Accuracy of Wet Troposphere Radio Path Delay Estimated from Infrared Emission

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Introduction

Several radio science applications require determination of the excess radio-propagation path delay caused by the earth's atmosphere, These include very long baseline interferometry, spacecraft tracking, and potentially detection of gravitational waves utilizing a link to a distant interplanetary spacecraft. At Ka band, the major source of variability of path delay is the fluctuations in the moisture content of the troposphere. The path-delay characterization requirements for a planned gravitational wave experiment are novel and challenging. The error contribution to the phase observations due to path delay variation must be reduced by nearly two orders of magnitude over that occurring naturally on time scales of 100 to 10,000 seconds. Current approaches relying on microwave water vapor radiometry with ancillary data can deliver one order of magnitude calibration of these fluctuations, and more advanced systems are under development within the 2001-2002 time frame of the Cassini mission to Saturn. The current work evaluates the potential for an alternative observational approach, using a ground-based Fourier transform spectrometer.

Approach

The tropospheric wet path delay d in cm, for purposes of error analysis, may be represented by

$$d = \int_0^\infty \left[k_1 \frac{\rho(l)}{T(l)} + k_2 \frac{\rho(l)}{T^2(l)} \right] d, \tag{1}$$

where ρ is the water vapor pressure in millibars, 7’ is the temperature in Kelvin, l denotes distance along observing path, k_1 is 7.2x1 O-s, and k_2 is 0.375. We propose a sequence of observations with a moderate resolution (-0.25 cm^{-1}) commercial Fourier transform spectrometer, sensitive to an ensemble of hundreds of water vapor and carbon dioxide lines and water vapor continuum emission from approximately 600-1400 cm^{-1}. It has been shown that such observations may form the basis of water vapor and temperature profiling [1], although with a vertical resolution that rapidly decreases with altitude (not necessarily a problem for path delay determination). Such profiles form the basis of an estimator according to (1). Note that the error analysis methodology below, with similar relative error would apply equally to determining total precipitable water, However, due to the temperature dependence inside the integral, the total water content is not an adequate surrogate for the path delay,

Extensive simulations were performed with a high-quality line-by-line emission model and parameter estimation code [2]. Relevant features of the software are a) line parameters are from the HITRAN 92 data base, b) water vapor continuum modeling is included, c) radiative transfer is performed through a sequence of atmospheric layers at each frequency, d) convolutional instrumental line shapes are supported, and e) analytic derivatives of observable with respect to parameters are computed for input to the parameter estimation task. Least-squares parameter estimation is performed with user-specified a priori constraints, which may be in the form of multiparameter mean and covariance information. The parameter estimates include an a posteriori covariance matrix, which may be regarded as the error covariance conditioned on the assumptions, for example (at this stage) that instrumental properties are perfectly known.

Results

We show two examples of the relevant information gained from the computer simulations. First, the radiative transfer model is applied to show zero-order sensitivity of the spectral observations to a perfectly uniform 1 %

fractional increase in water vapor content at all altitudes, for a 0.25 cm^{-1} (line shape full-width at half height) instrument, The expected observation spectrum and difference spectrum are shown in Fig. 1, together with indications of the rms. noise measured with an unoptimized commercial 0.25 cm-1 Mattson instrument at 120 s. The retrieval sensitivity to a uniform fractional change in water vapor content is computed to be one part in 3000. The sensitivity observed in Fig. 1 is found to be from a variety of physical effects: near 700 cm^{-1}, it is due to enhanced water vapor continuum emission, inversely amplitude-modulated by saturating carbon dioxide lines. Beyond 800 cm^{-1}, the sensitivity is largely due to water lines, of widely varying optical depth. While this extremely high zero-order sensitivity is not an attainable retrieval error (water vapor does not fluctuate with vertical uniformity), the magnitude. of this sensitivity, and the variety of its physical causes, suggest that there is a considerable amount of data strength to spread among the higher-order statistical parameter space.

