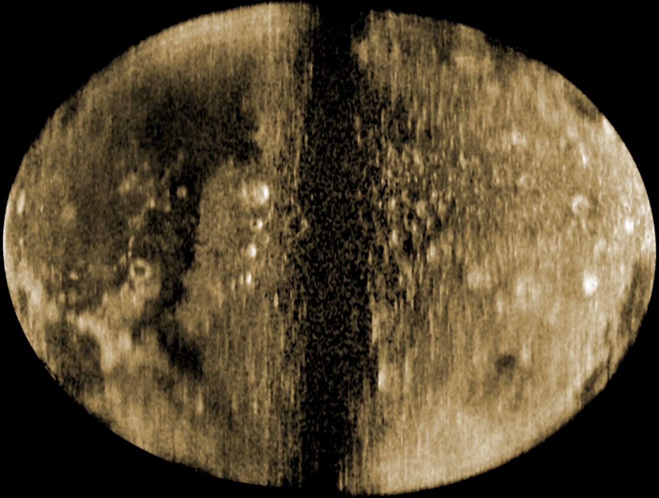
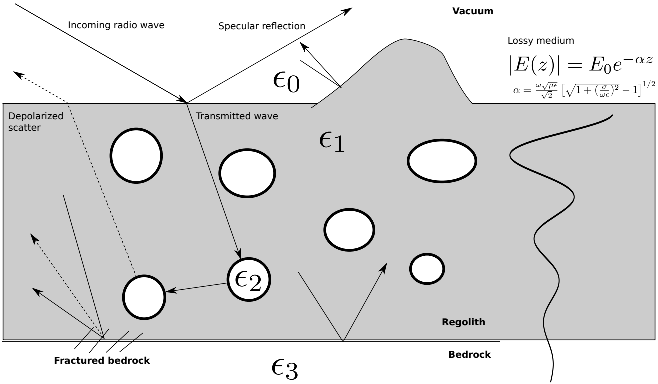
Radar images of the Moon at 6-meter wavelength

J. Vierinen[1], Torbjørn Tveito, Björn Gustavsson, Saiveena Kesaraju, Marco Milla, Karim Kuyeng, and Jorge L. Chau



Why long wavelength planetary radar

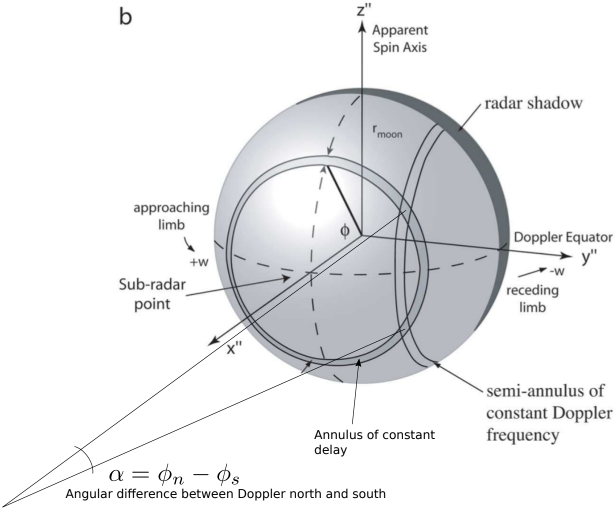


- Longer wavelengths penetrate deeper into the subsurface
- Probes Bragg wavelength scale irregularities
- Polarization orthogonal to the polarization of the specular reflection tells us about the subsurface scatter

