N84 27293

# A NEW TECHNIQUE FOR MONITORING THE WATER VAPOR IN THE ATMOSPHERE

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## ABSTRACT

In correcting satellite doppler data for tropospheric effects, we have found that we can infer the precipitable water vapor (PWV) at the tracking site. The determination proceeds via a least-squares fit of a refraction parameter to each fifteen-minute pass of data.

For its success, the technique depends on having: 1) an ephemeris for the satellite, 2) an analytic model for the refraction range effect that is good to a few centimeters, 3) doppler (range difference or cycle count) data with noise level below 10 centimeters, and 4) a surface pressure/temperature measurement at the tracking site.

The PWV is a by-product of the computation necessary to correct the doppler data for tropospheric effects. We have tried for a number of years to reliably isolate the tropospheric refractive effect in the doppler shift measurement. It is only recently that we have succeeded in doing this. Our recent success was due to a formulation of the refraction integral which minimized the necessity for explicit water vapor, temperature and pressure profiles.

## 1. THE DOPPLER SHIFT AND THE REFRACTIVE EFFECT

A common and convenient model of the doppler shift measurement contains the range to the satellite at two contiguous times. These ranges are corrupted by tropospheric effects which can be written:

$$\Delta s = 10^{-6} \int (N_d + N_w)\, d\rho \tag{1}$$

wherein

$N_d$ is the "dry" refractivity

$N_w$ is the "wet" refractivity

The Smith-Weintraub expressions for these are:

$N_d = 77.6\ P/T$

$N_w = (3.73 \times 10^5\ °K^2/\text{mbar})\ e/T^2$

wherein

(e,T,P) are the (water vapor pressure, temperature total atmospheric pressure) at a point within the troposphere. Units consistency requires e and P in millibars and T in °K

Physical rigor (Fermat's principle) insists that the integration path be an extremum. Except at low elevation angles, this requirement is not important as ray-tracing studies show; we can use the instantaneous straight line connecting the satellite and observer for the integration path. If we then change variables from $\rho$ to h (see Fig. 1), we obtain

$$\Delta s = 10^{-6} \int_0^{h_d} (N_d + N_w) \frac{dh}{\left| 1 - \left( \frac{\cos E}{1 + h/_{Re}} \right)^2 \right|^{1/2}} \tag{2}$$

Since both the wet and dry troposphere extend to heights that are small compared to the radius of the earth, $h/Re < h_{d/Re} \simeq 0.007$, we replace eq. (2) with

$$\Delta s = 10^{-6} \cdot I_{dw} \cdot \int_0^{h_d} (N_d + N_w)\ dh \tag{3}$$

wherein

$$I_{dw} \triangleq \left| 1 - \left( \frac{\cos E}{1 + \chi_{dw}\ h_{d/Re}} \right) \right|^{-1/2} \tag{4}$$

