A COMPARISON OF TWO MODELS USED TO PREDICT ATMOSPHERIC REFRACTION IN VLBI

by

JOEL BERMAN

B.S., University of New Hampshire
B.A., University of New Hampshire
(1976)

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE
DEGREE OF MASTER OF SCIENCE
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

JUNE 1979

Signature of Author ______________________________
Dept. of Earth & Planetary Science, June 1979

Certified by ______________________________
Thesis Supervisor

Accepted by ______________________________
Chairman, Department Committee

A COMPARISON OF TWO MODELS USED TO

PREDICT ATMOSPHERIC REFRACTION IN VLBI

by

Joel Berman

Submitted to the Department of Earth and Planetary Science on May 29, 1979, in partial fulfillment of the requirements for the Degree of Master of Science

ABSTRACT

Data from 12 very-long-baseline interferometry (VLBI) experiments performed between September 1976 and January 1978 are used to compare two models predicting neutral atmospheric refraction. The two models are compared using antenna separation distance, called baseline, as a presumed constant. Clock polynomials are determined first. A solution using all observations is performed in order to estimate a new set of source coordinates. These source coordinates are then used to compare the two models on three baselines. Two baselines show one model to be superior while the third baseline supports the other model. The results contain several problems which must be resolved in order to determine which model is superior. Evidence is presented that the baseline scatter may be able to be reduced further by making small modifications or additions to one model.

Thesis Supervisor: Charles C. Counselman, III Ph.D.
Title: Associate Professor of Earth and Planetary Sci.

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to his advisor, Chuck Counselman, for the latter's guidance and counsel during the course of this study.

He also wishes to acknowledge the assistance of Sergei Gourevitch and Peter Ford for acquainting him with the intricacies of the computer. Thanks are also extended to Bill Snow for his assistance.

Sincere appreciation is given to Curt Knight, Tom Clark and Doug Robertson for their help in providing the author with necessary data.

Last but not least, the author, wishes to express appreciation to Sandy Rosenbaum, who besides providing assistance in keypunching, editing and typing gave the author her advice, concern, and most of all support through the duration of this study. She is also responsible for the phrasing of these acknowledgements.

TABLE OF CONTENTS

CHAPTER 1

INTRODUCTION

1.1 OUTLINE OF THE EXPERIMENT

One of the major problems in making geodetic measurements using Very Long Baseline Interferometry (VLBI) (ref. 1) is refraction by the neutral atmosphere. In the VLBI experiments used in this paper, two or three stations separated by one to four thousand kilometers observed extra-galactic sources and measured relative delays and delay rates. The delay is the difference between the readings of clocks at two different stations corresponding to arrivals of a particular wave front at each station. The delay rate is the rate of change of delay with respect to the reading of one of the station clocks. In the simplest case of a rigid, isolated, non-rotating Earth with perfect clocks, the antenna separation distance (referred to as the baseline) could be determined easily from the delays be simple trignometry.

The real calculation is not so simple. First, the geometry in which the observations are made is set up. Models are written to account for the effects of the neutral atmosphere, ionosphere, clock drifts, tides and of the rotation, wobble, precession and nutation of the Earth. Many of these models have unknown parameters which have to be estimated. An initial calculation of a theoretical set of delays and delay rates is performed using a priori parameter values, source coordinates and site coordinates. These theoretical delays and delay rates are subtracted from the measured values to form what are called the "pre-fit delay and delay rate residuals." Next, a simultanious least-squares calculation is performed estimating new parameters and coordinate values in order to minimize the delay and delay rate residuals. This produces a new set of theoretical delays and delay rates along with a new set of residuals called "post-fit delay and delay rate residuals." This whole calcualtion is performed using a computer program, named VLBI3, written primarily by Robertson (ref.2). The program allows us to estimate almost as many or as few parameters as we wish. A typical VLBI3 solution might consist of the estimate of three site coordinates, a few clock parameters representing initial clock offsets and rate errors, and several atmospheric parameters.

1.2 PURPOSE

This paper is concerned with the modelling of the neutral atmosphere. The contribution of the neutral atmosphere to the delay and delay rate observables must be modelled if we want the post-fit delay and delay rate residuals to be as small as possible.

