Toward Commissioning Solar Observations with MeerKAT: Opening a New Frontier in Solar Radio Physics

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Solar Emissions at Centimetre Wavelength

- Originate from several layers of solar atmosphere – chromosphere, transition region and lower corona.
- Mostly optically thick thermal free-free emission.
- Total flux density is ~100 SFU (1 Solar Flux Unit = 10^4 Jy) at 1.4 GHz and increases with frequency.
- Gyrosynchrotron (GS) / gyroresonance (GR) emissions from active regions (ARs) and/ or coronal mass ejections (CMEs) are also present.
- Centimetre wavelength solar emission provides crucial diagnostics on electron density, magnetic fields, localization of nonthermal electrons and energy release, etc.

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MeerKAT Radio Telescope

- MeerKAT is a radio interferometer with 64-antenna dishes, 13.5 m in diameter each, distributed over a region ~8 km in diameter.
- It is located in the MeerKAT National Park in the Northern Cape of South Africa.
- It is precursor instrument of the upcoming Square Kilometre Array (mid) Observatory (SKAO)
- At present, MeerKAT has three observing bands – UHF (*580–1015 MHz*), L (*900–1670 MHz*) and S (*1750–3500 MHz*) bands.
- Centrally condensed array configuration with 39 dishes within ~1 km region makes it very sensitive to emissions at large angular scale.

