N90-19971

TROPOSPHERIC MONITORING TECHNOLOGY FOR GRAVITY WAVE EXPERIMENTS

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ABSTRACT

Tropospheric refractivity fluctuations are an important error source for gravity wave detection by Doppler tracking in that they alter the phase and phase rate of electromagnetic signals. The goals of this paper are to present estimates of the effect of tropospheric fluctuations on the Doppler signal and to suggest some examples of methods which minimize the effect. A model of the fluctuations is utilized to achieve those goals. The levels of wet and dry fluctuations for a single path through the atmosphere are estimated to be approximately 4×10^{-14} and 9×10^{-15} sec/sec for 20 degree elevations at 1,000 seconds. At the 40 degree elevations intended for the gravity wave experiment, the wet and dry fluctuation levels are approximately 2×10^{-14} sec/sec and 6×10^{-15} sec/sec at 1,000 seconds, respectively. Four possible methods for reducing the fluctuation effect are suggested: 1) observation and analysis strategies, which separate the atmospheric and gravity wave signatures; 2) water vapor radiometry for the wet component; 3) calibration using Global Positioning System (GPS) satellites; and 4) Doppler observations from multiple antennas to average fluctuation effects. The last two techniques could be used to calibrate both wet and dry fluctuations, or could be used in conjunction with water vapor radiometry to calibrate only the dry component. For example, combining water vapor radiometry and the proposed GPS technique could reduce the total 1,000 second fluctuation effect to approximately 6×10^{-15} sec/sec at 20 degree elevations, or 2×10^{-15} sec/sec at 40 degree elevations.

I. APPROACH

Fluctuations in the refractivity at microwave frequencies are an important nondispersive error source for Doppler tracking gravity wave experiments. A model devised to provide a quantitative description of the wet tropospheric fluctuation effect on the path delay of radio signals is used to assess the magnitude of both wet and dry fluctuations on various time scales (Treuhaft and Lanyi 1987). Normalized to daily Deep Space Network (DSN) water vapor radiometer (WVR) measurements, the model for wet fluctuations has agreed with WVR and very long baseline interferometry (VLBI) data on shorter time scales. The extension of the model to account for dry fluctuations is achieved by employing appropriate values for dry spatial variations and the scale height of the dry component. While this extension seems reasonable, it should be verified by experiment. It is the aim of this paper to estimate the magnitude of the problem and present potential solutions. The solutions presented do not span the set of all possibilities, but are discussed to establish the level to which the fluctuations might be removed.

II. THE LEVEL OF UNCALIBRATED TROPOSPHERIC FLUCTUATION

The essence of the model used to evaluate the level of tropospheric fluctuations as well as some of the calibration alternatives is found in Fig. 1. Wet or dry refractivity irregularities are envisioned as being frozen and blown across a site by the wind. Propagation delay statistics are obtained by integrating refractivity statistics over the geometry of the raypaths through the atmosphere. It is important to realize that temporal fluctuations, over a time interval T, are caused by spatial fluctuations of dimension $V \times T$ where V is the wind speed.

Typical Allan standard deviations from the model for DSN sites are shown in Fig. 2. The wet fluctuation was normalized by assuming an 8 m/sec wind speed and a 1 cm daily zenith delay fluctuation. With the caveats noted in Section I, the dry fluctuation was normalized by assuming an 8 m/sec wind speed and a 3 mm daily zenith fluctuation. This daily fluctuation level was derived from a very limited set of barometric pressure data and should be more extensively studied. As can be seen in the figure, which represents a calculation for 20 degree elevations, the single-path fluctuation level is 4×10^{-14} sec/sec and 9×10^{-15} sec/sec for the wet and dry components respectively at 1,000 seconds. At 40 degree elevations, the wet and dry 1,000 second Allan standard deviations are 2×10^{-14} sec/sec and 6×10^{-15} sec/sec respectively. This average DSN value is roughly 1.8 times that derived from Very Large Array (VLA) data, if the same wind speed is used (Armstrong and Sramek 1982). The difference is probably due to the higher altitude of the VLA site.