Until recently, almost all solutions were performed estimating atmospheric parameters, which are the delays introduced by the atmosphere for a source at the zenith. Most sources are not at the zenith, hence a mapping function is employed which depends on the zenith delay and the elevation of the source at a particular site. One limitation of modelling the atmosphere this way is that zenith delays can be estimated only every four to eight hours. This time interval depends on how often observations are made because we need a sufficient number of observations for the number of parameters to be estimated. Also, it is necessary to wait until observations of sources are made over a range of elevation angles so that the signature of the atmosphere is established. Each zenith delay is used in all theoretical calculations of delays and delay rates until a subsequent zenith delay is determined. Because of this, atmospheric changes occurring on a time scale smaller than four to eight hours are not modelled.

Several models predicting atmospheric delay based on surface conditions have been proposed. Snow (ref. 3) compared various atmosheric models at low elevation angles using the signal from several closely spaced Apollo Lunar Surface Experiment Packages (ALSEPs). He found a model proposed by Saastamoinen (ref. 4) to be the best. Preliminary work by this author confirmed Snow's conclusion. Saastamoinen's model was later modified by Marini and Murray (ref. 5). This paper will present the results of work comparing the old parameter estimation model with Marini and Murray's model.

CHAPTER 2

THE MODELS

2.1 OLD MODEL

As noted above, the atmospheric model used until now consisted of solving for a zenith delay at each site every four to eight hours. This time was determined by how long it took for 25 observations to be made. For sources not at the zenith, this model used a mapping function derived by C. C. Chao (ref. 6):

$$\text{Delay at elevation angle E above horizon} = \frac{\text{Delay at Zenith}}{\sin E + \dfrac{0.00143}{\tan E + 0.0445}}$$

Chao started with a cosecant function, which is a good first order approximation, then added a correction derived from tracing the path of a radio wave through an "average" atmosphere determined from radiosonde data taken during 1967 and 1968. He found this function to agree to within 1% of the ray tracing for elevation angles of greater than one degree. In ray tracing, Chao tried to account for the curvature of the Earth. By using an "average" atmosphere, he considered the curve of the radio wave's path and the variation of the wave's velocity through the atmosphere. Under different atmospheric conditions, a radio signal seen at a given elevation angle would travel a different path at a different velocity and therefore be delayed a different amount of time. Two ways in which to improve the computed atmospheric delay are to use a model which allows for updating of weather data as often as observations are made and to use a mapping function which takes into account the present state of the atmosphere.

2.2 MARINI AND MURRAY'S MODEL

The model presented by Marini and Murray predicts the atmospheric delay of a radio signal as a function of zenith angle based on the temperature, relative humidity and total atmospheric pressure at the receiving site. Their model is based on a model presented by Saastamoinen (ref. 4). Saastamoinin set up an integral of the refractivity along the path of an electromagnetic wave traveling through the atmosphere as follows:

$$\Delta s = c\Delta t = \int_{path}(n-1)\, ds$$

- Δs - additional path length introduced by the atmosphere
- Δt - time delay
- n - index of refraction of the air along the path
- $n-1$ - refractivity

He then integrated this equation through both the troposphere and the stratosphere using both Snell's Law and the equation of hydrostatic equilibrium to get the following:

$$\Delta s = 0.002277\ (\sec z)\ [p + (1255/T + 0.05)e - 1.16 \tan^2 z]$$

- Δs - additional path length
- z - zenith angle
- p - total atmospheric pressure at the site in millibars
- T - temperature in Kelvins
- e - partial pressure of water vapor in millibars

