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A VLBI VARIANCE-COVARIANCE ANALYSIS INTERACTIVE COMPUTER PROGRAM

by

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DEDICATION

To Lydia and Jonathan

PREFACE

This project is under the supervision of Professor Ivan I. Mueller, Department of Geodetic Science, The Ohio State University. The science advisor is Dr. David E. Smith, Code 921 and technical officer, Mr. Edmond C. Holweck, Code 902.2, NASA, Goddard Space Flight Center, Greenbelt, Maryland 20771.

This report is a modified version of a thesis submitted to the Graduate School of The Ohio State University as partial fulfillment of the requirements for the M.Sc. degree.

ABSTRACT

An interactive computer program (in FORTRAN) for the variance-covariance analysis of VLBI experiments is presented for use in experiment planning, simulation studies and optimal design problems. The interactive mode is especially suited to these types of analyses providing ease of operation as well as savings in time and cost. The geodetic parameters include baseline vector parameters and variations in polar motion and earth rotation.

A discussion of the theory on which the program is based provides an overview of the VLBI process emphasizing the areas of interest to geodesy. Special emphasis is placed on the problem of determining correlations between simultaneous observations from a network of stations. A model suitable for covariance analyses is presented. Suggestions towards developing optimal observation schedules are included.

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1. INTRODUCTION

"A marriage of convenience has been consummated between the disparate fields of geodesy and radio astronomy. The radio technique of very-long-baseline interferometry (VLBI) promises to have a profound effect on studies of the Earth. Whether such promises will be fulfilled remains to be seen."

[Counselman and Shapiro, 1978b]

1.1 Background

The application of VLBI to geodesy, geodynamics, and geophysics is an outgrowth of developments in the fields of radio astronomy. In order to obtain fine angular resolution in the study of the structure and size of extragalactic radio sources, discovered by Jansky in the early 1930's [Kraus, 1966], radio astronomers turned to interferometry. In conventional interferometry, two (or more) radio antennas, acting as one impractically large single antenna (increasingly finer angular resolution is roughly proportional to antenna diameter) are connected by cables whereby signals received from a radio source are compared instantaneously. The maximum separation in this mode is 10-20 km. With the development of very stable frequency standards and wide-band tape recorders, the real-time link between the antennas could be eliminated. Thus, the concept of very-long-baseline interferometry where antenna separation of thousands of kilometers is possible. In this mode, the received radio signals are tape recorded at each site and cross-correlated later at a central processing facility to recover the VLBI "observables" described in Chapter 2.

VLBI measurements, besides their radio-astronomy applications, supply information about baseline components and distances, radio source coordinates, polar motion, UT1, precession and nutation, and solid earth tides. However, except for baseline distances and radio-source declinations, all the remaining geodetically relevant parameters are non-estimable unless defined as variations (in polar motion, etc.) as will be explained in Chapter 3. Anticipated observational accuracies, resulting from increasingly better instrumentation, and improved mathematical models should make the monitoring of a global tectonic plate motions, continental drift and crustal deformations feasible.

The astronomic applications of VLBI include the possibility of classifying a number of radio sources as fixed, in order to define an absolute extra-galactic coordinate system. A list of such sources has been proposed in [Elsmore and Ryle, 1976]. There are presently several hundred known radio sources. With the Mark I recording system less than 20 sources were of sufficient strength for geodetic applications. With the state-of-the-art Mark III recording and processing system (see [Ma, 1978; Clark, 1979a] for a description), this number should be increased considerably, thereby improving the distribution of sources in the sky.

The first VLBI experiments were conducted in the late 1960's [Broten et al., 1967; Bare et al., 1967; Hinteregger et al., 1972]. Since then, many experiments have been performed by groups in the United States (the "East coast" and "West coast"), Canada and Europe, too numerous for all to be described here. At present, baseline lengths of up to several thousand kilometers have been measured with a repeatability of under 5 cm [Shapiro, 1978]. A 1.24 km baseline vector has been determined with approximately 5 mm repeatability from VLBI observations [Rogers et al., 1978]. Measurements of the same baseline by conventional geodetic techniques compared encouragingly well at the few millimeter level [Carter, 1979]. A 42-km baseline measured with portable VLBI antennas and conventional methods compared to within a decimeter in length [Niell, 1979]. Variations in polar motion and UT1 have been estimated at the decimeter and millisecond levels respectively. In a series of experiments, polar motion results agreed well with IPMS and Doppler results, but a systematic difference was detected with BIH values [Robertson et al., 1978]. From the same experiments, VLBI and BIH UT1 results were found to differ by about $0^s.002$ rms. Fanselow et al. [1979] reported measurements of earth rotation parameters at the $0''.01$ accuracy level that compared well with lunar laser ranging (LURE) results. Although the accuracy of VLBI parameter estimation is not yet completely clear, the above results are good indications that "promises will be fulfilled." Recent VLBI-satellite laser intercomparison experiments using the Mark III system will provide independent checks on accuracy and hopefully point to unmodelled systematic errors. At present, the primary limiting factors on accuracy are clock behavior and the propagation medium, particularly the wet component of the troposphere. Other factors include uncalibrated instrumental errors, inadequate modelling of geophysical and relativistic effects, source structure and gravitational flexure of the larger telescopes.

Besides its excellent angular resolution and impressive accuracy, VLBI provides several other advantages. VLBI measurements are independent of the Earth's gravity field. In addition, since the antennas receive microwave radiation, VLBI has practically all weather capabilities. On the other hand, the necessary equipment is expensive and the availability of permanent antennas is limited. The latter problem can be remedied by the use of portable antennas such as those of the Astronomical Interferometric Earth Survey (ARIES) system [MacDoran et al., 1978]. An interesting list of radio interferometry "advantages and disadvantages" as well as for Doppler, satellite laser ranging and lunar laser ranging techniques is given in [Mulholland, 1978].

The next decade will see VLBI move into the operational stage as the following examples illustrate. The NASA Geodynamics Program will concentrate on the detection of crustal movements by VLBI and satellite laser techniques. A Crustal Dynamics Project has been established at Goddard Space Flight Center for this purpose [NASA, 1979a]. The Polar Motion Analysis by Radio Interferometric Surveying (Polaris) project is planned for the early 1980's [Carter, 1978]. Its goal is to establish and operate a three-station VLBI network to monitor polar motion and earth rotation on a regular basis. It is anticipated that small portable interferometer terminals, receiving signals from Global Positioning System (GPS) satellites, will yield several millimeter accuracy for baseline lengths up to several hundred kilometers. These systems, operating on the same basic principles of VLBI as described in this thesis, are now being developed. They include Miniature Interferometer Terminals for Earth Surveying (MITES) [Counselman and Shapiro, 1978a] and Satellite Emission Radio Interferometric Earth Surveying (SERIES) [MacDoran, 1978].

For a detailed history of VLBI development as well as an extensive bibliography, see [Benjauthrit, 1978a and b]. A list of the various agencies participating in VLBI development and a description of several of their experiments are found in [Campbell, 1979]. Fanselow [1978] gives a summary of completed as well as current VLBI programs. The proceedings of the Radio Interferometry Techniques for Geodesy conference contains the most up-to-date description of the present status of VLBI [NASA, in press]. Other valuable references, especially for geodetic applications, include [Thomas, 1972a and b, 1973; Whitney, 1974; Robertson, 1975; Dermanis, 1977; Ma, 1978; Shapiro, 1978].

1.2 Purpose of the Report

A VLBI covariance analysis Interactive Program (VIP) is presented for use in simulating and planning VLBI experiments. An explanation of the theory and mathematical models on which this program is based is intended to provide an overview of VLBI for those interested in applying the VLBI technique to geodetic activities.

VIP provides an upper limit on accuracy attainable for the VIP parameter set given the planned station configuration and source schedule of a particular experiment and the a priori noise estimates of delay and delay rate measurements. Only random errors are assumed and there is no provision for systematic effects except for a simple two-term polynomial to model errant clock behavior. Therefore, it is not expected that this type of analysis will reflect the actual performance of a particular experiment which may be several times worse than the a priori numbers indicate. Nevertheless, a covariance analysis is useful in comparing the relative effects of different station locations and observation schedules. Ultimately, the geometrical strength of a given experiment is of primary importance in optimal parameter estimation.