and

$$0 < \left| \chi_{dw} = \chi_{dw}\ (e,T) \right| < 1$$

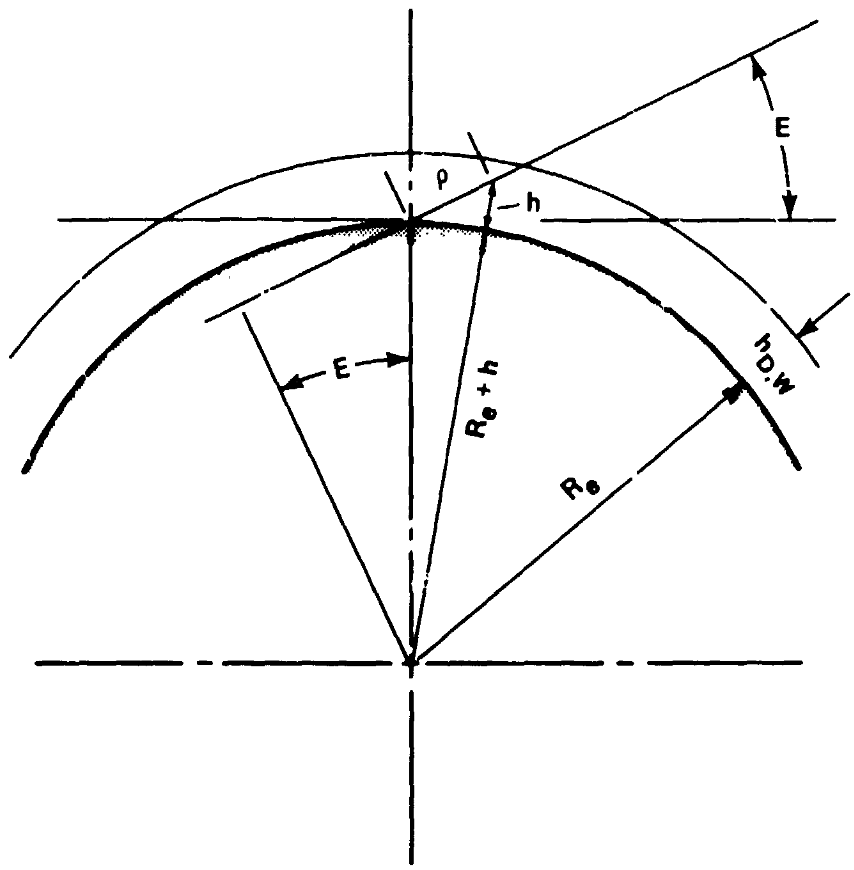


**Fig. 1 Tropospheric geometry.**

Using explicit models of $N_d$ and $N_w$ which, in turn, require models for the atmospheric state, we were able to show that eq. (3) and (4) could be written

$$\Delta s = \left[ 10^{-6} \int (N_d+N_w)\ dh \right] \cdot \left[ 1 - \left( \frac{\cos E}{1 + 0.001} \right)^2 \right]^{-1/2} \quad (5)$$

with an error which did not exceed a few centimeters if we do not use elevation angles less than 7.5°. Above 20° the form is practically exact, i.e., the error is, at most, a few millimeters.

Equation (5) is a convenient separation (amplitude . geometry), moreover, in the amplitude

$$\Delta s_h = 10^{-6} \int_0^{h_d} (N_d+N_w)\ dh \quad (6)$$

We have absorbed, "buried", the difficult problems of modeling the atmospheric state as a function of the surface conditions. We say difficult'; the water vapor is not uniformly distributed in the half space above the observing site, and modeling has fundamental limitations.

We used eq. (5) as a model of the tropospheric range effect and associated an amplitude, eq. (6), with each fifteen-minute pass of data. We fitted the amplitude without any a priori constraints on the value of $\Delta s_h$; although we have, with a surface pressure measurement, a lower bound

(the dry effect = $10^{-6} \int_0^{h_d} N_d\ dh$) which is 85-90 percent of the combined wet-dry integral. This dry integral is very closely 2.305 (meters) times the surface pressure in atmospheres. To isolate the tropospheric amplitude, we performed a four-parameter fit; the three additional parameters absorbed orbit, position and frequency biases.

## 2. RESULTS

We have used doppler data characterized as follows:

1. Obtained at a globally-distributed set of tracking sites from two of the Transit satellites, 30140 and 30180.

2. One two-day data span was obtained during February 1980 (days 48-49) and another during July 1982 (days 197-198). Each span contained approximately eighty passes.

Results of the amplitude fitting for days 197-198 are shown in Fig. 2. The lower bound, the straight line, is a consequence of the Hopfield theory (see Refs. 2 and 4). Data points falling below this straight line are "wild" (invalid). There are four of these. The distance from each of the valid data points to the straight line is the wet term

$$10^{-6} \int N_w \, dh$$

We then computed the mean value (for the valid data) at each of the sites; mean over two days for each of the two data sets. Four stations were represented in both data sets: Johannesburg, South Africa; Las Cruces, New Mexico; San Jose Dos Campos, Brazil; and Herndon, Virginia. The data at these four sites agree with the (usually true) finding that the atmosphere contains more water vapor in the summer than it does in the winter, Fig. 3. A tabulation of the results shown in Fig. 3 is given in Table 1. From Fig. 3 we see that synoptically the wet term is about 10 percent of the dry.

