GPS Meteorology: Mapping Zenith Wet Delays onto Precipitable Water

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(Manuscript received 8 April 1993, in final form 27 July 1993)

ABSTRACT

Emerging networks of Global Positioning System (GPS) receivers can be used in the remote sensing of atmospheric water vapor. The time-varying zenith wet delay observed at each GPS receiver in a network can be transformed into an estimate of the precipitable water overlying that receiver. This transformation is achieved by multiplying the zenith wet delay by a factor whose magnitude is a function of certain constants related to the refractivity of moist air and of the weighted mean temperature of the atmosphere. The mean temperature varies in space and time and must be estimated a priori in order to transform an observed zenith wet delay into an estimate of precipitable water. We show that the relative error introduced during this transformation closely approximates the relative error in the predicted mean temperature. Numerical weather models can be used to predict the mean temperature with an rms relative error of less than 1%.

1. Introduction

The Global Positioning System (GPS) consists of a constellation of satellites that transmit radio signals to large numbers of users engaged in navigation, time transfer, and relative positioning (Leick 1990). These L-band radio signals are delayed by atmospheric water vapor as they travel from GPS satellites to ground-based GPS receivers. Geodesists have devised techniques for estimating this time-varying "wet delay" (Tralli and Lichten 1990; Dixon and Kornreich Wolf 1990). Similar techniques have been developed for very long baseline interferometry (VLBI) (Herring et al. 1990). Since the zenith wet delay (ZWD) at a radio receiver is nearly proportional to the precipitable water, that is, the vertically integrated water vapor overlying the receiver (Hogg et al. 1981; Askne and Nordius 1987), the possibility arises of using emerging networks of geodetic GPS receivers for remote sensing of atmospheric water vapor (Bevis et al. 1992; Rocken et al. 1993). We present here a new method for mapping an observed ZWD onto an estimate of precipitable water, using numerical weather forecasts to tune the transformation. We also consider, in greater detail than previously, the probable level of error associated with this transformation.

By the end of this decade, continuously operating GPS receivers will exist in large numbers and with a wide spatial distribution. Exploiting these networks for meteorological purposes could provide an important new data stream, which would complement those derived from regional radiosonde networks and from ground- and space-based water vapor radiometers. The resulting improvement in our knowledge of water vapor distribution would enable more accurate forecasts of rainfall and severe weather and would contribute to studies of climate change (Bevis et al. 1992; Yuan et al. 1993).

The motivation for ground-based GPS meteorology, the background physics, the theoretical basis for the technique, comparisons with other measurement techniques, and potential applications have been discussed by Bevis et al. (1992), and for purposes of brevity we will minimize repetition of this material.

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2. Mapping zenith wet delays onto precipitable water

The possibility of using continuously operating geodetic GPS networks for remote sensing of atmospheric water vapor is based upon the development of "deterministic" least-squares and Kalman filtering techniques in which the ZWD affecting a VLBI or GPS receiver is retrieved from the observations recorded by that receiver. The physical basis for this measurement is the simultaneous observation of the signal delays at a given receiver from multiple radio sources that differ in their angles of elevation. Using these techniques it is now possible to retrieve, on a routine basis, the ZWD at each station in a continuously operating GPS network with less than 10 mm of long-term bias in equivalent excess pathlengths, and less than 10 mm (rms) of random noise.

If the vertically integrated water vapor overlying a receiver is stated in terms of precipitable water (PW), that is, as the length of an equivalent column of liquid water, then this quantity can be related to the ZWD at the receiver; thus,

$$\mathrm{PW} = \Pi \times \mathrm{ZWD}, \tag{1}$$

where the ZWD is given in units of length, and the dimensionless constant of proportionality Π, which is the focus of this paper, is given by

$$\Pi = \frac{10^6}{\rho R_v[(k_3/T_m) + k_2']} \tag{2}$$

(Askne and Nordius 1987), where ρ is the density of liquid water, R_v is the specific gas constant for water vapor, and T_m is a weighted mean temperature of the atmosphere; T_m is defined (Davis et al. 1985) as

