Interplanetary scintillation observation and analysis using Martian spacecraft downlink signal from VLBI station

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Interstellar scintillation vs. Interplanetary scintillation

ISM: among stars, galaxy, very far from us
Pulsar: high stability

IPS: among solar system, solar wind
Signal from spacecrafts: high stability, point source.

Interstellar medium and Interplanetary medium: plasma, electron density, magnetic field, Kolmogorov turbulence…
Could the model, method and ideas in ISM be used in IPS research?
1. Introduction
   1.1 Solar wind
   1.2 Interplanetary scintillation
   1.3 MEX Interplanetary scintillation observation
2. Data analysis
   2.1 Phase scintillation
   2.2 Theory to explain phase scintillation
   2.3 TEC
3. Introduction of EVN IPS observation
4. Conclusion
1. Introduction
1.1 Solar wind

The solar wind is the supersonic outflow into interplanetary space of plasma from the Sun's corona. This plasma consists of mostly electrons, protons, embedded in the solar-wind plasma is the interplanetary magnetic field. Solar wind varies in density, velocity, temperature, and magnetic field properties--with the solar cycle, heliographic latitude, heliocentric distance, and rotational period. It also varies in response to shocks, waves, and turbulence that perturb the interplanetary flow.

Solar wind observation:
Solar has great influence on humans. Many researchers are interested in solar physics. Some international institution are observing solar wind, such as Advanced Composition Explorer (ACE) satellite in NASA, Solar and Heliospheric Observatory, Solar-B projects, and so on.
1.2 Interplanetary scintillation

Scintillation in radio waves firstly observed by Antony Hewish (Hewish, et al. 1951). When radio wave travel through solar wind, the variation in the density of plasma leads to a wide variety of observed phenomena such as spectral broadening, intensity and phase scintillation, angular broadening, etc. Observation of scintillation phenomena can be used to study the turbulence in the solar wind. Ooty radio telescope in India, Incoherent SCATter radar in European, Fuji, Kiso, Sugadaira, Toyokawa in Japan Solar-Terrestrial Environment Laboratory, engaged in IPS research.
Since 80’s last century, deep space navigation provided a new chance for IPS observation. When the spacecraft flying around planet moved to the opposite side of the Sun, the signal transmitted from spacecraft will pass through solar wind, and caused amplitude, frequency and phase scintillation. Nearly every deep spacecraft is used to observe solar conjunction. Such as Viking, Galileo, Cassini, Mars Express, VEX, Mariners, etc.
1.3 MEX Interplanetary scintillation observation

MEX is an European satellite. It experienced solar conjunction during 2014.11~2015.09.
The solar elongation decease from 55 to 0.6 deg. The black dot is the data we observed, the heliocentric distance is in the range of 11R⊙~160R⊙.

Solar elongation and minimum heliocentric distance vary from 2014.11~2015.09
2. Data analysis
2.1 Phase scintillation

![Graph showing phase scintillation with Modulation signals and Main carrier]

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**Small and big solar elongation**

<table>
<thead>
<tr>
<th>Phase</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>11R☉</td>
<td>21.2rad</td>
</tr>
<tr>
<td>160R☉</td>
<td>0.1rad</td>
</tr>
</tbody>
</table>
\[
\sigma_v = \frac{0.73c\sqrt{C_{\text{band}}} \cdot [\sin(\theta_{SEP})]^{-1.225}}{f_{\text{obs}}T^{0.175}}
\]

minimum heliocentric distance/R⊙

(202, Rev.B 34-m and 70-m Doppler)

Compare with NASA DSN model. The formula is applicable for SEP > 5°. The frequency measurement accuracy are consistent well with model, the correlation index is about 0.9.
Phase spectral power density at $R=11\,R_\odot$ and $160\,R_\odot$

Slope of phase spectral power density

Kolmogorov Turbulence:
Integral length scales, Taylor microscales, Kolmogorov length scales
$3\,\text{mHz} \sim 0.3\,\text{Hz}, \, 1300\,\text{km} \sim 130000\,\text{km}$

