National Aeronautics and Space Administration

Origin of Titan's Superrotation, and OSSE for Titan Sub-mm Instrument Development

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Program: FY22 R&TD Topics
Strategic Focus Area: Planetary Atmospheres and Geology

Objectives: (Year-One)
(1) Identify the dominant atmospheric wave modes driving and maintaining superrotation on Titan
(2) Create a orbital submillimeter spectrometer point design to measure vertical profiles of winds, temperature, gases, and to detect waves in Titan's atmosphere
(3) Begin developing an Observation System Simulation Experiment (OSSE) to evaluate the efficacy of the sub-mm point design (to be completed in year-2)

Background A defining feature of Titan's atmosphere is the presence of strong superrotation. To achieve and sustain equatorial superrotation, angular momentum must be transported upgradient by wave transport [1]. Yet the the exact mechanisms driving stratospheric superrotation and whether these waves correlate to waves observed in the upper atmosphere, remain unknown. Cassini observations of the stratosphere were limited to intermittent flybys. Ultimately, the atmospheric dynamics must be measured to identify the actual processes controlling superrotation. A sub-millimeter sounder instrument designed to directly observe vertical profiles of temperature, winds, and composition would be exactly the right instrument to characterize trace gas transport processes and wave dynamics on Titan. Direct observations of waves and their impact on Titan's atmospheric circulation, as well as instrument development for the next generation of measurements at Titan, are of high strategic priority for NASA and its 'Roadmap to Ocean Worlds'.

Approach and Results

Objective 1 Analyses: We performed wave analysis using a combination of cospectral and a spherical harmonic wave analysis methods to characterize dominant atmospheric waves modes that are thought to drive and maintain superrotation in Titan's atmosphere. We analyzed Titan Weather Research and Forecasting (WRF) Global Circulation Model (GCM) winds and temperature output to determine the global zonal and meridional atmospheric flow over the span of one Titan year, and detected angular momentum transfer events that are hypothesized to cause super-rotation in the Titan atmosphere [1; Fig 1]. Our combined space-time cross spectral and Fourier transformation wave analyses extracted both vertical and horizontal wave properties. We identified that the dominant atmospheric wave modes are transient waves that have the highest power spectral density at vertical wavenumbers one and two (Fig 2). A strong source region for eddy momentum flux is observed near 55N latitude where the zonal wind may violate shear stability criterion at L_s=260°. This eddy momentum flux subsequently increases the mean zonal winds that contribute to driving equatorial superrotation.

