A Sub-millimeter sounder for vertically measuring Mars winds, water vapor, and temperature

Leslie K. Tamppari[1], Nathaniel J. Livesey[1], William G. Read[1], Goutam. Chaottopadhyay[1], R. Todd Clancy[2], François Forget[3], Paul Hartogh[4], Scot C. R. Rafkin[5], Don Banfield[6]

[1] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA (*Leslie.K.Tamppari@jpl.nasa.gov*) [2] Space Science Institute,
[3] Laboratoire de Météorologie Dynamique du CNRS, Université Paris [4] Max-Planck-Institut für Sonnensystemforschung [5] South West Research Institute [6] Cornell University, Ithaca, NY.

1 Introduction and motivation

- Much has been learned about Mars' atmosphere and climate in recent decades thanks to Mars-orbiting instruments such as the *Mars Climate Sounder* and *Thermal Emission Spectrometer*.
- However, key outstanding knowledge gaps remain related to the Martian water and dust cycles.
- Observations of the vertical profile of wind and water vapor would provide important insights into these knowledge gaps and be directly with aligned with the MEPAG goals to
  - "Characterize the state of the present climate of Mars' atmosphere and surrounding plasma environment, and the underlying processes, under the current orbital configuration", and for
  - "…future orbital measurements…should provide new measurements (e.g., wind)…" MEPAG goals document.
- A submillimeter limb sounding instrument has the potential to provide such measurements with daily near-global coverage.
- Submillimeter limb sounding has a strong heritage for Earth atmospheric science [e.g., *Waters et al.*, 2006].
- Technology advances in recent years (largely fueled by advances in the communications industry) have enabled dramatic reductions in mass/power/volume needs for such instruments.
- This opens up possibilities for small (e.g., "CubeSat"-scale) instruments for future missions.

2 Survey of potential spectral regions

- Wind information is best obtained from measurements of strong but sub-opaque (and ideally narrow) spectral lines.
- The lines do not necessarily need to be from well-mixed or well-known molecules.
  - To first order, abundance information (line amplitude) and wind information (line position) are separable.
- The four isotopes of carbon monoxide have lines meeting these needs well, providing a mix of strong lines (for upper atmosphere measurements) and weak lines (lower atmosphere).
- The CO lines are opaque from the surface up to ~20 km, as are water vapor lines at the surface.
- Measurements of HDO, O_3, and H_2O_2 can fulfill additional science objectives.
- We have surveyed the spectrum from ~300–1200 GHz and identified six candidate regions providing a useful combination of lines within ~5% of a nominal band center (i.e., Local Oscillator) frequency.
- Table 1 details the six spectral regions identified.
- Figure 1 shows the spectral lines of interest in the 450 GHz region as an example.

Table 1: Target line positions (in GHz) for 6 radiometer frequencies

Molecule	335 GHz	450 GHz	550 GHz	900 GHz	1000 GHz	1130 GHz
$OC^{18}O$	332	441	574	904	1014	1124
CO	346	461	576	922	1037	1152
^{13}CO	331	441	551	881	991	1101
$C^{18}O$	329	439	562	878	988	1097
$C^{17}O$	337	449	562	899	1011	1123
H_2O (strong)	325	443	557	916	988	1097
H_2O (weak)	321	448	572	906	970	1147
HDO	335	465	560	894	984	1162
$H_2{}^{18}O$	322	NA	548	908	995	1137
O_3	327	441	571	908	1009	1145
H_2O_2	327	446	550	908	1018	1131
Bandwidth / GHz	26	27	29	45	67	68
Bandwidth /% RF	7.7%	6.0%	5.2%	5.0%	6.7%	6.0%
Noise temperature	1400 K	1700 K	2000 K	3600 K	4200 K	5000 K

