The effect of Martian ionospheric dispersion on SAR imaging

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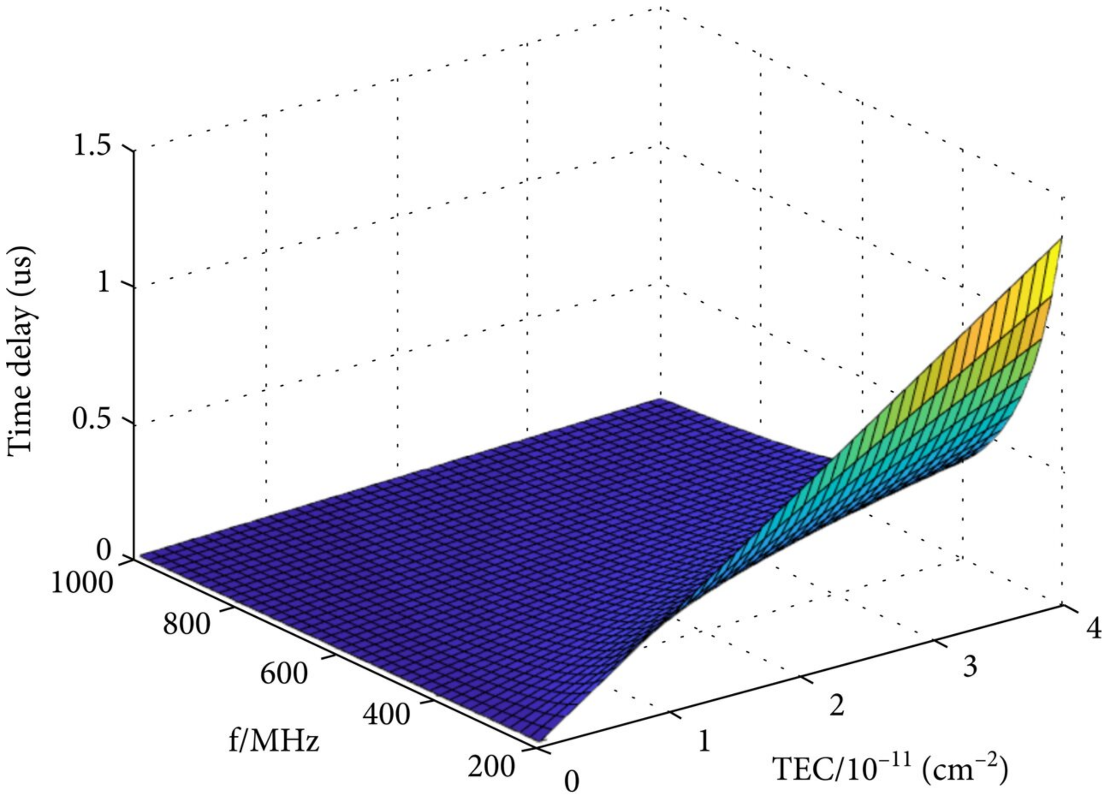
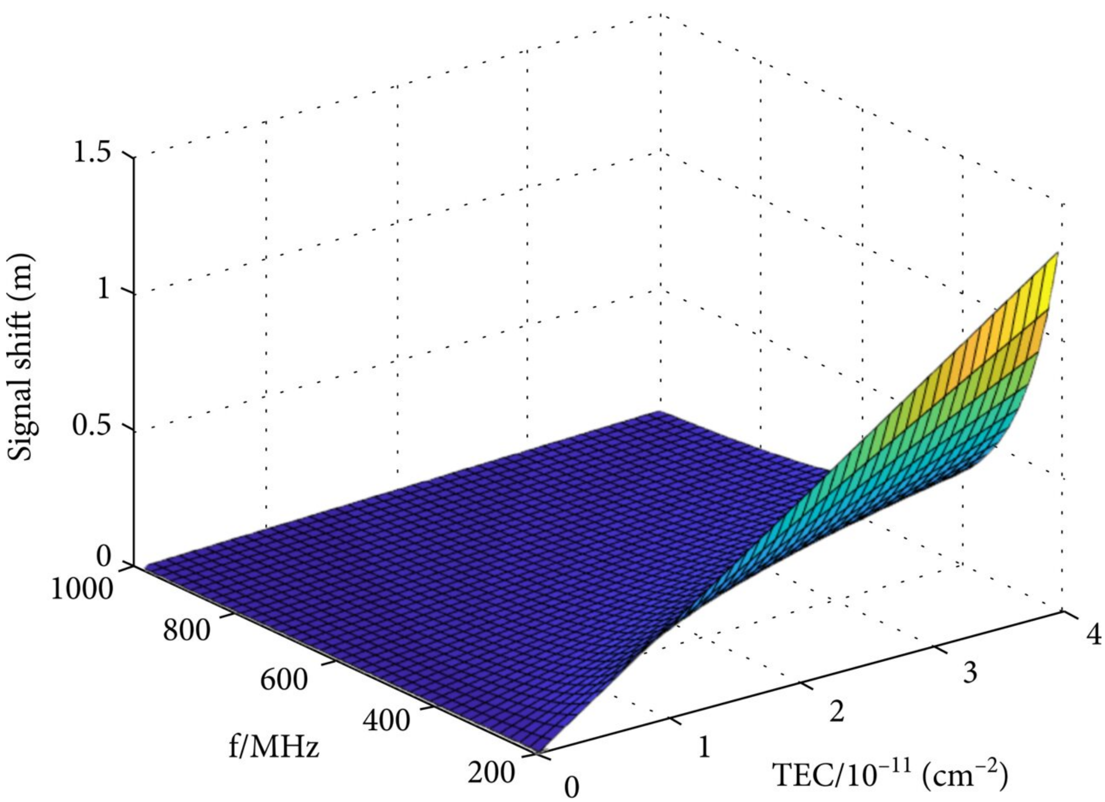