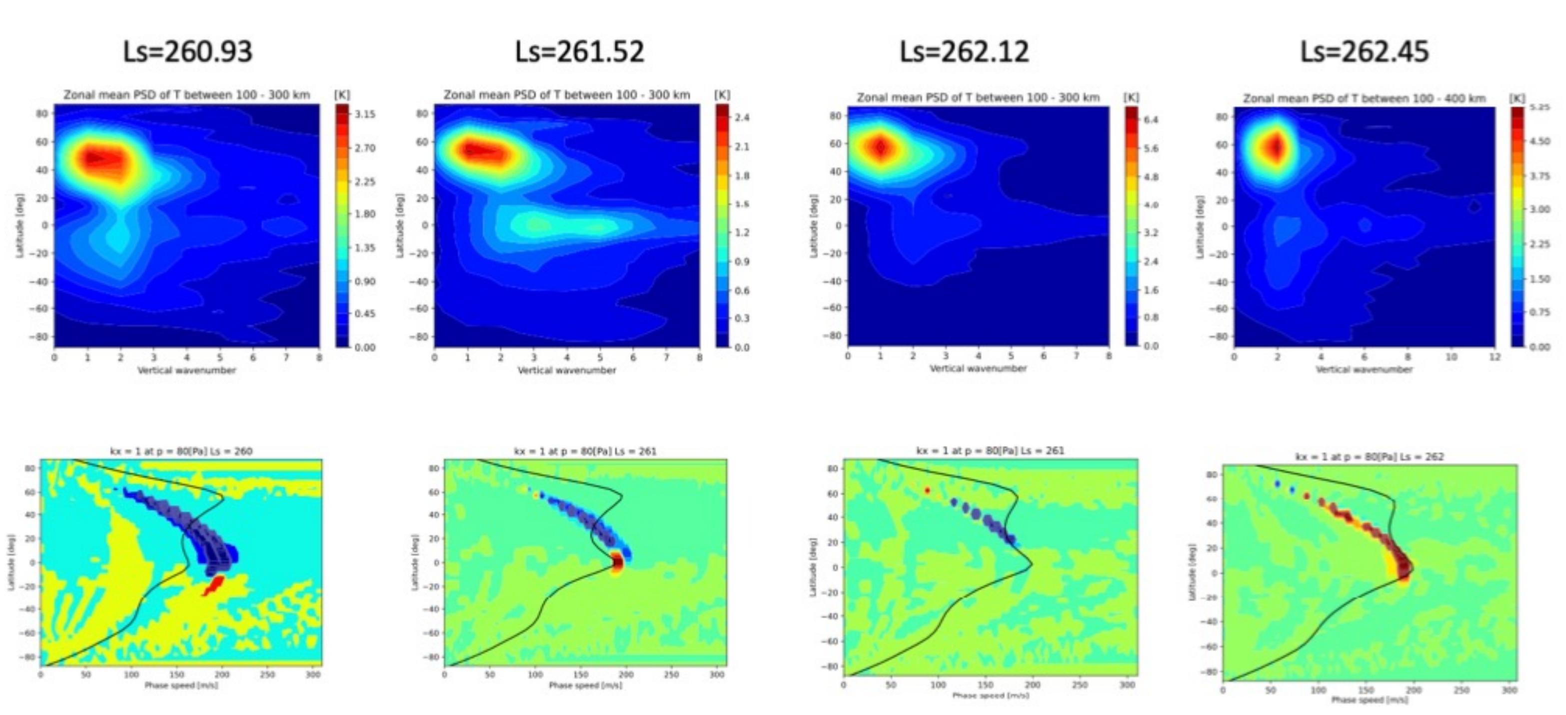

Fig 2. Top row: The zonal-mean power spectral density of atmospheric temperature, over several time stamps, indicating the dominant vertical wavenumbers as a function of latitude associated with the large momentum transfer event near L_s=260 deg. Bottom row: For the 80 Pa pressure level, this row shows the time evolution of the zonal wavenumber 1 phase speed. Blue=southward flow, red=northward flow, and convergence of the two along with phase speeds faster than the mean wind speed (black line) indicate eastward "pumping" of the zonal winds when waves break. The "pumping" is thought to be the mechanism that maintains Titan's atmospheric superrotation.

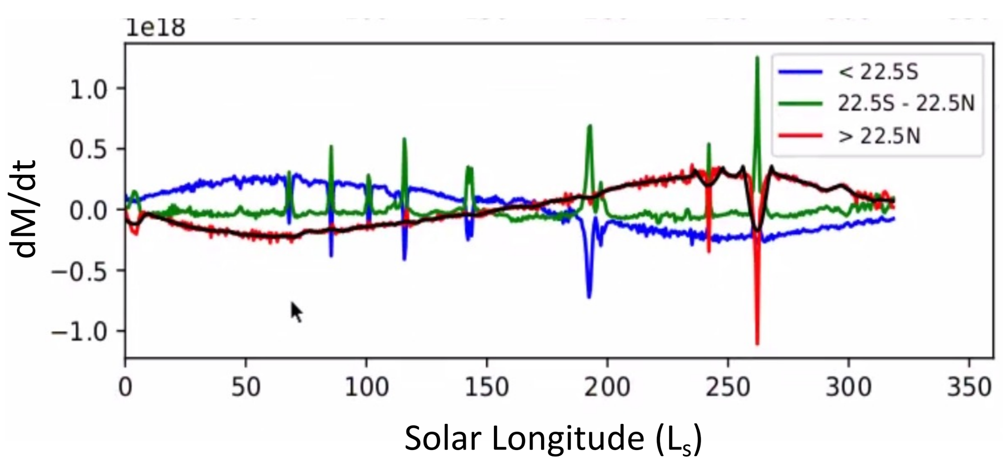

Fig 1. TitanWRF change in atmospheric momentum with time as a function of solar longitude (L_s; a proxy for season). The spikes are the momentum transfer events that are thought to force and maintain superrotation on Titan.