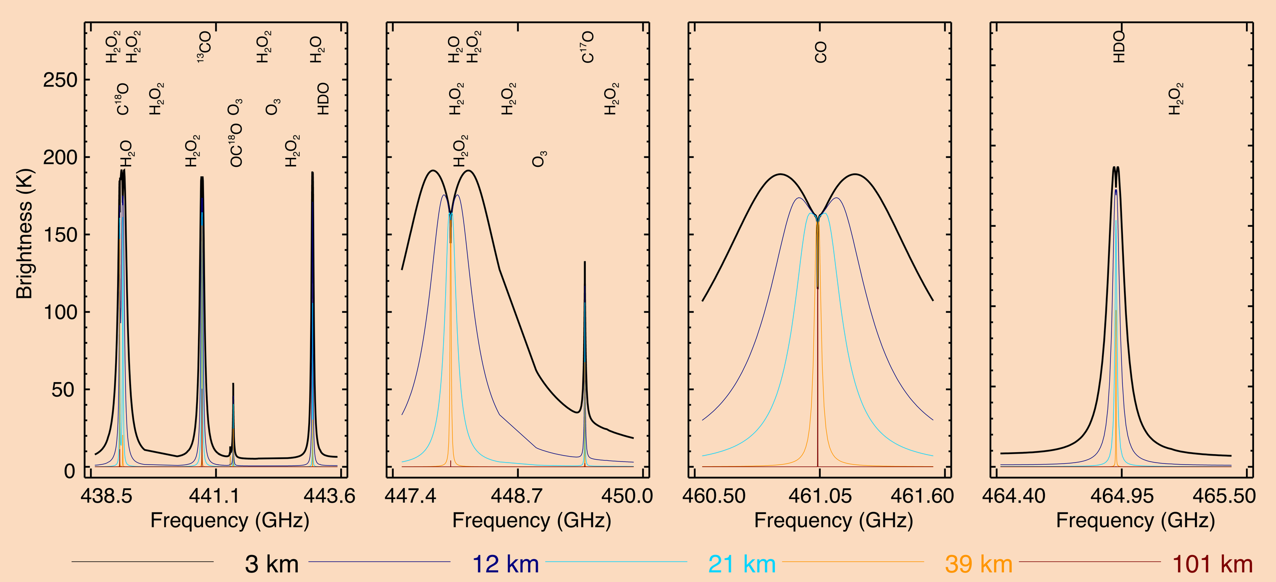

Figure 1: Limb radiative transfer calculations in the 430–470 GHz range for a climatological Martian atmosphere Frequency locations of molecular lines are indicated above the spectra. Colored lines show the spectra for the given limb tangent.

3 Quantifying measurement capabilities

- Next we quantify the theoretical performance of limb sounding instruments making measurements in these spectral regions.
- For this we use the standard "optimal estimation" approach [*Rodgers*, 2000], based on the same forward model used for the Aura MLS instrument [*Read et al.*, 2006].
- We assume an instrument that vertically scans the limb with a 23 cm antenna, measuring limb radiances over 0 to 150 km tangent altitude during a 76 s scan.
- The (single sideband) receiver noise temperatures assumed are given in Table 1.
- Each line is assumed to be measured by a 1 GHz-wide spectrometer, having 100 kHz resolution within ±12.8 MHz of the line center, and 8 MHz resolution beyond.