The choice of parameter set was influenced by studies of different observation schedules for the Polaris network mentioned above. Therefore, the main emphasis is on estimation of earth orientation parameters including variations in polar motion and earth rotation as well as on baseline vector parameters.

At its early stages of development, VIP was run in the batch mode. It was decided to modify the various routines to run in the interactive mode using the Time Sharing Option (TSO) and Tektronix terminals at the OSU Instruction and Research Computer Center (IRCC). In this mode, the user is able to simulate an experiment, view the results in real-time, and rerun through the program with the option of changing any or all of the initial input parameters. This process may be repeated as many times as desired with one loading of the program. Thus, the interactive mode is found to be ideal for this type of analysis, offering ease and flexibility of operation as well as savings in time and cost.

In all of the modern geodetic "space" systems, the geodesist has moved further away from the actual measurement process. In VLBI we are presented with a list of "observables," themselves estimated by a complex procedure requiring sophisticated instrumentation developed by electrical engineers and radio astronomers. It is important to obtain familiarity with this measurement process (summarized in Chapter 2). With this background, the geodesist can address such problems as optimal experiment simulation and planning, development of improved mathematical models, sound statistical analysis of data and correct adjustment philosophy, and, finally, can apply VLBI data to geodesy and its related fields. These problem areas will be discussed and topics for future research presented.

1.3 Organization and Scope

Chapter 2 covers the basic geometry of VLBI observations, the necessary instrumentation, and explains the process by which the raw observed data is transformed into the "observables" of the least squares adjustment from which the geodetic parameters are estimated. In Chapter 3 the mathematical models used in VIP are described as well as possible model refinements. A summary of VLBI estimable parameters is included. A model, suitable for covariance analyses, is presented for determining the correlations between simultaneous VLBI observations at a given epoch. Singularity problems arising from coordinate system definition, observability conditions and critical configurations are enumerated. An approach to observation schedule optimization is described in Chapter 4. This last chapter also discusses the problems related to obtaining correlations between simultaneous VLBI observations. Appendix A includes a documented listing of VIP plus explanatory tables and figures. Appendix B contains the hard copy of a sample run as viewed on the interactive screen.

2. THE MEASUREMENT PROCESS

2.1 Introduction

In this chapter the basic VLBI observables are described. First, their purely geometric interpretations are presented followed by a discussion of the quantities that are actually measured. A brief description of the VLBI hardware is given, as well as the process by which the observables are estimated. This will be of a general nature only and the technical details may be found in the references. Expressions for the precision of the observables are included. Finally, systematic errors that affect the measurement process and, thus, the estimation of geodetic parameters are summarized. Figure 2.1 (from [Fanselow, 1978]) illustrates the measurement process and, therefore, the contents of this chapter. The parameter solution will be described in the next chapter.

2.2 Observables

2.2.1 Basic Observables

A VLBI baseline consists of one antenna at each end, simultaneously observing the random radio signals emitted from a compact extra-galactic source (e.g., a quasar). A particular segment of a wavefront will arrive at one antenna later than at the other as a result of the difference in path length to each station. This time delay is

DATA ACQUISITION AND PROCESSING FLOW FOR VLBI

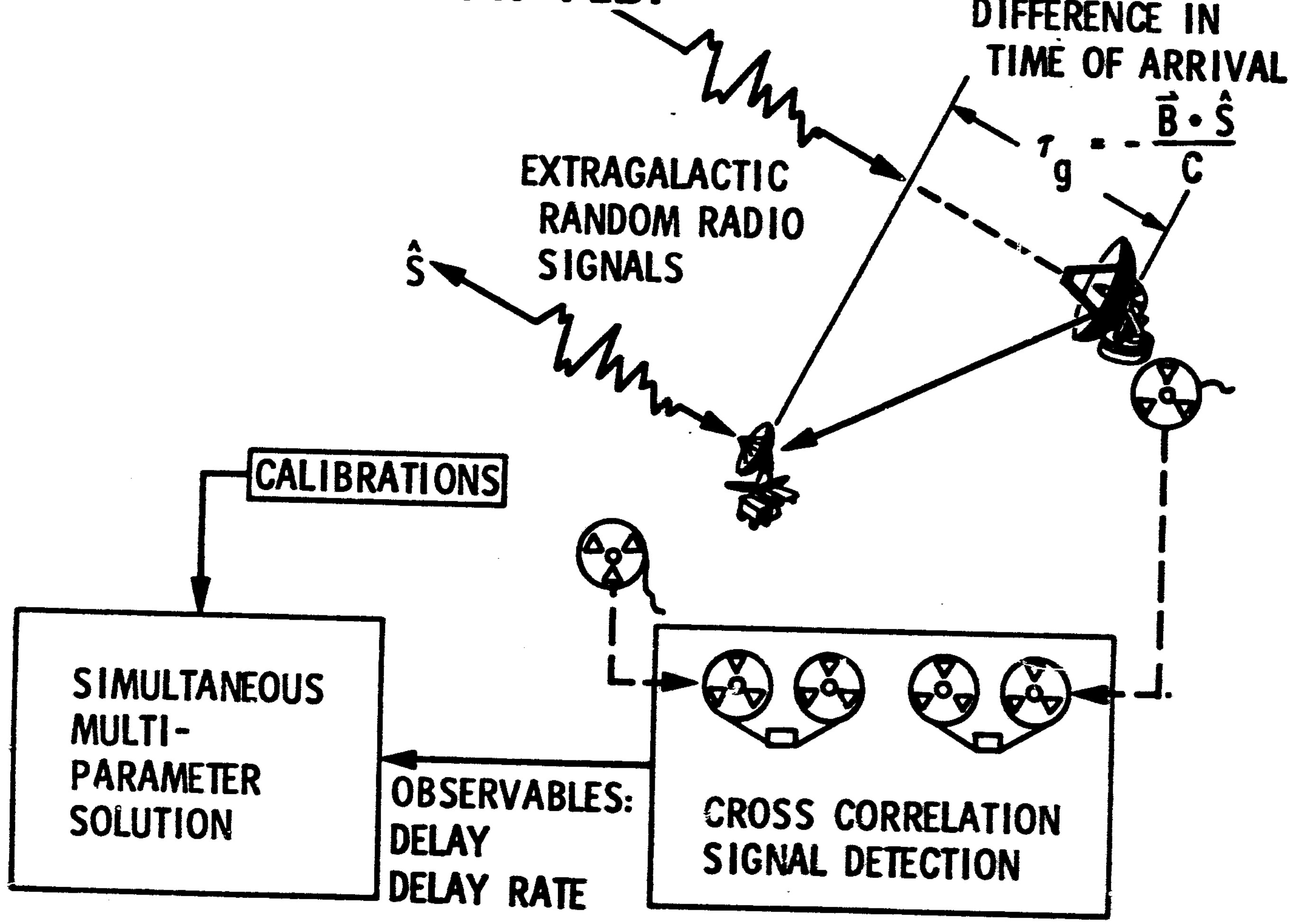

Figure 2.1

primarily a function of the location of the source in the extra-galactic frame and the baseline vector fixed to the rotating deformable earth. In Figure 2.2, from [Ma, 1978], we view the equatorial projection of a VLBI baseline at two different epochs. The path length difference is given by $c\tau_1$ and $c\tau_2$, respectively, τ_1 and τ_2 are the time delays at the two epochs and c, the speed of light. As can be seen in the figure, the time delay changes with time. Its rate of change is called the time delay rate.

The time delay and time delay rate contain the geodetically relevant information. Any phenomena that affects these quantities can be theoretically parameterized in the mathematical model. The orientation of the baseline with respect to the "inertial" frame is affected by polar motion and UT1 variations. Therefore, the observables are sensitive to these changes although not to the absolute orientation of the baseline, as will be explained in the next chapter. The baseline vector is affected by solid earth tides and geodynamic phenomena such as crustal motion. The source unit vector is affected by precession and nutation. The estimable parameters will be defined in the next chapter, but it suffices to mention here that the observables are sensitive to these and other phenomena as well as to baseline vector and source coordinate parameters.

