National Aeronautics and Space Administration

D/H IN COMETS: A VVUQ APPROACH FOR JPL MISSION CONCEPTS

Principal Investigator: Robert A. West (322)

Paul A. von Allmen (398), Imran Mehdi (386), Gaël M. Roudier (326), Seyedeh Sona Hosseini (322), Jacob Kooi (386)

Topic Area: Primitive solar systems bodies

Project Objective:

- Implement a framework for quantifying the uncertainties of individual items to be listed in the Science Traceability Matrix (STM).
- Explore the interactions among them, for each of two small mission proposals being developed for the measurement of D/H in comets.
- The work is split into two parts.
  1. In FY 19 our focus was on the sub-mm instrument.
  2. In FY 20 we will focus on a UV instrument concept in the same way.

FY19 Results:

The work is composed of three sub-tasks. Tasks (1) and (2) are inputs to task (3).

(1) Comet model and uncertainties

We developed a numerical model to compute the microwave emission from molecules in the coma of comets. The model consists of 4 components with the following functions: 1) compute the outgassing rate of the nucleus, 2) compute the distribution of gas in the coma, 3) compute the population of the molecular rotational levels, and 4) compute the optical emission spectrum.

(2) Instrument model and uncertainties

We drive the radiometric sensitivity calculation with recognized uncertainties (see Tables I and II below). All of the significant uncertainties that have been included in our current work include (1) Telescope: emissivity, temperature, illumination, edge taper, secondary blockage, (2) Hot load temperature: emissivity, temperature, coupling beam, (3) Cold load temperature: emissivity, temperature, coupling beam, (4) Optical elements such as mirrors: emissivity, (5) Statistical noise on spectrometer output voltage.

(3) Synthesis for UQ

The parameters (H_2O and HDO production rates, maximum surface temperature) that determine the D/H ratio are retrieved using a Monte Carlo Markov Chain (MCMC) sampling method, which also provides the inter-parameter correlations. We propagate uncertainties from the instrument model (see tables below) and science model (uncertainty in water ortho to para ratio) by randomly perturbating the nominal value with its associated error distribution and assessing the D/H recovery performances (Monte Carlo simulations of MCMC retrievals).

Benefits to NASA and JPL and significance of results:

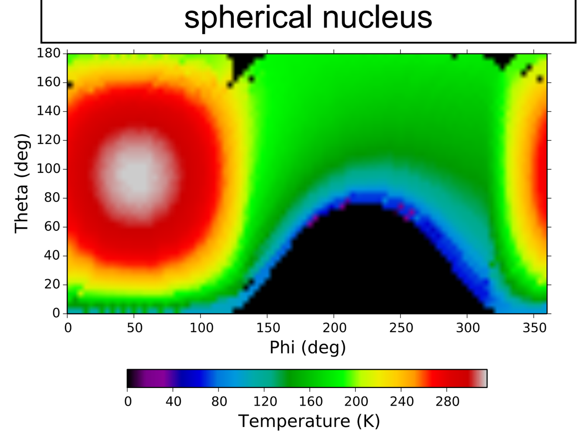
Support mission concept

Comets are primitive solar system bodies. Study of D/H in comets has the potential to illuminate processes in the early solar nebula during planet formation. One question to be addressed: does the earth's water come from comets? D/H has already been a key focus for that question. Our study addresses remote sensing mission concepts rather than in situ measurement because of the need to build up statistics of the cometary D/H ratio rather than to add one or two more measurements by flying to a comet. A remote sensing mission on earth orbit or at a Lagrange point carries the expectation of measuring D/H on several tens of comets. Other isotopes (Oxygen, Carbon, Nitrogen) can also be measured by adding channels to the instrument if the cost/benefit ratio favors doing so. We demonstrate how the SIS technology vastly improves the ability of a remote-sensing mission to measure D/H with sufficient precision to compete with mass spectrometer measurements (which require a mission to a comet), and we estimate, based on comet orbital parameters from the Horizons database, that a 3-year Discovery or SmallSat mission in earth orbit can retrieve D/H for more than 50 comets.

