A laser heterodyne radiometer for sampling plumes of icy moons

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We propose to develop an instrument capable of passively sampling plumes in icy moon environments for the components needed for life and habitability. The compact, low-mass and power, orbital instrument would be an occultation-viewing laser heterodyne radiometer (LHR) that collects sunlight passing through the plumes of icy moons to measure abundancies of key trace gases such as water vapor, methane, ethane, carbon dioxide, and their isotopes.

Laser heterodyne radiometers are based on radio receiver technology and have been applied to measurements of trace gases in Earth and planetary atmospheres since the 1960s. Our team has recently adapted this technology into a 4U (20cm x 20cm x 10cm) CubeSat instrument to measure carbon dioxide, methane and water vapor in the Earth's atmosphere (launching on Virgin Orbit in 2019) and have the experience to develop this into a compact science payload to monitor gases emerging from icy moons of Saturn and Jupiter.

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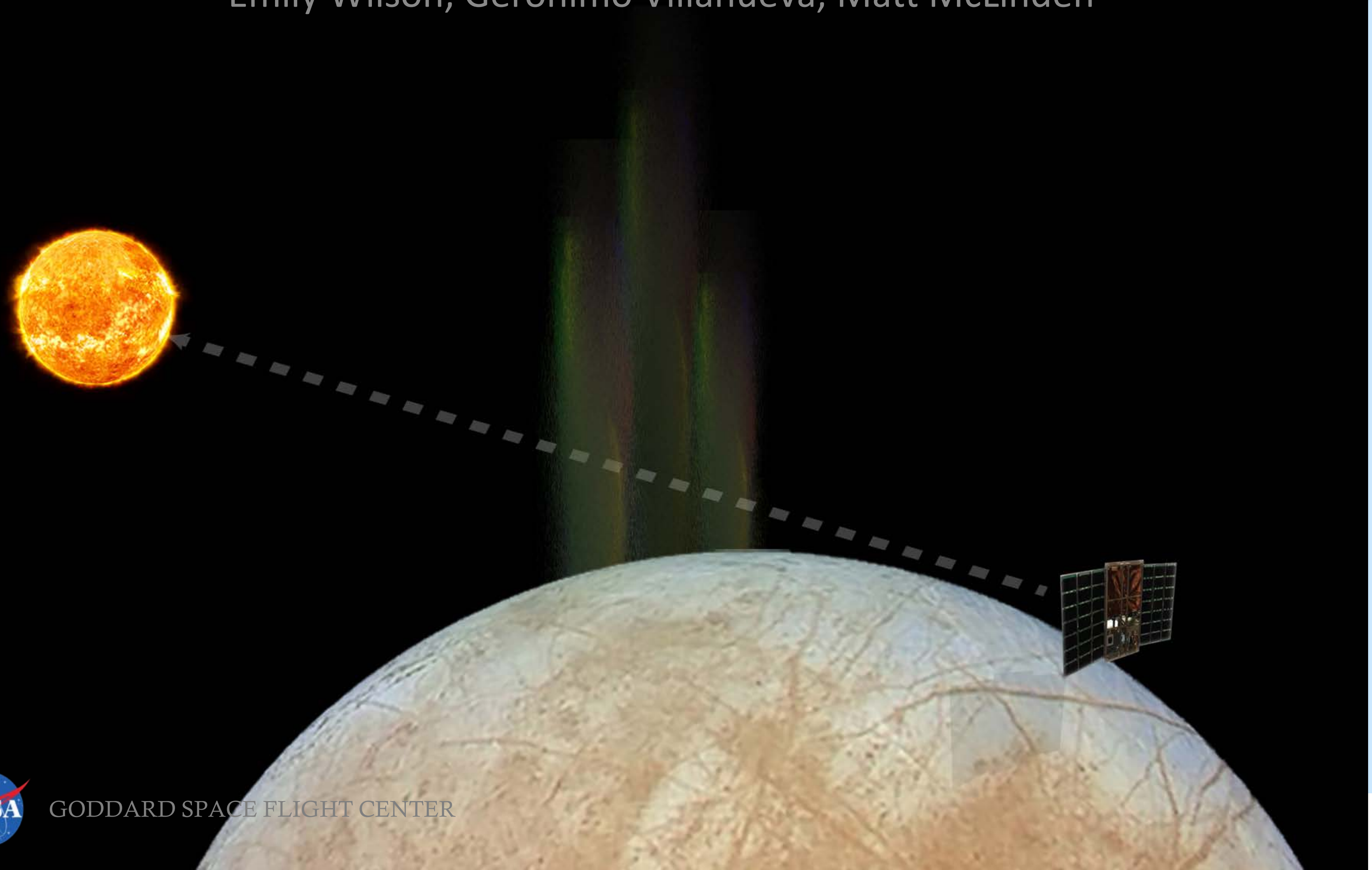
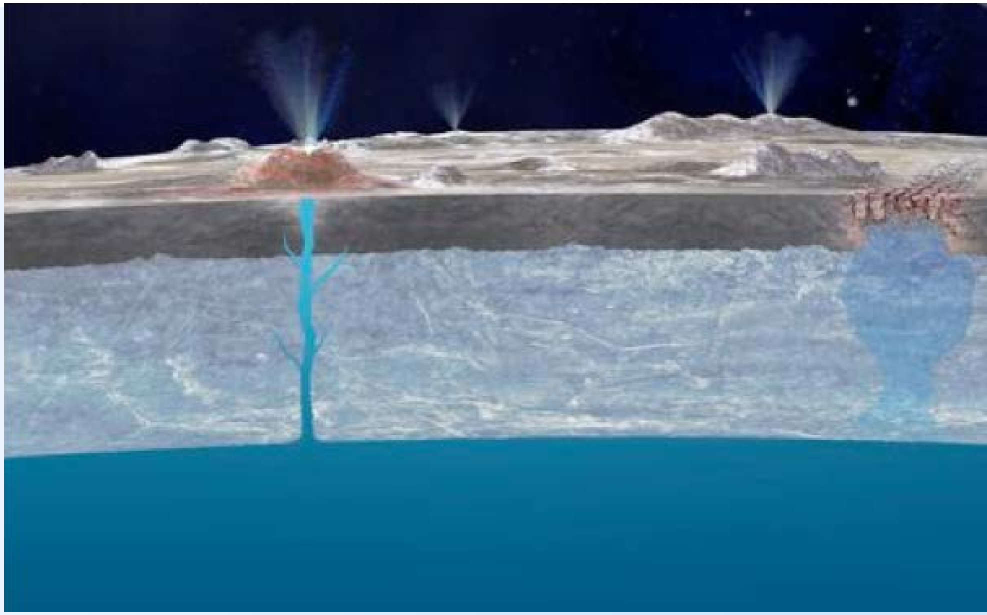
Emily Wilson, Geronimo Villanueva, Matt McLinden