2.2.2 Geometric Observables

In this section, the geometric definition of the observables are presented under the assumption of perfect instrumentation and of radio waves propagating in vacuum from a point source. The actual physical

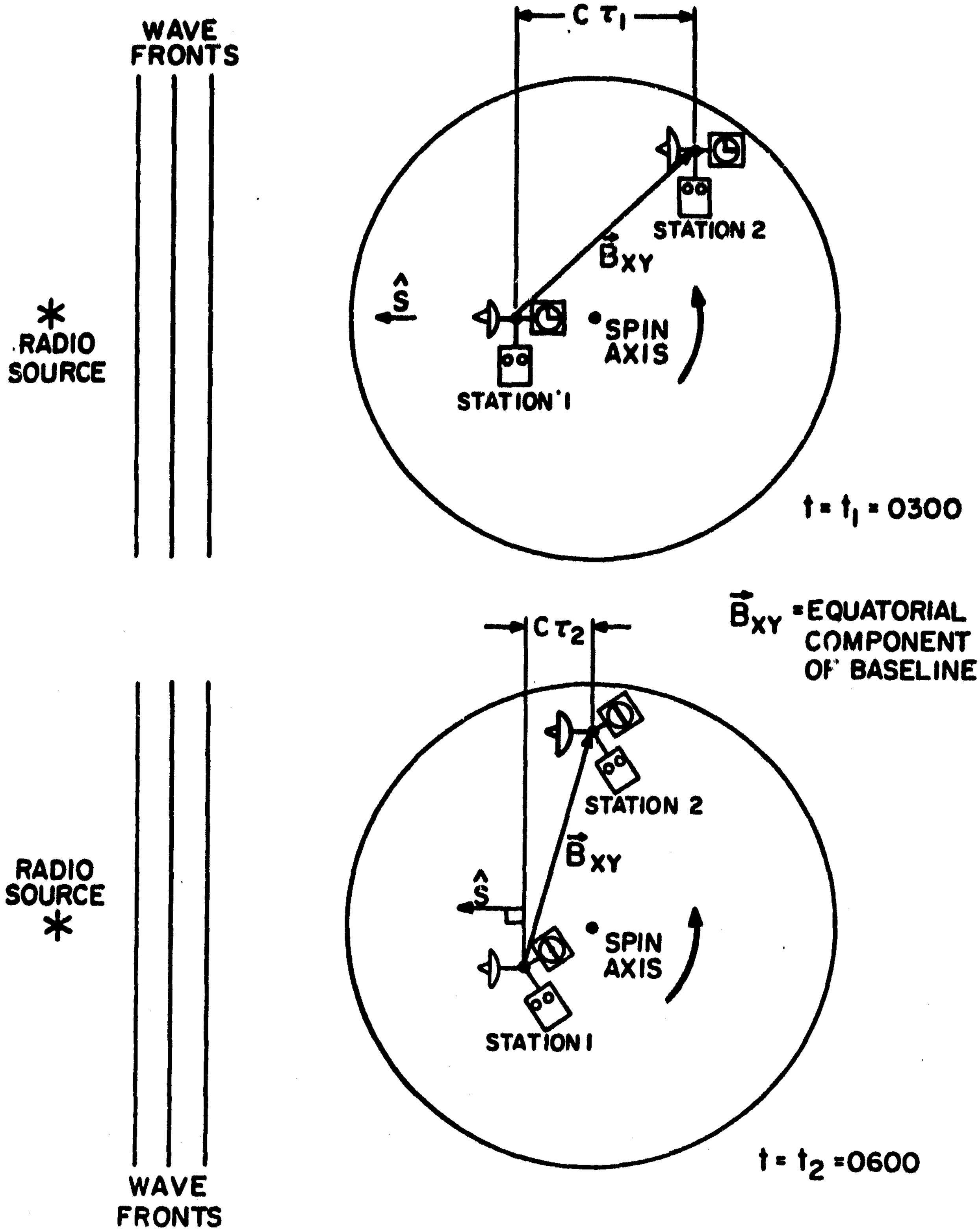

Figure 2.2 VLBI Geometry on a Rotating (Earth) Platform

conditions are, of course, quite different making the measured observables vary considerably from their geometric counterparts. Some of these effects may be modelled better than others but all serve to complicate geodetic parameter estimation. They are described in section 2.4. The measured observables, as will be seen in the next two sections are estimated by cross correlation of the tape recordings of the received signals.

The basic geometry for a typical baseline is shown in the figure below.

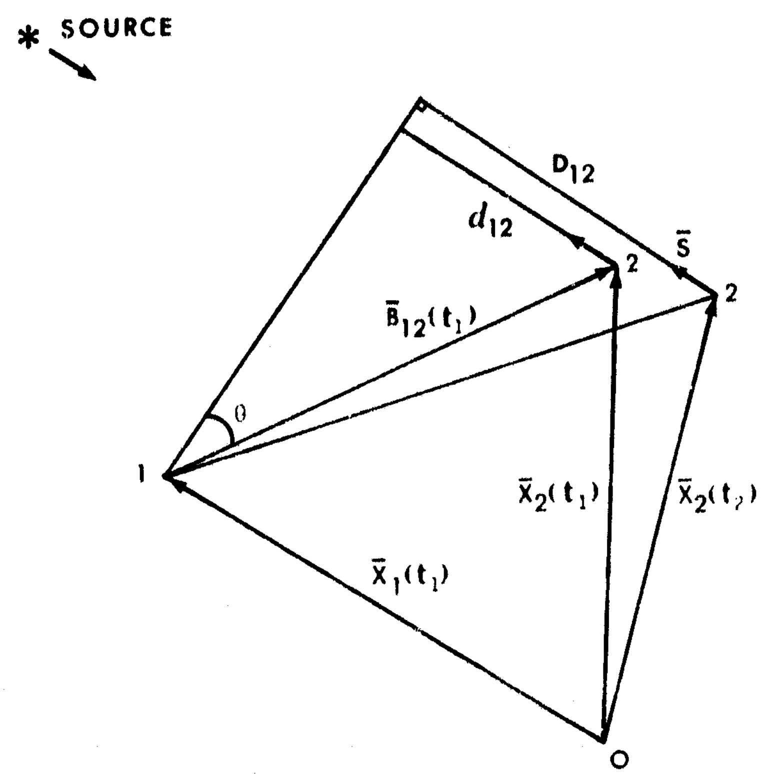

Figure 2.3. Geometry of a Time Delay Observation

A certain segment of a wavefront arrives at antenna 1 at time t_1 and antenna 2 at time t_2. The station 1 vector at time t_1 is $\bar{X}_1(t_1)$, the station 2 vector at time t_2, $\overline{X}_2(t_2)$. The station position vectors are assumed for this discussion to be given in a geocentric Cartesian reference frame fixed with respect to the radio sources (assumed to be an inertial frame). From Figure 2.3

$$D_{12} = -[\overline{X}_2(t_2) - \overline{X}_1(t_1)] \cdot \overline{s} \tag{2.2-1}$$

where $\overline{s}$ is the unit vector in the direction of the source. The geometric time delay is, therefore

$$\tau_g = t_2 - t_1 = \frac{D_{12}}{c} \tag{2.2-2}$$

In the interval of time, τ_g, station 2 has rotated by a small amount due to the earth's rotation. Since τ_g is small (its maximum value is approximately 0.02 sec) we can write as a linear approximation

$$\overline{X}_2(t_2) = \overline{X}_2(t_1) + \frac{d\overline{X}_2(t_1)}{dt}\tau_g \tag{2.2-3}$$

From (2.2-1) - (2.2-3)

$$\tau_g = -\frac{\overline{B}_{12}(t_1) \cdot \overline{s}}{c} + \frac{\tau_g \overline{V}_2(t_1) \cdot \overline{s}}{c} \tag{2.2-4}$$

where

$$\overline{B}_{12}(t_1) = \overline{X}_2(t_1) - \overline{X}_1(t_1) \tag{2.2-5}$$

is the instantaneous baseline vector at epoch t_1 and

$$\overline{V}_2(t_1) = \frac{d\overline{X}_2(t_1)}{dt} = \overline{\Omega} \times \overline{X}_2(t_1) \tag{2.2-6}$$

$\overline{\Omega}$, the earth rotation vector (at t_1). Notice that $\overline{V}_2(t_1)/c$ multiplied by the frequency of the received signal is the Doppler frequency shift.