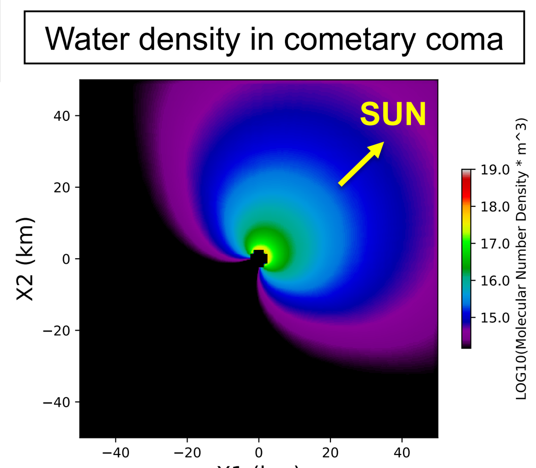
Quantify uncertainties

Our study is a deep-dive into all uncertainties that can contribute to a remote-sensing mission to study cometary D/H. Through the use of the MCMC formalism we are able to quantify how the uncertainties are correlated and how they contribute to total uncertainty in the outcome of the measurements. This study puts us well along the road to a mission proposal. Our results fulfill our objectives to apply VVUQ techniques to construction of a Science Traceability Matrix. Our quantification of the errors can be used to judge the merits of a sub-mm mission relative to merits of other technologies directed to the same science goals. In FY20, we will perform UQ for a near-UV mission and this will allow a quantitative comparison.

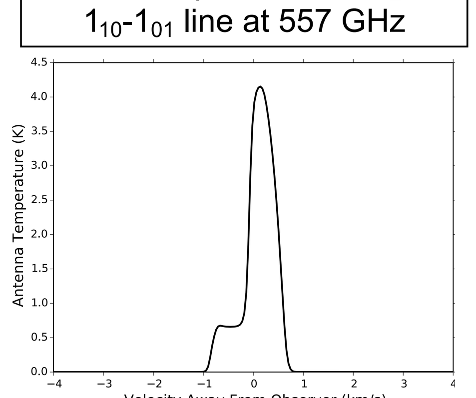
Surface temperature for spinning spherical nucleus



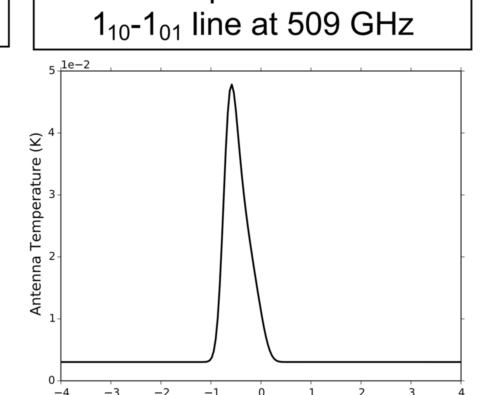
Water density in cometary coma



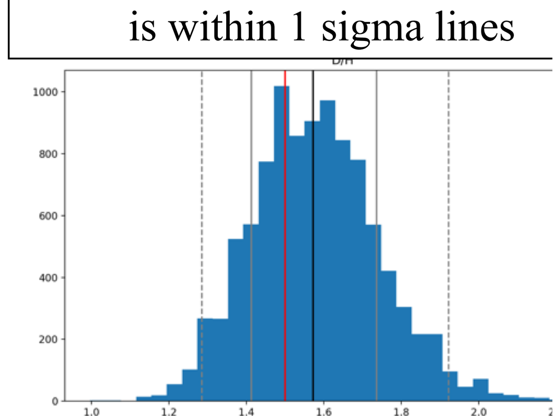
Emission spectrum for $H_2^{16}O$ 1_{10}-1_{01} line at 557 GHz



Emission spectrum for HDO 1_{10}-1_{01} line at 509 GHz



D/H posterior probability density function. No bias: red line (truth) is within 1 sigma lines