3. PRECIPITABLE WATER VAPOR

The 'wet' range integral for a vertical path can be written, using the Smith-Weintraub expression for the refractivity:

$$\Delta s_w = 0.373 \int_0^{h_d} \frac{e}{T^2} \, dh \tag{7}$$

and assuming the water vapor obeys the perfect gas law:

$$e = \rho_e RT \tag{8}$$

we have

$$\Delta s_w = 0.373 \, R \int \frac{\rho_e}{T} \, dh \tag{9}$$

and, in turn, a linear decrease of temperature with height facilitates an expansion in terms of the moments of the water vapor distribution.

$$\Delta s_w = \frac{0.373}{T_0} R\rho_w \left\{ \frac{1}{\rho_w} \int \rho_e \, dh + \frac{L}{T_0 \rho_w} \int h \, \rho_e \, dh + \ldots \right\} \tag{10}$$

alternately,

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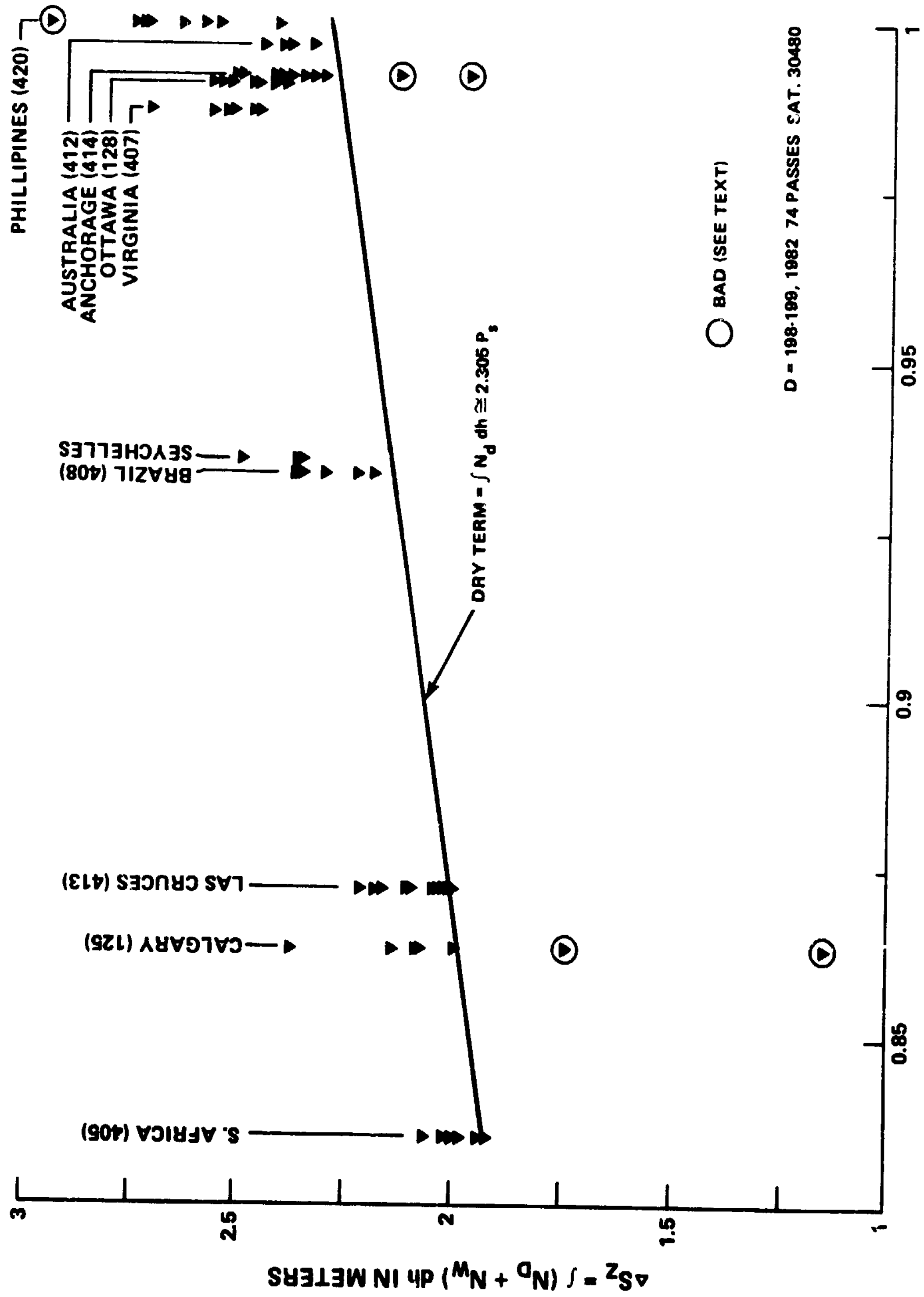


