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# Study of ICME by spacecraft radio signals

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Tracking radio communication signals from planetary spacecraft with ground-based telescopes offers, among others, the possibility to study the electron density and the interplanetary scintillation of the solar wind. Observations of the telemetry link of spacecraft have been conducted regularly with ground antennae from the European Very Long Baseline Interferometry Network (EVN), aiming to characterize the propagation of radio signals in the solar wind at different solar elongations and distances from the Sun. We have studied the phase fluctuations of Mars Express spacecraft radio signal while an interplanetary coronal mass ejection (ICME) crossed the radio path during one of our observations on 6 April 2015. Our measurements showed that the Doppler measurements and phase scintillation indices increased by a factor of 4 during the passage of the ICME. Thus, it is confirmed that the phase scintillation technique based on spacecraft signals provides information of the properties and propagation of the ICMEs in the heliosphere, and can be used to detect and monitor the presence of ICMEs in the near future.

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## 1. Introduction

Interplanetary coronal mass ejections (ICMEs) are a manifestation of active processes in the Sun where a substantial amount of matter is released from the outer atmosphere as coronal mass ejections (CMEs) [2] to the heliosphere. These large-scale magnetic structures are one of the most important space weather phenomena as they can cause large geomagnetic storms on Earth.

Characterizing the properties of ICMEs is therefore a very important field of research, however, in-site measurements are difficult because this would require multiple spacecraft around the heliosphere. Measurements of phase scintillation using radio signals of human origin transmitted by a spacecraft provide an additional tool to measure solar corona, heliosphere plasma, CMEs, and ICMEs by radio tracking techniques at ground stations [4].

Observations of planetary spacecraft have been carried out systematically since 2009 by the Planetary Radio Interferometry and Doppler Experiment (PRIDE) team by means of Very Long Baseline Interferometry (VLBI) instrumentation on ground radio telescopes [1, 3, 4]. The propagation of the radio signal in the interplanetary medium has been used to estimate the electron density fluctuations in the solar wind [5]. The study presented here shows the analysis of variations in the radio signal transmitted by MEX in April 2015 as it propagated through the interplanetary plasma during the passage of an ICME across its line of sight [6] .

## 2. Methods and observations

### 2.1 Methodology

The setup of our observations is known as three-way radio link, where the radio signal transmitted by a spacecraft to a ground station telescope is tracked by a secondary radio telescope, in this case a VLBI antenna. Sessions are planned accordingly to the transmission schedule provided by the space mission support team.

Data are recorded locally at the telescope and transferred offline to the processing center, minutes after the end of the session. The data processing is conducted at the Joint Institute for VLBI ERIC and at the Aalto University Metsähovi Radio Observatory. The narrowband data processing of the single dish open-loop data collected by a radio telescope is divided into three blocks: the SWSpec, SCTracker, and digital PLL software[1] [4].

The outputs of the analysis are the fluctuations of the recorded Doppler residual and the residual phase variations of the signal for the particular line of sight (Earth-spacecraft) in intervals of 20 min. The accuracy of the detections of the Doppler residual and the fluctuations in the signal phase allows us to extrapolate the electron density variations.

### 2.2 Observations

In April 2015, three consecutive sessions targeting MEX were conducted with the same radio telescope, the 15m antenna at the Hartebeesthoek radio astronomy observatory (Ht, South Africa). Exceptional results were seen in the data detected on 6 April 2015. That day also the Badary 32 m radio telescope (Bd, Russia) participated on the session, so we had data for comparison. Badary's

[1] https://github.com/gofrito/swspec

observation yielded similar results to the ones at Ht, being namely the phase scintillation higher than in standard conditions. The matching of results between both radio telescopes suggested that a plasma anomaly, later identified as an ICME, may have been detected.

Figure 2.2 shows the phase residuals measured at Hartebeesthoek (top) on 4 April 2015 (blue line) and 6 April 2015 (red line), and at Badary (bottom) on 6 April 2015 (red line) and 9 April 2015 (blue line). Several scans during the ICME pass show phase fluctuations that are 10 times higher than during undisturbed solar wind conditions. The data provided on 9 April 2015 reflect nominal conditions, since the results are in good agreement with spacecraft data collected since 2009.