What is a habitable environment?

Methane producing organisms have been found at the bottom of Ace lake in Antarctica in a near-freezing, saline, oxygen-free environment (*photo: Rick Cavicchioli*).

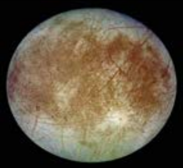


Sub-surface lakes on icy moons could also host habitable environments (credit: *Artist's concept, NASA/JPL-Caltech*).

What lies beneath?

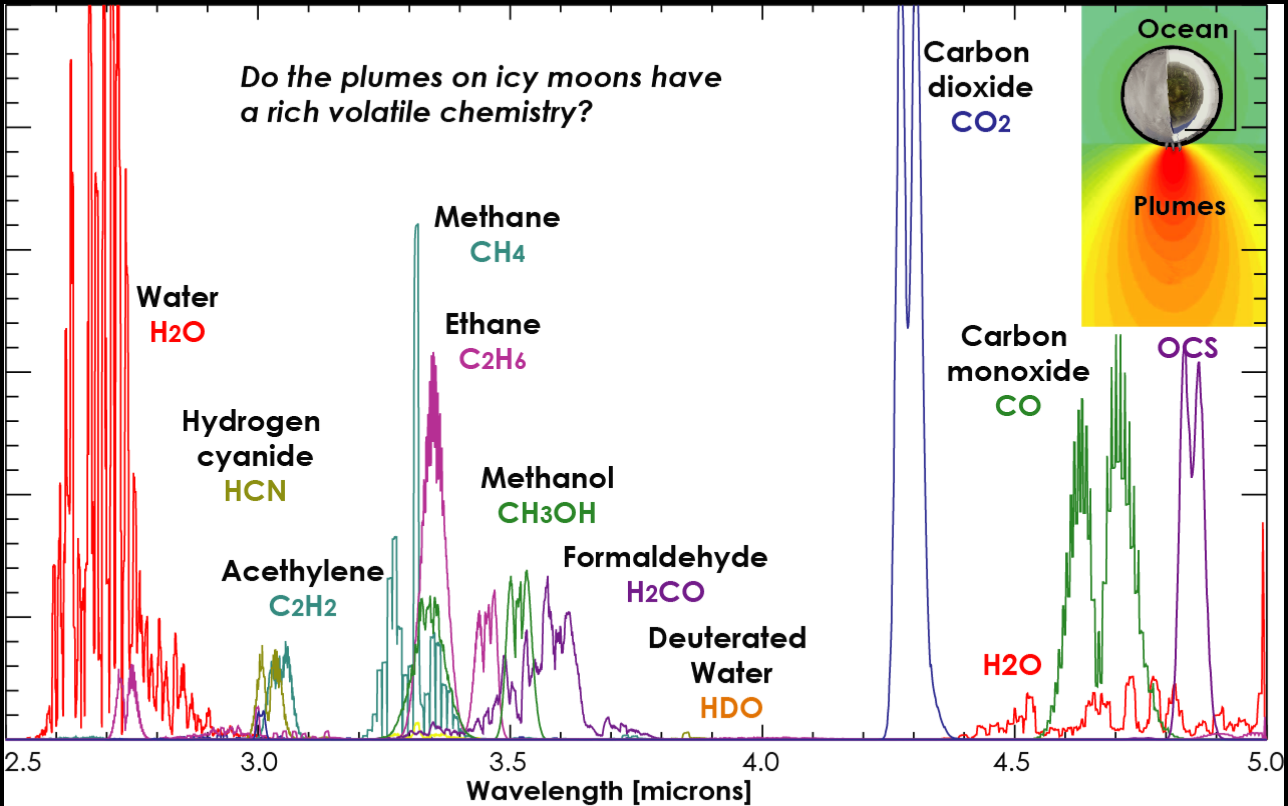
What is the source of organics on ***Enceladus*** *and do the underground oceans have conditions that could support life?*

What is the source of ***Titan****'s methane and could life exist in an underground ocean?*



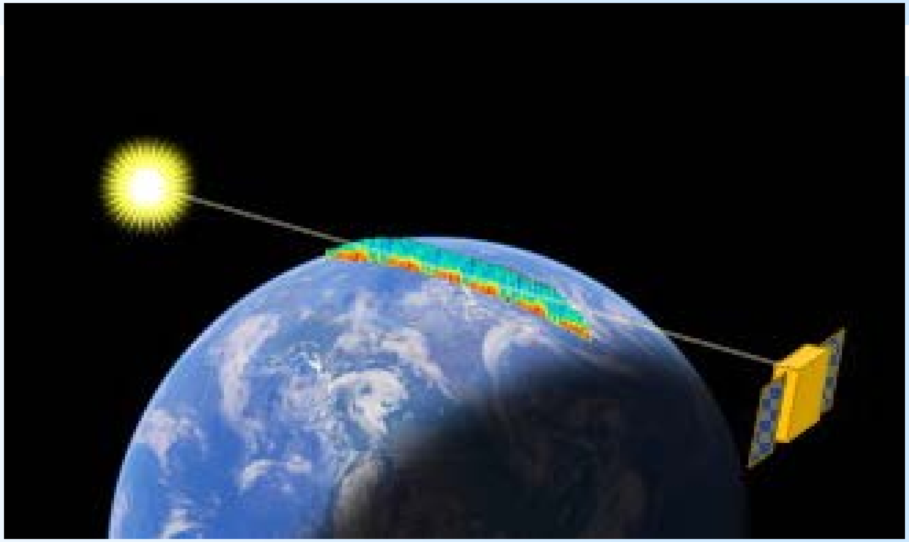
Does ***Europa*** *contain a liquid-water subsurface ocean?*