In the derivation, he assumed a constant lapse rate of "6.5° Kelvin per kilometer as the tropospheric gradient of temperature for all latitudes and all seasons" (ref. 7). He also includes a table of corrections for the coefficient of $\tan^2 z$ as a function of height above sea level. Marini then used Saastamoinen's model to predict the zenith delay, but reworked the mapping function using a continued fraction expansion. Marini also made use of a few corrections such as the change in the acceleration of gravity (g) with changes in altitude and latitude as discussed be Saastamoinen. In this VLBI experiment, we are trying to estimate baselines to an accuracy of a few centimeters of less. Saastamoinen evaluated his constants estimating zenith delays at the 0.1 meter error level, which would affect the baseline adversely at very low elevation angles only. As a result of this, Saastamoinen used averages wherever possible. For example, "Considering the present accuracy limitations of radio ranging, an average value g=978.4 centimeters/second^2 can be accepted for all latitudes and all station heights" (ref. 4). Marini used the explicit corrections in his model and obtained the following:

$$\Delta s = [1/f(\phi,H)]\,\frac{A + B}{\sin E + \dfrac{B/(A+B)}{\sin E + 0.015}}$$

$A = 0.002277[p + (1255/T + 0.05)e]$ Saastamoinen's function

$B = 2.644 \times 10^{-3} \exp(-0.14372\ H)$ Altitude correction

$f(\phi,H) = 1 - 0.0026\ (1 - 2\sin^2\phi) - 0.00031\ H$

- Correction of g for latitude and elevation

E - elevation angle

ϕ - latitude of receiving station

H - height of receiving station above sea level (kilometers)

0.015 - empirical constant that serves to compensate for the neglect of higher order terms in the continued fraction expansion.

T,p,e are the same as in Saastamoinen's model

One question which arises at this point is how much Marini's prediction differs from that of Saastamoinen. Evaluating data from a randomly selected day at Haystack this author found the following to be true. At the zenith, Saastamoinen's model predicts a path length which is 0.8 millimeters longer than that of Marini. However, at elevation angles of 45° and 20°, Saastamoinen's model predicts path lengths respectively 1.2 millimeters and 6.3 millimeters longer than those of Marini. Fxcept for very high elevation angle sources, the two models, therefore, are very close.

Marini's model does not rely on any estimated parameters. However, the model requires input weather data which turned out to be much more difficult to obtain than had been anticipated.

2.3 DISCUSSION

Saastamoinen's and Marini's models attempt to predict refraction based on surface weather conditions. This has an advantage over the old model in that it allows us to predict the delay as often as observations are made.

There are several problems, however, with attempting to describe the state of the whole local atmosphere with one observation made at one spot. One problem is that for most observations we are looking at sources at elevation angles of less than 90°, therefore the signal passes through atmosphere of up to tens of kilometers downrange. In the case of Owens Valley, which is adjacent to two mountain ranges, the state of the atmosphere over the mountains may be substantially different from that of the atmosphere over the valley. A grid of observing stations might help to solve this problem. Another problem is that most ground-based models assume the lapse rate is constant and that it applies from the surface to the tropopause. Berman (ref. 8) published a series of tropospheric temperature profiles determined from balloon measurements taken at Edwards Air Force Base in 1969. These profiles show that the lapse rate can vary from -6.782° centigrade per kilometer to -7.792° centigrade per kilometer. Also, there are variations from day to night which can affect the lapse rate up to an altitude of 3 kilometers. The tropopause occurs at 10 to 11 kilometers. These variations of the lapse rate in the lower atmosphere are not uniform and may be difficult to model. Berman wrote, "To formulate an expression for T(z) which would account for the local surface effect would be an almost impossible task". The lapse rate varies from place to place and from day to day. An attempt to determine more accurately the local lapse rate at the time of observation might significantly improve the model.

CHAPTER 3

ANALYSIS

3.1 DATA AND OBSERVATIONS

Varying amounts of weather data and observations were obtained from 12 experiments between September 1976 and January 1978 the dates of which are listed below:

	Date and Time (UT) Started	Date and Time (UT) Completed
1.	1976 September 9 0129	1976 September 10 1033
2.	1976 September 29 2140	1976 October 1 0053
3.	1976 October 4 2309	1976 October 6 0255
4.	1976 October 9 0522	1976 October 10 0754
5.	1976 October 11 0749	1976 October 12 0446
6.	1976 October 14 0741	1976 October 15 1442
7.	1976 December 13 2329	1976 December 15 1250
8.	1976 December 15 2203	1976 December 17 1045
9.	1977 March 27 1800	1977 March 31 0540
10.	1977 June 26 1032	1977 June 27 1159
11.	1977 December 13 1105	1977 December 16 0455
12.	1978 January 13 1618	1978 January 15,1978