$b$ is close to Kolmogorov index $-8/3$
2.2 Theory to explain phase scintillation

Refraction index  $n(x,t)$, Taylor frozen-in hypothesis. Structure function  

$$D_n(x) = \left\langle |n(x+\Delta x) - n(x)|^2 \right\rangle = C_n^2(x) x^{2/3}$$

$$C_n(x) = c_{n0} \exp \left[ - \left( \frac{x - L_2}{a_1 R} \right)^2 \right]$$

$$W_S(f) = 0.033 c_{n0}^2 k^2 \frac{8 \pi^2 a_1 R}{\nu} \left( \frac{2 \pi f}{\nu} \right)^{1-p} \frac{\Gamma[(p-1)/2]}{\Gamma(p/2)}$$

$$\sigma_S^2 = \int_{f_1}^{f_2} W_S(f) df$$  

(Woo R, Yang F C. et al.1976)

The phase scintillation could be explained by turbulence theory. The input signal is refracted by inhomogeneous random medium. Woo R’s model related phase scintillation spectrum to refraction index structure constant, solar wind velocity and spectrum index.
Refraction structure constant

\[ c_{n0} = c \left( \frac{R}{R_{\odot}} \right)^d \]

\[ c = (3.8 \pm 2.7) \times 10^{-10} \quad d = -1.98 \pm 0.27 \]

In Woo’s paper(1976), \( d \) is close to -2.1

Compared the theory model with observational spectrum, and using solar wind velocity from SOHO website, we got refraction structure constant. It has a relation of with \( R \), similar with the relationship in Woo R’s paper.
We calculated the phase scintillation index, it increase significantly with small SEP, which shows the turbulence is stronger near the sun.
We estimated the TEC with phase scintillation index. The black dot is TEC from phase scintillation index, red line is TEC estimated with a model in solar active, and blue line with a model in solar quiet. The green dot is TEC from earth ionosphere. The change trend of TEC was consistent with the TEC calculated using models from both solar active and quiet periods.
3. Introduction of EVN IPS observation
Four Mars satellites: Odyssey, MEX, ExoMars, MRO, were observed by EVN stations at the same time. EVN stations are: Hh, Ys, Nt, T6, Ur.
<table>
<thead>
<tr>
<th>solar elongation</th>
<th>Date</th>
<th>Stations</th>
<th>Observation mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>RM012a</td>
<td>2017.7.29 UTC 06:16~13:16</td>
<td>TM、UR、Hh、Ys、Nt</td>
<td>Total 16 channels, Frequency band X/S, bandwidth 16MHz, Samplerate 32MHz, 2bit, Single polarization</td>
</tr>
<tr>
<td>RM012b</td>
<td>2017.8.3 UTC06:16~13:16</td>
<td>TM、UR、Hh、Ys、Nt</td>
<td></td>
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<tr>
<td>RM012c</td>
<td>2017.8.8 UTC06:16~13:16</td>
<td>TM、UR、Hh、Nt</td>
<td></td>
</tr>
</tbody>
</table>

**Research objectives:**
How to use VLBI and satellite signals to research turbulence in the inner solar wind?
Will VLBI contribute to position determination of satellites during solar conjunction?
Ht-Nt chan1~chan16 quasar fringe
MRO at Ht station

Exomars and MEX at Ht station
Ur-T6 spacecraft fringe
4. Conclusion

We used VLBI single station to observe the ingress and egress process of MEX during 2014~2015.

Frequency, phase scintillation and its power spectral were extracted from VLBI broadband recording system.

The phase scintillation spectral were power low in the range of 3mHz~0.3Hz, and the corresponding refraction spectral index were keep constantly with 3.3+/-0.25, over the full range of solar offset from 11R⊙~160R⊙, which was consistent with Kolmogorov turbulence.

The structure constant of refractive index fluctuation had a relation of $\sim R^{-1.98\pm0.27}$ with $R$.

We used EVN 4~5 stations to observe Mars spacecrafts and nearby quasars, the data is still on process.
Thanks you for attention!