In the remainder of the thesis, the speed of light will be set to unity so that the time delay will be expressed in units of distance. From (2.2-4) the time delay is seen to be composed of two parts. The first term is the projection of the instantaneous baseline vector (at t_1) in the direction of the source. The second term is the motion of station 2 during the wave transit. It is of small magnitude and can be accurately calculated based on a priori information. Therefore, it can be neglected in developing the mathematical models in the next chapter. The time delay which is now in distance units will be expressed there as

$$d_{ijk} = -\bar{B}_i(t_j) \cdot \bar{s}_k \qquad (2.2\text{-}7)$$

where the subscript i refers to the i^{th} baseline, k to the k^{th} source and j to the j^{th} epoch of observation.

The time delay rate is then

$$\dot{d}_{ijk} = -\frac{d\bar{B}_i(t_j)}{dt_j} \cdot \bar{s}_k \qquad (2.2\text{-}8)$$

assuming that $\dot{\bar{s}}_k = 0$.

2.2.3 Measured Observables

The velocity of electromagnetic radiation passing through the atmosphere (a dispersive medium) can be divided into two categories, the group velocity and the phase velocity. Therefore, measurement of the difference in times of arrival may be of two types: the phase delay difference (called simply the phase delay) or the group delay difference (group delay) [Shapiro, 1978]. Theoretically, the phase delay could be calculated by dividing the phase difference of the recorded data streams (called the fringe phase) at a particular epoch by the (angular) frequency of the incoming signal. However, the fringe phase is ambiguous to some integer multiple of 2π, thereby inflicting closely spaced ambiguities on the phase delays which are difficult to resolve. The group delay, the derivative of the fringe phase with respect to angular frequency can be, theoretically, estimated unambiguously by measuring fringe phase over a wide band of frequencies. A simple example, based on a discussion by [Molinder, 1978], will illustrate these points. Suppose that ϕ_{f_1} and ϕ_{f_2} are the fringe phases at frequencies f_1 and f_2. Then

$$\begin{aligned} \phi_{f_1}(t) &= 2\pi f_1 \tau + 2\pi m \\ \phi_{f_2}(t) &= 2\pi f_2 \tau + 2\pi n \end{aligned} \tag{2.2-9}$$

where τ is the time delay, $2\pi m$ and $2\pi n$ the ambiguities, m and n integers. If the uncertainty in the slope of fringe phase versus frequency is less than $2\pi/(f_2-f_1)$ then the ambiguities may be resolved and the time delay is given by

$$\tau = \frac{\phi_{f_2} - \phi_{f_1}}{2\pi(f_2-f_1)} \tag{2.2-10}$$

Thus, f_1 and f_2 must be spaced close enough so that the ambiguities may be resolved based on a priori information. A third frequency f_3 can then be spaced at an interval larger than $f_2 - f_1$ because of the more accurate slope available from the previous determination. This procedure can be extended over several frequency bands, thus, the bandwidth synthesis technique [Rogers, 1970; Whitney et al., 1976]. The wider the bandwidth, the more accurate the measurement of group delay. In the

Mark III system, 28 narrow frequency bands, each 2 MHZ wide, are distributed over a total of up to 400 MHZ [Shapiro, 1978].

Thus, the group delay is the measured time delay. In practice, the group delays do have ambiguities but these can be eliminated by examination of their residuals from an initial least squares adjustment [Robertson, 1975].

The fringe rate is the second, and less important, estimated observable. It is the time derivative of the fringe phase. We will deal with the phase delay rate which is the fringe rate divided by the angular frequency. The phase delay rate is the measured time delay rate. One advantage of the phase delay rate (or the fringe rate) is that it can be determined unambiguously without resorting to bandwidth synthesis, and therefore requires relatively simple equipment. However, it suffers from several geometric disadvantages described in section 3.2.4 and is much less precise compared to the group delay.

From this point on, we shall use the terms delay and delay rate for the measured observables.

2.3 Data Acquisition and Observable Estimation

The Mark III field system (see Figure 2.4 taken from [Ma, 1978]) is the state of the art in VLBI data acquisition hardware. This system, in conjunction with a radio antenna and environmental sensors, consists of basically a receiver, a frequency standard, a recorder and a phase calibrator. The entire system is run by the VLBI controller, an HP 1000 mini-computer. Using schedule input, the controller sets the receiver and recorder configurations, directs the telescope to a particular

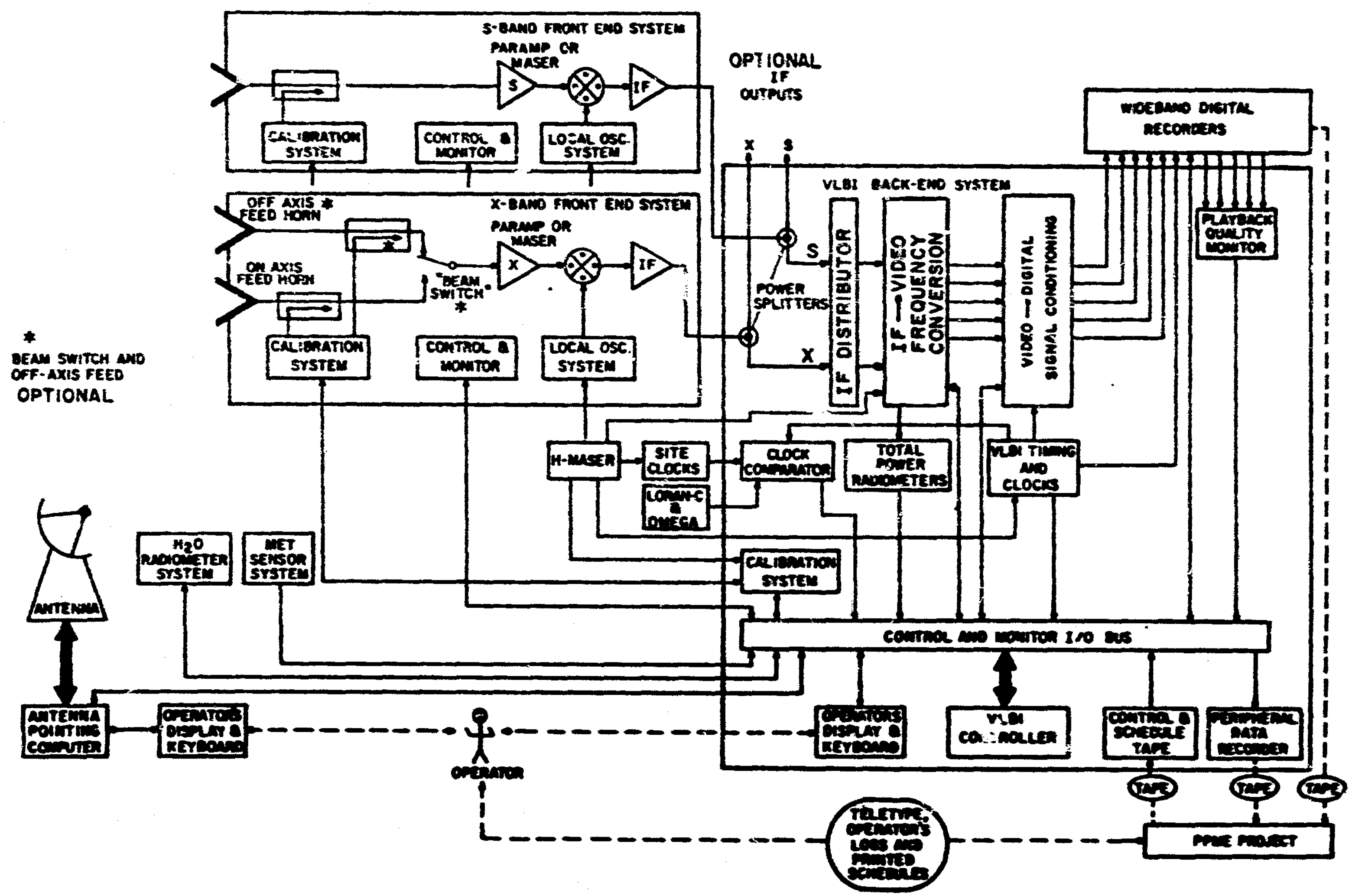

Figure 2.4 Mark III Field System

source, starts and stops the data drives, monitors the system's functions and logs all necessary information [Ma, 1978].