III. METHODS FOR REDUCING THE EFFECT OF TROPOSPHERIC FLUCTUATIONS

One possibility for reducing the effect of tropospheric fluctuations is to design an observation or analysis strategy which can separate the tropospheric signature from the gravity wave signature. In the Treuhaft and Lanyi (1987) reference, expressions for the statistical properties of tropospheric fluctuations are given. If the statistics of the gravity wave signature are significantly different, an observation sequence and/or parameter estimation filter can be designed to estimate the level of gravity wave and tropospheric signature. A simple example of this approach is the detection of gravity waves from binary stars or black holes (Wahlquist 1987, Wahlquist this volume). In that case, the periodic signature of the gravity wave can be extracted by observing for long periods of time and averaging the signal.

If the signature of the gravity wave is unknown or highly correlated with the tropospheric signature (*i.e.*, if the gravity wave and troposphere have similar power spectra), external calibration techniques should be considered. The most obvious external calibration technique is water vapor radiometry. While theoretical estimates of WVR performance indicate that the Allan standard deviation of fluctuations can be calibrated to 1×10^{-16} sec/sec for 1,000 second intervals, the data which demonstrate this capability are scarce. WVR data were successful in calibrating Very Large Array (VLA) phase fluctuations for some of the data sets examined (Resch *et al.* 1984). But in the Resch reference, there were times when the application of WVR data increased the phase residual. Recent comparisons of VLBI data (Herring 1988) to WVR zenith estimates show low frequency discrepancies on the order of 1 to 2 cm. Similar conclusions can be drawn from GPS data (Tralli *et al.* 1988). It may be necessary to understand the nature of these discrepancies and how they apply to fluctuation calibration. In short, although WVRs seem promising, a data base showing consistent reduction of VLBI or Doppler residuals by applying WVR calibrations is missing.

Another possibility for calibration of both wet and dry fluctuations is using GPS satellite path delays along lines of sight close to that of the spacecraft. It will be assumed that GPS geometric, ionospheric, and instrumental effects are perfectly calibrated and that tropospheric fluctuations are the only source of residual delay error. The degree to which this assumption applies must be investigated. From the schematic picture of Fig. 1, one expects that, as two lines of sight get farther apart, the time scales on which they will have substantial correlation will get longer. That is, if, during their traversal of the troposphere, the average distance between a GPS raypath and that of a spacecraft is d, then there will be differential cancelling between the delays of each signal for time scales greater than d/v where v is the wind speed. Fig. 3 shows the model calculation for the difference between spacecraft and GPS delay rates induced by the dry troposphere. The delay rate for the tropospheric power spectrum is about 20% higher than the Allan standard deviation. The figure shows the total rate and the differenced rate for 20 degree and 40 degree elevations. It was assumed that the GPS satellite was 20 degrees in azimuth from the spacecraft line of sight, at the same elevation. It can be seen that for longer time scales, there is indeed differential cancelling between the GPS and spacecraft lines of sight. In particular, for 20 degree and 40 degree elevations, the dry fluctuation can be reduced to the level of 6×10^{-15} sec/sec and 2×10^{-15} sec/sec respectively. Data from GPS satellites and VLBI or Doppler experiments would be necessary to test this approach.

A third instrumental possibility is to use multiple receiving antennas separated by distances greater than the wind speed times the time scale of interest. For example, to reduce the fluctuation on time scales greater than 1,000 seconds, antennas separated by more than 8 km must be used. The fluctuation effect in the average of all the Doppler signals would be reduced relative to that in a single antenna by approximately $1/\sqrt{N}$ where N is the number of antennas used. If, for example, 2 to 3 antennas at Goldstone were used with 4 to 5 antennas at the VLA, a factor of 2 to 3 reduction in fluctuation error might be realized.