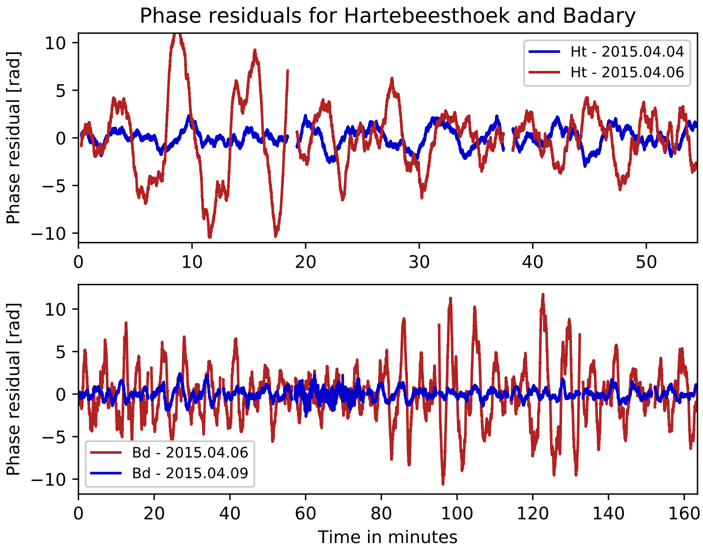


**Figure 1:** Phase residuals extracted from the radio telescope at (top) Hartebeesthoek and (bottom) Badary data observed during the days around the ICME. Data during the ICME on 6 April 2015 are shown in red. Data observed on 4 and 9 April 2015 are in blue.

## 3. Interpretation of the results

CACTUS online software [2] registered a solar eruption produced on the surface of the Sun at 23:48 UTC on 4 April 2015. This solar eruption evolved into a flare of intensity of type C and with a coronal mass ejection with an average speed of 400 km/s. Further information about the ICME is available online at the Integrated Space Weather Analysis System (iSWA[3]).

According to the computer simulation, shown in Figure 3, at 00:00 UTC on 6 April 2015, the ICME crossed the line of sight (shown by a black arrow) between Mars (red circle) and Earth (yellow circle). Badary started the observations at 05:00 UTC. The radio communications signal between Mars Express and the ground station crossed the ICME in both directions. At that time, Mars was at a solar elongation of 17.23 degrees and a distance of 2.39 AU with respect to the

[2]http://sidc.oma.be/cactus/

[3]http://iswa.gsfc.nasa.gov/



PoS(EVN2018)139

Earth, and the ICME was at a distance of 0.5-0.6 AU from the Sun or at 1/5 of the path between the spacecraft and the observer, moving toward the latter.