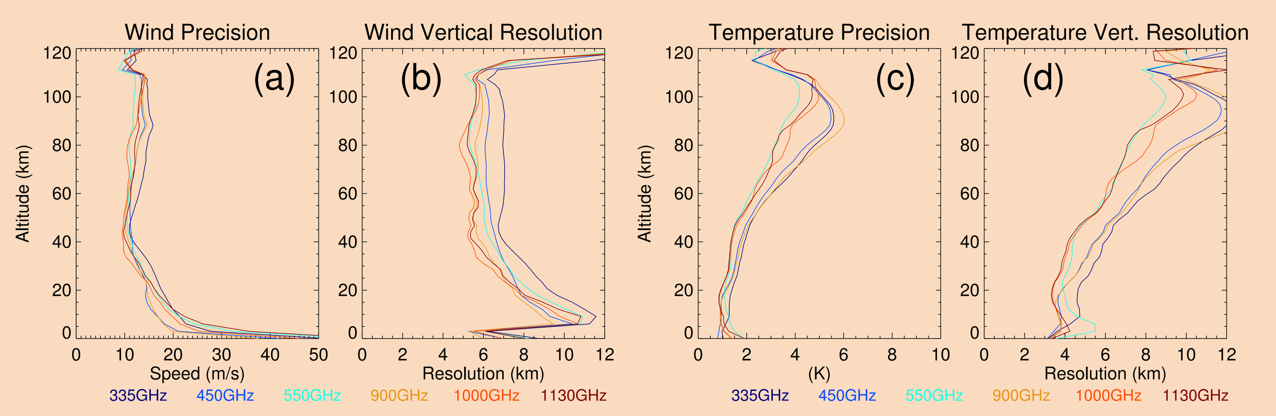

Figure 2: Estimated wind (a,b) and temperature (c,d) precision (a,c) and vertical resolution (b,d) for the frequency ranges considered here. Colored lines correspond to the various radiometer frequencies show beneath. The expected vertical resolution is based on the full width, half height of the averaging kernel. The a priori uncertainty for wind is 100 m/s with a 10 m/s smoothing constraint. The corresponding numbers for temperature are 20 K and 2 K.

- Figure 2 shows the estimated precision and vertical resolution for wind and temperature measurements for the various instruments.
- The 450, 900, and 1000 GHz frequency choices generally produce the best results for wind.
- The improved performance at higher frequencies is to be expected because:
  1. The Doppler shift scales with observation frequency while pressure broadening effects do not, and
  2. we have assumed the same antenna size for all configurations, giving a field of view width that narrows with increasing frequency.
- Temperature performance generally improves with higher observing frequency.

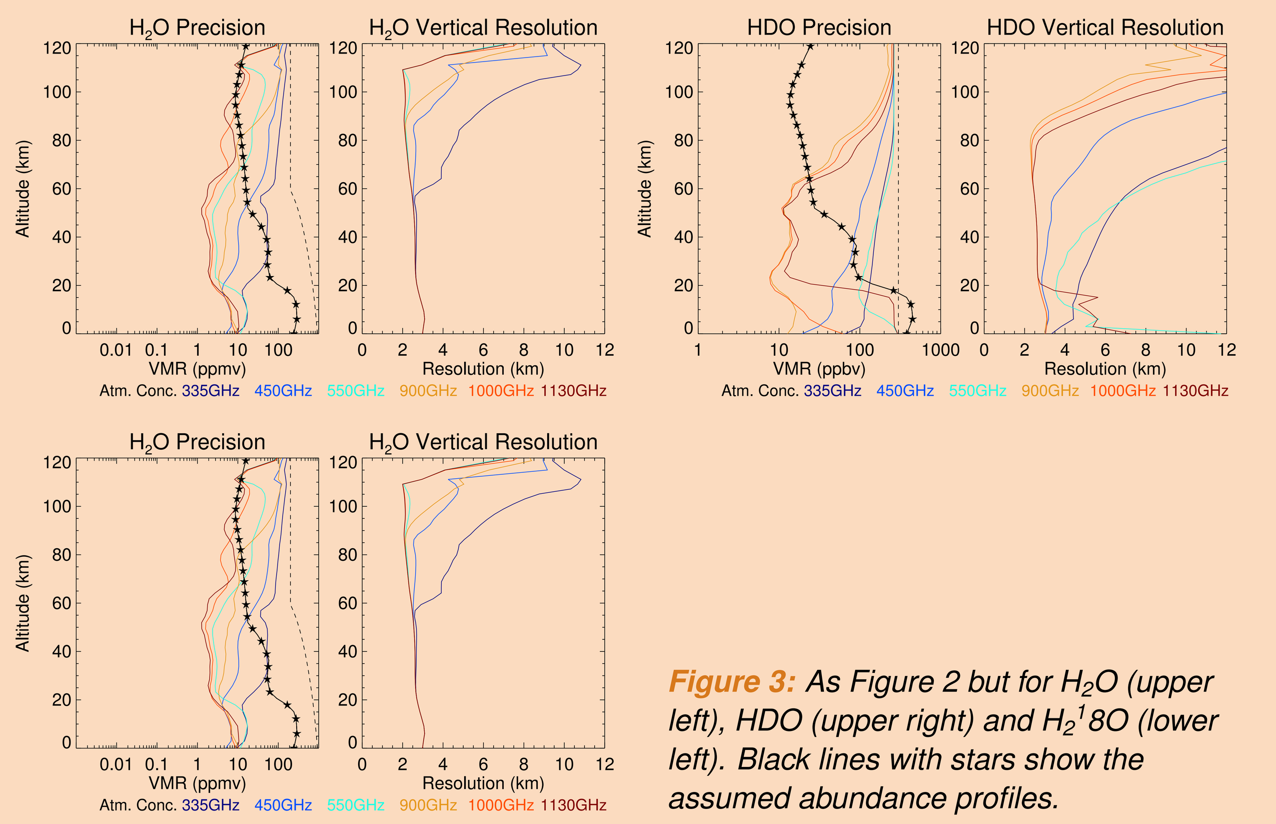

Figure 3: As Figure 2 but for H_2O (upper left), HDO (upper right) and $H_2{}^{18}O$ (lower left). Black lines with stars show the assumed abundance profiles.