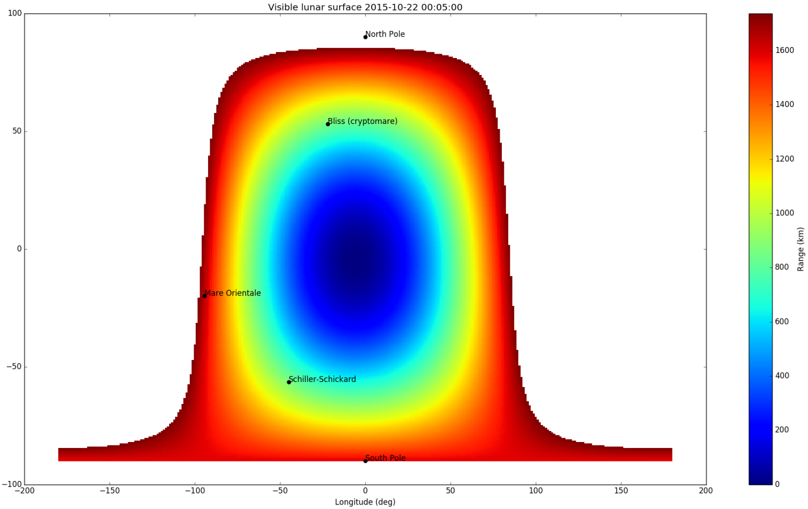
Why Jicamarca?

- Jicamarca is the lowest frequency incoherent scatter radar
- Interferometry is available for disambiguating Doppler north-south
- Full polarization diversity, necessary for separating specular vacuum-surface boundary echoes from subsurface volume scattering
- Polarimetric radar maps exist for 3.8 cm, 12.6 cm, and 70 cm (Campbell et.al., 2007). No polarimetric observations existed for 6-meter wavelength.
- With 6-meter wavelength penetration up to 1 km below the lunar surface is possible.

Lunar synthetic aperture radar

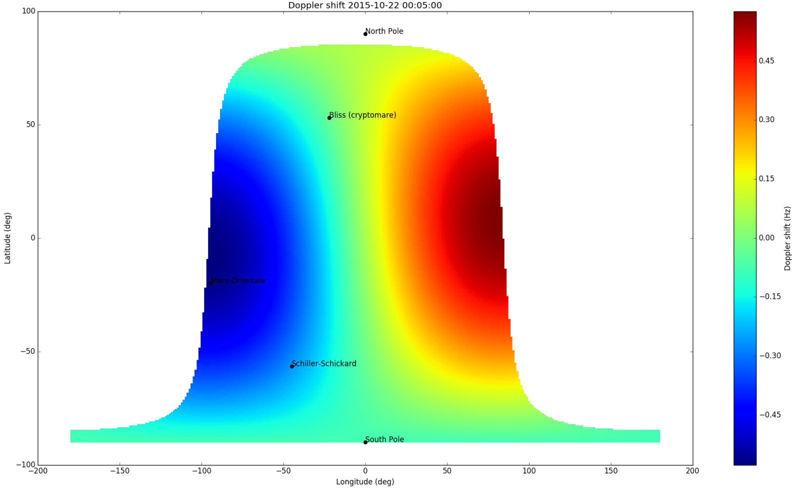


Range



Visible lunar surface 2015-10-22 00:05:00
North Pole
Bliss (cryptomare)
Mare Orientale
Schiller-Schickard
South Pole
100
50
0
−50
−100
−200
−150
−100
−50
0
50
100
150
200
Longitude (deg)
Range (km)
1600
1400
1200
1000
800
600
400
200
0

Doppler shift



Signal processing

In discrete time, the radar measurement equation for a moving range-spread target with no Doppler spread during a single IPP can be represented as

$$m_t = \sum_{r=r_0}^{R_M} \epsilon_{t-r}\sigma_r e^{i\tau\omega(t-r)} + \xi_t. \tag{1}$$

Inverse filtered:

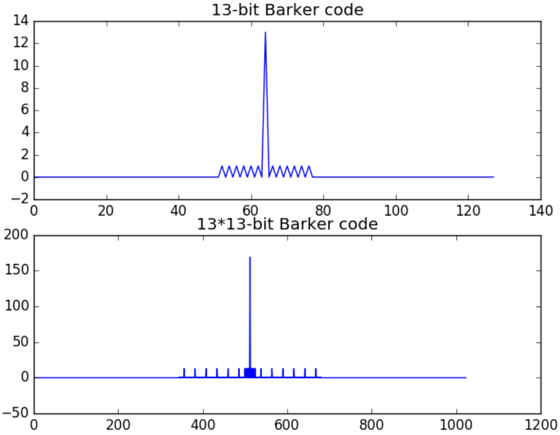
$$\sigma_r + \xi'_r = e^{i\tau\omega r}\sum_t h_{r-t}e^{-i\tau\omega t}m_t, \tag{2}$$