Challenges of Observing the Sun with MeerKAT

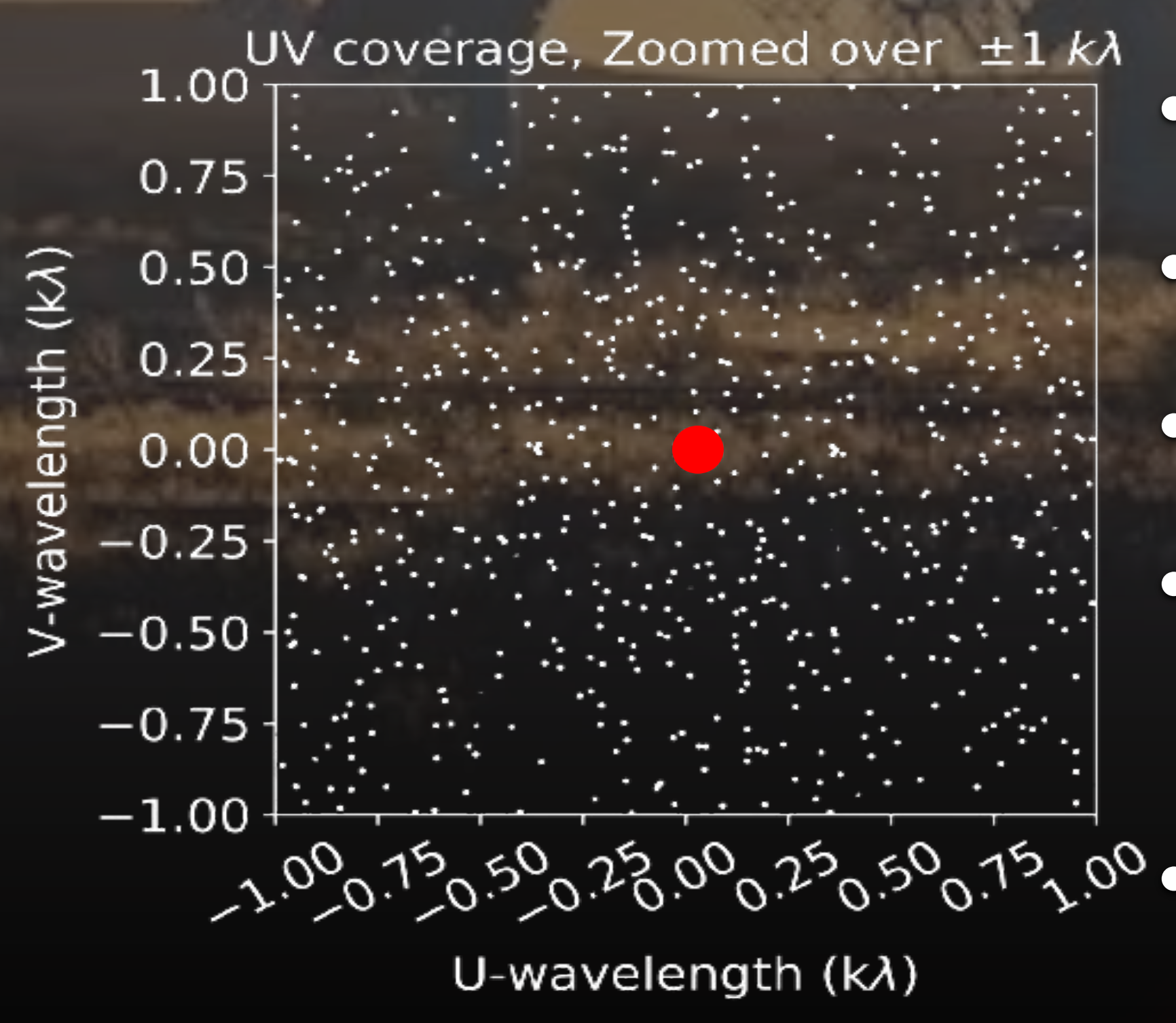


Figure 1 : MeerKAT sampling in Fourier space (*uv*-plane). The red circle corresponds to the uv-cell for the size of the solar disk (32 arcmin).

- Solar radio emissions are highly variable in spectral and temporal domains.
- Span a large range of angular scales, from few arcseconds to arcmins.
- This requires spectroscopic snapshot imaging with high-fidelity.
- Centrally dense array configuration of MeerKAT provides extremely good sampling in Fourier plane (*uv*-plane) shown in Figure 1.
- At present, MeerKAT is globally best suited for high fidelity spectroscopic snapshot imaging at centimeter wavelength.
- Solar flux density at centimeter wavelengths is orders of magnitude higher than typical astronomical sources.
- This requires the solar signal to be attenuated to maintain the instrument in the linear regime.
- While solar flux density increases with frequency, flux density of all astronomical calibrators decreases.
- It is not feasible to observe standard astronomical calibrators and the Sun with same attenuation.
- Here, instead of using solar attenuators, the Sun is observed through the sidelobes of primary beam to attenuate the signal.

