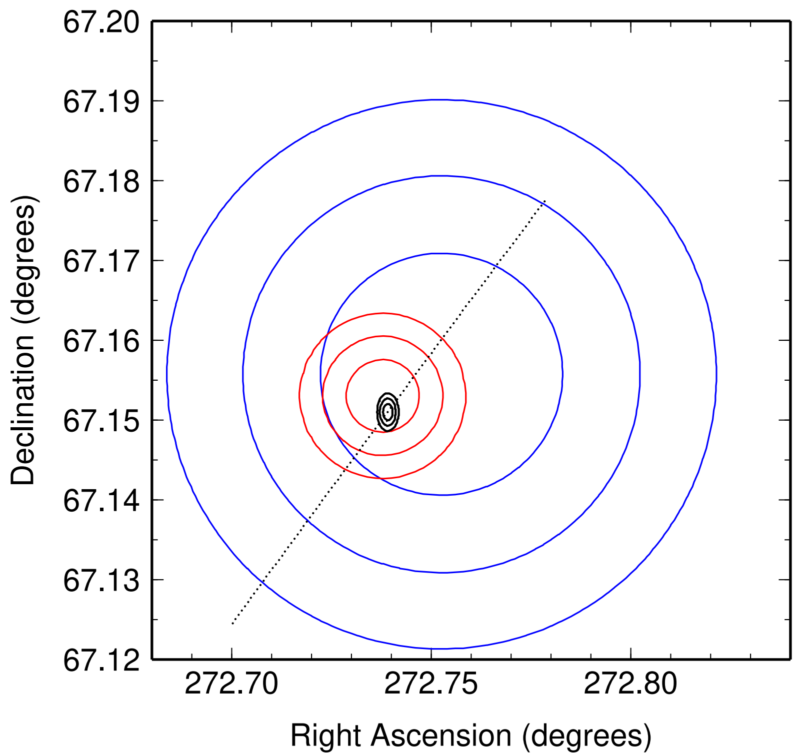




Margot et al., in Mercury – The view after MESSENGER (eds S. C. Solomon, B. J. Anderson, L. R. Nittler), 2018

Venus Spin Axis Orientation





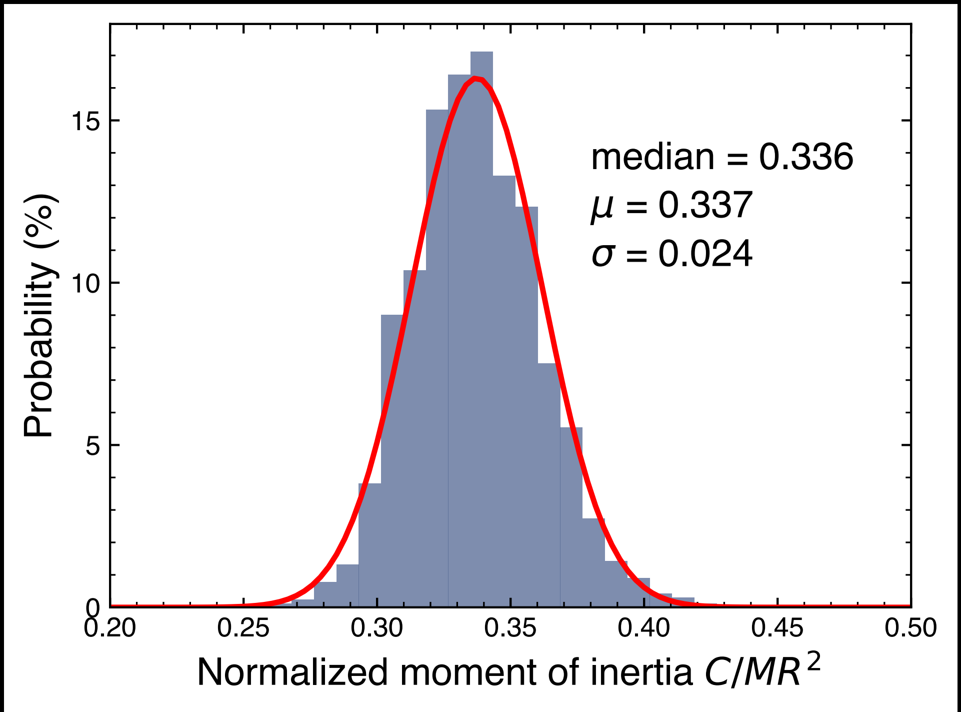
Davies et al. 1992
Magellan radar (46”)

Konopliv et al. 1999
Magellan gravity (14”)

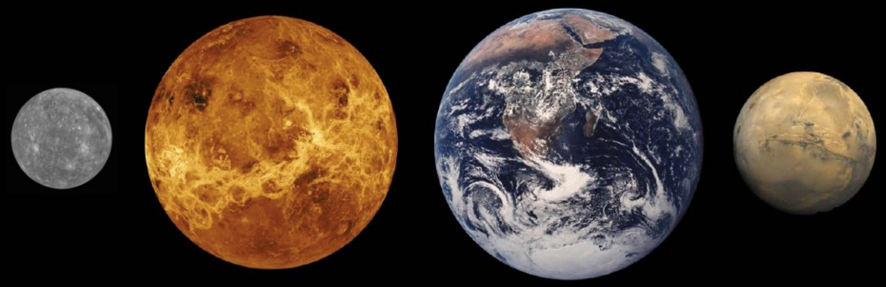
Earth-based radar (3”)
(80 m on the surface)

Margot et al., *Nature Astronomy* **5**, 2021.