Observations were carried out at the Haystack Observatory in Tyngsboro, Massachusetts; the Owens Valley Radio Observatory in Big Pine, California; and the National Radio Astronomy Observatory (NRAO) in Green Bank, West Virginia. Complete sets of delay and delay rate observations of 13 extra-galactic sources for the nine experiments were obtained. The sources observed are listed below:

1. 3C84
2. 0150
3. C120
4. J287
5. 4C89
6. C273
7. C279
8. C345
9. C418
10. 2134
11. VRO
12. C446
13. C454

The two-station experiments typically contained 100 to 200 observed delays and delay rates with observation made irregularly but usually every 5 to 20 minutes. All observation were made between elevation angles of 10° and 90°; the distribution of these elevation angles was fairly uniform.

The atmospheric data was obtained from Doug Robertson at the Goddard Space Flight Center via the VLBI data base at the Haystack Observatory. Robertson received the data from at or near each of the three sites. The weather data from NRAO was recorded at the site whereas the Owens Valley data was recorded at Bishop Airport, located 8 miles away. At Haystack there was a problem with the instrument that was recording the atmospheric pressure; the pressure data was obtained from Concord, New Hampshire, because of this. A comparison of the existing data from Haystack with the data from Concord demonstrated that using pressure data from the latter did not affect significantly the predicted path length. Making use of a weather map, this author found an atmospheric pressure difference of approximately two or three millibars to be characteristic for a 50 mile separation in New England. This produced an error in the predicted path length of 0.5 centimeters at the zenith. Concord, however, lies in a long valley, striking north-south, which may reduce this effect further. The lack of an increased post-fit delay residual size at medium to low elevation angles also indicates that measuring pressure in Concord may not introduce any significant errors. The temperature and dew point were recorded at Haystack. Robertson received the data from all of these places in increments of one hour. He then linearly interpolated the weather data to get the temperature, pressure and dew point at the time of observation. Roberston and I later found errors in some of the atmospheric data inserted into the data base by Robertson. At the of this writing, the temperatures and dew points at Haystack and Owens Valley on October 11 and at all three sites on October 9 were the only unreliable data. This data, however, was used regardless of the errors because the atmospheric pressures, which are used to account for 80% of the atmospheric delay, were accurate.

3.2 METHODS

The first step in this analysis was to gather all the observations and atmospheric data, organize it and write the data handling programs. The analysis began by producing a two-station VLBI3 solution for each experiment. The purpose of this was to determine the degree and number of clock polynomials necessary to model station clock behavior. This was done by looking for systematic drifts and breaks in the post-fit delay residuals. In the case of three station experiments, such as March 1977, a solution for each of the three baselines was obtained. The coordinates of the extra-galactic sources used here were taken from a set whose exact origin is unknown; they probably were computer estimates from a previous VLBI3 solution of some or all of the September-October 1976 experiments. The coordinates are close to those presented in a paper by Clark (ref. 10). About half are the same as those in Clark's paper, the other half vary by about 1 millisecond in right ascension and as much as 0.07 arc seconds in declination from those presented by Clark. After the clock polynomials were determined, this author spend many hours battling to produce a

VLBI3 solution using all 4303 observations. The purpose of producing this grand solution was to determine a new set of source coordinates. The grand solution estimated 34 clock polynomials, the 3 site coordinates of Owens Valley and NRAO, 11 UT1 epochs and 11 X-wobble parameters. In addition, the right ascension and declination of all the sources were estimated with the exception of the right ascension of C273 which was fixed. In all, 145 parameters were estimated. The corrections to the right ascensions ranged from 1.8 seconds to 0.00009 seconds; the corrections to the declinations varried from 2.6 arc seconds to 0.0002 arc seconds. The grand solution used Marini's model with atmospheric data updated every hour in order to minimize the number of estimated parameters. The three baseline lengths are given in Table I.

With the sources coordinates fixed at their newly determined values, two-station, single-experiment solutions were obtained for all experiments and all baselines using each atmospheric model. Atmospheric data was updated every 30 minutes in the solutions using Marini's model. When different atmospheric models were employed, solutions using the same observations had identical clock and site parameters estimated.