$$T_m = \frac{\int (P_v/T)dz}{\int (P_v/T^2)dz}, \tag{3}$$

where

$$k_2' = k_2 - mk_1, \tag{4}$$

and m is M_w/M_d, the ratio of the molar masses of water vapor and dry air. The physical constants k_1, k_2, and k_3 are from the widely used formula for atmospheric refractivity N (Smith and Weintraub 1953; Boudouris 1963):

$$N = k_1 \frac{P_d}{T} + k_2 \frac{P_v}{T} + k_3 \frac{P_v}{T^2}, \tag{5}$$

where P_d and P_v are the partial pressures of dry air and water vapor, respectively, and T is absolute temperature.

3. The error budget for parameter Π

The values of the constants ρ, R_v, m are well determined, and their experimental uncertainties have no potential impact on the parameter Π of (1). The uncertainties in Π derive from the uncertainties in the mean temperature of the atmosphere T_m and in the physical constants k_1, k_2, and k_3. Let the errors in these quantities be σ_T, σ_1, σ_2, and σ_3, respectively. Let σ be the error in the derived constant k_2'. Assuming the errors in k_1 and k_2 are uncorrelated, then propagating these errors (Bevington 1992) through (4) we find

$$\sigma^2 = \sigma_2^2 + m^2\sigma_1^2. \tag{6}$$

A similar analysis of (2) yields the following expression for the relative error in the important parameter Π in (1):

$$\frac{\sigma_\Pi}{\Pi} = \frac{\Pi \rho R_v}{10^6}\left(\frac{\sigma_3^2}{T_m^2} + \sigma^2 + k_3^2\frac{\sigma_T^2}{T_m^4}\right)^{1/2}. \tag{7}$$

By neglecting the small contribution of k_2' (versus k_3/T_m) to the value of the leading term Π on the right-hand side of (7) we find

$$\frac{\sigma_\Pi}{\Pi} \approx \left(\frac{\sigma_3^2}{k_3^2} + \frac{T_m^2\sigma^2}{k_3^2} + \frac{\sigma_T^2}{T_m^2}\right)^{1/2}, \tag{8}$$

which approximates (7) to better than 2%. Although we use (7) to evaluate the probable error in Π, we can gain interesting insight into the evolution of this error by examining (8). In particular we can see that if σ_T is sufficiently large and the term σ_T^2/T_m^2 dominates σ_3^2/k_3^2 and $T_m^2\sigma^2/k_3^2$, then the relative error in Π will closely approximate the relative error in T_m.

4. The values of the refractivity constants

In order to determine the probable level of error in the parameter Π we must be able to specify values for the refractivity constants k_1, k_2, and k_3, and their associated uncertainties, for frequencies in the radio–microwave region of the spectrum. These constants have been determined by direct measurements made using microwave cavities (Boudouris 1963). Nearly all of these measurements were made prior to 1960. Smith and Weintraub (1953) compiled and averaged the early measurements, and Hasegawa and Stokesbury (1975) compiled and characterized a significantly larger number of experimental results. The nominal values and uncertainties adopted by these authors are given in Table 1. The two sets of values are broadly consistent.

Thayer (1974) developed an alternative and hybrid approach in which the value of k_2 was extrapolated from optical frequencies rather than measured using microwave techniques. His results (Table 1) have very high nominal precisions compared to those of Smith and Weintraub (1953) and Hasegawa and Stokesbury (1975), and for this reason they have been widely quoted. But Hill et al. (1982) have disputed Thayer's results on the grounds that extrapolating the value of k_2 across the infrared band is theoretically unjustifiable. Furthermore, Thayer's result for k_2 is far removed from

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TABLE 1. Values and uncertainties (standard errors) for the atmospheric refractivity constants k_1, k_2, and k_3 adopted by previous authors and in this study.