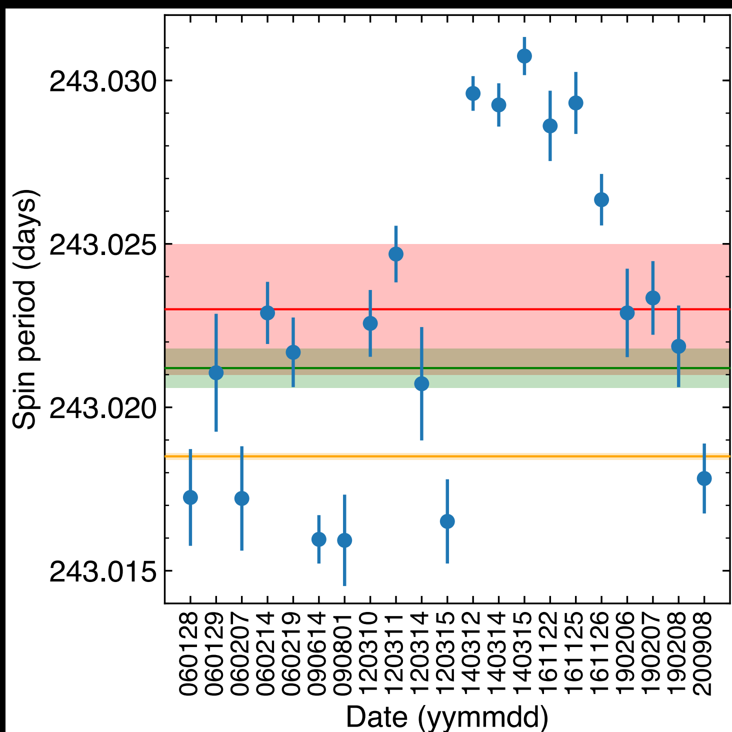
Venus Moment of Inertia

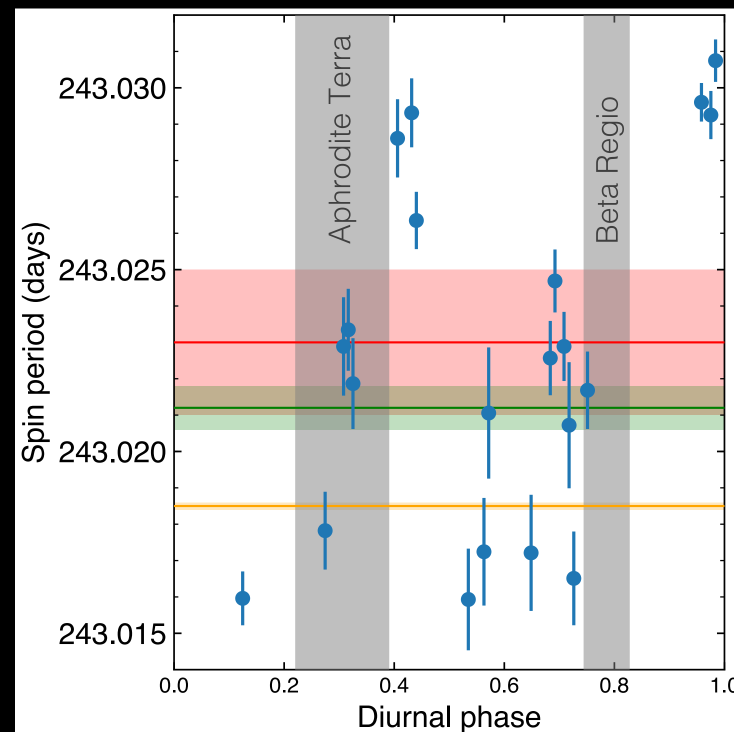


Quantity	Least squares	Bootstrap mean	Std. dev.
RA (deg)	272.73911	272.73912	0.0008
DEC (deg)	67.15105	67.15100	0.0007
$d\psi/dt$ ($''$/y)	-44.89	-44.58	3.3
C/MR^2	0.3350	0.3373	0.024
C (10^{37} kg m^2)	5.972	6.013	0.43



Venus Length-of-Day Variations

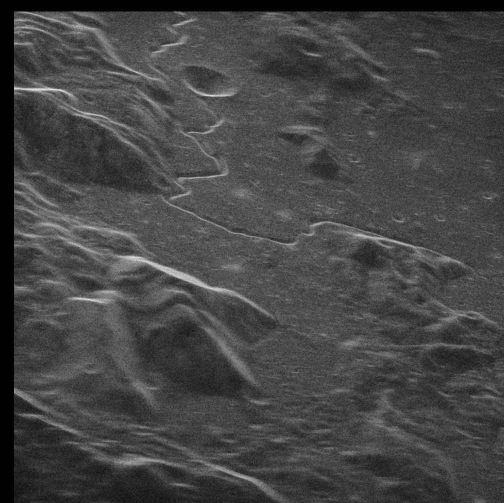




Margot et al., *Nature Astronomy* **5**, 2021.

A New Era for Planetary Radar

Transmit from low-power (~1kW) Ku-band (13.9 GHz) prototype at GBT prime focus (with Raytheon) and receive at VLBA antenna in Hancock, NH.



Courtesy Flora Paganelli

Happy Anniversary!

With deep gratitude to all the scientific and technical staff who have enabled radar observations at the GBT for more than 20 years.