Local oscillator signals, derived from the frequency standard, are mixed with the received radio-frequency signals. Several or all of the 28 possible channels are selected at all stations and are sampled, one channel per record of tape. The resulting intermediate-frequency signals are converted to video signals which are recorded on magnetic tape. For each tape record, the time epoch, derived from the frequency standard, is recorded. See [Whitney et al., 1976] for a detailed description of the system components.

The phase calibration system is used to reduce the dispersive effects of the instrumentation and to measure the timing cable length [Whitney et al., 1976; Thomas, 1978; Rogers, 1979].

At each station environmental sensors record temperature, humidity and pressure. A water vapor radiometer, if available, measures water vapor path delay [Claflin et al., 1978; Resch et al., 1979; Moran, 1979].

The tapes from the participating stations are sent to a central processing facility for cross correlation. This involves reconstructing the radio-signal transmission process. A model delay $\hat{\tau}$ is computed to a good approximation based on a priori information. The data streams from two tapes are offset by $\hat{\tau}$ and the signals are multiplied together. The theoretical cross correlation function is given by

$$\int_{-\infty}^{\infty} X_1(t)X_2[t + (\tilde{\tau}+\dot{\tilde{\tau}}t)]dt \qquad (2.3\text{-}1)$$

where X_1 and X_2 are the signals received at station 1 and 2, respectively. Over the integration period (typically 3 minutes) the model time delay is approximated by

$$\hat{\tau} = \tilde{\tau} + \dot{\tilde{\tau}} t \qquad (2.3\text{-}2)$$

where $\tilde{\tau}$ is a constant delay and $\dot{\tilde{\tau}}$ is the delay rate. Maximizing the correlation function with respect to $\tilde{\tau}$ and $\dot{\tilde{\tau}}$ results in the maximum likelihood estimates of delay and delay rate [Whitney, 1974]. The actual cross correlation process is described in [Thomas, 1972a,b; Whitney et al., 1976]. The statistical model for the estimation of the observables is developed in [Whitney, 1974].

Precision estimates for the delay and the delay rate can be computed as a function of the system characteristics. However, they do not include error sources such as the propagation medium, instrumental effects and modelling errors all described in section 2.4. The precision for delay is given in [Counselman et al., 1979] as

$$\sigma(\tau) = \frac{1}{\Delta f_{sp} \frac{S}{N}} \qquad (2.3\text{-}3)$$

indicating that it is inversely proportional to the spanned bandwidth Δf_{sp} and the signal-to-noise ratio (S/N) where

$$\frac{N}{S} = \sigma(\phi) \simeq 3.2 \times 10^3 \left(\frac{T_{s_1} T_{s_2}}{N_t}\right)^{1/2} \frac{1}{D_1 D_2 (\varepsilon_1 \varepsilon_2)^{1/2} F} \text{ seconds (s)} \qquad (2.3\text{-}4)$$

where

D_i the antenna diameter at the i^{th} station (m)

Δf_{sp} spanned bandwidth (Hz)

N_t number of tape-recorded and cross correlated samples

T_{s_i} the system temperature at the i^{th} site (°K)

ε_i the antenna efficiency at site i

F the correlated flux density (Janskys)-(that fraction of the total flux density from the source that "survives" cross correlation)

$\sigma(\phi)$ is the uncertainty in the estimation of the fringe phase, ϕ, from each of the narrow separate bands. As an example for a typical Mark III 3-minute observation,

$D_1 = D_2 = 50$ m

$\varepsilon_1 = \varepsilon_2 = 0.5$

$F = 1$ Jansky

$T_{s_1} = T_{s_2} = 100°K$

$\Delta f_{sp} = 400$ MHz

$N_t = 14(7.2 \times 10^8)$ bits (based on a 4 mbit/s sampling rate per track)

we arrive at $\sigma(\tau) \simeq 6.4$ picoseconds (ps).

At the present state of the art, the delay precision ranges below the cm level for a 3 minute integration period. It can be seen from (2.3-4) that an increase in the spanned bandwidth will allow deployment of a smaller antenna at one of the sites and not incur any loss in precision. The precision of delays is inversely proportional to the correlated flux density. However, on long baselines many of the compact sources are partially resolved since angular resolution improves with baseline length. This results in a decrease of F so that sources which show strong fringes on baselines of a few hundred km become very weak on intercontinental baselines.

An expression for delay rate precision is

$$\sigma(\dot{\tau}) = \frac{\sqrt{12}}{\omega_k t \frac{S}{N}} \text{ s/s} \qquad (2.3\text{-}5)$$

where t is the total integration time and ω_k is the root-mean square of the sampling frequencies [Whitney, 1974].

2.4 Deviations from the Geometric Model

The product of cross correlation is a set of estimated delay and delay rates, and their precision estimates. The geometric observables have been described in section 2.2.2. It is left to describe those physical effects that cause the group delay and phase delay rate to differ from their corresponding geometric counterparts. These arise from instrumental imperfections, source structure, the propagation medium and other factors, all described briefly in this section. For more details, appropriate references are given.

The frequency standards located at the various sites must have short- and long-term stability. The former insures that the relative phase of the signals can be accurately recovered through cross correlation. The use of hydrogen masers effectively eliminates errors of this sort. The long-term stability of the clocks is necessary in order to keep accurate time and prevent drifts in the relative clock behavior. This stability may falter at intervals of time as short as eight hours. In this time period, if the long-term stability of the clock was approximately 1×10^{-14}, as can be achieved (or better) at present in the laboratory, this would lead to an error of 0.3 nanoseconds (ns) in time delay corresponding to an error of several cm in baseline length depending on the baseline chosen, if not corrected. Hydrogen masers, moreover, have been found in field work to be influenced by atmospheric conditions and other environmental factors. Systematic patterns in the least-squares residuals may indicate poor clock behavior. The usual remedy is to model these errors by polynomials as done in the next chapter. Other techniques include differencing of observations [Robertson, 1975] and the use of "clock stars" [Shapiro, 1979]. Anticipated technical improvements in frequency standards and improved models will substantially reduce clock errors. See [Robertson, 1975] for a good example of how errant clock behavior is handled. The performance of hydrogen masers is discussed in [Vessot, 1979] and [Reinhardt et al., 1979].

Other instrumental errors are caused by retardation and dispersion of the signal as it passes through the cables and receiver components. These effects which can be of the order of several tenths of nanoseconds can be reduced significantly by phase calibration and cable measurement systems [Rogers, 1979].

Source structure introduces unwanted noise (from the geodetic point of view) into the observables. The radio-sources are not generally point-sources as assumed in section 2.2.2, and may exhibit complicated structure. Source structure maps are developed by radio astronomers which can be used to define a reference point for the source coordinates. Most of this information is derived by examining phase closures around a triangle of stations since all other systematic errors cancel out. See [Hutton, 1976] and [Cotton, 1979] for more details on source structure.