Reference	k_1 Value (K mb^{-1})	k_1 Error (K mb^{-1})	k_2 Value (K mb^{-1})	k_2 Error (K mb^{-1})	k_3 Value (10^5 K^2 mb^{-1})	k_3 Error (10^5 K^2 mb^{-1})
Smith and Weintraub (1953)	77.607	0.013	71.6	8.5	3.747	0.031
Thayer (1974)	77.604	0.014	64.79	0.08	3.776	0.004
Hasagawa and Stokesbury (1975)	77.600	0.032	69.40	0.15	3.701	0.003
Present study	77.60	0.05	70.4	2.2	3.739	0.012

Note: constant k_2' is derived via Eqs. (4) and (6). We find $k_2' = 22.1 \pm 2.2$ K mb^{-1}.

the values determined by averaging direct measurements (Table 1). For these reasons we choose to abandon Thayer's values for the less precise but more justifiable values derived from direct measurements. We wish to utilize a result derived from the later and more comprehensive of the two surveys discussed above, but, like Hill et al. (1982), we disagree with the details of the statistical approach taken by Hasegawa and Stokesbury (1975) in their averaging of the previously published experimental determinations of k_1, k_2, and k_3. Accordingly we have reanalyzed their compilation with increased emphasis on obtaining robust results and conservative estimates of the uncertainties involved (Appendix). The values and uncertainties we adopt as the result of this analysis are given in Table 1. We believe that the best way to assess our nominal values and nominal standard errors for the various refractivity constants is by visual inspection of the reported values and uncertainties and their relation to our nominal ±2 standard error intervals (Figs. A1–A3). We feel comfortable with the notion that there is an approximately 95% probability that the true values lie within our ±2 standard error intervals.

The constant k_2' is derived from the values and uncertainties of k_1 and k_2 via (4) and (6). We find $k_2' = 22.1 \pm 2.2$ K mb^{-1}. By substituting our nominal values for k_2' and k_3 into (2) we can determine the value of Π as a function of T_m (Fig. 1). Note that the relationship is very nearly linear.

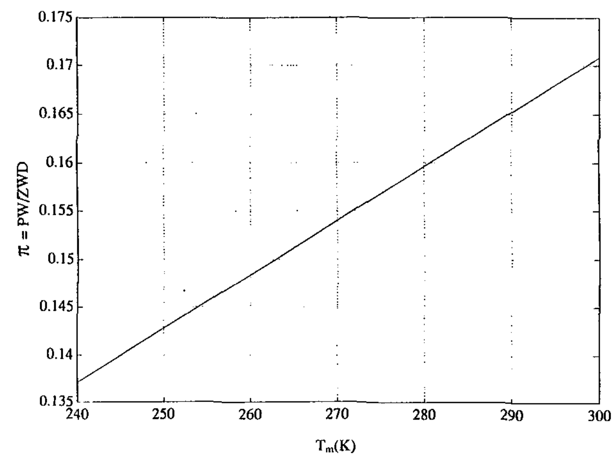

FIG. 1. The ratio PW/ZWD = Π as a function of the mean atmospheric temperature T_m.

5. The uncertainty in parameter Π

We can now evaluate the relative error in parameter Π as a function of the relative error in T_m [Eq. (7)]. We do this by setting the refractivity constants and their standard errors to our nominal values (Table 1), and this produces the solid curve in Fig. 2. We also consider the possibility that the actual errors are twice their nominal values, and this produces the dashed curve (Fig. 2). In the former case we can see that if the relative error in T_m exceeds about 1%, then the relative error in Π closely approximates the relative error in T_m. This is because $k_3^2\sigma_T^2/T_m^4$ in (7) is dominating σ_3^2/T_m^2 and σ^2. Note that σ_3^2/T_m^2 and σ^2 are of comparable magnitude. The situation is modified if we set the errors to double their nominal values. Now the relative error in Π does not closely approximate