Fig. 2 Fitted tropospheric.

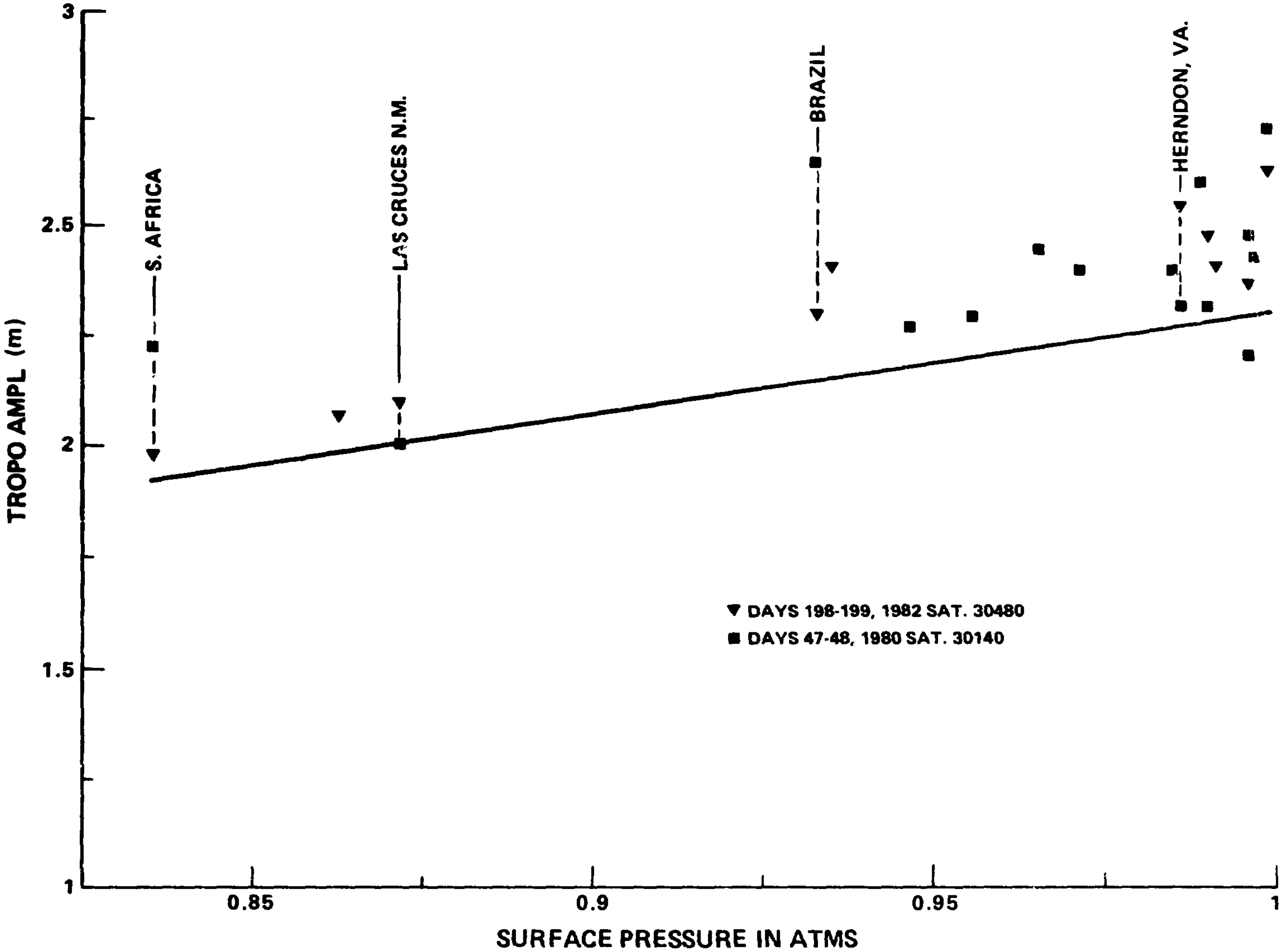
TROPO AMPL (m)
3
2.5
2
1.5
1
0.85
0.9
0.95
1
SURFACE PRESSURE IN ATMS
S. AFRICA
LAS CRUCES N.M.
BRAZIL
HERNDON, VA.
DAYS 198-199, 1982 SAT. 30480
DAYS 47-48, 1980 SAT. 30140