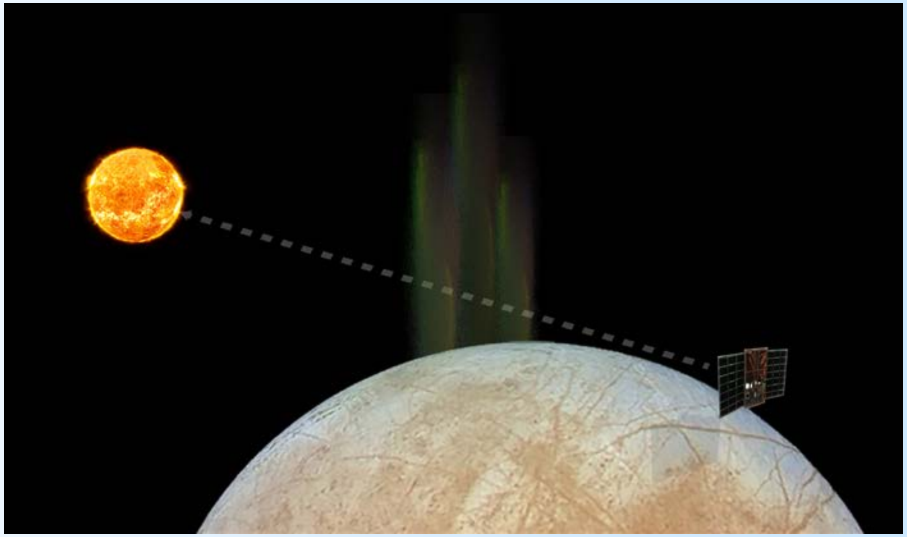
What we can measure with LHR



Do the plumes on icy moons have a rich volatile chemistry?

Occultation-Viewing CubeSat





Thematically, viewing gases in plumes is similar to viewing gases in the Earth's atmosphere. Our Earth-orbiting CubeSat (Mini-Carb) is scheduled to launch via Virgin Orbit in October 2019.

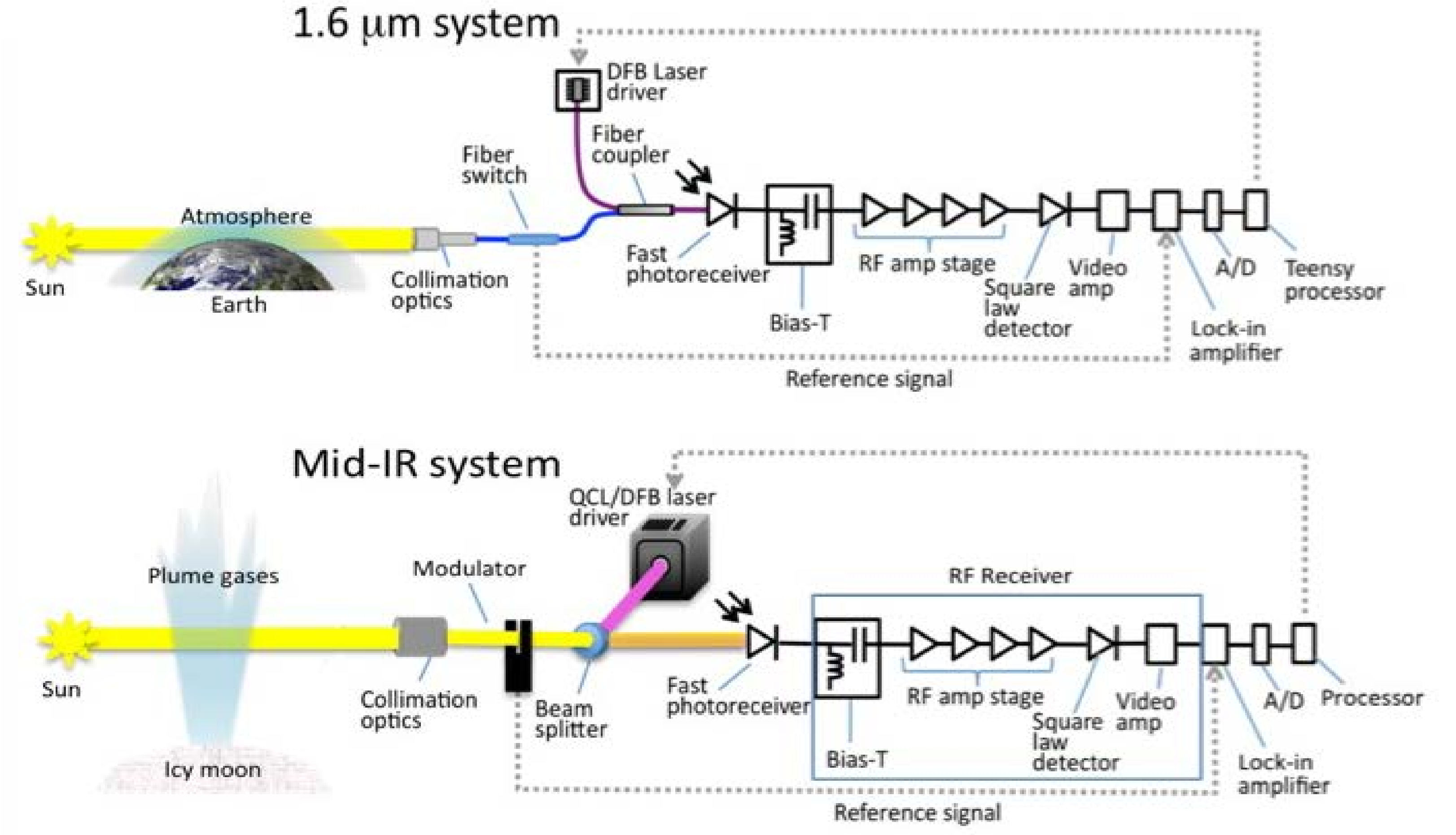
Above: High-inclination orbits provide lengthy observation times when the ascending node is oriented 90° from the sun (~1-4 min observations).