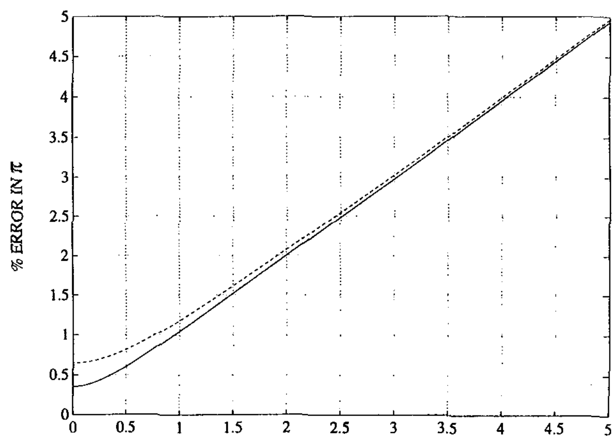

FIG. 2. The relative error in parameter Π as a function of the relative error in T_m assuming (i) errors in the refractivity constants have the nominal values given in Table 2 (solid line), and (ii) errors in the refractivity constants have twice their nominal values (dashed line).

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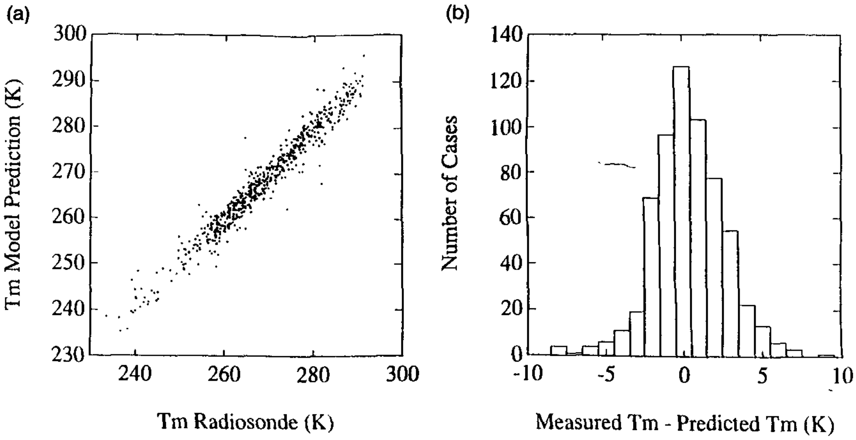

FIG. 3. A comparison of the mean atmospheric temperature T_m predicted using the 12-h forecast of the National Meteorological Center's Nested Grid Model and T_m obtained directly from 502 radiosonde launches (a). The distribution of errors (measured T_m minus predicted T_m) is indicated in the histogram (b).

the relative error in T_m until this latter quantity reaches about 2%.

Given that it is unlikely that we will ever be able to predict T_m routinely with an error much less than 1%, and given that our nominal values and uncertainties for the refractivity constants (Table 1) are not radically incorrect, we have confirmed the assertion of Bevis et al. (1992) that the relative error in Π is to a very good approximation the relative error in T_m. Nevertheless, given the central role in GPS meteorology of the mapping between ZWD and PW [Eq. (1)], we would like to see some contemporary experimental determinations of the refractivity constants. Very little work of this kind has taken place since 1960; thus, we are fortunate that we are working in a regime in which we are not strongly sensitive to the values of these constants.

6. A priori estimation of the mean temperature T_m using numerical weather models

As a rough rule of thumb, the ratio PW/ZWD = $\Pi \approx 0.15$, but the actual value of Π can vary by as much as 20% since it is a function of T_m, which varies with location, altitude, season, and weather. Given that water vapor pressure serves as a weighting factor in the definition of T_m [Eq. (3)] and the fact that most water vapor is located in the lower 2–3 km of the atmosphere, it is obvious that T_m should be correlated with surface temperature T_s. Bevis et al. (1992) investigated the strength of this correlation by analyzing a suite of 8718 radiosonde stations obtained over a 2-yr interval from 13 stations in the United States, from Fairbanks, Alaska, to West Palm Beach, Florida. They found a linear relation $T_m = 70.2 + 0.72T_s$ (temperatures are in kelvins) with an rms scatter about this regression of 4.7 K, corresponding to a relative error of less than 2%. Thus it should be possible to predict the value of Π at a given place and time, with an rms relative error of not more than 2%, given only surface temperature observations at the site.