IV. SUMMARY

The levels of wet and dry tropospheric fluctuations have been estimated with the aid of a fluctuation model. The single-path wet fluctuation signatures at 20 degrees and 40 degrees elevation are 4×10^{-14} sec/sec and 2×10^{-14} sec/sec respectively, for 1,000 second intervals. The dry signatures are 9×10^{-15} sec/sec and 6×10^{-15} sec/sec. The wet signatures are of the order of the plasma contribution to the gravity wave detection error budget for Galileo experiments (*e.g.*, Armstrong this volume and references therein), but both wet and dry contributions will have to be addressed for potential K-band experiments.

Methods for reducing the contribution of atmospheric fluctuations in the Doppler data include observation and analysis techniques, water vapor radiometry, GPS tropospheric monitoring, and observations with multiple antenna systems. The level of remaining 1,000 second dry fluctuations using GPS calibration along a line of sight 20 degrees from the Doppler spacecraft was estimated to be 6×10^{-15} sec/sec and 2×10^{-15} sec/sec for 20 degree and 40 degree elevations. It was assumed that WVRs could calibrate the 1,000 second wet fluctuation to approximately 1×10^{-16} sec/sec.

This assertion must be validated with data. The GPS technique for tropospheric calibration must also be tested. What is suggested, in this paper, is that it may be possible to reduce the total fluctuation effect to the levels quoted. Experiments are required to justify choosing one calibration scenario and adopting it for gravity wave Doppler experiments. Other possibilities such as barometric arrays for calibrating the dry component should also be investigated.

ACKNOWLEDGEMENTS

This work was performed at the Jet Propulsion Laboratory, under contract with NASA.

REFERENCES

Armstrong, J. W., and Sramek, R. 1982, *Radio Science*, **17**, 1579.
Armstrong, J. W. "Advanced Doppler Tracking Experiment" (this volume).
Herring, T. A. 1988, private communication.
Resch, G. M., Hogg, D. E., and Napier, P. J. 1984, *Radio Science*, **19**, 411.
Tralli, D. M., Katsigiris, E. C., and Dixon, T. H. 1988, *EOS*, **69**, 332.
Treuhaft, R. N., and Lanyi, G. E. 1987, *Radio Science*, **22**, 251.
Wahlquist, H. 1987, *General Relativity and Gravitation*, **19**, 1101.
Wahlquist, H. "Detecting Gravity Waves from Binary Black Holes" (this volume).

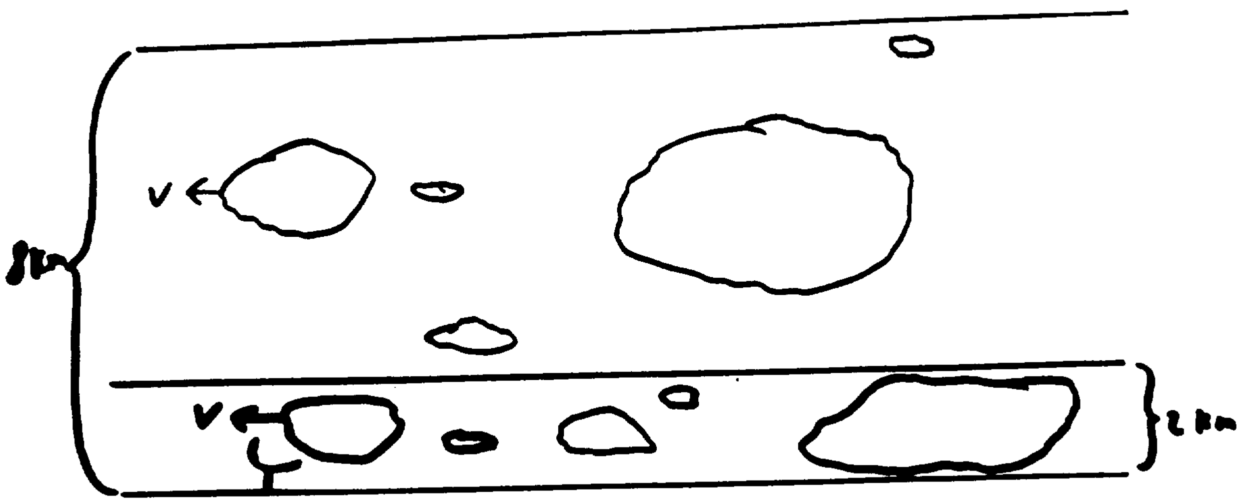

FIG. 1 — Schematic picture of the frozen flow model. The patches represent inhomogeneities in tropospheric refractivity, blown across a site with wind speed v. The 2 km and 8 km scale heights of the wet and dry tropospheres are indicated.