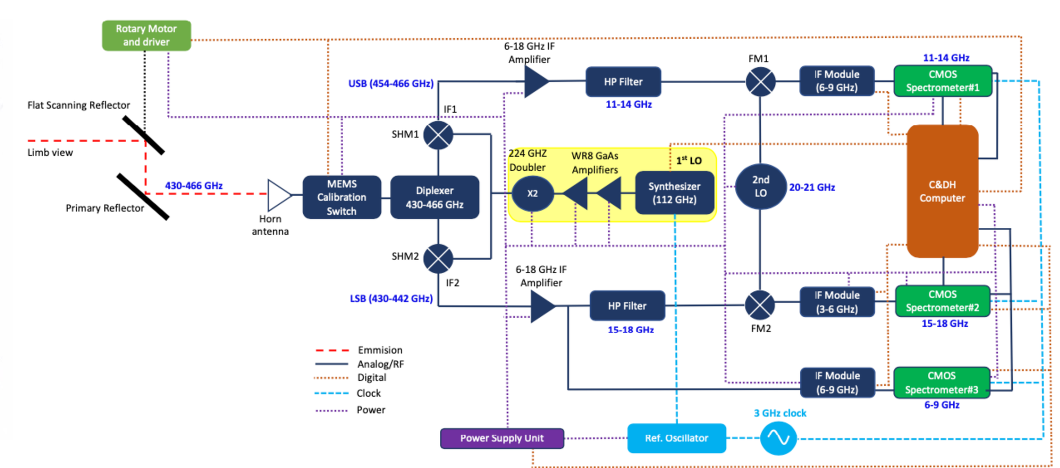

Fig 3. Block diagram for our point design submm sounder with a single, fixed-antenna system operating at ~450GHz to measure line-of-sight winds, temperature, and CO, HCN, and methane from 100-500 km in the Titan atmosphere.

Objective 2 Analyses: We created a point design for a JPL orbital sub-mm spectrometer for use at Titan by adapting the capabilities of the JPL-developed sub-mm spectrometer for orbit around Mars [2-3; Fig 3]. We identified the 430-470 GHz frequency region (Fig 4) as providing the region offering the best sensitivity and the highest TRL instrument components. The sub-mm would measure winds, temperature, and composition: isotopologues of CO (CO, ^{13}CO, C^{18}O), HCN (H^{13}CN, HC^{15}N), and methane (CH$_3$D; Fig 5).

Objective 3 Analyses: We began developing an OSSE to evaluate the efficacy of the sub-mm point design. This work will be completed in year 2.

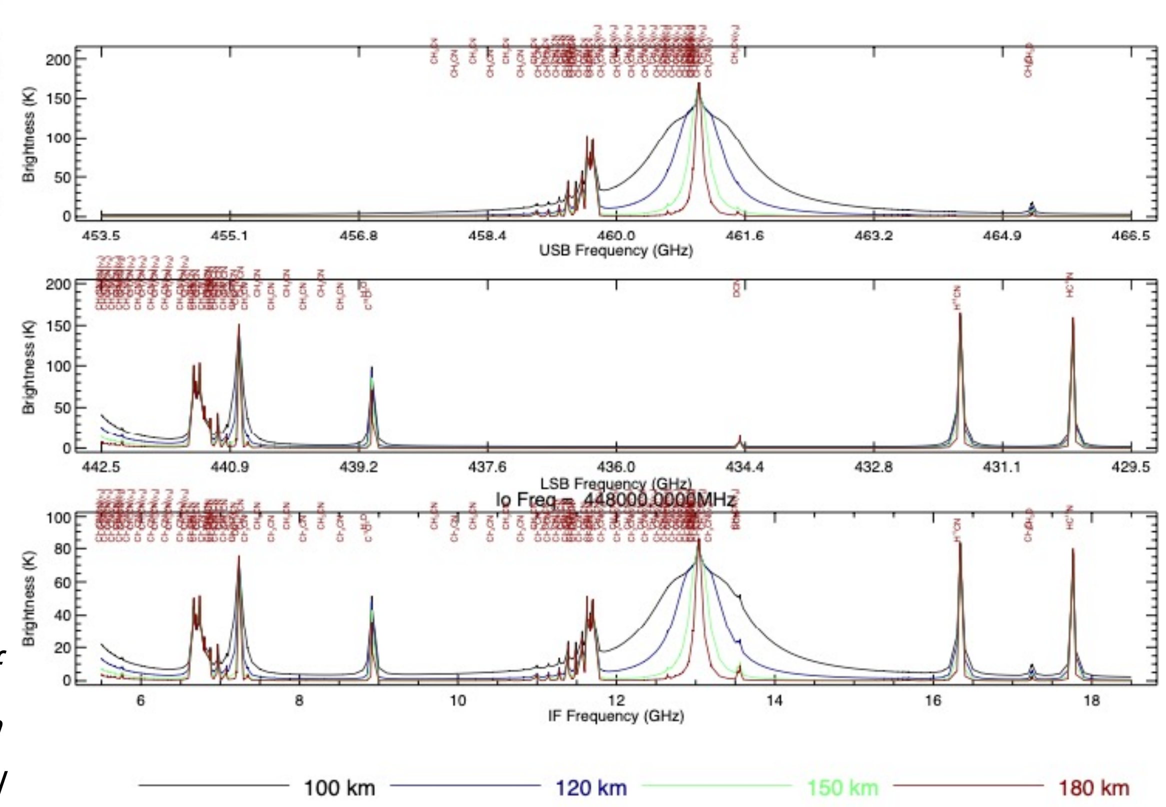

Fig 4. Double side band spectrum for target line positions (GHz) selected for our submillimeter point design.