The strong linear correlation between T_m and T_s prompted us to consider whether operational numerical weather models, which predict the three-dimensional distribution of temperature as a function of time, could provide a better estimate of T_m than can be obtained given only knowledge of T_s. Accordingly we compared T_m computed from the 12-h forecast from the National Meteorological Center's Nested Grid Model (NGM) with values obtained directly from radiosonde launches. (The model that is initialized with the data from the 0000 UTC launch is used to predict T_m at 1200 UTC, and so forth.) The distribution of errors for five separate model runs, and a total of 502 radiosonde profiles (Fig. 3) is approximately normal; the rms error of 2.4 K constitutes a relative error of 0.9%. Because the radiosonde measurements incorporate instrumental error, the rms error represents an upper bound on the errors in the prediction. Furthermore, the numerical weather predictions used for this analysis were obtained from an archive in which only a subset of the full output of the NGM is preserved. Our analysis is based on predictions with a lateral spatial resolution of 190.5 km and nine vertical levels. We can assume that further improvement in the prediction of T_m is possible with the use of the NGM's full spatial resolution of 90 km and 16 vertical levels, and more generally as operational models continue to gain resolution in the future.

7. Discussion

It is unlikely that it will ever be possible to predict the mean temperature of the atmosphere, T_m, with a level of error much below 1% in a routine operational setting. Unless we have seriously underestimated the

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probable levels of error in our estimates of the relevant refractivity constants, the implication is that the dominant source of error affecting the transformation of observed ZWDs into estimates of PW is our ability to form an a priori estimate for T_m for each receiver and at each epoch. We have shown that it is possible to estimate T_m with an rms relative error of at most 1% using numerical weather models. Combining our previous estimate of the likely level of error in the ZWDs retrieved from GPS data (Bevis et al. 1992), with the error added during the mapping of the ZWD onto PW, we conclude that it should now be possible to recover PW from GPS data with an rms error of less than 2 mm + 1% of the PW and long-term biases of less than 2 mm. That is, nearly all of the error in the estimated PW derives from the error introduced previously during estimation of the ZWD. Although atmospheric scientists might contribute to the development of GPS meteorology by better determining the values of the refractivity constants, it is clear that the greatest potential improvement in our ability to estimate PW from GPS observations lies in the development of superior techniques for estimating ZWDs.

Throughout this formal analysis of the errors associated with transforming an estimated ZWD into an estimate of PW, we have assumed that (1) is, in fact, correct. Implicitly we have assumed that the wet delay is entirely due to water vapor and that liquid water and ice do not contribute significantly to the wet delay. Although it is widely believed among the radio science and geodesy community that this is an excellent approximation most of the time, much of the reasoning behind this opinion seems to be anecdotal, and more work needs to done on determining the frequency with which the assumption can break down, and the likely magnitude of the resulting errors in these special circumstances.

Acknowledgments. This work has been supported by NSF Grant ATM-9207111. MB would like to thank Drs. Jim Davis, Hans Leibe, and Steven Walter for the valuable insights they provided into the experimental uncertainties associated with the atmospheric refractivity constants. We thank the reviewers for their comments and suggestions.

APPENDIX

Values and Uncertainties of the Refractivity Constants

Hasegawa and Stokesbury (1975) compiled published experimental determinations of the refractivity constants k_1, k_2, and k_3. This compilation included 20 direct measurements of k_1 (Table A1) and 7 direct measurements of k_2 and k_3 (Table A3). In all but three determinations (all of k_1) the experimentalists estimated a standard error as well as a value. These results are presented graphically in Figs. A1–A3. An inspection of these data indicates that we should be careful in averaging them to find a most likely value. The k_1 values contain at least one gross outlier (Fig. A1), and some of the uncertainties reported for measurements of k_2 and k_3 seem unrealistically small (Figs. A2 and A3).