Inverse filter obtained using

$$h_t = \mathcal{F}_D^{-1}\left\{\frac{1}{\mathcal{F}_D\{\epsilon_t\}}\right\}, \tag{3}$$

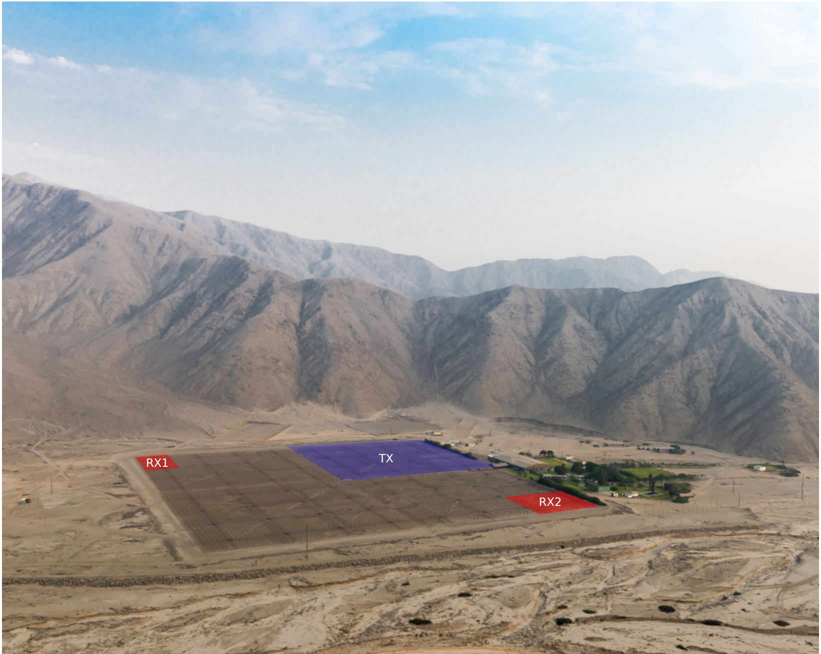
which represents division in frequency domain. The a posteriori error is ξ'_r, which is a convolution of the inverse filter with receiver noise $\xi'_r = \sum h_{r-t}\xi_t$, which is to first order independently distributed Gaussian random noise.

Radar coding

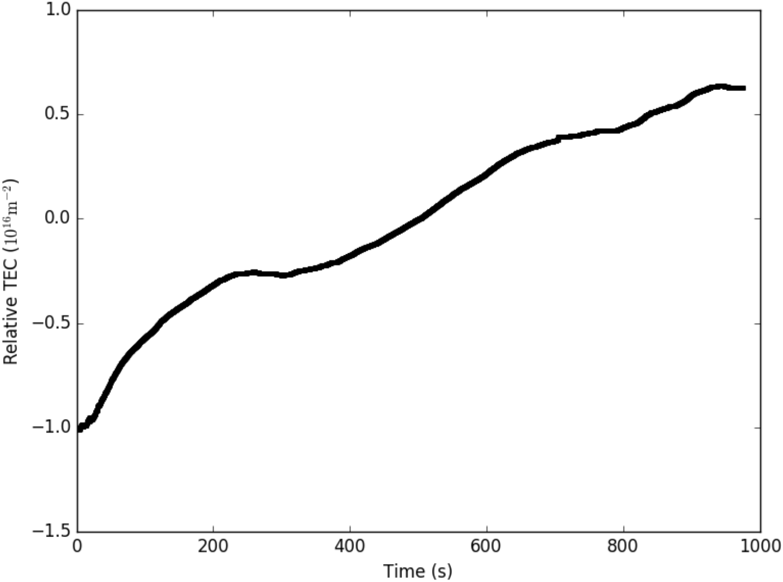


- Kroenecker self-product of 13-bit barker code (169-bits)
- 10 μs bit length, 1.5 km resolution