Time delay (us)
1.5
1
0.5
0
1000
800
600
400
200
f/MHz
0
1
2
3
4
TEC/10⁻¹¹ (cm⁻²)

(a)


Signal shift (m)
1.5
1
0.5
0
1000
800
600
400
200
f/MHz
0
1
2
3
4
TEC/10⁻¹¹ (cm⁻²)

(b)

Time delay and signal shift caused by the ionosphere. a) and b) show the relationship between the time delay and the carrier frequency and TEC and that between the signal shift and the carrier frequency and TEC, respectively. Credit: *Space: Science & Technology*

The subsurface of Mars records important historical information on the formation and evolution of the planet. As an ionized medium, the Martian ionosphere plays a special role in radio wave propagation and is directly related to the local communication on Mars and the communication between Mars and Earth.

Therefore, the information on the subsurface and the Martian ionosphere provides a scientific basis for understanding and exploring Mars, as well as for studying the history of geological evolution. The multiband low-frequency down-looking Synthetic Aperture Radar (SAR) mounted on the Mars Orbiter can emit low-frequency radio waves that can penetrate the surface of Mars and propagate downwards.

When passing through the ionosphere, the High-Frequency (HF) pulse signal of the Mars Exploration Radar is affected by the dispersion effect error, which results in signal attenuation and time delay and brings about a phase advance in such a way that the echo cannot be matched and filtered.

In a research paper recently published in *Space: Science & Technology*, Zhijun Yan from Nanjing University of Aeronautics and Astronautics, researched the characteristics of ionospheric distortion and constructed an effective model for the HF waveband to simulate and analyze the influence of the ionospheric dispersion effect on the single SAR signal and imaging under different bandwidths, carrier frequencies, path incidence angles and the ion concentration in the Martian ionosphere.

First of all, the author introduced the ionospheric dispersion effect and signal path change in the ionosphere. The ionosphere was a special dispersive medium with anisotropic characteristics. For a radio signal with a wide frequency spectrum, different frequency components of the signal propagated at different phase velocities in the ionosphere, and thus, different frequency components had different phase relationships. The signal would be distorted, and the pulse was broadened in time and space.

This was the dispersion phenomenon of the ionosphere. Afterwards, mathematical and statistical methods were applied to describe ionospheric impacts on echoes. Ionospheric dispersion had the effects such as signal distortion, turbulence amplitude, and phase fluctuations.

Echoes cannot match the matched filter function, which directly leaded to the degradation of the image quality after pulse compression and the range resolution of the radar which seriously affected its detection capability. The refractive index of electromagnetic wave propagation in the Martian ionosphere can be expressed as a function of the frequency and the electron density.

Considering the working frequency band (MHz) of the Mars Exploration Radar, the high-order terms of the refractive index cannot be ignored. As the refractive index changed with frequency and position, the SAR signal deviated from the normal signal in a vacuum, which affected the result of SAR imaging. The Martian ionosphere was constantly changing and had a certain degree of randomness, which caused the echo phase to be random and indeterminate. Therefore, it was necessary to use statistical models to study the influence of the Martian ionosphere on SAR imaging.

Then, the author simulated signal transmission paths and used the Mars' real ionospheric data to develop the Martian ionospheric model. The path tracking method was used to obtain the influence of the dispersion effect on the radar signal. The additional phase error of the signal was obtained by simulation of the high-order Taylor series approximation.

The key step was to establish the spatial distribution of the refractive index and determined the true influence of signal propagation on the SAR echo. The spatial distribution of the refractive index can be determined by the spatial distribution of electron density and signal frequency. The signal propagation path can be obtained by path tracking technology. On the basis of the above analysis, the actual simulation steps were as follows:

1. According to the ion concentration distribution data of Mars, the Chapman model was used to build the relationship model.
2. According to the system simulation parameters and Ne (Martian ionospheric model of different solar activity periods and different zenith angles), the path tracking method was used to simulate the path of the detection signal refracted in the ionosphere and to calculate the two-way phase advance caused by the dispersion effect.
3. Multiplied the ideal signal and the additional phase advance in the range frequency-domain.
4. Inverse Fourier transform was performed on the frequency-domain signal to obtain the affected signal in the time-domain, and then compare it with the ideal signal.

Moreover, analyses of the phase error as well as the effects on the position of points targets are made. Simulation of the pulse compression processing mode of the point target echo signal are conducted to simulate the SAR echo processing.

The phase error caused by the ionospheric dispersion effect brought about different degrees of time-domain frequency shift, which presented difficulties in pulse compression and echo correction. The pulse compression can effectively separate strong point targets at a relatively close distance, but the phase error made it impossible to clearly distinguish point targets after echo processing.

Through the simulations, the author held that the influence of the chromatic dispersion effect on the signal is mainly the introduction of phase errors, signal shift and time delay. Besides, a low-frequency signal shift was greatly affected by total electron content (TEC) and carrier frequency.

The broadening of the main lobe of the pulse after the signal was affected was also related to the bandwidth, carrier frequency, and TEC. In conclusion, the model can effectively estimate Mars without considering the effects of magnetic fields and anomalous solar activity and the effect of the ionosphere on synthetic aperture radar (SAR) echoes.

More information: Bo Wang et al, The Effect of Martian Ionospheric Dispersion on SAR Imaging, *Space: Science & Technology* (2022). DOI: 10.34133/2022/9860932

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