As in most geodetic systems, the propagation medium is the ultimate limit on accuracy. The effects of the ionosphere can be virtually eliminated by observing enough sources in two widely spaced frequency bands or by choosing a relatively high center frequency for which the ionospheric effects would be small [Whitney et al., 1976]. These errors can be reduced to well under 0.03 ns in delay [Counselman, 1976]. The dry component of the troposphere which introduces an error in the time delay of up to 7 ns at the zenith can be modelled quite well based on recordings of surface metereological data. In addition, it can be parameterized by a zenith distance thickness parameter scaled as a function of elevation angle [Ma, 1978]. The wet component of the troposphere poses the most serious problems though its effect is less than 1 ns in delay. The water vapor in the troposphere changes with respect to time and direction of observation. It is hoped that with water vapor radiometry the total uncertainty in tropospheric error can be reduced from about 0.1 ns for the zenith direction to 0.03 ns. These errors map particularly into the vertical component of the baseline.

As the accuracy of VLBI observations increases and especially for longer baselines, relativistic effects must be considered. Electromagnetic waves are deflected by the gravitational field of the sun according to Einstein's theory of general relativity, thereby affecting the time delay. For further details, see [Thomas, 1972], [Robertson, 1975] and [Gourevitch et al., 1979].

Another effect includes the gravitational flexure of large radio telescopes which changes the location of the VLBI antenna reference point [McGinnis et al., 1979]. For example, in the comparison of the Haystack-Westford baseline vector measured with VLBI and classical geodetic methods there was a difference in the vertical component of 19 mm as compared to 2 and 4 mm in the two horizontal components.
By correcting for the gravitational flexure of the Haystack antenna the discrepancy in the vertical component was reduced to 6 millimeters [Carter, in press].

Inadequate geophysical modelling will also introduce systematic errors into the estimation process. These include errors in nutation, precession, UT1 and polar motion as well as incorrect earth tide and ocean loading models. These effects will be discussed in more detail in Chapter 3.

The adequate modelling or elimination of systematic effects will determine the attainable accuracies for geodetic and related parameters. This is especially crucial for the detection of geodynamic phenomena.

3. MATHEMATICAL MODELS

3.1 Introduction

In this chapter, the various mathematical models used in the VLBI Interactive Program (VIP) are described. In section 3.2, the mathematical models for the VLBI observables are derived. In section 3.3, singularity problems due to coordinate system definition, observability conditions and critical configurations are summarized. Finally, in section 3.4, the radio-source observability equations are given.

The choice of a parameter set for VIP was influenced by optimization studies related to the Polaris network. Therefore, the stress is on earth orientation variation parameters. Of course, baseline parameters are also of primary interest. Source coordinates are needed in order to develop a reasonably accurate catalogue from which more accurate geodetic parameter estimation will follow. Clock parameters, though of no direct interest here, are necessary to make the analysis more realistic. Atmosphere parameters, though not included in VIP, may be useful if metereological data is not sufficient [Ma, 1978]. Smaller effects that require long observational campaigns (e.g., geodynamic phenomena, precession, nutation) have not been parameterized.

The adjustment philosophy has been to avoid weighted parameters, rather to define estimable parameters which implicitly supply the minimal constraints needed for invertibility of the normal matrix. All parameters are estimated from the observations themselves without resorting to external information.

3.2 Least Squares Adjustment Mathematical Models

3.2.1 Introduction

In section 3.2.2 the "inertial" and terrestial coordinate systems are defined. The mathematical models for delay and delay rate observations are presented in section 3.2.3 and 3.2.4, respectively. For each observable, the estimable parameters are defined. Section 3.2.5 is a description of the least squares algorithm. In section 3.2.6 a simple model, suitable for covariance analyses, is presented for computing the correlation between delays observed simultaneously at a given epoch, from a multistation configuration. Possible model refinements are discussed in section 3.2.7.

3.2.2 Coordinate Systems Definition

In analyzing VLBI observations an "inertial" and terrestial coordinate system need to be defined. In practice, a "nearly" inertial frame is defined with its origin at the solar system barycenter. The first axis is directed towards the mean vernal equinox at some reference epoch, conventionally 1950.0 and the third axis is perpendicular to the mean equator and positive northward. The second axis completes a right-handed Cartesian coordinate system. The theoretical calculation of delay and delay rates are performed according to the laws of general relativity in this coordinate system [Counselman, 1976].

Expressions for these observables are derived relativistically by [Robertson, 1975]. Since arrival times are measured by atomic clocks at the various stations, they must be transformed to coordinate time of solar-system barycentric coordinates [Robertson, 1975, appendix B]. The transformations from the geocentric origin to the solar-system barycenter is done using a planetary ephemeris. It should be noted that the use of the above coordinate system implicitly includes the effects of annual and diurnal aberration [Ma, 1978]. The reason for this coordinate system definition is to be able to easily combine VLBI observations with spacecraft tracking and interplanetary radar data.

In VIP, it is assumed that the source positions have been updated to their true-of-date coordinates at the initial epoch of observation (precession and nutation corrections are not applied in the program). In addition, it is assumed that the observables have been corrected for aberration and for relativistic effects. Therefore, the "inertial" coordinate frame is taken as a true-of-date geocentric system defined at the initial epoch of observation.

The terrestial (earth-fixed) coordinate system is defined with the X-axis directed towards the Greenwich mean astronomic meridian determined by the BIH. The Z-axis is towards the average north terrestial pole (the CIO pole). The Y-axis completes a right-handed Cartesian coordinate system. The origin of this system is arbitrary since the mathematical models only contain baseline coordinate differences. In the VIP experiments the station coordinates are taken in NASA's Spacecraft Tracking and Data Network System (STDN) system. In practice, the origin is usually defined by the adopted coordinates of one VLBI antenna, given in some terrestial system.

The reference orientation of the baseline vector with respect to the true-of-date system must be defined externally at the initial epoch since VLBI observations are only sensitive to the relative orientation of the baseline vector as will be discussed in the next section.

3.2.3 Time Delay Model

The geometric delay was defined by (2.2-7) as

$$d_{ijk} = -\overline{B}_i(t_j) \cdot \overline{s}_k$$

which represents the inner product of the i^{th} baseline vector in the terrestial frame and the k^{th} source unit vector transformed from the true-of-date system into the terrestial frame at epoch t_j. Remember that the delay is given in units of distance. Adding a two term polynomial, whose coefficients Δc_{0i} and Δc_{1i} correspond to a relative offset and rate, respectively, between the two clocks at the ends of the i^{th} baseline, the delay can be written as,

$$d_{ijk} = -\overline{B}_i^T R_2(-\xi_j) R_1(-\eta_j) R_3(\theta_j) \overline{s}_k + c[\Delta c_{0i} + \Delta c_{1i}(t_j - t_0)] \qquad (3.2\text{-}1)$$

where θ_j is the Greenwich Apparent Sidereal Time (GAST) at epoch t_j

ξ_j, η_j are the components of polar motion that relate the true celestial pole ("instantaneous" rotation axis of the earth) to the average terrestial pole at epoch j (ξ_j is defined as positive along the Greenwich meridian and η_j along the 270°E meridian) c the speed of light

t_0 the initial epoch of observation (in VIP taken as 0^h UT of initial day of observations)

The R_i matrices represent (right-hand) rotations about the subscripted i^{th} axis by the angular argument in parentheses [Mueller, 1969]. The GAST, θ_j can be rewritten as follows

$$\begin{aligned}\theta_j &= \theta_0 + W_d UT1_j \\ &= \theta_0 + W_d[TAI-(TAI-UTC) - (UTC-UT1)]_j \\ &\quad + Eq.\ E.\end{aligned} \tag{3.2-2}$$

where θ_0 GAST at 0^h UT of the initial day of observations

Eq. E. equation of the equinoxes

TAI international atomic time

UTC coordinated universal time

UT1 observed universal time corrected for polar motion

W_d conversion factor from universal to sidereal time.