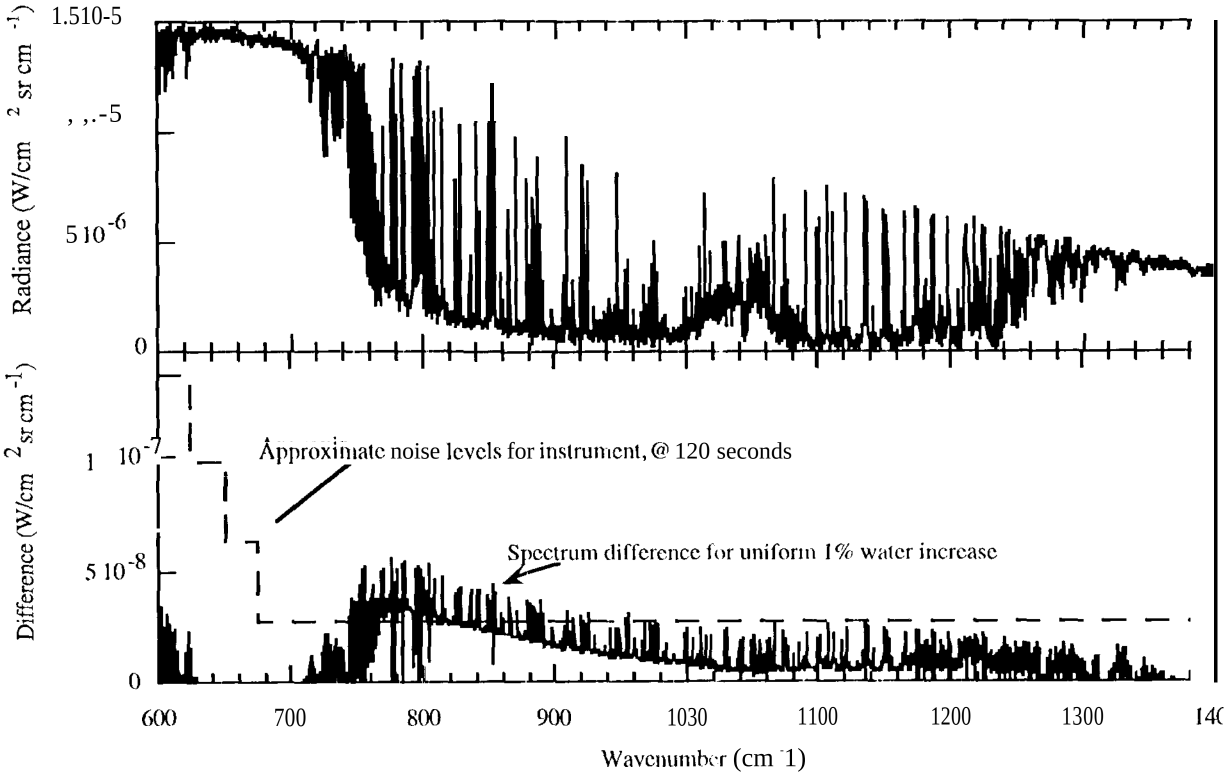

Fig. 1. Simulated spectrum and difference showing 1% water vapor sensitivity.

A more complete analysis relies on the parameter error covariance matrix resulting from parameter estimation with simulated observations. The a priori covariance matrix is loosely based on the sample covariance of a set of -140 daytime radiosonde measurements at Desert Rock, NV (a prime application site is Goldstone, CA: a less-extreme desert location). The temperature covariance is simplified to a model in which layer-to-layer correlation is an exponential decay with distance (1/e in 8 km). The water a priori covariance is similarly simplified to an exponential correlation (1/e in 4 km), and shifted to a more moist climate, by scaling the mean and variance by a constant, while preserving the correlation of two-layer variations. The a priori water and temperature parameter categories are considered uncorrelated. A covariance error analysis of retrieved water and temperature profiles is computed, based on temperature and water parameter samples at heights 0.0, 0.1, 0.2, 0.5, 1.0, 2.0, 3.0, 5.0, 7.0, and 10.0 km. Pressure, nominal quantities of eight additional molecular species, and all parameters above 10 km are held to be fixed. Without the a priori covariance constraint, this parametric sampling results in a very poorly conditioned estimation problem. The covariance constraint may be considered to reduce the effective parameter space. Modes of variation in the unconstrained parameter space which are highly oscillatory or at the higher altitudes have very little spectral observability, and are chiefly constrained by the a priori model. Such modes contribute little to the integrated path delay, a derived quantity which smoothes out vertical oscillations and has very little high altitude sensitivity. Observations were simulated for spectra with noise as in Fig. 1, at a variety of observation angles. The a posteriori covariance matrix $\mathbf{C}$ is converted to a path delay variance σ^2 according to