We first consider the value of k_1. In Table A2 we obtain various estimates of the most likely value of k_1, derived from all 20 observations and from three subsets in which one, two, and three outliers are removed. In

TABLE A1. Experimental determinations of the refractivity constant k_1 compiled by Hasegawa and Stokesbury (1975). The uncertainty is the nominal standard error on the experimental result. No uncertainties were provided for determinations 2, 4, and 6. References for the individual determinations can be found in Boudouris (1963) or Hasegawa and Stokesbury (1975).

Number	Author(s)	Reference date	k_1 (K mb^{-1})	Uncertainty (K mb^{-1})
1	Barrel	1951	77.54	0.03
2	Watson, Rao, and Ramaswamy	1934	77.6	
3	Hector and Woernley	1946	76.38	0.13
4	Crain	1948	77.1	
5	Lyons, Birnbaum, and Kryder	1948	77.73	0.13
6	Philips	1950	80.6	
7	Birnbaum, Kryder, and Lyons	1951	77.57	0.19
8	Essen and Froome	1951	77.636	0.027
9	Gozzini	1951	77.95	0.40
10	Ziemann	1952	77.57	0.27
11	Hughes and Armstrong	1952	76.65	0.54
12	Gabriel	1952	77.54	0.03
13	Essen	1953	77.639	0.027
14	Jasinski and Berry	1954	77.67	0.05
15	Froome	1955	77.504	0.030
16	Saito	1955	77.33	0.32
17	Battaglia, Boudouris, and Gozzini	1957	77.60	0.08
18	Boudouris	1958	77.60	0.08
19	Newell and Baird	1965	77.631	0.013
20	Wingfield and Zieman	1970	78.113	0.124

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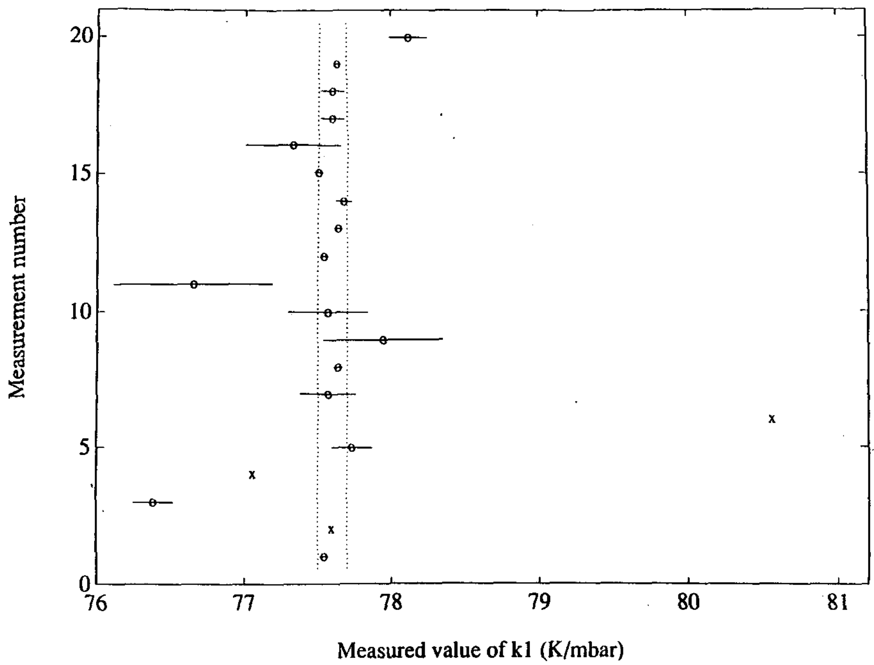

FIG. A1. Experimental determinations of the refractivity constant k_1. The measurement number refers to listing of experimental results in Table A1. The solid horizontal lines indicate the reported standard error for each measurement. For the three values indicated by an "X" the standard error is unknown. The vertical dashed lines indicate the ±2 standard error interval adopted in this study (Table 2).