Below: Goal is to view sun through the plume – orbit or fly-by works.

History of Laser Heterodyne Radiometers

Early work		Menzies, R. T. & Shumate, M. S. Usefulness of the infrared heterodyne radiometer in remote sensing of atmospheric pollutants. *Joint Conference on Sensing of Environmental Pollutants*, 1-4 (1971).
Infrared applications	Diode	Weidmann, D. & Courtois, D. Infrared 7.6-um lead-salt diode laser heterodyne radiometry of water vapor in a CH4-air premixed flat flame. *Applied Optics* **42**, 1115-1121 (2003). Ku, R. T. & Spears, D. L. High-sensitivity infrared heterodyne radiometer using a tunable-diode-laser local oscillator. *Optics Letters* **1**, 84-86 (1977).
	Quantum cascade	Sonnabend, G., Wirtz, D. & Schieder, R. Evaluation of quantum-cascade lasers as local oscillators for infrared heterodyne spectroscopy. *Applied Optics* **44**, 7170-7172 (2005).
Trace gases in the atmosphere	O_3	Weidmann, D., Reburn, W. J. & Smith, K. M. Retrieval of atmospheric ozone profiles from an infrared quantum cascade laser heterodyne radiometer: results and analysis. *Applied Optics* **46**, 7162-7171 (2007). Delahaigue, A., Courtois, D., Thiebeaux, C., Kalite, S. & Parvitte, B. Atmospheric laser heterodyne detection. *infrared Physics and Technology* **37**, 7-12 (1996).
	H_2O & CH_4	Seals Jr., R. K. Analysis of Tunable Laser Heterodyne Radiometry: Remote Sensing of Atmospheric Gases. *AIAA Journal* **12**, 1118-1122 (1974).
	NH_3	Zeninari, V., Parvitte, B., Courtois, D., Delahaigue, A. & Thiebeaux, C. An instrument for atmospheric detection of NH3 by laser heterodyne radiometry. *J. Quant. Spectros. Radiat. Transfer* **59**, 353-359 (1998).
	ClO	Menzies, R. T. A Re-Evaluation of Laser Heterodyne Radiometer ClO Measurements. *Geophysical Research Letters* **10**, 729-732 (1983).
Work at GSFC		Abbas, M. M., Mumma, M. J., Kostiuk, T. & Buhl, D. Sensitivity limits of an infrared heterodyne spectrometer for astrophysical applications. *Applied Optics* **15**, 427-436 (1976). Kostiuk, T. & Mumma, M. J. Remote sensing by IR heterodyne spectroscopy. *Applied Optics* **22**, 2644-2654 (1983). Livengood, T. A. et al. High-resolution infrared spectroscopy of ethane in Titan's stratosphere in the Huygens epoch. *Journal of Geophysical Research* **111**, 1-10 (2006).

