Detecting Solar Modes in the D-Region using a Relative Ionospheric Opacity Meter

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Introduction

- Relative ionospheric opacity meters (riometers).
- Normal modes in space-physics data.
- Statistical test for normal modes in a process.
- Validation of mode detections.
The Ottawa Riometer

• Radio-wave opacity of the D-region.
• Accepts $30.0 \pm 0.1$ MHz frequencies, and reads at 60 sps.
The Voltage Response

• 27-day record.

• Daily variation from Earth’s rotation.

Data provided by Dr. Donald Danskin. NRCaN Geomagnetic Laboratory.
Solar Oscillations in Space Physics

• Doppler helioseismology.

• Thomson et. al 1995 – Normal modes of the Sun propagate through the interplanetary medium.

• Thomson & Vernon 2015 – Normal modes are present on the ground on Earth.

• Question: What happens at the interface? – Ionospheric waves.
Mode Detection: Physical Considerations

- Mode frequencies shift with solar activity.
- In 2011, solar activity is on the rise.

Data provided by Dr. Ken Tapping. NRC observatory in Penticton, BC.
Spectrum of the Voltage Series

• 0.7 < f < 1.7:
  • Fourier harmonics of Earth's rotation.

• 3.0 < f < 3.5:
  • Normal modes.
A Statistical Test for Normal Modes

Time domain

\[ X(t) = \zeta(t) + \sum_{j=1}^{J} X_{M,j}(t) \]

\( \zeta(t) \) is the noise process at time, \( t \).

\( X_{M,j}(t) \) is the \( j \)'th modulated Fourier series.

Frequency domain

\[ S(f) = H(f) \, S_\zeta(f) \]

\( S(f) \) is the spectrum of \( X(t) \).

\( S_\zeta(f) \) is the spectrum of \( \zeta(t) \).

\[ H(f) \overset{d}{=} \begin{cases} \chi^2(\nu; \lambda), & f \text{ a mode frequency} \\ \chi^2(\nu), & \text{otherwise} \end{cases} \]
Evidence of Normal Modes

• >93% confidence for the Kolmogorov-Smirnov test.

• $\nu = 18$

• $7.2 \leq \lambda \leq 8.7$

• $0.24 \leq \epsilon \leq 0.29$

$F_H(h; \nu, \lambda, \epsilon) = \epsilon F_{nc}(h; \nu, \lambda) + (1 - \epsilon) F_c(h; \nu)$

$\lambda, \epsilon = (7.8, 0.25)$

Thomson et. al, “Interplanetary magnetic field: Statistical properties and discrete modes”, 2001
Validation: Optical Detections

• Michelson Doppler Imager (onboard SOHO).

• $l \leq 10$

• Cross-correlations are high ($\sim 0.6-0.9$) for the matched peaks.

Conclusion

• The quiet-day curve is defined by a Fourier series with five high-SNR Fourier harmonics of the sidereal day.

• Kolmogorov turbulence is manifest as a linear trend in the spectrum of the voltage series.

• At >93% confidence of the Kolmogorov-Smirnov test, around one quarter of the background noise is caused by modal phenomena.

• Some of this modal behaviour is likely due to transportation of solar-oscillation energy via the solar wind.
References & Acknowledgements

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• Tapping, K. F. "The 10.7 cm solar radio flux (F10. 7)." *Space Weather* 11.7 (2013): 394-406.