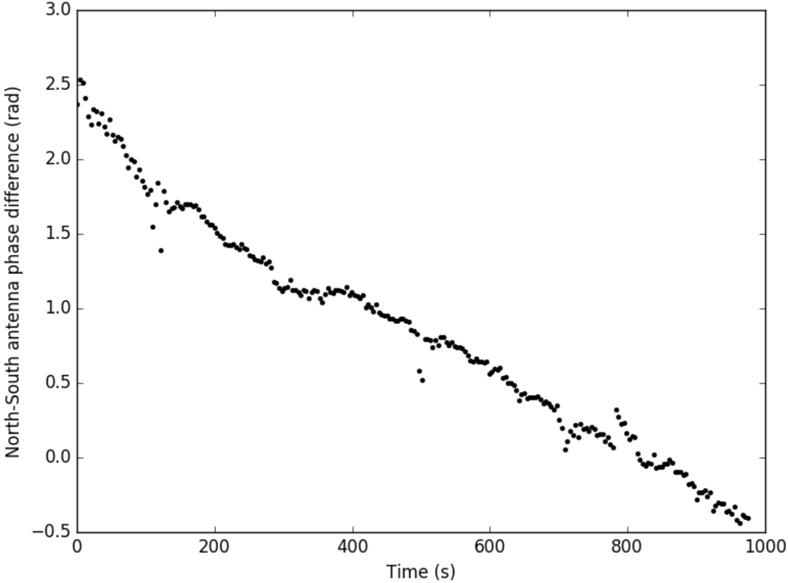
Jicamarca experiment



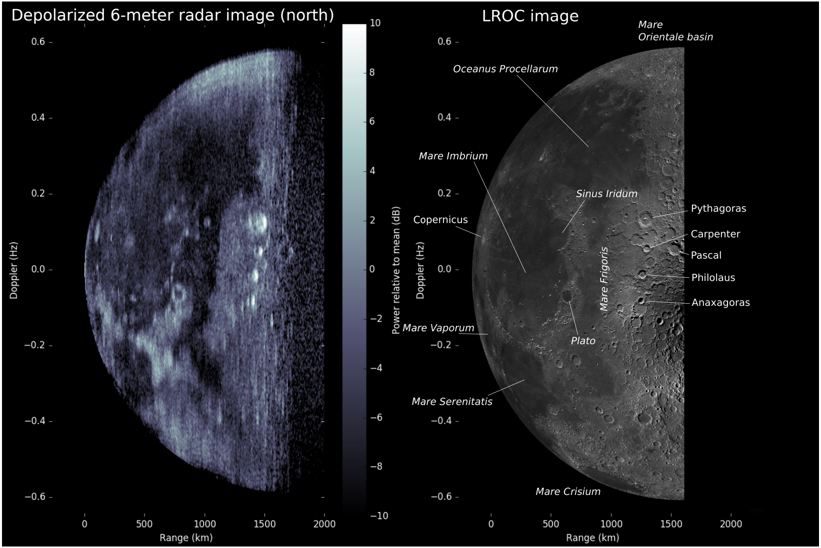
Ionospheric radio propagation mitigation: variation in ionospheric delay



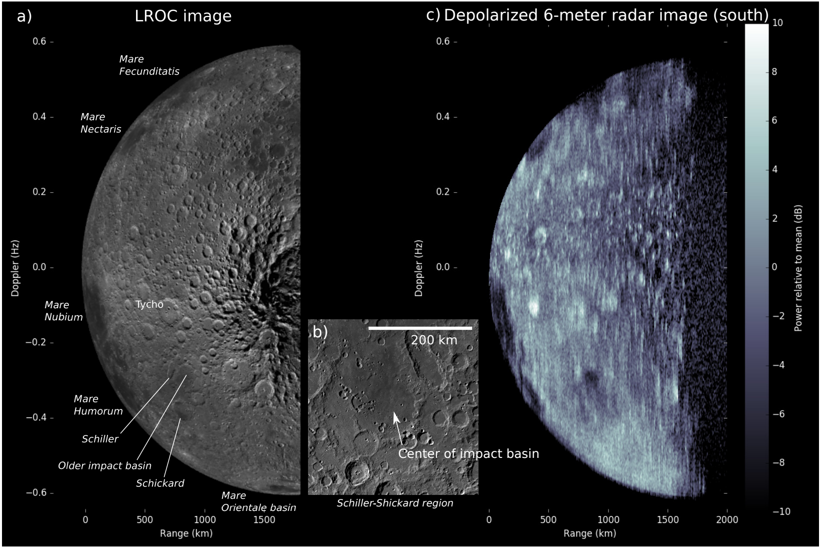
Ionospheric radio propagation mitigation: ray-bending