How it works


1.6 µm system
DFB Laser driver
Fiber coupler
Fiber switch
Atmosphere
Sun
Earth
Collimation optics
Fast photoreceiver
Bias-T
RF amp stage
Square law detector
Video amp
A/D
Teensy processor
Lock-in amplifier
Reference signal
Mid-IR system
QCL/DFB laser driver
Plume gases
Modulator
RF Receiver
Sun
Icy moon
Collimation optics
Beam splitter
Fast photoreceiver
Bias-T
RF amp stage
Square law detector
Video amp
A/D
Processor
Lock-in amplifier
Reference signal

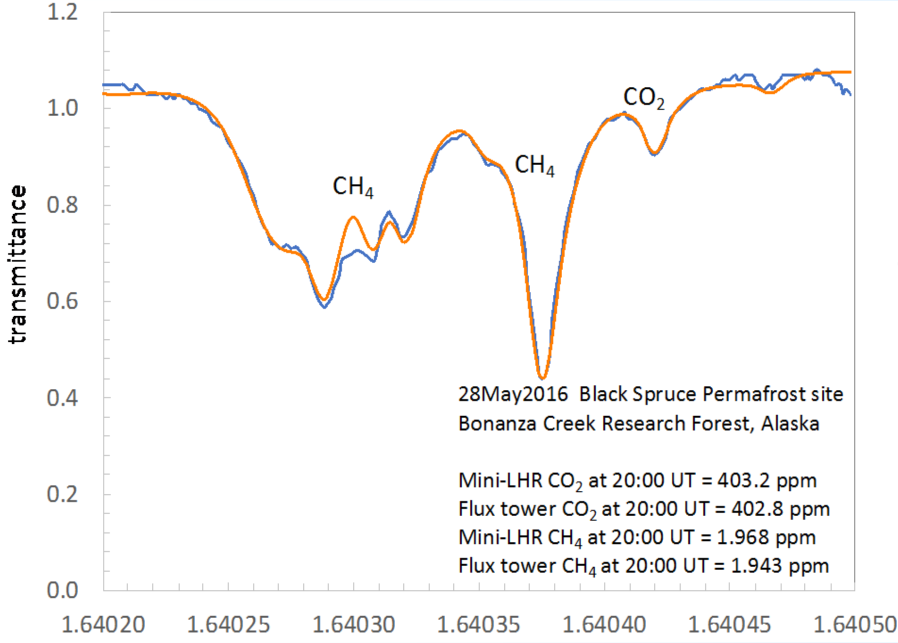
Our past efforts

Ground LHR instrument observing CO_2 and CH_4 in atmospheric column over thawing permafrost in Alaska.

Testing LHR as part of Hi-SEAS (Hawai’i Space Exploration Analog and Simulation): LHR as ground instrument for monitoring atmospheric conditions on a planetary mission.