Breakdown of error budget

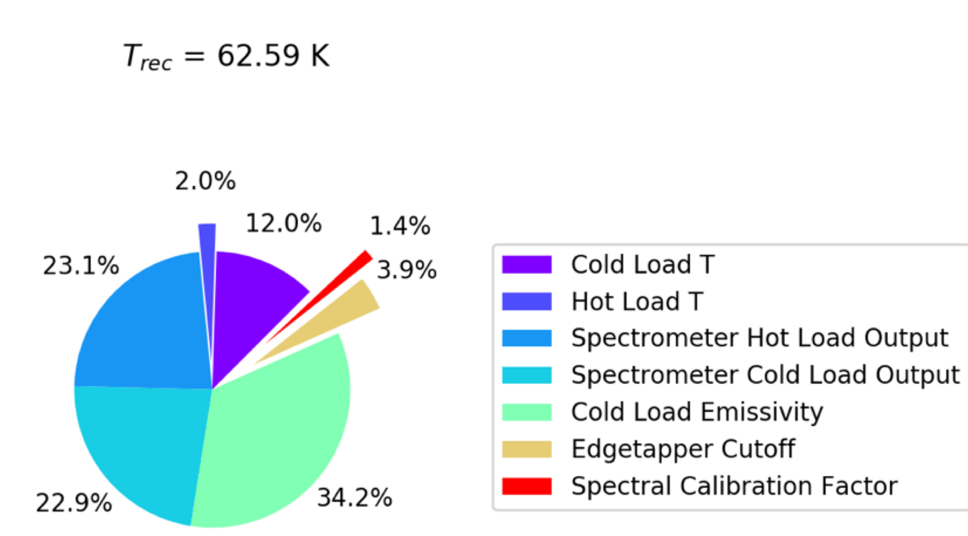
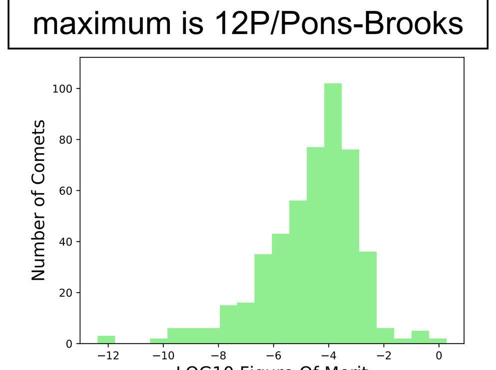
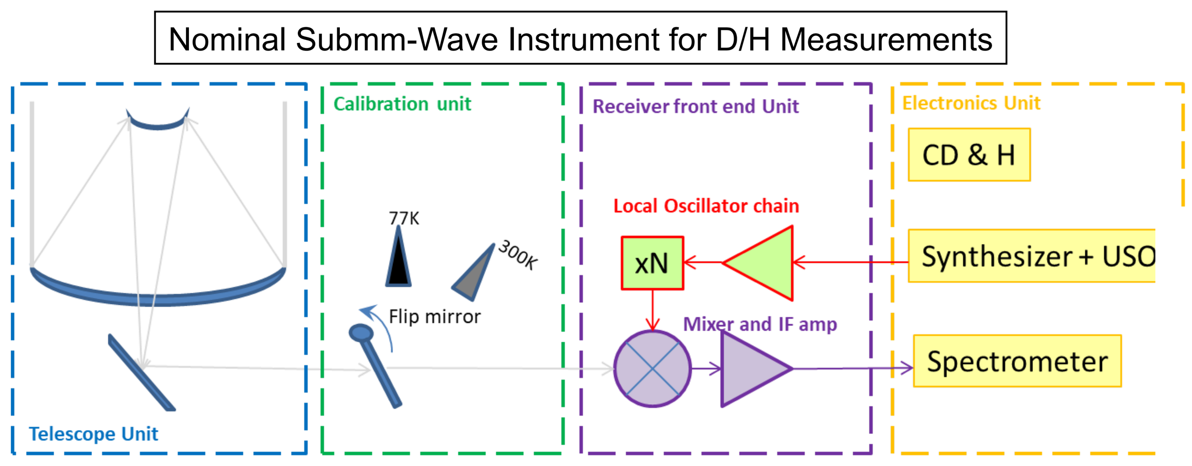