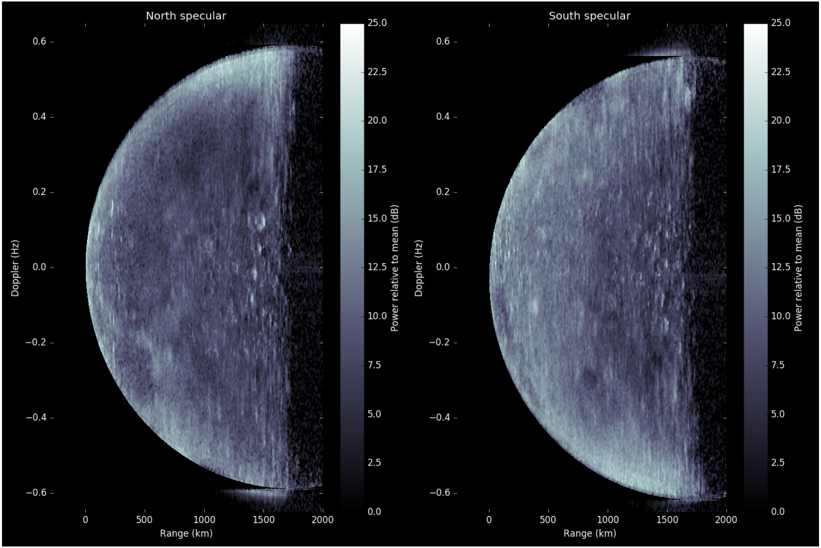
Radar-optical comparison



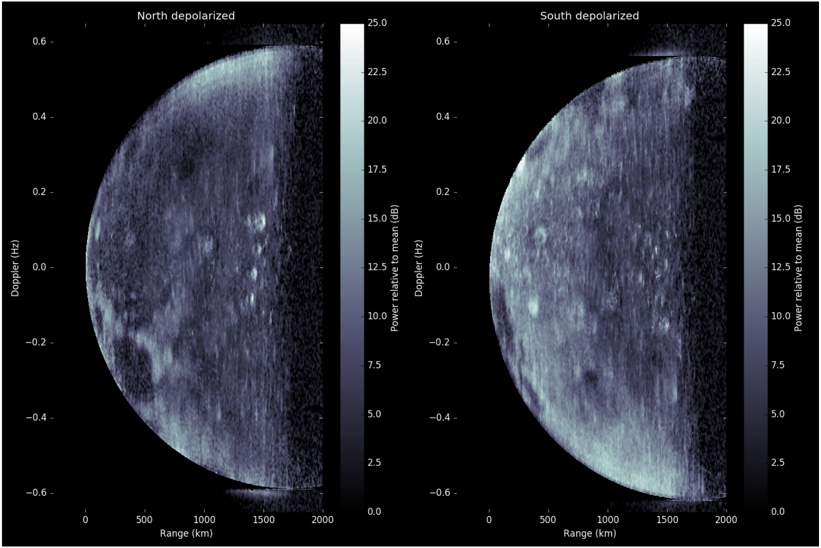
Radar-optical comparison



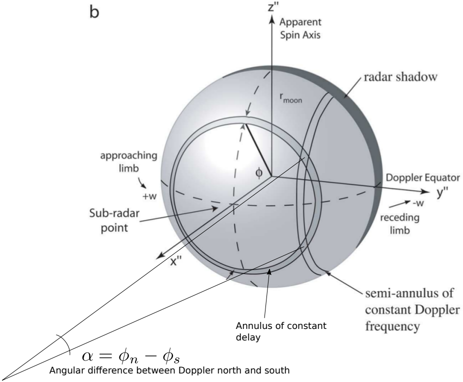
Polarized radar image



Depolarized



Doppler north-south disambiguation



$$\langle z_0 z_1^* \rangle = p_\mathrm{n} e^{i\phi_\mathrm{n}} + p_\mathrm{s} e^{i\phi_\mathrm{s}} \quad (4)$$