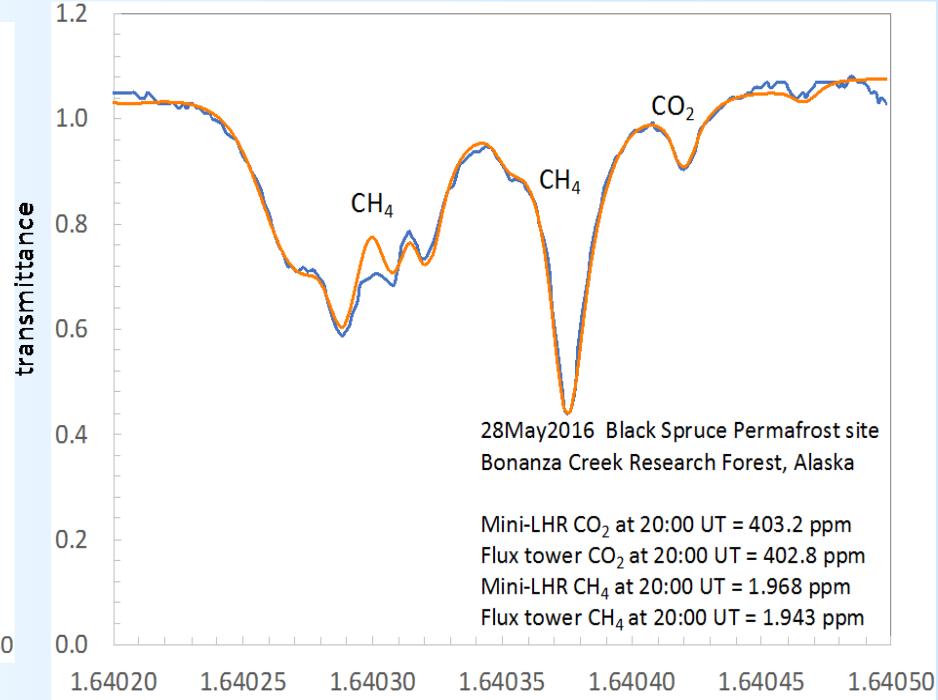
CubeSat LHR (Mini-Carb) after integration. Occultation-viewing. Will monitor CO_2, CH_4, and H_2O in limb from LEO.

Sample data – both CH_4 and CO_2 with single laser



28May2016 Black Spruce Permafrost site
Bonanza Creek Research Forest, Alaska

Mini-LHR CO_2 at 20:00 UT = 403.2 ppm
Flux tower CO_2 at 20:00 UT = 402.8 ppm
Mini-LHR CH_4 at 20:00 UT = 1.968 ppm
Flux tower CH_4 at 20:00 UT = 1.943 ppm



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Analysis using Planetary Spectrum Generator (PSG) based Algorithm