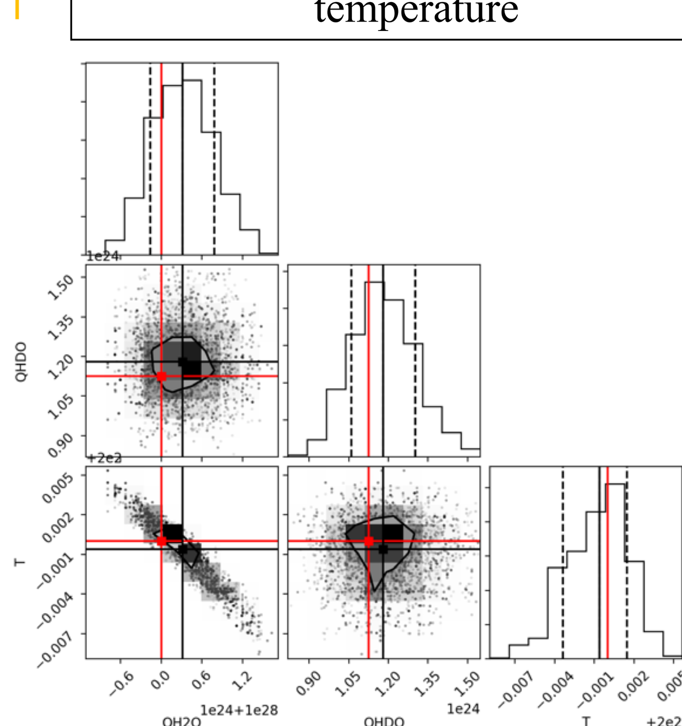
Figure of merit for the comets in Horizons DB. Comet at maximum is 12P/Pons-Brooks



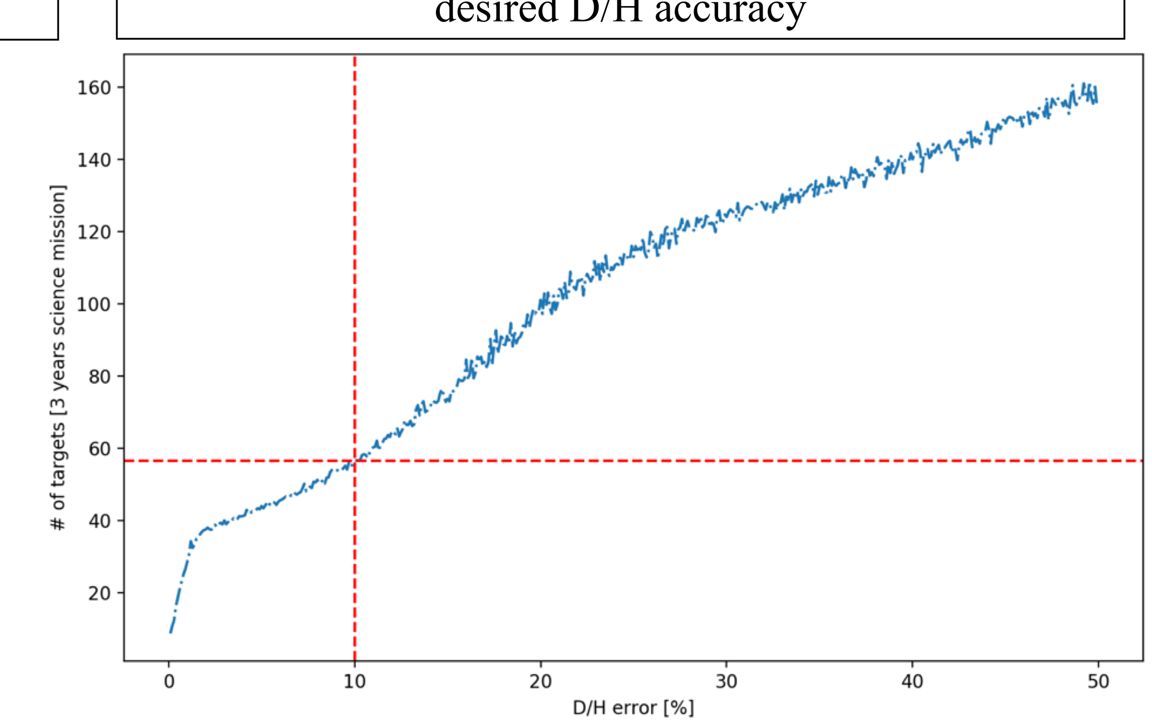
Nominal Submm-Wave Instrument for D/H Measurements



MCMC sampling shows strong correlation between H_2O production rate and maximum surface temperature