$$\langle z_0 z_0^* \rangle = p_\mathrm{n} + p_\mathrm{s} + \nu \quad (5)$$

$$\langle z_1 z_1^* \rangle = p_\mathrm{n} + p_\mathrm{s} + \nu \quad (6)$$

Doppler north-south disambiguation

The contributions to the real and imaginary parts of the cross- and self correlation estimates between signals z_0 and z_1 can be written as a system of linear equations in matrix form:

$$\begin{bmatrix} \mathrm{Re}\left\{\langle z_0 z_1^* \rangle e^{-i\theta}\right\} \\ \mathrm{Im}\left\{\langle z_0 z_1^* \rangle e^{-i\theta}\right\} \\ \langle z_0 z_0^* \rangle - \nu \\ \langle z_1 z_1^* \rangle - \nu \end{bmatrix} = \begin{bmatrix} \cos(\varphi) & \cos(\varphi) \\ \sin(\varphi) & -\sin(\varphi) \\ 1 & 1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} P_N \\ P_S \end{bmatrix} + \begin{bmatrix} \xi_1 \\ \xi_2 \\ \xi_3 \\ \xi_4 \end{bmatrix} \qquad (7)$$

Here $\theta = \frac{1}{2}(\phi_n + \phi_s)$ and $\varphi = \frac{1}{2}(\phi_s - \phi_n)$.
Rogers & Ingalls (1969) and Thompson (1970).

Doppler North-South disambiguation

$$\boldsymbol{m} = \boldsymbol{A}\boldsymbol{x} + \boldsymbol{\xi} \tag{8}$$

To estimate the power originating from the northern hemisphere p_n and the southern hemisphere p_s a maximum likelihood estimate is used:

$$\hat{\boldsymbol{x}}_{ML} = \left(\boldsymbol{A}^T \boldsymbol{\Sigma}^{-1} \boldsymbol{A}\right)^{-1} \boldsymbol{A}^T \boldsymbol{\Sigma}^{-1} \boldsymbol{m}, \tag{9}$$

where the error covariance matrix $\boldsymbol{\Sigma} = \langle \boldsymbol{\xi}\boldsymbol{\xi}^T \rangle$ is defined as

$$\boldsymbol{\Sigma} = \begin{bmatrix} \frac{1}{2N_m}(p_n + p_s)^2 & 0 & 0 & 0 \\ 0 & \frac{1}{2N_m}(p_n + p_s)^2 & 0 & 0 \\ 0 & 0 & \frac{1}{N_m}(p_n + p_s)^2 & 0 \\ 0 & 0 & 0 & \frac{1}{N_m}(p_n + p_s)^2 \end{bmatrix}$$

Here N_m is the number of measurements that are averaged together. We have calculated these using Isserlis' theorem for fourth moments of normal distributed random variables. We assume that the receiver noise is much smaller than the lunar echo power, and does not contribute to the error budget.