3.3 RESULTS

The results of the two-station, single experiment solutions are given in Table I and Table II. Table I contains the baselines and RMS delay residuals from the solutions employing Marini's model. The results of the solutions using the Old model are presented in Table II.

As noted previously, the atmospheric data was updated every 30 minutes in the solutions using Marini's model. Previous work by this author updated atmospheric data at 10, 20 and 30 minutes intervals. Solutions of the October 4-5. 1976 and October 14-15, 1976 observations were used to determine the effect of updating atmospheric data at different time intervals. Updating every 30 minutes as opposed to every 10 minutes produced a baseline shift of 1-2 millimeters and a decrease of approximately 5 picoseconds in the RMS scatter of the post-fit delay residuals. Atmospheric data, therefore, was updated every 30 minutes in order to minimize computation time. The Haystack-Owens Valley solutions using Marini's model show a mean baseline of 3928881.804 meters with a standard deviation (S.D.) of 9.5 centimeters while those using the Old model had a mean baseline of 3928882.050 meters (S.D.= 10.7 centimeters). In the grand solution using Marini's model, a Haystack-Owens Valley baseline of 3928881.792 meters was obtained. The mean RMS delay residual was 0.471 nanoseconds and 0.404 nanoseconds for Marini's model and the Old model respectively.

The results of solutions on the Owens Valley-NRAO baseline using Marini's model show a different standard deviation in mean baseline length. The mean baseline of the solutions using Marini's model was 3324244.225 meters (S.D.= 16.5 centimeters) while those using the old model have a mean baseline length of 3324244.507 meters (S.D.= 10.5 centimeters). The mean RMS delay using Marini's model as opposed to the Old model have the same approximate ratio as on the Haystack-Owens Valley baseline: 1.2 to 1. The grand solution has an Owens Valley-NRAO baseline of 3324244.262 centimeters.

The results of the Haystack-NRAO baseline show a different result from the two other baselines. The mean baseline lengths estimated by the solutions using Marini's model and the Old model are 845130.03 meters (S.D.= 11.5 centimeters) and 845129.99 meters (S.D.= 17.8 centimeters) respectively. The respective mean RMS delay residuals of 0.778 nanoseconds and 0.658 nanoseconds have a ratio of 1.2 to 1. The grand solution estimated a Haystack-NRAO baseline length of 845130.010 meters.

3.4 DISCUSSION

The results presented above are inconclusive as to the usefullness of Marini's model as opposed to the Old model. In this analysis, the reliability of the baseline length is being used as a measure of how well each model predicts the atmospheric delay. All three stations are assumed to be on the same lithospheric plate and hence the baseline length between any two stations is assumed to be a constant. On the Haystack-Owens Valley baseline, the standard deviation of the mean baseline length indicates that Marini's model is predicting atmospheric delay slightly better. The Haystack-NRAO baseline solutions indicate the Old model is doing a superior job predicting atmospheric delay while the Owens Valley-NRAO results show the opposite. One possible answer to this inconsistency is that Marini's model may be more applicable to certain climates.

Although the solutions using the two models should estimate the same mean baseline length, the solutions on the Haystack-Owens Valley and Owens Valley-NRAO baselines differ by 20 to 30 centimeters. The two mean baseline lengths differ by only four dentimeters on the Haystack-NRAO baseline. The Haystack-NRAO baseline, however, is shorter than the other two by a factor of four or five.

The mean RMS delay residuals seem to follow a consistent, understandable pattern. In all three cases, the mean RMS delay residuals from the solutions using Marini's model are approximately 1.2 times greater than those of the solutions using the Old model. The solution with the greatestnumber of adjusted parameters can usually be expected to have smaller delay residuals than a solution with less adjusted parameters. In this case, the Old model solutions always had more adjusted parameters than the solutions using Marini's model. In all cases, the solutions using the Old model had a smaller RMS delay residual than those using Marini's model. One problem in allowing the computer program to estimate the atmospheric delay is that non-atmospheric effects may be absorbed into the atmospheric correction. For instance, there was no explicit correction for the effect of the ionosphere although it is also a function of elevation agnle. The Old model could absorb some of the ionospheric delay into the neutral atmosphere parameter. No parameters are estimated in Marini's model and therefore it is unable to absorb an ionospheric delay.