Estimate of the number of comets as a function of desired D/H accuracy



Dynamics of figure of merit and $H_2^{18}O$ line area for 12P/Pons-Brooks

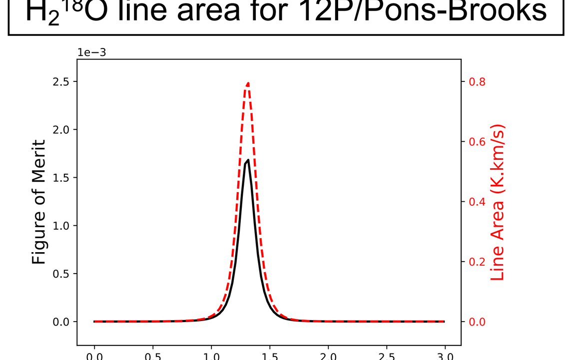


TABLE I
T_a TUNING PARAMETERS

Parameter	Value / [Range]	Unit
T_h	[245 – 293]	Kelvin
T_c	[50 – 100]	Kelvin
σ_{T_c}	[0 – 2]	K
σ_{T_c}	[0 – 3]	K
PIF_{hot}	100	mW
PIF_{cold}†	[30 – 99]	mW
σ_{ph}	[0 – 5]	%
σ_{pc}	[0 – 5]	%
ϵ_h	[0.95 – 0.99]	—
ϵ_c	[0.95 – 0.99]	—
σ_{ϵ_h}	[0 – 2]	%
σ_{ϵ_c}	[0 – 5]	%
T_{amb}	[245 – 273]	Kelvin
$\sigma_{T_{amb}}$	[0 – 1]	K
T_{atm}	[275 – 280]	Kelvin
$\sigma_{T_{atm}}$	[0 – 3]	K
ρ_h	[-40 – -10]	dB
ρ_c	[-40 – -10]	dB
σ_{ρ_h}	[5 – 20]	%
σ_{ρ_c}	[10 – 50]	%
T_e	[10 – 16]	dB
σ_{T_e}	[0 – 2]	dB
R_{DSB}‡	[0.8 – 1.2]	—
σ_{DSB}	[0 – 20]	%
R_{USB}‡	[-30 – -5]	dB
σ_{USB}	[0 – 5]	dB
R_{LSB}‡	[-30 – -5]	dB
σ_{LSB}	[0 – 5]	dB
n	1 - 5	—
t_{opt}	[0.98 – 1.0]	—
η_l	[0.92 – 1.0]	—

†For SIS: $T_{rec}^{DSB,SSB}$ = [40 – 200] K, for HEB $T_{rec}^{DSB,SSB}$ = [600 – 1500] K, for Schottky $T_{rec}^{DSB,SSB}$ = [800 - 3000] K.

‡ Will fluctuate within σ across the RF and IF frequency ban

TABLE II
INTENSITY CALIBRATION TUNING PARAMETERS

Parameter	Value / [Range]	Unit
$V_{load_1}^k$	1	V
$\sigma_{V cal_1}^k$	[0 – 5]	%
$\sigma_{V cal_2}^k$	[0 – 10]	%
R_i	[0.8 – 1.2]	—
$T_{load_1}^s$	[245 – 293]	Kelvin
$T_{load_1}^i$	[245 – 293]	Kelvin
$\sigma_{T_1}^L$	[0 – 3]	K
$T_{load_2}^s$	[50 – 100]	Kelvin
$T_{load_2}^i$	[50 – 100]	Kelvin
$\sigma_{T_2}^L$	[0 – 5]	K
T_{amb}	[245 – 293]	Kelvin
$\sigma_{T_{amb}}$	[0 – 1]	K
ϵ_1^L	[0.95 – 0.99]	—
ϵ_2^L	[0.95 – 0.99]	—
$\sigma_{\epsilon_1}^L$	[0 – 2]	%
$\sigma_{\epsilon_2}^L$	[0 – 5]	%
$\eta_{s_1}^L$	[0.95 – 1.0]	—
$\eta_{s_2}^L$	[0.95 – 1.0]	—
m	1 - 5	—
t_{opt}	[0.98 – 1.0]	—
Δ_ν	[1E6 – 4E9]	Hz

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

PI/Task Mgr. Contact Information:

818 354 0479 Robert.A.West@jpl.caltech.edu

Poster No. RPC-082