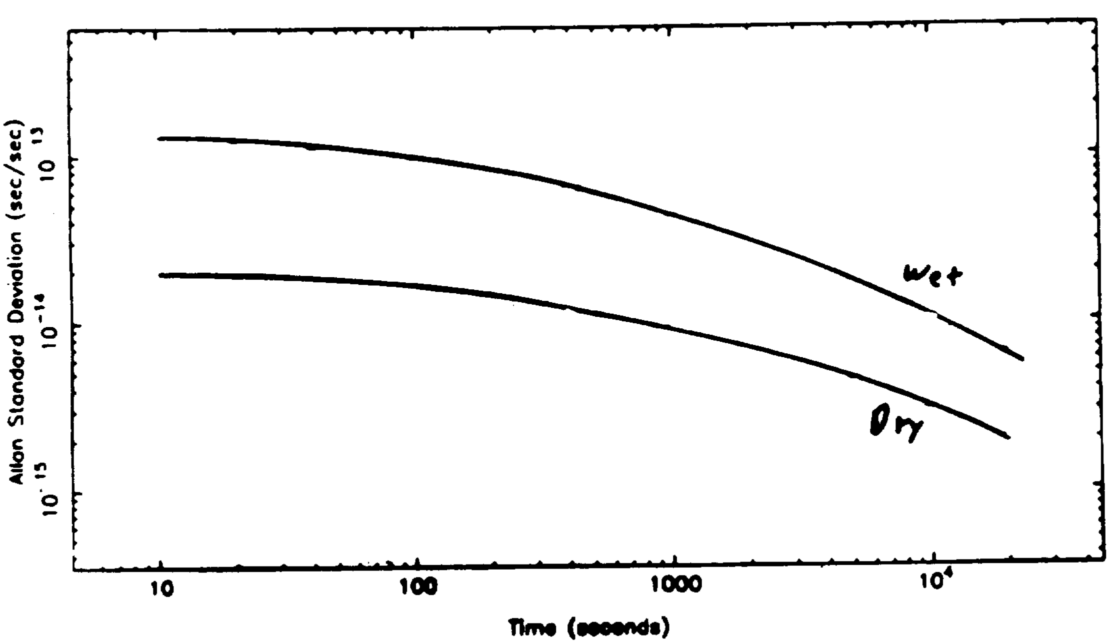

FIG. 2 — The model Allan standard deviation of the wet and dry tropospheres at 20 degrees elevation.