Several of the solutions show this very problem. The June 1977 Owens Valley-NRAO delay residual plot of the solution using Marini's model shows a clear systematic residual drift resembling two sinudoids, one with a period of six hours, and the other with a period of 12 hours. The same plot taken from the solution of the data using the Old model does not show the systematic drift quite as clearly. The March 1977 Haystack-NRAO delay residual plot of the solution using Marini's model shows a clear systematic drift for approximately 48 hours. The same drift is totally absent from the delay residual plot using the Old model. It appears that the Old model is absorbing some unmodelled effect whether it is atmospheric or not. One possible explanation is that the Old model is absorbing a six hour or 12 hour Earth tide. One solution was run allowing Love numbers to be estimated and using Marini's model. VLBI3 found a set of Love numbers drastically different from the accepted values and the six hour delay residual drifts remained. Another solution, when using the Old model, may be to use a different criterion for dtermining when to allow VLBI3 to calculate a new zenith delay. It is also possible that Marini's model may not be taking into account some unknown atmospheric effect. At the time of this writing, the question has not be answered.

Previous work by this author on the Haystack-Owens Valley baseline showed Marini's model could be used to estimate the baseline length to an accuracy of 5.2 centimeters. The results presented here do not support the 5.2 centimeter accuracy previously attained. An RMS scatter of approximately three centimeters in the baseline length was obtained by Doug Robertson, who also has been doing work in this area (ref. 9). He used Marini's model plus an estimated constant. The constant was added to the zenith delay and adjusted once per experiment. Robertson also used a different computer program which contained several improvements over VLBI3, among which were a new precession constant, a different Earth tide model and shorter period UT1 and nutation corrections.

In an attempt to see any differences in the two models, a few plots were made of elevations angles at Haystack and Owens Valley versus delay residuals. At low elevation angles, the effect of the atmosphere is greater because we are looking through more atmosphere. We expect to see a gradual increase in delay residual scatter at lower elevation angles. Theoretically, the scatter, which is more apparent at low elevation angles, will appear to be less in the model which is predicting the delay better. The plots, however, which did not show the expected pattern for the most part, are inconclusive and therefore have not been presented here.

CHAPTER 4

CONCLUSIONS

On the basis of this work, one cannot conclude that either model is superior in predicting atmospheric delay. Additional work must be done to determine what the large systematic drifts are in the delay residual plots of the solutions using Marini's model. The 20 to 30 centimeter baseline discrepancy, noted earlier, also must be resolved. Weather data should be taken more carefully and regularly at each site. Robertson's method of using Marini's model plus an adjusted constant should be investigated further. Work should also procede in the effort to use water vapor radiometers to measure refraction introduced by water vapor along the line of sight. Clearly, a good method of modelling the neutral atmosphere must be found before baseline length can be used to measure lithospheric plate motion.

Table I: Marini's Model Solutions

Haystack-Owens Valley

Date	Baseline(m.) 3928880 m. +	RMS Delay Residual(nsec.)
September 9-10, 1976	1.780	0.421
September 29-30, 1976	1.774	0.441
October 4-6, 1976	1.791	0.380
October 9-10,1976	1.770	0.556
October 11-12,1976	1.716	0.337
October 14-15, 1976	1.748	0.425
December 13-15, 1976	1.884	0.407
December 15-17, 1976	1.852	0.486
March 27-31, 1977	1.621	0.715
June 26-27, 1977	1.914	0.525
December 13-16, 1977	1.978	0.406
January 13-15, 1978	1.820	0.798
Mean	1.804	0.491
Standard Deviation	0.095	0.139

Haystack-NRAO

Date	Baseline(m.) 845100 m. +	RMS Delay Residual(nsec.)
October 9-10, 1976	30.173	0.700
October 11-12, 1976	29.933	0.515
December 13-15, 1976	30.044	0.395
December 15-17, 1976	29.965	1.020

