Postprint: Impact of Solar Wind on Mars Exploration Communication Channels and Anti-scintillation Strategies

Authors: Xue Xiping, Li Chunlai, Kong Deqing, Zhang Hongbo

Date: 2017-09-26T00:00:00+00:00

Abstract

During solar superior conjunction, solar wind severely impacts deep space communication links, potentially causing communication link interruption under severe conditions. The discussion establishes that the distance between the communication channel and the Sun is the primary factor determining solar wind' s influence on deep space communication channels, and analyzes the specific characteristics of this impact. Finally, using China' s Mars exploration mission as a background, theoretically feasible strategies for improving communication channels to resist solar wind effects are analyzed.

Full Text

Preamble

Vol. 14 No. 1 Jan. 2017
ASTRONOMICAL RESEARCH AND TECHNOLOGY
ISSN 1672-7673
ChinaXiv Cooperative Journal

Impact of Solar Wind on Deep Space Communication Signals and Anti-Interference Techniques

Xue Xiping[1],[2], Li Chunlai[1], Kong Deqing[1], Zhang Hongbo[1]
[1] National Astronomical Observatories, Chinese Academy of Sciences, Beijing
[2] University of Chinese Academy of Sciences, Beijing

Abstract

During solar superior conjunction, solar wind severely degrades deep space communication links and may cause complete link interruption. This paper demonstrates that the distance between the communication channel and the Sun is the primary factor determining the severity of solar wind effects on deep space communication channels, and analyzes the specific characteristics of these impacts. Finally, using China' s Mars exploration mission as a case study, we theoretically evaluate feasible communication channel improvement strategies to mitigate solar wind effects.

Keywords: solar wind; deep space exploration; intensity scintillation; phase scintillation; frequency expansion

1. Introduction

China' s deep space exploration program has officially commenced, with Mars and other small celestial body exploration missions already initiated. Deep space communication features extremely long transmission distances, low signal-to-noise ratios, and significant propagation delays, making it particularly vulnerable to solar wind effects. During solar superior conjunction, when the Sun lies directly between Earth and the spacecraft, communication signals must pass through the solar corona, resulting in severe degradation of communication quality. For example, during the Galileo mission, when the Sun-Earth-Probe (SEP) angle was 2.9°, the spacecraft signal could only be acquired after multiple retransmissions. When the SEP angle decreased to 0.6°, the signal-to-noise ratio fluctuations became so severe that the spacecraft signal could not be acquired at all.

With China' s deep space exploration program now underway, research on the impact mechanisms of solar wind on communication signals and corresponding anti-interference techniques is essential for mission planning and implementation. This paper systematically analyzes the influencing factors and scope of solar wind effects on communication signals, and proposes several technically feasible mitigation strategies for China' s Mars exploration mission.

2. Impact of Solar Wind on Deep Space Communication Signals

Solar wind plasma exhibits non-uniform electron density distribution and turbulent motion within the solar corona. When communication signals propagate through this medium, the irregularities cause rapid fluctuations in signal amplitude and phase, known as scintillation. Phase scintillation refers to rapid phase variations caused by the solar wind, which leads to frequency shifts in the received signal. Since both the spacecraft and Earth are in relative motion, phase scintillation can also be interpreted as Doppler noise. For instance, during Cassini' s solar conjunction in 2000, significant phase scintillation was observed at SEP = 0.6°.

Frequency expansion occurs when signals propagate through the irregular plasma distribution of solar wind, causing the signal' s power spectral bandwidth to increase. The degree of frequency expansion depends on plasma density fluctuations and solar wind velocity. If the transmitted signal experiences large frequency expansion, a wider receiver bandwidth is required to capture the signal, but excessive bandwidth introduces more thermal noise and degrades receiver performance. Cassini observations in 2000 showed frequency expansion effects at SEP = 0.6° and SEP = 3.1°.

[Figure 1: see original paper] Schematic diagram of solar wind impact on deep space communication
[Figure 3: see original paper] Frequency residuals in X and Ka bands from Cassini reflection phase scintillations during first solar conjunction (SEP = 0.6°)
[Figure 4: see original paper] Frequency expansion of signals during Cassini' s first solar conjunction observed in 2000 (SEP = 0.6° and SEP = 3.1°)

3. Anti-Interference Techniques

3.1 Frequency Selection

The impact of solar wind on radio signals is frequency-dependent, with lower frequencies experiencing greater effects. Therefore, selecting higher frequency bands can enhance resistance to solar wind interference. Under the same channel conditions, the scintillation index for Ka-band signals is only 0.064, while for X-band it is 0.37—meaning Ka-band experiences significantly less attenuation. However, higher frequencies suffer greater atmospheric attenuation. For deep space missions, using a relay satellite to receive the spacecraft' s Ka-band signal and down-convert it to X-band before transmission to Earth can substantially reduce atmospheric attenuation. Ka-band communication represents the future trend for deep space communications, offering both improved communication quality and reduced spacecraft power requirements.