Doppler North-South disambiguation

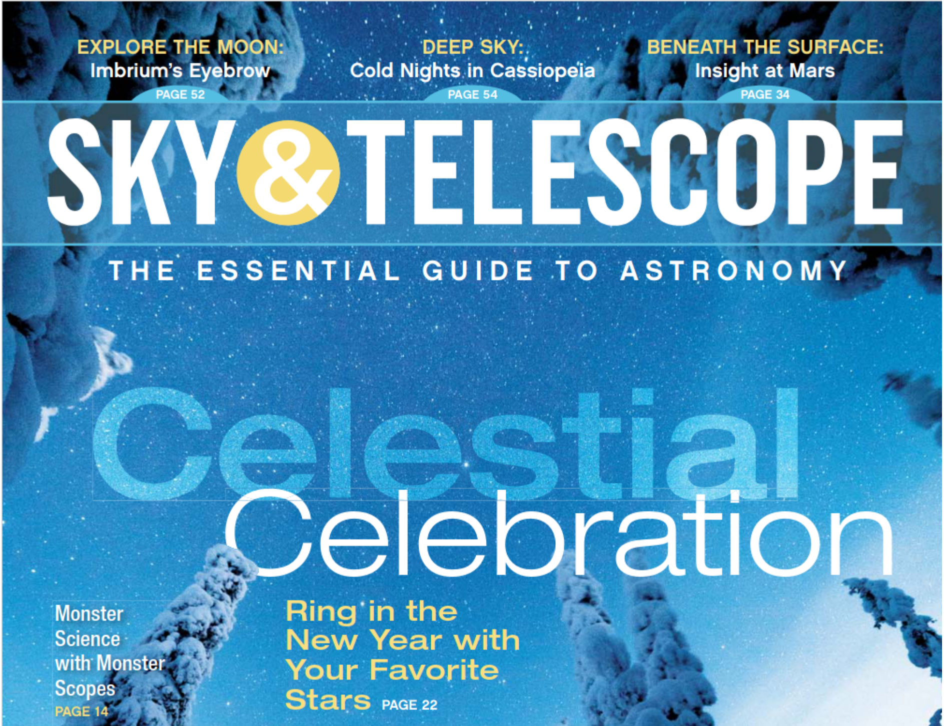
To estimate cross-talk between hemispheres, we calculate the covariance of the estimated power in the north and south hemispheres, which is given by

$$\boldsymbol{C} = \left(\boldsymbol{A}^T \boldsymbol{\Sigma}^{-1} \boldsymbol{A} \right)^{-1} . \tag{10}$$

We make the assumption that there is power originating only from one of the hemispheres ($p_n = 0$, and $p_s = 1$) and compare the a posteriori standard deviation of the northern hemisphere power to the power of the southern hemisphere to obtain an estimate of interhemisphere cross-talk

$$\mu = \frac{\sqrt{\boldsymbol{C}_{1,1}}}{p_s} . \tag{11}$$

The cross-talk μ measures the ratio of the standard deviation of the power estimate of the northern hemisphere p_n, which is assumed to have no power, to the power eminating from the opposite hemisphere p_s. For most of the lunar surface, the interhemispheric cross-talk is about -11 dB.



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Imbrium's Eyebrow

Is oddly shaped Mare Frigoris part of the Imbrium impact basin?

Although its name means cold, we only see **Mare Frigoris** when illuminated by sunlight and therefore quite hot. In fact, we see Frigoris so often because it stretches about 1,600 km (1,000 miles) between the crater **Atlas** near the Moon's northeastern limb and **Sinus Roris** along the northwestern limb. You can spot some part of Mare Frigoris typically every night between day 4 and 12 of each lunation. Its ease of visibility, however, is not matched by an easy understanding of why it has such an elongated shape, like an eyebrow over **Mare Imbrium**.

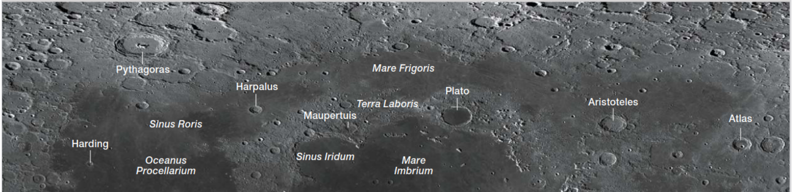
Most large maria appear to be roughly circular because they fill the circular depressions of impact basins. This is most readily seen at **Mare Crisium,** where the basin's surrounding rim is nearly continuous. Similarly, the curved **Montes Apenninus** range and its continuation along **Montes Caucasus** and the fragmentary **Montes Carpatus** clearly define half of the circular Imbrium basin that lavas filled long ago. Frigoris appears to be the odd mare out.