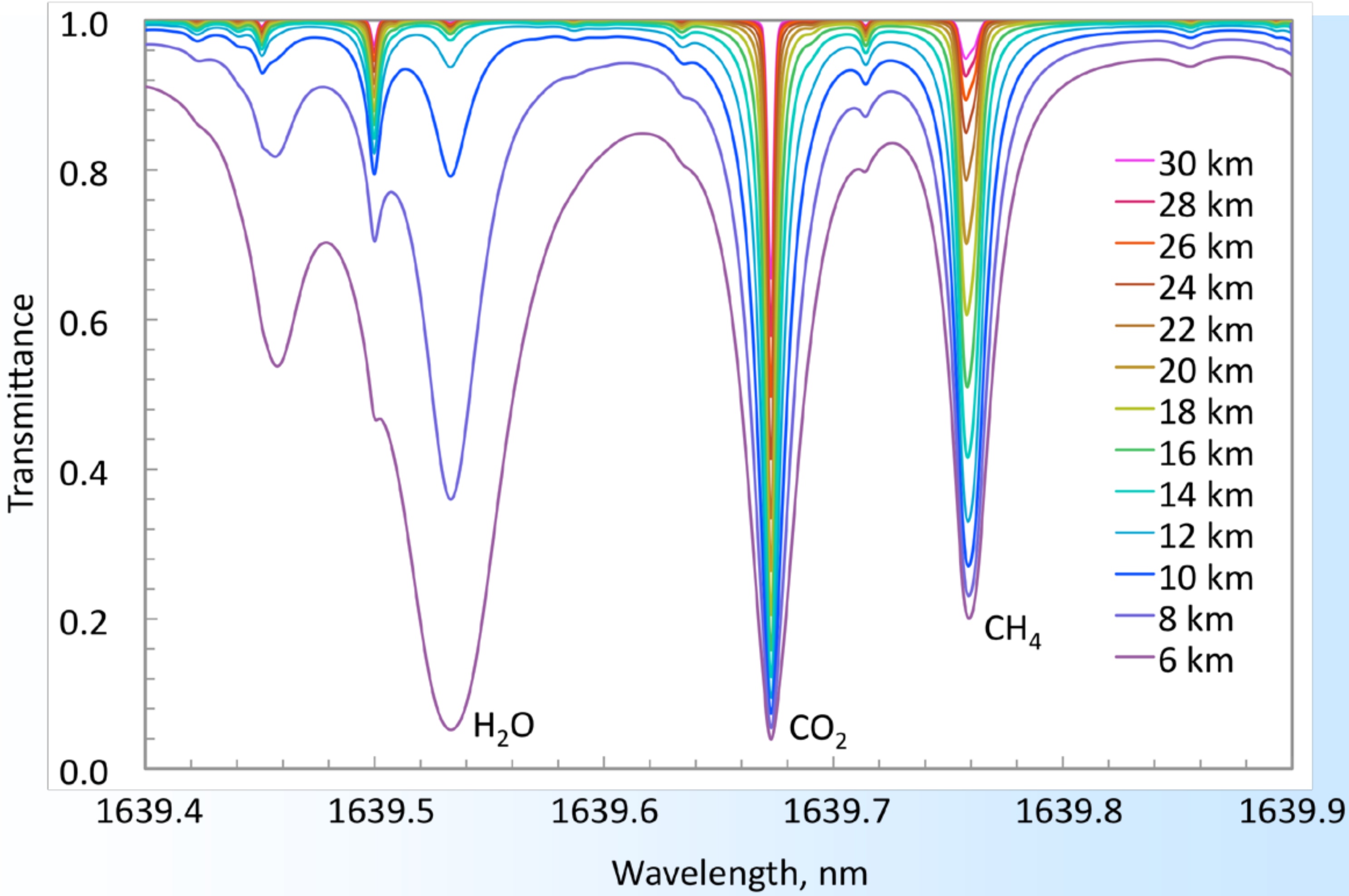
Simulating Spectra with PSG

- PSG (https://ssed.gsfc.nasa.gov/psg) developed at NASA/GSFC – PI: Geronimo Villanueva
- Combines several state-of-the-art radiative transfer models, spectroscopic databases and planetary database
- Includes meteorological data from MERRA (Modern Era Retrospective-Analysis for Research and Applications)
- Includes refraction of sunlight through atmosphere
- Includes computationally efficient scattering package

Fitting Simulation to Data

- Code generates an initial configuration file with geometry parameters (airmass, phase angle, etc.) and an *a priori* vertical profile based on date and location
- Fitting routine perturbs each of the abundances using Levenberg-Marquardt algorithm (an iterative least-squares curve fitting procedure.

Planned CubeSat Spectral Region



CubeSat Integration at LLNL

Photo Credit: Dan Linehan/LLNL

Recent Publications

Palmer, P. I., Wilson, E. L., Villanueva, G. L., Liuzzi, G., Feng, L., DiGregorio, A. J., Mao, J., Ott, L., Duncan, B. Potential improvements in global carbon flux estimates from a network of laser heterodyne radiometer measurements of column carbon dioxide. Atmos. Meas. Tech. 12, 2579-2594 (2019).

Wilson, E. L., DiGregorio, A. J., Riot, V. J., Ammons, M. S., Bruner, W. W., Carter, D., Mao, J. –P, Ramanathan, A., Strahan, S. E., Oman, L. D., Hoffman, C., Garner, R. M. A 4U laser heterodyne radiometer for methane (CH4) and carbon dioxide (CO2) measurements from an occultation-viewing CubeSat. Meas. Sci. Technol. 28, 035902, doi:10.1088/1361-6501/aa5440 (2017).

Melroy, H. R., Wilson, E. L., Clarke, G. B., Ott, L. E., Mao, J., Ramanathan, A. K., McLinden, M. L. Autonomous field measurements of CO2 in the atmospheric column with the miniaturized laser heterodyne radiometer (Mini-LHR). Applied Physics B: Lasers & Optics, DOI 10.1007/s00340-015-6172-3 (2015).

Wilson, E. L. et al. Miniaturized Laser Heterodyne Radiometer for Measurements of CO2 in the Atmospheric Column. Applied Physics B: Lasers & Optics 114, 385-393, doi:10.1007/s00340-013-5531-1 (2014).

Clarke, G. B., Wilson, E. L., Miller, J. H. & Melroy, H. R. Uncertainty analysis for the miniaturized laser heterodyne radiometer (mini-LHR). Measurement Science and Technology 25, 055204-055209 (2014).

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