Fig. 3

## Table 1

### Troposphere Fitting Results

| STATION | | LATITUDE (DEGREES) | ALTITUDE (METERS) | SAT 30140 FITTED TROPO D = 47-48 1980 METERS | SAT 30140 No. OF PASSES | SAT 30480 FITTED TROPO D = 198-199 1982 METERS | SAT 30480 No. OF PASSES |
|---|---|---|---|---|---|---|---|
| 414 | ANCHORAGE, AL. | +61° | 69 | | | 2.34 ± 0.16 | 11 |
| 125 | CALGARY, CANADA | +51° | 1272 | | | 1.95 ± 0.37 | 8 |
| 021 | BRUSSELS, BELGIUM | +51° | 116 | 2.40 ± 0.40 | 7 | | |
| 128 | OTTAWA, CANADA | +45° | 86 | | | 2.47 ± 0.06 | 9 |
| 3[illegible]0 | MINNESOTA, USA | +45° | 300 | 2.45 ± 0.15 | 5 | | |
| 641 | FLORENCE, ITALY | +44° | 100 | 2.60 ± 0.33 | 6 | | |
| 313 | MAINE, USA | +44° | 24.7 | 2.43 ± 0.12 | 6 | | |
| 407 | HERNDON, VA | +39° | 119 | 2.32 ± 0.12 | 8 | 2.54 ± 0.09 | 6 |
| 027 | JAPAN | +39° | 83 | 2.32 ± 0.33 | 7 | | |
| 330 | CALIFORNIA | +34° | 462 | 2.27 ± 0.18 | 5 | | |
| 113 | N. MEXICO | +32° | 1206 | 2.00 ± 0.22 | 5 | | |
| 413 | N. MEXICO | +32° | 1206 | | | 2.10 ± 0.08 | 8 |
| 192 | AUSTIN, TEXAS | +30° | 245 | 2.40 ± 0.30 | 6 | | |
| 341 | HAWAII | +21° | 401 | 2.29 ± 0.24 | 4 | | |
| 422 | SAN MIGUEL, P.I. | +15° | 12 | | | 2.67 ± 0.16 | 8 |
| 023 | GUAM | +13° | 38 | 2.48 ± 0.07 | 5 | | |
| 420 | SEYCHELLES, ISLAND | − 4° | 593 | | | 2.55 ± 0.29 | 4 |
| 424 | AMERICAN SAMOA | −14° | 12 | 2.73 ± 0.17 | 4 | | |
| 008 | BRAZIL | −23° | 613 | 2.65 ± 0.23 | 3 | | |
| 408 | BRAZIL | −23° | 613 | | | 2.30 ± 0.08 | 6 |
| 105 | S. AFRICA | −26° | 1581 | 2.23 ± 0.21 | 7 | | |
| 405 | S. AFRICA | −26° | 1581 | | | 1.98 ± 0.05 | 7 |
| 412 | SMITHFIELD, AUSTRALIA | −34° | 34 | | | 2.37 ± 0.05 | 8 |
| 019 | ANTARCTICA | −78° | 38 | 2.21 ± 0.31 | 6 | | |
| | | | | 2.39 ± 0.23 | 84 | 2.33 ± 0.23 | 75 |