Table I continued:

Date	Baseline(m.) 845100 m. +	RMS Delay Residual(nsec.)
March 27-31, 1977	30.153	0.890
June 26-27, 1977	29.899	1.15
Mean	30.03	0.778
Standard Deviation	0.115	

<u>Owens Valley-NRAO</u>

Date	Baseline(m.) 3324240 m. +	RMS Delay Resdiual(nsec.)
October 9-11, 1976	4.066	0.916
October 11-12, 1976	4.128	0.763
December 13-15, 1976	4.328	0.499
December 15-17, 1976	4.470	0.772
March 27-31, 1977	4.061	0.793
June 26-27, 1977	4.296	1.00
Mean	4.225	0.791
Standard Deviation	0.166	

Table II: Old Model Solutions

Haystack-Owens Valley

Date	Baseline(m.) 3928880 m. +	RMS Delay Residual(nsec.)
September 9-10, 1976	1.973	0.272
September 29-30, 1976	1.978	0.448
October 4-6, 1976	1.943	0.247
October 9-10, 1976	1.945	0.383
October 11-12, 1976	1.978	0.226
October 14-15, 1976	2.075	0.308
December 13-15, 1976	2.122	0.365
December 15-17, 1976	2.108	0.398
March 27-31, 1977	1.926	0.576
June 26-27, 1977	2.215	0.521
December 13-16, 1977	2.226	0.401
January 13-15, 1978	2.114	0.698
Mean	2.050	0.404
Standard Deviation	0.107	

Haystack-NRAO

Date	Baseline(m.) 845100 m. +	RMS Delay Residual(nsec.)
October 9-10, 1976	30.172	0.712
October 11-12, 1976	29.889	0.417
December 13-15, 1976	30.094	0.442

Table II continued:

Date	Baseline(m.) 845100 m. +	RMS Delay Residual(nsec.)
December 15-17, 1976	30.003	0.918
March 27-31, 1977	30.112	0.420
June 26-27, 1977	29.692	1.04
Mean	29.993	0.658
Standard Deviation	0.178	

Owens Valley-NRAO

Date	Baseline(m.) 3324240 m. +	RMS Delay Residual(nsec.)
October 9-10, 1976	4.506	0.715
October 11-12, 1976	4.471	0.552
December 13-15, 1976	4.578	0.487
December 15-17, 1976	4.652	0.535
March 27-31, 1977	4.342	0.696
June 26-27, 1977	4.494	1.13
Mean	4.507	0.691
Standard Deviation	0.105	

REFERENCES

1. Meeks, M.L. (Editor): Experimental Methods of Physics: Astrophysics Part C: Radio Observations, 1976 Academic Press.

2. Robertson, D.S.: "Geodetic and Astrometric Measurements with Very Long Baseline Interferometry", MIT Ph. D. Thesis, August 1975.

3. Snow, W.R.: "Atmospheric Refraction Errors in DLBI Observations at Low Elevation Angles", MIT Master Thesis, September 1977.

4. Saastamoinen, J.: "Atmospheric Correction for the Troposphere and Stratosphere in Radio Ranging of Satellites", American Geophysical Union Monograph 15, p.247.

5. Marini, J.W. and Murray, S.W. Jr.: "Correction of Radio Range Tracking Data for Atmospheric Refraction at Elevations Above 10^{o}", Memo, February 4, 1974.

6. Chao, C.C.: "A Model for Tropospheric Calibration from Daily Surface and Radiosonde Balloon Measurements", JPL Technical Memorandum 391-350, August 8, 1972.

7. Saastamoinen, J.: "Introduction to Practical Computation of Astronomical Refraction", International Union of Geodesy and Geophysics: Bulletin Geodesique 106, p.385.

8. Berman, A.L.: "The Prediction of Zenith Range Refraction From Surface Measurements of Meteorological Parameters", JPL Technical Report 32-1602, July 15, 1976.

9. Robertson, D.S.: Personal Communication, September 1978.

10. Clark, T.A. and others: "Radio Source Positions from Very Long Baseline Interferometry Observations", The Astronomical Journal 81 No. 8, p.599, August 1976.