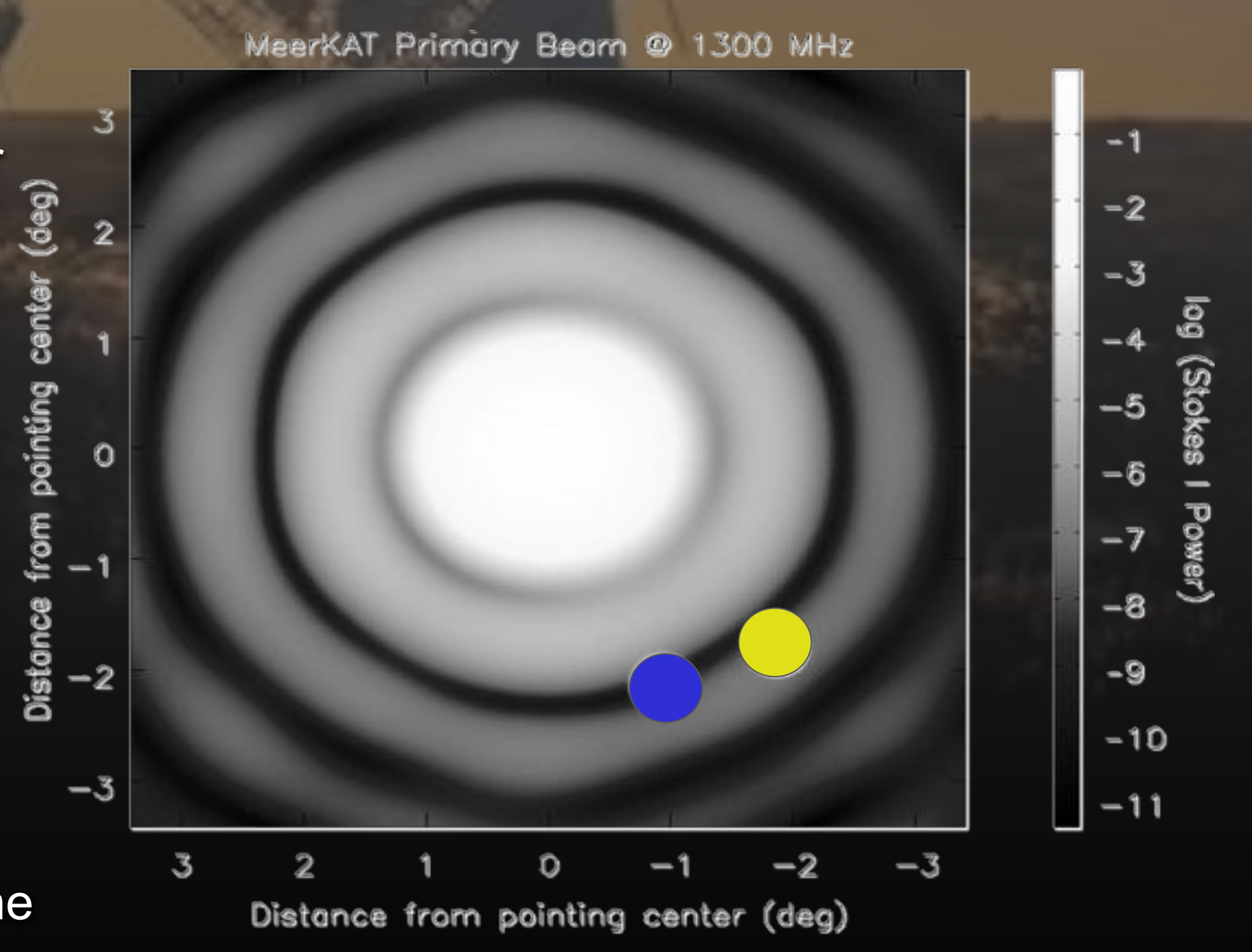


Figure 2 : Locations of the Sun in the MeerKAT primary beam at 1.3 GHz. Yellow and blue circles represent observations on, 26th and 27th September, 2020, respectively.

Qualitative Comparison with a Synthetic Image

- Simulated images are generated considering only thermal emission both from corona and chromosphere using differential emission measure (DEM) inversion using SDO/AIA extreme ultraviolet images.
- A synthetic MeerKAT image is made from simulated image by sampling it using MeerKAT array configuration.
- Similarities between the observed and the synthetic images are very evident.
- The most striking similarities are the locations and relative intensities of the various bright points; some of them have been marked by cyan circles in both panels of Figure 3.