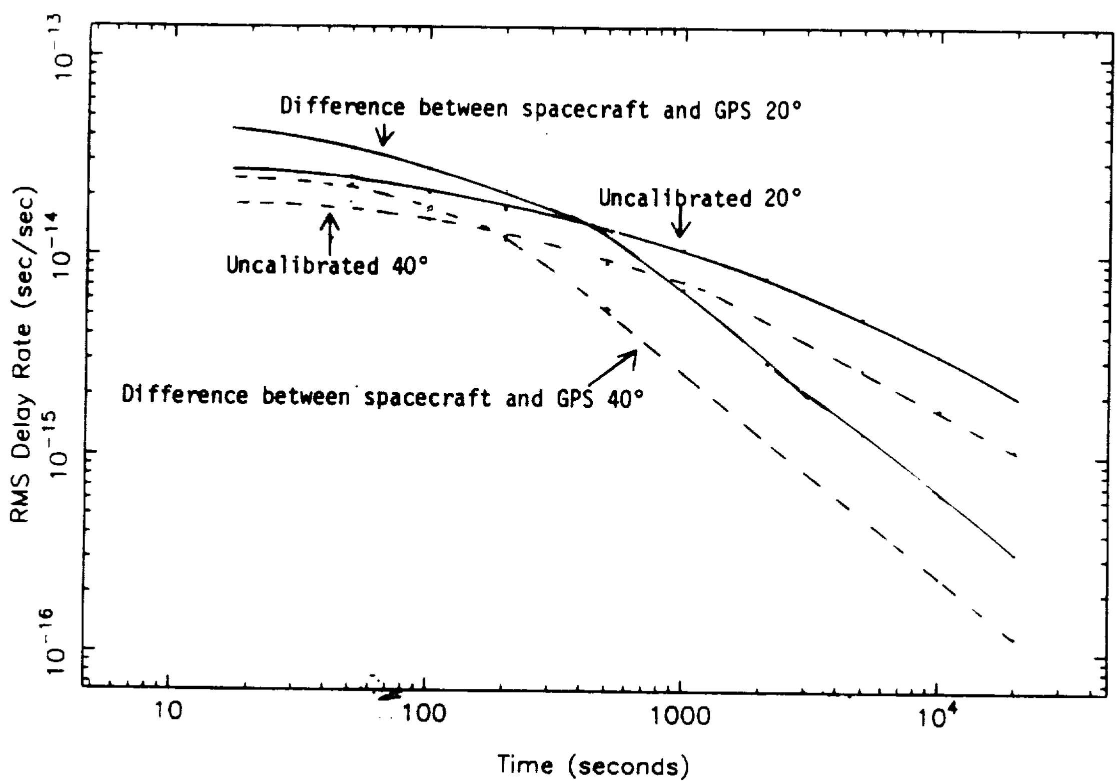

FIG. 3 — The model delay rate spectrum of the uncalibrated dry troposphere, and of the difference of the dry signature between the spacecraft and GPS lines of sight separated by 20 degrees in azimuth. The solid curves are for 20 degrees elevation and the dashed curves are for 40 degrees elevation.

DISCUSSION

BERTOTTI: You have mentioned the importance of correlating Doppler measurements at two different sites to reduce the tropospheric noise. I wish to report on a pilot experiment that will take place next month: the two Voyager spacecrafts will be tracked from Madrid (up and down) and from the VLBI station in Bologna, Italy (down) for eight passes. The correlation between the two Doppler signals will be measured.

SHAPIRO: Another method for troposphere calibration that would "work" (at a "useful" level) was conceived about two decades ago in the VLBI context: Horizontal arrays of long vertical tethers w/balloons at "well-spaced" vertical intervals on each tether, with each balloon instrument to measure relevant variables (temperature, relative humidity, pressure). This solution is, of course, horrendously expensive and would also pose a hazard to aircraft.

MALEKI: Do you mean that dispersion in the troposphere is identically zero at microwave wavelengths or is it too small to measure. If your answer is the latter, could you say how small it is?

TREUHAFT: I do not know the exact dispersion effect at X-band for water vapor. I believe it is a few orders of magnitude below 1 mm of delay. It should be checked. (Shapiro agreed with this qualitative assessment).

MATZNER: I'd like to point out that there is another method to probe the troposphere. This is atmospheric SONAR. This technique samples the lower few hundred meters of the atmosphere. It is being used, for instance, at Bell Laboratories to understand radio propagation through the atmosphere. Since the SONAR is responsive to density inhomogeneity, it presumably provides information in a linear combination of wet and dry contributions.

TREUHAFT: We would need density inhomogeneity information for altitudes greater than a few 100 meters, but SONAR is worth investigating. I should point out that gravity wave experiments at K-band will require extremely high precision tropospheric monitoring. So any technique which might work must be scrutinized for its ultimate accuracy, which would have to be at about 10^{-16} sec/sec at 1000 seconds to be useful.