URSI AP-RASC, Sydney, Australia, 17-22 August 2025

Mixed Total Variation Regularization Method for an Interferometer Array on Lunar Orbit

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Ultra-long waves refer to electromagnetic waves with a frequency below 30 MHz. They are the last almost unexplored electromagnetic window in astronomy. Due to the influence of the Earth's ionosphere and radio frequency interference (RFI), it is very difficult to conduct ultra-long wave observations on the ground. Furthermore, ultra-long wave observations in Earth orbit are still severely affected by RFI from the Earth. In contrast, conducting ultra-long wave observations in lunar orbit has many advantages. On the one hand, the Moon effectively blocks the interference from the Earth and can even shield against interference from the Sun and planets, which is conducive to detecting weak signals. On the other hand, satellites in lunar orbit can use solar cells as an energy source and communicate with the Earth in the arc segments that are not blocked by the Moon.

In 2015, scientists from China, Poland, the Netherlands and other countries jointly proposed the concept of Discovering Sky at Longest wavelength (DSL), which was later known as the “Hongmeng” mission. This mission will be composed of one mother satellite and nine subsatellites. The mother satellite is mainly responsible for data collection, processing, and communication with the Earth. One subsatellite measures the high-precision full-sky spectrum in the 30-120 MHz band. The remaining eight subsatellites perform both interferometry and spectral measurements in the 0.1-30MHz band. For interferometric measurements, the eight subsatellites form a linear satellite formation in lunar orbit. Through formation control and orbital plane precession, a three-dimensional baseline distribution ranging from 0.1 km to 100 km is formed. Then, the measured visibility function is transformed into a full-sky map using an imaging inversion algorithm.

However, the imaging of the interferometer array on lunar orbit faces the issues such as the whole-sky field of view (FOV) for the short dipole antenna, three-dimensional non-coplanar baselines and the sky blocked by the Moon changing over time. These issues mean that traditional wide-field imaging algorithms for ground interferometer arrays cannot be applied to the interferometer array on lunar orbit. Fortunately, there exists a linear mapping relationship between the visibility data and the sky brightness distribution. The brute-force and reweighted total variation (RTV) methods have been proposed to solve the linear inversion problem for an interferometer array on lunar orbit. Although the existing regularization methods can produce satisfactory results in general, there are still large residual errors and a slow computing speed, especially when dealing with large-scale data.

In order to efficiently obtain an accurate full-sky map, we propose a mixed total variation regularization method. This method combines the edge-preserving ability of first-order total variation (TV) with the smoothing constraint ability of second-order TV. It can enhance the stability and accuracy of image reconstruction while suppressing noise and artifacts. In addition, the alternating direction method of multipliers (ADMM) is adopted and combined with the Cholesky decomposition method to solve the optimization model, so as to improve the computational efficiency of the algorithm. The numerical simulation results show that, in terms of both reconstruction accuracy and calculation speed, the mixed total variation regularization method outperforms the existing brute-force and RTV methods.