SUMMER (dashed box)    WINTER (solid box)

$$\Delta s_w = \frac{1.722 \times 10^3}{T_0} \left[ \frac{1}{\rho_w} \int \rho_e \, dh \right] \left[ 1 + \frac{L\, h_{wv}}{T_0} \right]$$

$\rho_w$ is the density of (liquid) water. $T_0$ is the surface temperature (°K) and L is the (absolute value of the) temperature lapse rate (≈ 6.5°/km), $h_{wv}$ is the scale height of the water vapor in the atmosphere (≈ 2.2 km). Each of the terms in the expansion, eq. (10), has units of height. The first term, the dominant one, is the "precipitable water vapor". The dimensionless term in front is about 6.0. It is precisely 6.0 for $T_0$ = 287°K. The second term (the first moment in the expansion) is approximately 5 percent of the precipitable water vapor (Ref. 3). The second moment is a factor of ten less than the first. Consequently, we can, with surface temperature and pressure measurements, interpret our results for the (wet) range effect in terms of precipitable water vapor.

## 4. CONCLUDING REMARKS

In keeping with the spirit of this meeting, the significant findings from this study are:

1. It is possible to determine the total atmospheric water vapor using microwave doppler measurements. This measurement differs from the water vapor measurements made with radiosondes or with microwave radiometers. The latter two produce water vapor estimates along a profile through the atmosphere. The doppler technique produces a different sort of estimate; it is a 'bulk' estimate over that fraction of the troposphere swept out by the satellite-observer vector. Typically a region extending out to 150 km, on the satellite side of the observing site, will be sampled (see Ref. 1). Each of these kinds of measurements have their uses.

It would be interesting and useful to study the correlation between the different kinds of measurements. The data currently exists to do this.

2. It is possible to derive a model of the tropospheric range effect which is accurate to a few centimeters. The 'thinness' of the troposphere (compared with the radius of the earth) is an essential fact in developing the model. By model we mean one in which there is a clear separation of geometry on the one hand and an atmospheric-state-dependent amplitude on the other.

3. The tropospheric range amplitude is (demonstrably) separable from the other errors affecting the doppler shift. The accuracy with which the tropospheric range effect is isolated depends on the accuracy of the modeling and the noise level of the data. The existing data noise is about 10 cm (in range difference), and we are currently unable to fully exploit the accuracy implicit in the theory.

It is easily within the current state-of-the-art to build satellites and ground equipment which will reduce the noise level of the data. Equally important for these purposes would be raising the frequency pair from 150/400 MHz to (say) 400/1200 MHz to reduce the higher order ionospheric effects in the data.

## 5. REFERENCES


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This paper is a synopsis of: Black, H.D., and Eisner, A., 1983: Correcting satellite doppler data for tropospheric effects. APL/JHU Report SDO-6777. Also in press in the J. Geophys. Res.