- For the water vapor species (Figure 3), the best measurements are obtained by the 1000 and 1130 GHz measurement frequencies.

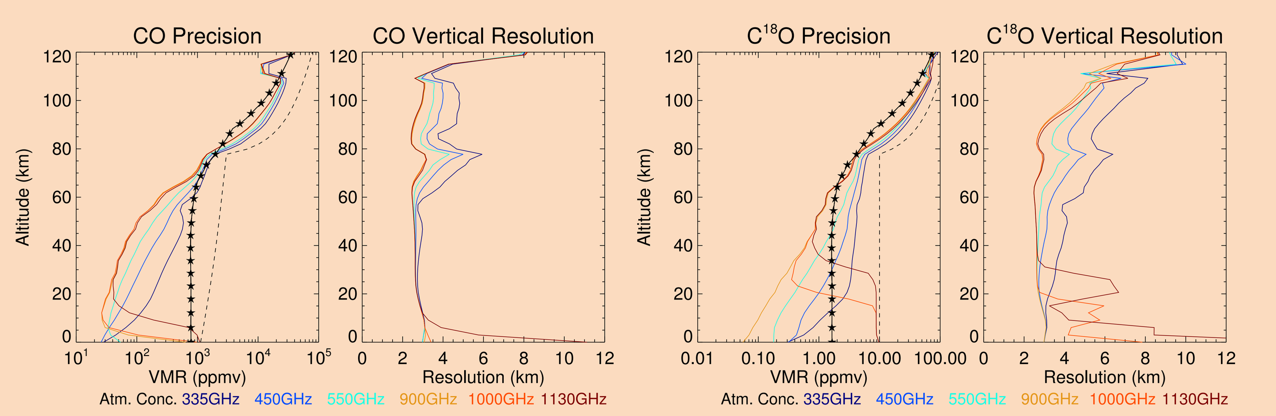

Figure 4: As Figure 3 but for CO and $C^{18}O$.

- Figure 4 shows the results for CO and $C^{18}O$, for which the best performance is seen for the highest frequencies, except in the lowermost regions of the atmosphere.
- $C^{17}O$ and ^{13}CO (not shown) give similar results.

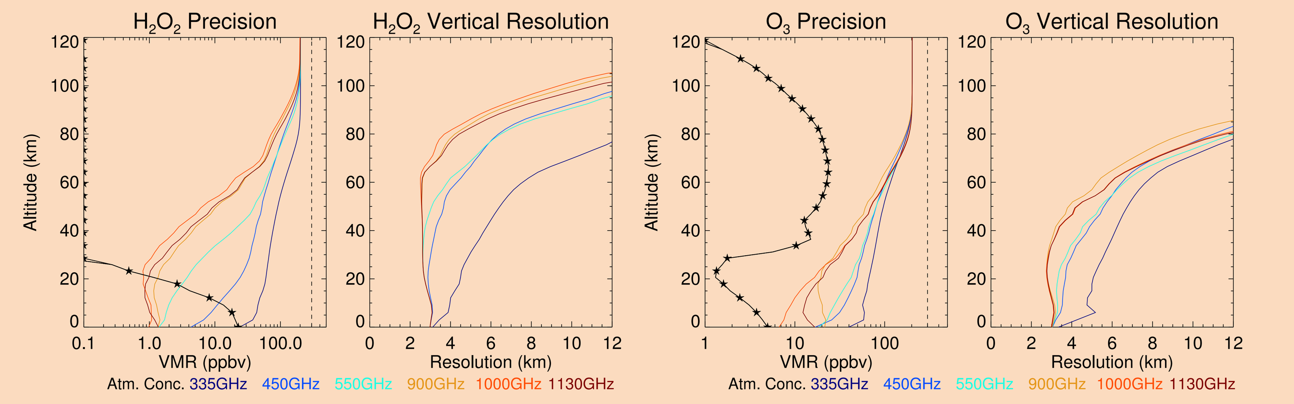

Figure 5: As Figure 3 but for H_2O_2O and O_3.