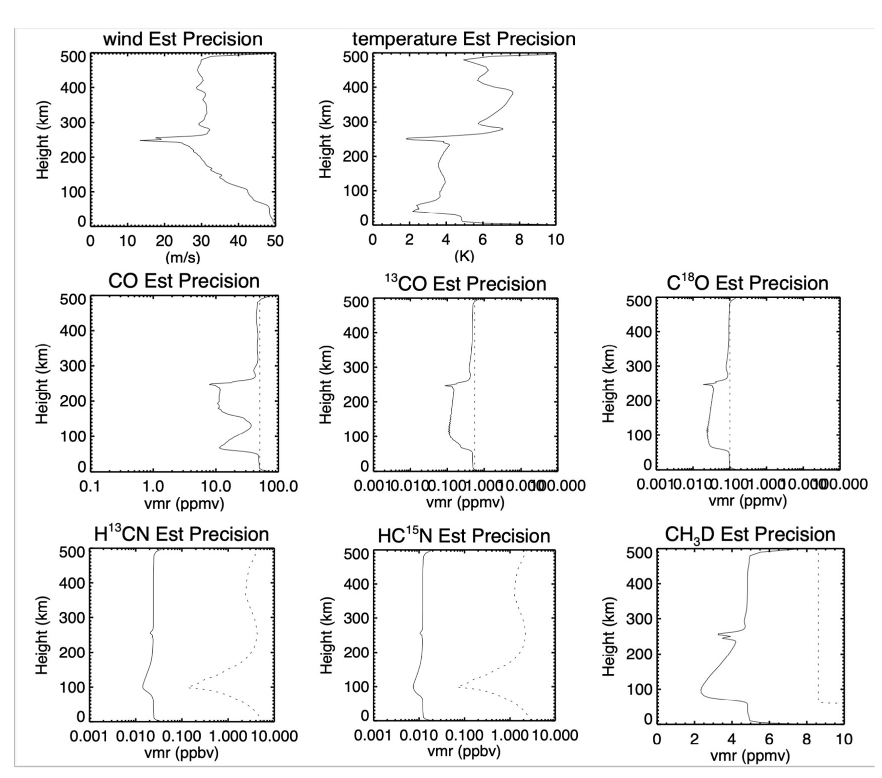

Fig 5. Estimated precision (solid lines; dotted lines are the assumed abundances) of temperature, wind, and composition of CO, HCN, and methane isotopologues for our point design submillimeter instrument.

Significance/Benefits to JPL and NASA

Our wave analysis results are significant for improving the understanding of the atmospheric circulation in Titan's atmosphere, since the origin and nature of these waves and the exact mechanisms driving superrotation and upper atmospheric wave forcing remain unknown. This project is helping to establish JPL personnel in Titan atmospheric research. The completion of our Titan sub-mm point design and plans to test it with an OSSE significantly benefit JPL by extending the range of application of the JPL sub-mm sounder.

References

[1] Claire Newman et al., "Stratospheric Superrotation in the TitanWRF Model," Icarus, 213(2), 2011, pp. 636–654.
[2] William Read et al., "Retrieval of wind, temperature, water vapor and other trace consituents in the Martian Atmosphere," Planet. Space Sci., 161, 2018, pp. 26–40
[3] Tamppari et al., "Testing the efficacy of a sub-mm sounder for Mars atmospheric measurements," Planet. Space Sci., in review.
[4] National Academies of Sciences, Engineering, and Medicine 2022. Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032. Washington, DC: The National Academies Press. https://doi.org/10.17226/26522.

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Publications

[A] Cecilia Leung, Leslie Tamppari, Claire Newman, and Yuan Lian. "Angular Momentum Transfer in Titan's Stratosphere,",Europlanet Science Congress 2022, Granada, Spain, 18–23 Sep 2022, EPSC2022-716, 2022.
[B] Cecilia W. S. Leung, Yuan Lian, Leslie K Tamppari, Claire E Newman, William G Read, Nathaniel J Livesey, Goutam Chattopadhyay, Sven van Berkel and Subash Khanal, (2022) "Angular Momentum Transfer Events in Titan's Stratosphere," Abstract ID# 1097675 presented at 2022 AGU Fall Meeting, Chicago, USA. 12-16 Dec 2022.