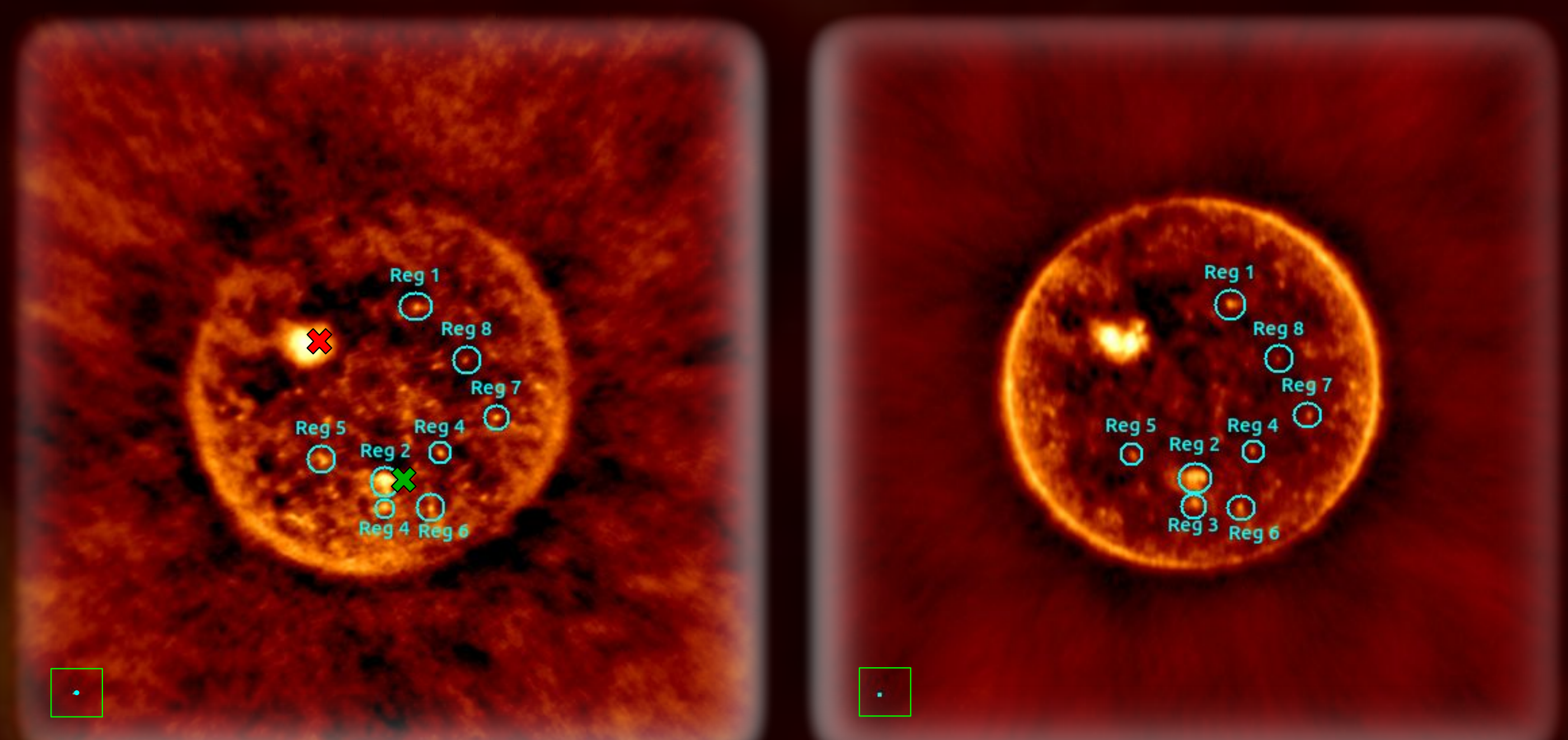


Figure 3 : A qualitative comparison between observed and synthetic MeerKAT radio images on 27th September 2020, 10:45 UTC. ***Left panel:*** synthetic MeerKAT solar radio image. ***Right panel:*** observed MeerKAT solar radio image. Both images are made using the entire frequency range from 880–1670 MHz. In both images, multiple bright regions have been detected. Some of them are marked by cyan circles. Small cyan-filled circles at the bottom left corner marked by a green box represent the PSF of the images. Brightness temperature spectra have been extracted from two regions marked by red and green crosses in the left panel. Both observed and synthetic spectra of these regions are shown in Figure 4.