$$\sigma^2 = \nabla d \bullet C \nabla d \qquad (2)$$

where ∇d denotes the path delay derivative (through (1)) with respect to each of the profile parameters. The implied path delay relative standard deviation is plotted in Fig. 2. Additional simulations considered the effect of improving the instrument SNR by a factor of 10, and of improving the resolution from 0.25 to 0.1 cm^{-1}, without changing the per-sample noise, either of which would present substantial technical challenges. Also considered (but not plotted) is the utility of direct surface-air measurements. In the limit of perfectly known ground temperature and humidity, the path delay uncertainty was reduced by negligible amounts (<2%). Evidently the spectrum alone carries an abundance of information about the surface atmosphere.

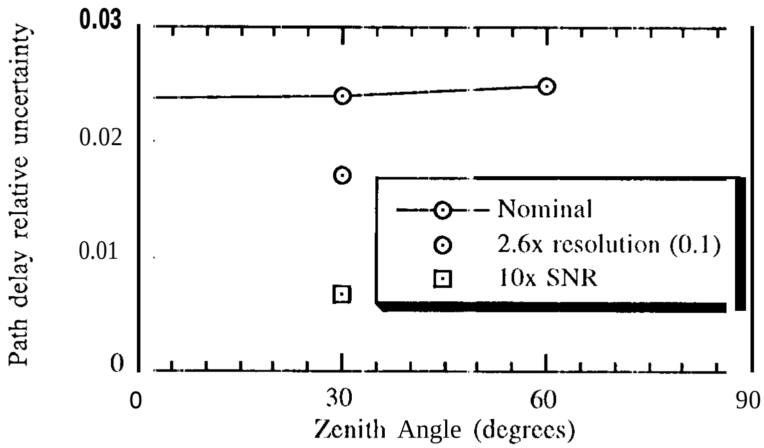

Fig. 2 Path delay uncertainty simulation with noise parameters from commercial instrument (nominal), plus hypothetical modifications. Nominal: 0.26 resolution, noise for 120 s scan.

Discussion and Conclusions

While limited to clear-air conditions, the spectrometer can sight along a radio path and gain high-accuracy estimates of the wet troposphere contribution to the radio path delay over a wide range of zenith angles. While at higher zenith angles or wetter conditions more of the lines saturate and therefore lose sensitivity to water vapor, the spectral range considered contains plenty of weakly, emitting regions whose sensitivity is enhanced. The noise found in an unoptomized commercial instrument is small enough for useful wet delay estimates. Further effects relevant to the gravitational wave experiment are under continuing investigation, including instrument stability, the impact of systematic errors from calibration and radiative transfer modeling (such as line parameter errors), and statistical characteristics of the atmospheric process time series. In the latter regard, the atmospheric state is not uncorrelated from epoch to epoch, so performance should be better than that predicted by the type of statistical a priori covariance constraint examined here. It is also anticipated that a higher throughput spectrometer with pass band optimization will further enhance performance. Future work will include multi-instrument data collection and comparison.

References

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[2] L. Sparks, P. Lyster, J.E. Patterson and J. L. , "Large-Scale Retrieval of Atmospheric Parameters from Remote Sounding Data", Technical Digest on Optical Remote Sensing of the Atmosphere, 1991 (Optical Society of America, Washington, D. C., 1991), Vol. 18, pp. 75-77].