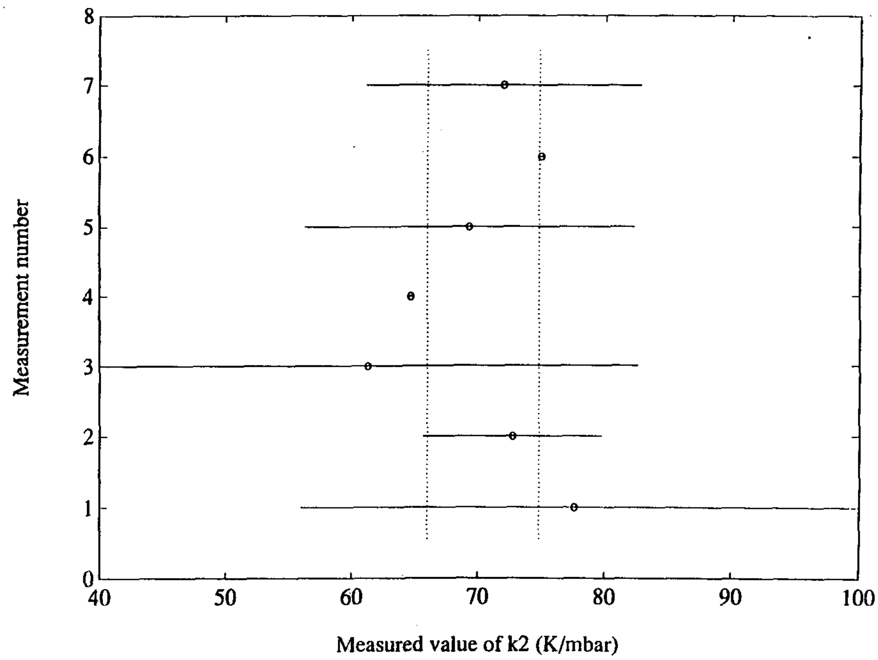

FIG. A2. Experimental determinations of the refractivity constant k_2. The format is as in the caption for Fig. A1.

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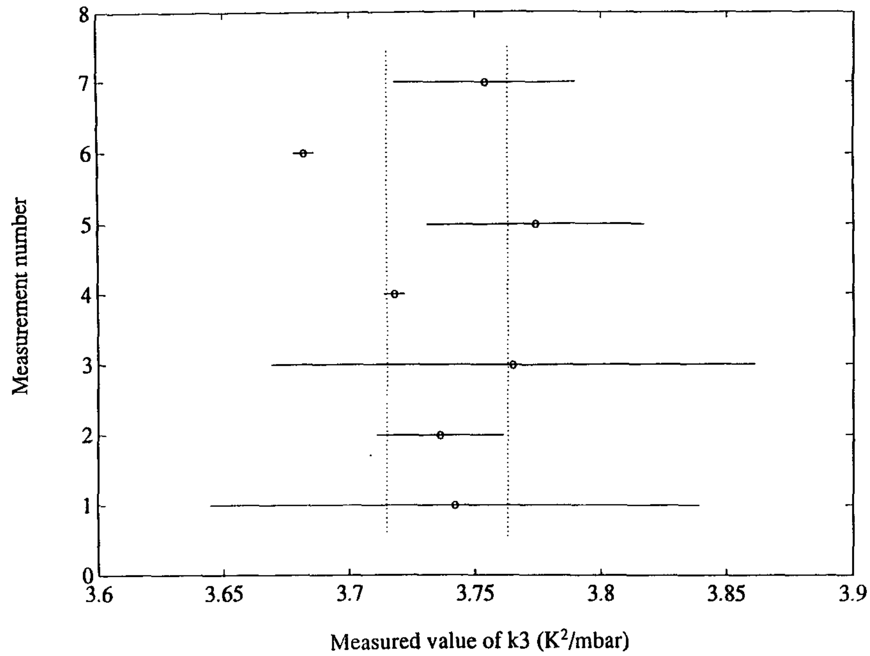

FIG. A3. Experimental determinations of the refractivity constant k_3. The format is as in the caption for Fig. A1.

each case we compute the weighted and unweighted mean and the median value (a robust estimator of the most likely value). We also compute the standard error on the (unweighted) mean from the (unscaled) dispersion about the mean. We choose to adopt a nominal value of 77.60 K mb^{-1} and a standard error of 0.05 K mb^{-1}. Our nominal ± 2 standard error interval ($\sim$95% confidence interval) is indicated by the dashed lines in Fig. A1. Note that our nominal uncertainty is more conservative than that adopted by Hasegawa and Stokesbury (1975) (Table 1).