- The best performance for H_2O_2 (Figure 5) is seen in the 1 THz region, where its lines are strongest.
- The same figure shows that the precision expected for ozone is poor compared to the typical abundances expected.

4 Instrument design implications

- A submillimeter limb sounder design can readily be tailored to various mission opportunities and classes.
- For example, for a *Discovery* class mission, a medium-sized instrument with a 2-D scanning antenna could potentially scan the limb in a wide range of directions, enabling measurement of vector winds.
  - Such an instrument could measure all the targeted lines simultaneously.
  - A potential design for such an instrument at 450 GHz is shown in Figure 6.
  - Novel antenna/optics designs enable, in principal, simultaneous observation of two limb views 90° apart, readily enabling vector wind measurements.
  - We estimate that such an instrument could be designed to fit within a 25 kg, 30 W, 100 kbps envelope.
- Alternatively for a SmallSat/CubeSat class opportunity, a smaller (e.g., "2U", not including the antenna) instrument could be built, with the vertical limb scan accomplished by "nodding" the entire spacecraft.
  - Various approaches exist for "timesharing" the measurements of the different spectral lines, making for a simpler/lighter instrument.

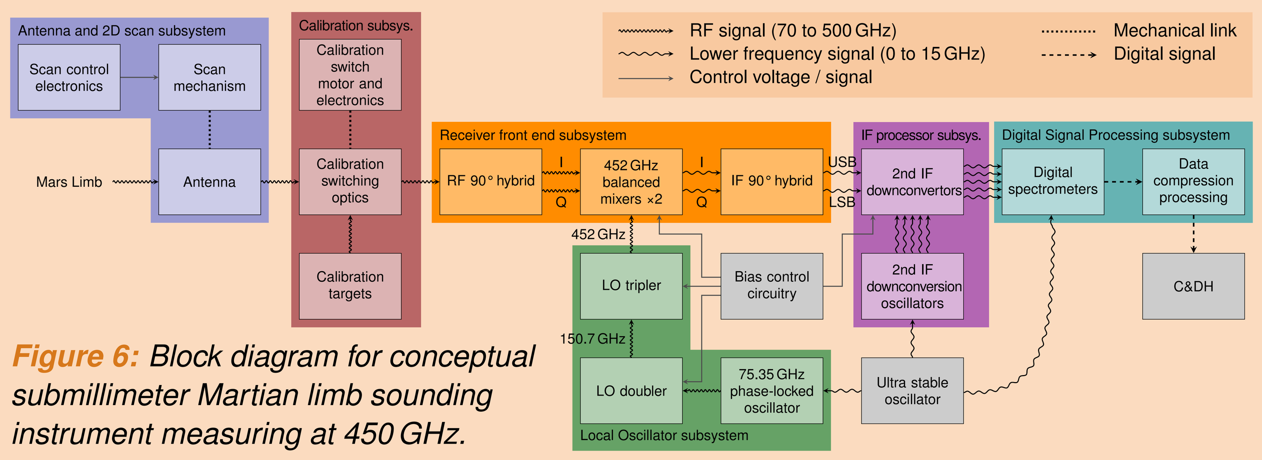

Figure 6: Block diagram for conceptual submillimeter Martian limb sounding instrument measuring at 450 GHz.

5 Summary

Science objectives: A submillimeter limb sounding instrument has the potential to make the first global measurements of vertically resolved wind and water vapor profiles in the Martian atmosphere, meeting long standing measurement needs prioritized by MEPAG and others.

Instrument approach: Such instruments have high heritage in Earth science, and now require far lower mass/power/volume than previously thanks to recent technology advances.

Instrument design: A Mars submillimeter sounder could range in size/complexity from a SmallSat-class sensor (with the scan accomplished through movement of the spacecraft) to a full multi-angle-viewing, multi-spectrometer instrument.

Measurement capabilities: Our simulation studies have quantified the expected performance (precision and vertical resolution) expected from such an instrument, for various choices of observing frequency.

6 References

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