Quantitative Comparison of Observed and Synthetic Spectra

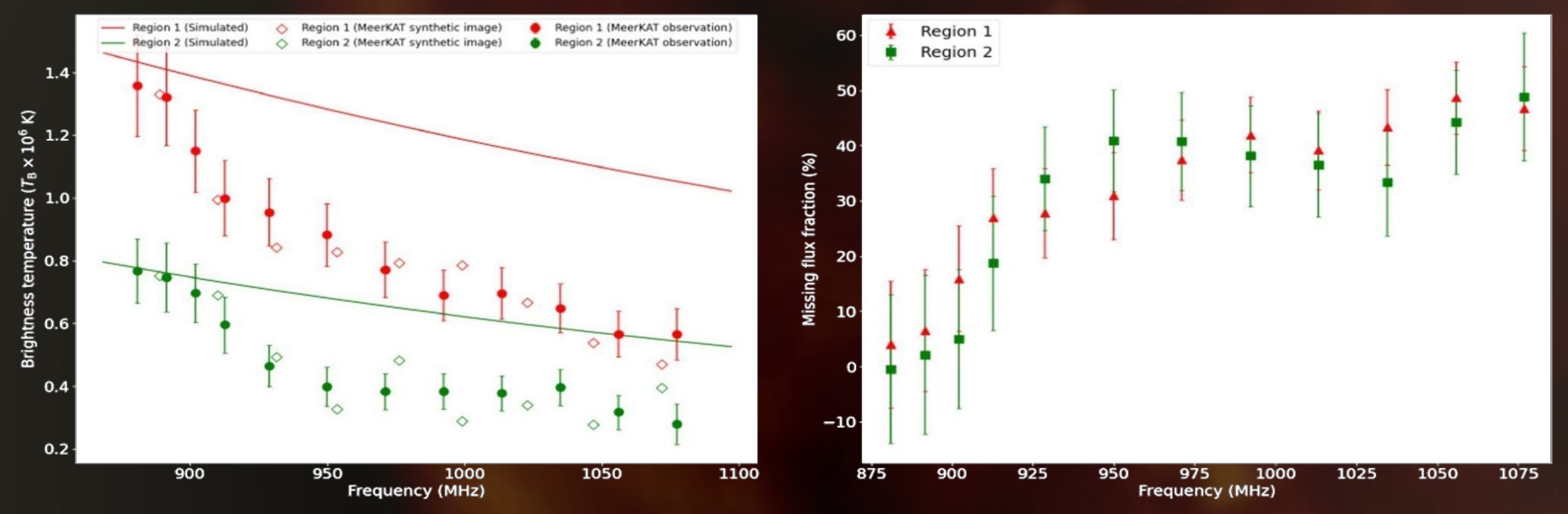
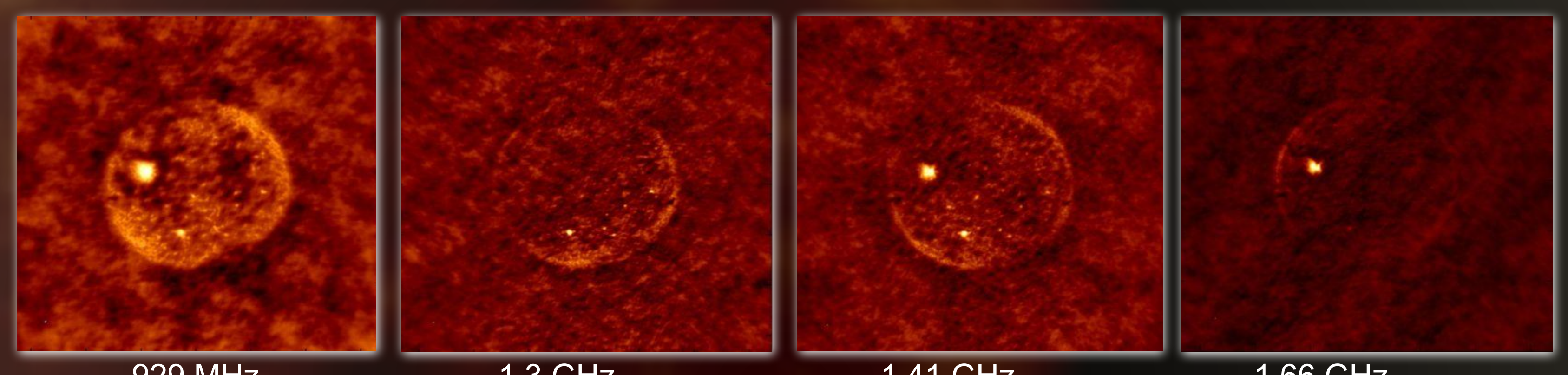


Figure 4 : ***Left panel:*** spectra for regions marked by red and green crosses in Figure 3. Solid lines represent the simulated spectra considering thermal emission. Unfilled diamonds represent spectra from synthetic MeerKAT maps obtained from the simulation and filled markers represent those from MeerKAT observation. ***Right panel:*** Missing flux fraction as a function of frequency.

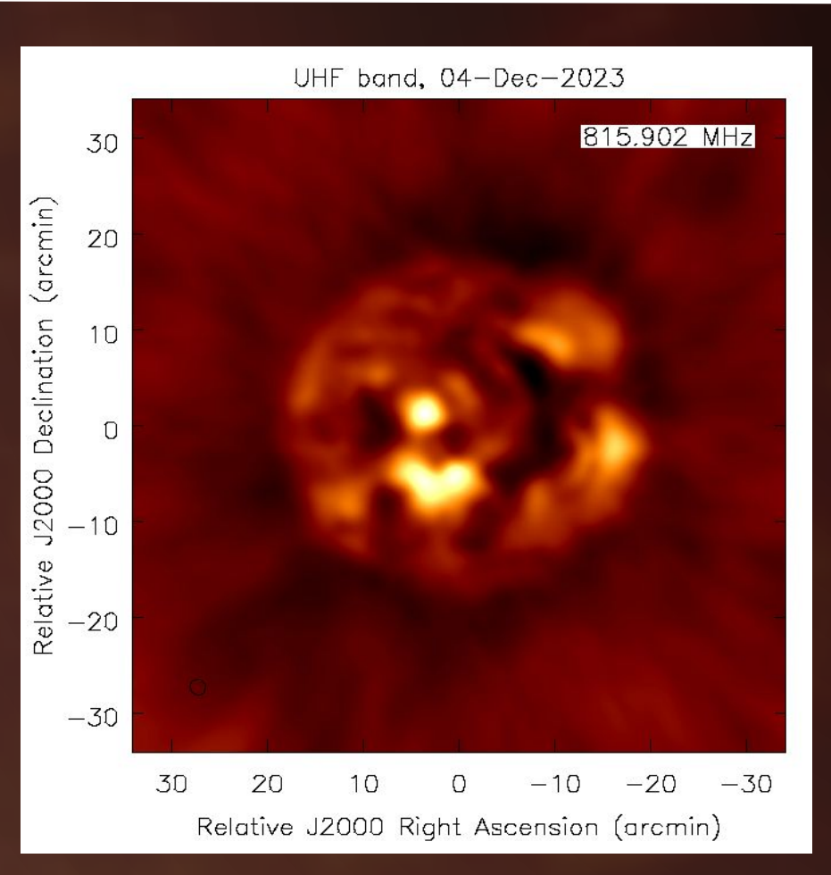
- Interferometers are sensitive only to the angular scales spanned by the available baseline range.
- Synthetic and observed spectra are consistent within uncertainty, but deviate from simulated spectra by a significant amount (~40%) at higher frequencies.
- MeerKAT solar images have significant missing flux above ~900 MHz.