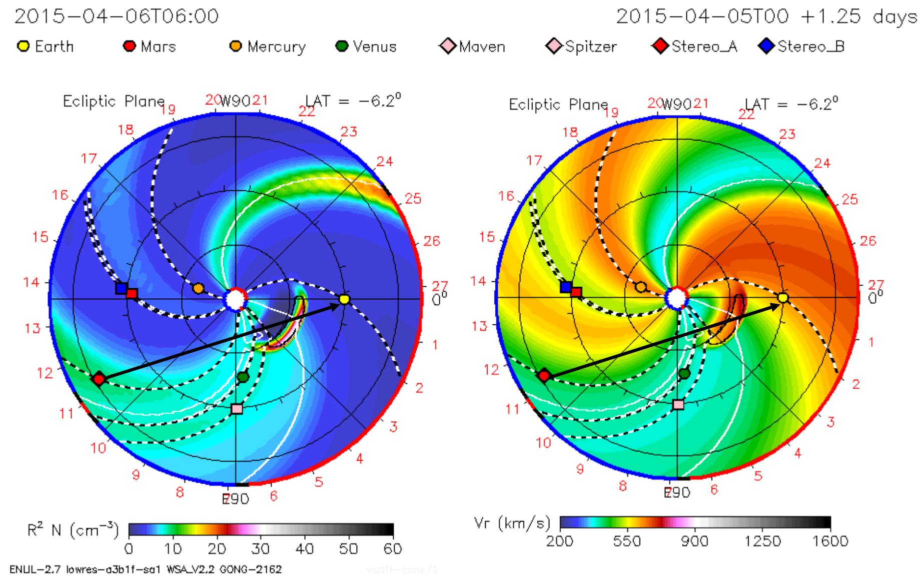


**Figure 2:** Geometrical configuration and plasma properties of the heliosphere when the ICME was at about 0.5 AU. (left) Electron density content times R2 [N(cm-3)]. (right) Solar wind radial speed on the elliptic plane in km/s. The simulation is for the time of our observations (6 April 2015 at 06:00 UTC). A black arrow is added to show the line of sight from Mars (red circle) to the Earth (yellow circle).

Based on the Doppler and phase residuals obtained by the Bd and Ht radio telescopes, we built a model of the ICME, as shown in Figure3. We associate the first peak seen in the phase scintillation measurements at around 05:00 to the transit of the transmitted radio signal through the sheath of the ICME (a). The peak is immediately followed by a bump that we attribute to the signal propagating through the plasma cloud/density enhancement with very high density region (b). The electron column fluctuations reduce when the radio signal propagates only through the sheath of the ICME again (c).

We can speculate that the spacecraft signal has passed transversally through a plasma cloud with very high density inside the ICME between the shockwave and the tail, which drastically enhances the disturbance of the signal. Why this high density region would have resulted with such a strong disturbance and how to quantify it is unclear. Unfortunately, we do not have enough information to associate this high density layer directly with the ICME's cloud.

## 4. Conclusions

The method presented here is sensitive to changes in the total electron column (TEC) density between the spacecraft and the Earth caused by the ICME. Electron density fluctuations can characterize the properties of the ICME, such as size, structure, intensity, and propagation speed. Our observations detected a phase scintillation index three times higher when crossing the ICME than during undisturbed solar wind conditions. In our study we calculated the TEC of the plasma anomaly, which is more than 3,000 TECU [6].

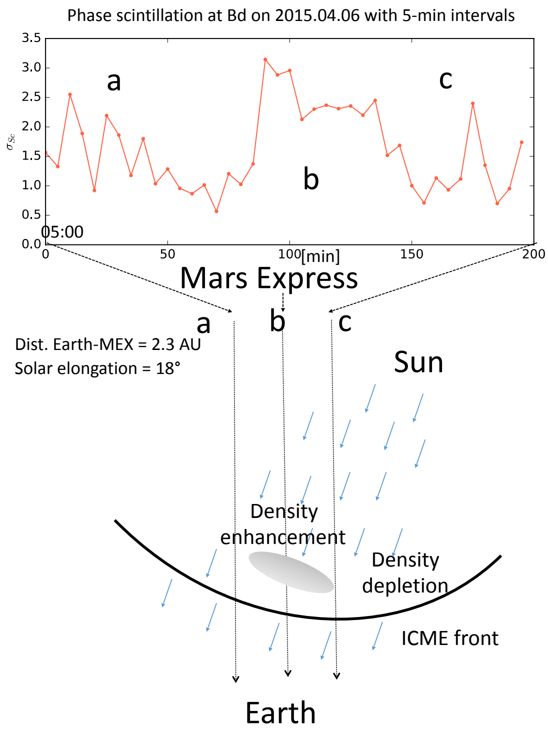


**Figure 3:** Sketch of the ICME based passing through the (bottom) Earth-Mars line and the phase variability during the full observation of MEX on 6 April 2015 at 5 min intervals, from 05:00 at the (top) Badary station. A density enhancement within the ICME was encountered during the middle of the observation, shown as region (b), lasting about 60 min.

Radio tracking is a valuable technique to study the properties of ICMEs with ground-based observations. However, it is worth noticing that the probability of detection of an ICME is low: over the past 7 years and 500 observations only one such event has been detected.

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