[Figure 5: see original paper] Communication link performance at X/Ka band (Rice distribution model)

3.2 Channel Coding

Traditional deep space communications have employed convolutional coding with Binary Phase Shift Keying (BPSK). However, under strong scintillation (scintillation index > 0.3), convolutional codes perform poorly. As signal attenuation and phase fluctuations intensify, receiver performance degrades significantly. Low-Density Parity-Check (LDPC) codes have emerged as a superior alternative, offering performance near the Shannon limit and excellent anti-interference capability. MATLAB simulations comparing different coding schemes under solar wind effects show that LDPC codes provide a 3.3 dB coding gain improvement over convolutional codes under the same channel conditions and information rate.

[Figure 6: see original paper] Communication link performance with different coding schemes under solar wind influence

3.3 Adaptive Compensation

Increasing spacecraft transmit power is one method to compensate for attenuation, but deep space spacecraft power is severely limited, and raising transmit power adversely affects other instruments. Adaptive power control based on channel characteristics offers a better solution. For deep space communications, channel attenuation exhibits slow variation due to distance, and fast variation due to solar wind scintillation. An adaptive compensation approach using a tapped delay line filter can estimate channel characteristics. Ground stations correlate received spacecraft signals with local reference signals to extract frequency and phase deviations, then compensate the data-bearing signal to restore normal performance.

[Figure 7: see original paper] Adaptive compensation principles of the data receiving system in ground station

3.4 Antenna Arraying

Increasing antenna aperture enhances ground station receiving capability, but large antennas face technical challenges including structural deformation and high costs. China has halted development of large single-aperture antennas. Antenna arraying technology using multiple smaller antennas offers equivalent performance with greater reliability and lower construction/maintenance costs. International successes include the Galileo mission, where arraying enabled reception of weak signals when the primary antenna was damaged. China has established an experimental antenna arraying system using the Miyun and Yunnan telescopes, achieving 2 dB signal-to-noise ratio improvement (92.5% combining efficiency) during Chang' e-3 lunar descent data reception.

[Figure 8: see original paper] Test system of the antenna array
[Figure 9: see original paper] Analysis of the antenna array' s synthesis effect

4. Conclusion

During solar superior conjunction, solar wind severely impacts deep space communication quality, causing signal attenuation and phase fluctuations. With China' s deep space exploration program underway, research on solar wind effects and mitigation techniques is crucial. Key strategies include using higher frequency bands (Ka-band), advanced channel coding (LDPC), adaptive compensation, and antenna arraying. Researchers should thoroughly investigate these anti-interference technologies to ensure reliable deep space communication during solar conjunction periods.

References

[1] Hastrup R. Communicating with Mars during periods of solar conjunction. Aerospace Conference Proceedings, 2002: 1271-1281.

[2] Morabito D. The study of solar scintillation effects on deep space communication. Beijing: University of Chinese Academy of Sciences (Center for Space Science and Applied Research), 2001.
[3] Morabito D. Solar scintillation effects on deep space communications. The Interplanetary Network Progress Report, 2001: 1-16.
[4] MacKay D J C, Neal R M. Near Shannon limit performance of low density parity check codes. IEEE Electronics Letters, 1996, 32(18): 1645-1646.
[5] Li Qi, Yin Liuguo, Lu Jianhua. Performance study of a deep space communications system with low-density parity-check coding under solar scintillation. Journal of International Communications, 2005, 12(4): 604-615.
[6] Liu Jiaxing. Features and main technical issues in deep space TT&C and communication systems. Journal of Spacecraft TT&C Technology, 2005, 24(3): 167-171.
[7] Eyceöz T, Dölinar S J. Real-time combining of residual carrier array signals. IEEE Transactions on Communications, 1996, 44(10): 604-615.
[8] Thompson A R, Moran J M, Swenson G W. Interferometry and Synthesis in Radio Astronomy. New York: Wiley, 2001.
[9] Vilnrotter V A, Rodemich E R. Eigen theory for optimal signal combining. The Telecommunications and Data Acquisition Progress Report, 1996: 1-16.
[10] Cheung K M. The SIMPLE algorithm for aligning arrays of receiving radio antennas achieved with less hardware and lower combining loss. The Interplanetary Network Progress Report, 2005: 1-16.
[11] Rogstad D H. The analysis of the influence of solar wind and anti-solar wind flicker strategy on the transmission channel of Mars probes. Telecommunication Engineering, 2005, 45(3): 16-21.
[12] Kubin G. Nonlinear prediction of mobile radio channels. IEEE International Conference on Acoustics, Speech and Signal Processing, 1999: 31-34.
[13] Hastrup R. Forward to the deep space: developing trend of TT&C&DC technology. Telecommunication Engineering, 2005, 45(5): 60-65.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.