Limitation of the Present Observing Strategy and the Ongoing Commissioning Efforts

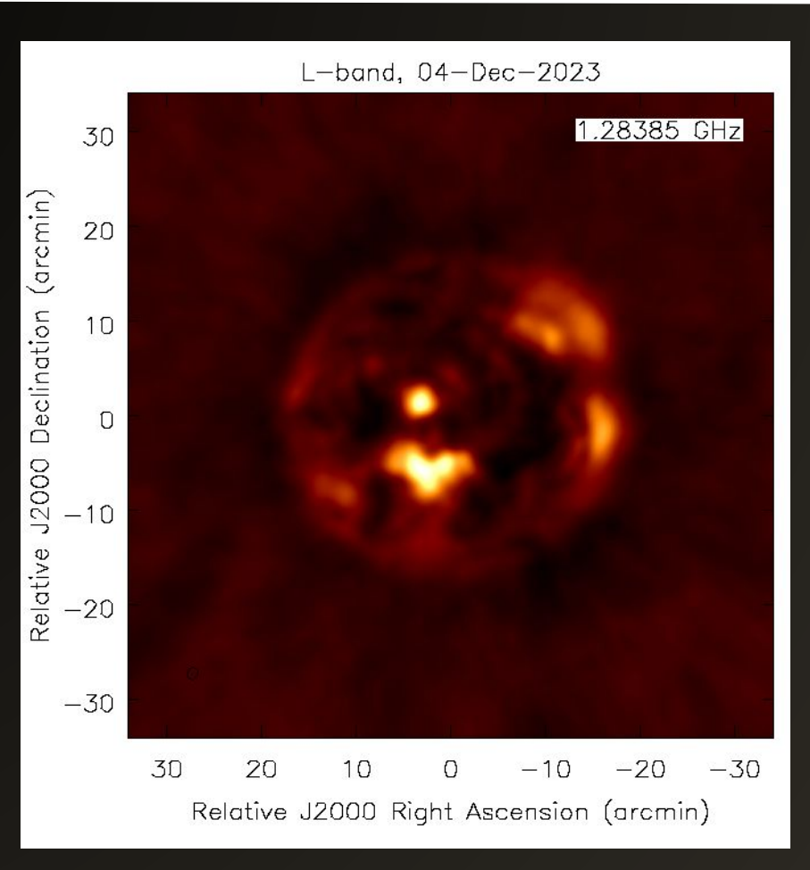


929 MHz 1.3 GHz 1.41 GHz 1.66 GHz

Figure 5 : Chromatic primary beam causes different attenuation varying with frequency. Hence, different parts of the solar disc are not observed with similar sensitivity.



The ideal way to observe the Sun is to keep it aligned with the telescope optical axis. This requires to use additional solar attenuation. We have successfully tested this mode and now toward commissiong it. Solar images keeping the Sun at the pointing center are shown in these adjacent images.



Example Science Cases Enabled by MeerKAT

- Independent diagnostic of thermal parameters of chromospheric and coronal plasma, both during quiet and active times.
- Studies of small flares with their associated GS/ GR emission – estimation of magnetic field and nonthermal parameters of the flaring plasma.
- Plasma parameters of CMEs at lower coronal heights using GS emission.
- Exploration of a relatively less explored phase space in solar physics – rich discovery potential.

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