Not so, says lunar geologist Don Wilhelms. He suggests that Frigoris is actually *within* the Imbrium basin, because the extrapolated rim of a circle defined by the Apenninus, Caucasus, and Carpatus ranges passes along the northern shore of Mare Frigoris roughly in the same radial position to the basin's rim as Palus Putredinis, just inside the mountains' long arc. But then what formed the broad arc of rugged terrain (once called Terra Laboris by lunar mapper Michael van Langren nearly 370 years ago) between **Plato** and **Sinus Iridum** that separates Imbrium from Frigoris? One proposal was that the arc slid as a mega-landslide south, opening up Mare Frigoris. This spectacularly outrageous interpretation implies Plato and Sinus Iridum must have formed afterward — otherwise they would have been crumpled by the wholesale movement. But much of the roughness of Terra Laboris consists of ejecta from the formation of these two undeformed impact craters.

Now three recent findings provide new evidence about the origin of Mare Frigoris. First, Juha Vierinen (University of Tromsø, Norway) led a team in

▼ *Top:* Mare Frigoris arches near the Moon's northern limb and is visible throughout most of each lunation. *Bottom:* Gravitational anomalies mapped by NASA's GRAIL orbiter, combined with a map highlighting wrinkle ridges (seen as orange lines), show that both features closely parallel the northern rim of Frigoris.

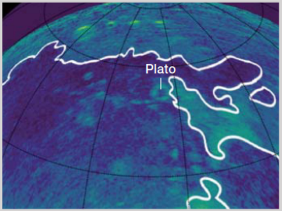
NASA / GSFC / ARIZONA STATE UNIVERSITY (2)



Thompson of Arizona State University and colleagues. This data set, and many others, is available in the Layers option of the recently updated LROC QuickMap (**quickmap.lroc.asu.edu**). Since many of Frigoris's ridges are parallel to the mare's northern margin, compressional forces were squeezing the crust from north and south. So Frigoris was not formed by extension — the megaslide theory doesn't work.

The third bit of evidence comes from a map of gravitational gradients produced by the Gravity Recovery and Interior Laboratory (GRAIL) spacecraft. Jeffrey Andrews-Hanna, then at Colorado School of Mines, and many colleagues unexpectedly discovered a series of long, narrow gravity anomalies — I call them "worms" — that border a region of the lunar nearside that has high concentrations of radioactive elements and contains most maria. One of the best-defined worms parallels the northern shore of Mare Frigoris from Atlas in the east all the way to **Harding**, considerably west of the official Imbrium and Frigoris are compositionally identical (iron-rich, titanium-poor) basalts of similar age (3.4 billion years). And the surface of Mare Imbrium slopes downward to the north. So the Terra Laboris lavas could have flowed in from either mare or might have erupted from their own vents.

The western end of Mare Frigoris is generally considered to be near **Harpalus**



▲ This deep-penetrating radar image shows mare lava as blue. The area west of the crater Plato (appearing as the greenish oval), previously known as Terra Laboris, is nearly invisible, implying mare lavas underlie the bright material we see at the telescope.

RADAR: J. VIERINEN / UNIVERSITY OF TROMSØ / JRO

Sinus Roris is simply a patch of darker, high-titanium lava that is part of Mare Frigoris, whereas Frigoris and the suggested western extension are all lighter, low-titanium mare lavas. This means that the northern limit of Oceanus Procellarum is near the crater **Rümker**. Indeed, the lavas just east of Rümker are rich in titanium and are less than 2 billion years old, like many of the Oceanus Procellarum flows farther south.

Frigoris is often the forgotten mare because it lacks the concentric fractures, sinuous rilles, and magnificent craters common to other major maria. But next time you observe it, look for the subtle wrinkle ridges that mark its buried worms, and the suggested extensions under Terra Laboris and west of Sinus Roris.

■ Contributing Editor **CHUCK WOOD** now has an asteroid to worry about: 363115 Chuckwood (formerly 2001 FW224) is a 16th-magnitude dark and icy mountain cruising around the Sun at an average distance of 3.1 a.u.

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