The values reported for k_2 and k_3 (Table A3) do not contain any obvious outliers but the magnitudes of the associated standard errors vary tremendously, and in the case of the measurements made by Essen and Froome (1951) and Essen (1953), the standard errors seem too small to be credible. (Certainly these two sets of measurements are statistically incompatible to a very high degree of confidence if we take the nominal errors at face value.) Hill et al. (1982) state that these small standard errors derive from deficiencies in the experimental approach of Essen and Froome, and they criticized Hasegawa and Stokesbury (1975) for using these errors in a weighting procedure. We do not feel that we are in a position to judge which reported standard errors are plausible and which are not, and therefore, we prefer to average the various values for k_2 and k_3 without weighting them and to estimate the standard errors from the dispersion of the data about the mean (Table A3). Our nominal ± 2 standard error intervals ($\sim$95% confidence intervals) for k_2 and k_3 are indicated by the dashed lines in Figs. A2 and A3.

We believe that the best way to assess our nominal values and nominal standard errors for the various re-

TABLE A2. Statistical analysis of the experimental determinations of the refractivity constant k_1. The original dataset listed in Table A1 has been used to generate three subsets. The individual experimental determinations deleted from Table A1 in order to produce each subset are indicated in column 2 by their associated reference numbers in Table A1. For each dataset and subset we have computed the mean, weighted mean, and median values for k_1 (columns 3–5) and the standard error on the mean value as computed from the dispersion of the results about the unweighted mean.

Number of measurements retained	Reference numbers of deleted measurements	Mean value (K mb^{-1})	Weighted mean value (K mb^{-1})	Median value (K mb^{-1})	Standard error (K mb^{-1})
20	none	77.64	77.60	77.60	0.18
19	6	77.49	77.60	77.60	0.09
18	6, 3	77.55	77.60	77.60	0.07
17	6, 3, 11	77.60	77.61	77.60	0.05

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TABLE A3. Experimental determinations of refractivity constants k_2 and k_3 compiled by Hasegawa and Stokesbury (1975). For each experimental determination we state the values and the nominal uncertainties on measurements of k_2 and k_3. At the bottom of the table we provide the weighted and unweighted mean values for k_2 and k_3, and the standard errors on the mean values as determined from the scatter of the measurements about their unweighted mean. References to the original papers can be found in Boudouris (1963) or Hasegawa and Stokesbury (1975).

		k_2		k_3	
Author(s)	Reference date	Value (K mb^{-1})	Uncertainty (K mb^{-1})	Value (10^5 K^2 mb^{-1})	Uncertainty (10^5 K^2 mb^{-1})
Groves and Sugden	1935	77.6	21.6	3.742	0.097
Stranathan	1935	72.70	7.04	3.736	0.025
Hurdes and Smyth	1942	61.3	21.3	3.765	0.096
Essen and Froome	1951	64.695	0.198	3.718	0.004
Birnbaum and Chaterjee	1952	69.28	12.99	3.774	0.043
Essen	1953	74.996	0.216	3.682	0.004
Boudouris	1958	71.98	10.82	3.754	0.036
Weighted mean value		69.4		3.701	
Mean value		70.4		3.739	
Standard error on mean		2.2		0.012	

fractivity constants is by visual inspection of the reported values and uncertainties and their relation to our nominal ±2 standard error intervals. We feel comfortable with the notion that there is an approximately 95% probability that the true values lie within our ±2 standard error intervals.

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