In practice, UTC-UT1 is interpolated from BIH Circular D five day values. For purposes of brevity, let us denote

$$\kappa_j = (UTC-UT1)_j$$

at the j^{th} epoch. Since ξ_j and η_j are small quantities, expression (3.2-1) may be rewritten as

$$d_{ijk} = -[\Delta X_i \Delta Y_i \Delta Z_i] \begin{bmatrix} 1 & 0 & \xi_j \\ 0 & 1 & -\eta_j \\ -\xi_j & \eta_j & 1 \end{bmatrix} \begin{bmatrix} \cos\theta_j & \sin\theta_j & 0 \\ -\sin\theta_j & \cos\theta_j & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\delta_k \cos\alpha_k \\ \cos\delta_k \sin\alpha_k \\ \sin\delta_k \end{bmatrix}$$
$$+ c[\Delta c_{0i} + \Delta c_{1i}(t_j - t_0)] \tag{3.2-3}$$

where $\Delta X_i, \Delta Y_i, \Delta Z_i$ are the coordinate differences of the i^{th} baseline in the terrestial frame

α_k, δ_k are the true right ascension and declination of the k^{th} source, respectively.

Equation (3.2-3) expresses the functional relationship between the delay observations and the parameters listed above. Of direct geodetic interest are the baseline coordinate differences, ΔX_i, ΔY_i, ΔZ_i (from which the baseline length can also be determined) and the earth orientation parameters, ξ_j, η_j, κ_j. The source coordinates, α_k, δ_k are of astrometric interest. Eventually, their accurate determination will provide a catalogue of well-distributed sources resulting in more accurate geodetic parameter estimation. The clock parameters, Δc_{0i}, Δc_{1i} are nuisance parameters, defined in order to make the mathematical model more realistic. We will now examine which of the above parameters are estimable. By estimability we mean that there exists a parameter estimate which is unbiased, i.e., that the expected value of the parameter estimate should be equal to the parameter itself ($E(\hat{X}) = X$). In other words, the parameters can be estimated directly from the observables without introducing external information (for example, parameter weights). It follows that for an estimable parameter set (i.e., each parameter is estimable) the normal matrix (see below) is invertible. It is enough for one parameter to be non-estimable for the normal matrix to be rank deficient (singular), thereby preventing parameter estimation. Using these properties, the estimable parameters corresponding to the VIP mathematical models will be determined.

The normal matrix is by definition

$$N = A^T P A$$

where A is the design matrix and P, the weight matrix of the observables. The elements of A are the partial derivatives of the observable with respect to the corresponding parameters of the mathematical model. In this case, the observable is the delay and the parameters of interest are

$$\Delta X_i\ \Delta Y_i,\ \Delta Z_i,\ \xi_j,\ \eta_j,\ \kappa_j,\ \alpha_k,\ \delta_k,\ \Delta c_{0i},\ \Delta c_{1i}$$

as described above. Equation (3.2-3) can be rewritten

$$\begin{aligned} d_{ijk} = & -\Delta X_i[\cos\delta_k \cos(\theta_j - \alpha_k) + \xi_j \sin\delta_k] \\ & +\Delta Y_i[\cos\delta_k \sin(\theta_j - \alpha_k) + \eta_j \sin\delta_k] \\ & -\Delta Z_i[\sin\delta_k - \xi_j \cos\delta_k \cos(\theta_j - \alpha_k) - \eta_j \cos\delta_k \sin(\theta_j - \alpha_k)] \\ & +c[\Delta c_{0i} + \Delta c_{1i}(t_j - t_0)] \end{aligned} \qquad (3.2\text{-}4)$$

Taking the differential of d_{ijk} with respect to the parameters listed above

$$\begin{aligned} d(d_{ijk}) = & A_{\Delta X_i} d\Delta X_i + A_{\Delta Y_i} d\Delta Y_i + A_{\Delta Z_i} d\Delta Z_i \\ & + A_{\xi_j} d\xi_j + A_{\eta_j} d\eta_j + A_{\kappa_j} d\kappa_j \\ & + A_{\alpha_k} d\alpha_k + A_{\delta_k} d\delta_k \\ & + A_{\Delta c_{0i}} d(\Delta c_{0i}) + A_{\Delta c_{1i}} d(\Delta c_{1i}) \end{aligned} \qquad (3.2\text{-}5)$$

where the A's are the required partial derivatives of the time delay with respect to the subscripted parameters as follows

$$A_{\Delta X_i} = -\cos\delta_k \cos(\theta_j - \alpha_k) - \xi_j \sin\delta_k \quad (3.2\text{-}6)$$

$$A_{\Delta Y_i} = \cos\delta_k \sin(\theta_j - \alpha_k) + \eta_j \sin\delta_k \quad (3.2\text{-}7)$$

$$A_{\Delta Z_i} = -[\sin\delta_k - \xi_j \cos\delta_k \cos(\theta_j - \alpha_k) - \eta_j \cos\delta_k \sin(\theta_j - \alpha_k)] \quad (3.2\text{-}8)$$

$$A_{\xi_j} = -\Delta X_i \sin\delta_k + \Delta Z_i \cos\delta_k \cos(\theta_j - \alpha_k) \quad (3.2\text{-}9)$$

$$A_{\eta_j} = \Delta Y_i \sin\delta_k + \Delta Z_i \cos\delta_k \sin(\theta_j - \alpha_k) \quad (3.2\text{-}10)$$

$$\begin{aligned} A_{\kappa_j} = {} & W_d \cos\delta_k [\Delta X_i \sin(\theta_j - \alpha_k) + \Delta Y_i \cos(\theta_j - \alpha_k) \\ & - \Delta Z_i \xi_j \sin(\theta_j - \alpha_k) + \Delta Z_i \eta_j \cos(\theta_j - \alpha_k)] \end{aligned} \quad (3.2\text{-}11)$$

$$A_{\alpha_k} = -A_{\kappa_j} / W_d \quad (3.2\text{-}12)$$

$$\begin{aligned} A_{\delta_k} = {} & \sin\delta_k [\Delta X_i \cos(\theta_j - \alpha_k) - \Delta Y_i \sin(\theta_j - \alpha_k) \\ & - \Delta Z_i \xi_j \cos(\theta_j - \alpha_k) - \Delta Z_i \eta_j \sin(\theta_j - \alpha_k)] \\ & - \cos\delta_k [\Delta Z_i + \Delta X_i \xi_j - \Delta Y_i \eta_j] \end{aligned} \quad (3.2\text{-}13)$$

$$A_{\Delta c_{0i}} = c \quad (3.2\text{-}14)$$

$$A_{\Delta c_{1i}} = c(t_j - t_o) \quad (3.2\text{-}15)$$

If there exist linear relationships between the coefficients listed above, the column rank of the design matrix will not be full and the normal matrix will consequently be singular--implying that not all of the above parameters are estimable. Neglecting the terms containing ξ_j, η_j and κ_j, being negligibly small, the following linear relationships are evident among the partial derivatives

$$A_{\xi_j} = \Delta X_i A_{\Delta Z_i} - \Delta Z_i A_{\Delta X_i} \quad (3.2\text{-}16)$$

$$A_{\eta_j} = -\Delta Y_i A_{\Delta Z_i} + \Delta Z_i A_{\Delta Y_i} \quad (3.2\text{-}17)$$

$$A_{\kappa_j} = W_d[-\Delta Y_i A_{\Delta X_i} + \Delta X_i A_{\Delta Y_i}] \quad (3.2\text{-}18)$$

$$A_{\alpha_k} = \Delta Y_i A_{\Delta X_i} - \Delta X_i A_{\Delta Y_i} = -A_{\kappa_j}/W_d \qquad (3.2\text{-}19)$$

Therefore, it is not possible to estimate all of the parameters of interest from VLBI delay observations. In order to circumvent these rank deficiencies, a set of estimable parameters, closely related to the set listed above is defined which will allow the normal matrix to be inverted without the use of external information.

Before defining this new parameter set, it is useful to present the geometric interpretations of the rank deficiencies, as expressed analytically by equations (3.2-16) to (3.2-19). The first three equations show a linear dependence between various combinations of ΔX_i, ΔY_i, ΔZ_i and ξ_j, η_j, κ_j. These indicate a rank deficiency of three due to lack of absolute orientation of the baseline with respect to the true-of-date frame which cannot be sensed by the observables. The origin of the terrestial system is arbitrary since the mathematical model is expressed in terms of coordinate differences. The scale, defined implicitly by the adopted speed of light, is inherent in the observables. It is left to account for the rank deficiency expressed by (3.2-19). This is due to a lack of reference direction (origin of right ascension) for the true-of-date frame--the observables are insensitive to any absolute direction in inertial space. Thus, it can be seen that of the initial 10 parameters of interest only six may be estimated simultaneously (see 3.3.2). Notice that the clock offset and rate parameters are differences and not absolute. Therefore, any common errors in the epoch setting of the station clocks will be indistinguishable from corresponding variations in earth rotation [Shapiro, 1979].

Let us then define an estimable parameter set related to the original set. The earth orientation parameters will be redefined as follows. The total interval of observations is divided into several adjacent periods to be referred to as earth orientation steps (or steps) [Dermanis, 1978]. The three earth orientation parameters ξ_j, η_j, κ_j will be rewritten as

$$\begin{aligned} \xi_\ell &= \xi_1 + (\xi_\ell - \xi_1) \\ \eta_\ell &= \eta_1 + (\eta_\ell - \eta_1) \qquad (\ell > 1) \\ \kappa_\ell &= \kappa_1 + (\kappa_\ell - \kappa_1) \end{aligned} \tag{3.2-20}$$

where ℓ refers to the ℓ^{th} step. The reference orientation of the baseline is defined by three parameters ξ_1, η_1, κ_1 referring to the average values of polar motion and UTC-UT1, respectively, over the first step. For each subsequent step, a set of three earth orientation parameters

$$\begin{aligned} \Delta\xi_{1\ell} &= \xi_\ell - \xi_1 \\ \Delta\eta_{1\ell} &= \eta_\ell - \eta_1 \\ \Delta\kappa_{1\ell} &= \kappa_\ell - \kappa_1 \end{aligned} \tag{3.2-21}$$

are estimated. They are interpreted as variations in earth orientation relative to the absolute orientation (implicitly provided by the first step) averaged over the interval of time encompassed by the ℓ^{th} step. These are the estimable earth orientation parameters and their estimates are influenced by the interval of time spanned by the first step and the number and spread of observations. By not including ξ_1, η_1, κ_1 in the parameter set, the linear relationships expressed in

(3.2-16)-(3.2-18) have been broken without resorting to external information. This eliminates 3 of the 4 normal matrix rank deficiencies. The earth orientation variations can be added to ξ_1, η_1, κ_1 determined from other sources, for example, BIH Circular D interpolated values. For the purposes of VIP we can assume that

$$\xi_1 = \eta_1 = \kappa_1 = 0 ,$$

although other values may be assigned in the program.

A similar formulation will circumvent the fourth rank deficiency. The right ascension of one source will be constrained implicitly to its initial value by not including it in the parameter set. We can write

$$\alpha_k = \alpha_1 + (\alpha_k - \alpha_1) \quad (k>1) \tag{3.2-22}$$

where α_1 is the fixed true right ascension. This value will provide the reference orientation of the origin of right ascensions. The corresponding estimable parameters are the right ascension differences given by $\alpha_k - \alpha_1$. Source right ascensions are non-estimable parameters. The declination of the reference source should be nearly equatorial to provide a strong definition for the reference direction. This can be seen by an examination of (3.2-12) since the right ascension partial is a function of $\cos\delta_k$.

This new set of estimable parameters is free of the rank deficiency of four exhibited by the initial set. Although the normal matrix is no longer singular, the estimation of baseline components is biased by any errors in the four parameters of orientation α_1, ξ_1, η_1, κ_1 as will be shown below. From this point of view, the baseline components ΔX_i, ΔY_i, ΔZ_i are non-estimable parameters and again we shall resort to defining a corresponding set of estimable ones, τ_i, ε_i, σ_i [Arnold, 1974], respectively, according to the following derivation. Let us rewrite (3.2-5), using (3.2-20), (3.2-21) and (3.2-22) in terms of the estimable parameters discussed above, neglecting terms containing ξ, η and κ

$$\begin{aligned} d(d_{ijk\ell}) = & A_{\tau_i}[d\Delta X_i + \Delta Y_i d\alpha_1 - \Delta Z_i d\xi_1 - W_d \Delta Y_i d\kappa_1] \\ & + A_{\varepsilon_i}[d\Delta Y_i - \Delta X_i d\alpha_1 + \Delta Z_i d\eta_1 + W_d \Delta X_i d\kappa_1] \\ & + A_{\sigma_i}[d\Delta Z_i + \Delta X_i d\xi_1 - \Delta Y_i d\eta_1] \\ & + A_{(\kappa_\ell - \kappa_1)} d(\kappa_\ell - \kappa_1) + A_{(\xi_\ell - \xi_1)} d(\xi_\ell - \xi_1) + A_{(\eta_\ell - \eta_1)} d(\eta_\ell - \eta_1) \\ & + A_{(\alpha_k - \alpha_1)} d(\alpha_k - \alpha_1) + A_{\delta_\kappa} d\delta_\kappa \\ & + A_{\Delta c_{0i}} d(\Delta c_{0i}) + A_{\Delta c_{1i}} d(\Delta c_{1i}) \end{aligned} \tag{3.2-23}$$

where the partial derivatives (the A's) correspond directly to those given in (3.2-6) to (3.2-15). The partial derivatives of τ_i, ε_i, σ_i correspond to those of ΔX_i, ΔY_i, ΔZ_i, respectively. The differential relationships between these two sets are given by the bracketed terms in (3.2-23)

$$\begin{aligned} d\tau_i &= d\Delta X_i - \Delta Z_i d\xi_1 + \Delta Y_i d\beta_1 \\ d\varepsilon_i &= d\Delta Y_i + \Delta Z_i d\eta_1 - \Delta X_i d\beta_1 \\ d\sigma_i &= d\Delta Z_i + \Delta X_i d\xi_1 - \Delta Y_i d\eta_1 \end{aligned} \tag{3.2-24}$$

where

$$d\beta_1 = d\alpha_1 - W_d d\kappa_1 \tag{3.2-25}$$

implying that these two rotations are inseparable. The differential relationships between the parameters can be re-written in matrix form as

$$\begin{aligned} \begin{bmatrix} d\tau_i \\ d\epsilon_i \\ d\sigma_i \end{bmatrix} &= \begin{bmatrix} d\Delta X_i \\ d\Delta Y_i \\ d\Delta Z_i \end{bmatrix} + R_2(d\xi_1)R_1(d\eta_1)R_3(d\beta_1) \begin{bmatrix} \Delta X_i \\ \Delta Y_i \\ \Delta Z_i \end{bmatrix} \\ &= \begin{bmatrix} d\Delta X_i \\ d\Delta Y_i \\ d\Delta Z_i \end{bmatrix} + \begin{bmatrix} 0 & d\beta_1 & -d\xi_1 \\ -d\beta_1 & 0 & d\eta_1 \\ d\xi_1 & -d\eta_1 & 0 \end{bmatrix} \begin{bmatrix} \Delta X_i \\ \Delta Y_i \\ \Delta Z_i \end{bmatrix} \end{aligned} \tag{3.2-26}$$

where $d\xi_1$, $d\eta_1$, $d\beta_1$ are errors in the initial reference orienation assumed to be of small magnitude. R_i are the rotation matrices described earlier. Of course, the smaller these errors the more closely τ_i, ϵ_i, σ_i will "resemble" the baseline components. The importance of accurate initial orientation parameters is especially apparent for long baselines. For example, from (3.2-24), for a baseline with $\Delta X_i = 4000$ km, an error $d\xi_1 = 0\overset{''}{.}001$ will contribute to a change of 2 cm in the "estimated" ΔZ component (see Appendix B.1).

Baseline lengths, on the other hand, are estimable quantities being unbiased by the errors in the reference orientation. This can be shown by writing the baseline length, ℓ_i as

$$\ell_i = (\Delta X_i^{\,2} + \Delta Y_i^{\,2} + \Delta Z_i^{\,2})^{1/2} \tag{3.2-27}$$

Then,

$$\frac{d\ell_i}{\ell_i} = \Delta X_i d\Delta X_i + \Delta Y_i d\Delta Y_i + \Delta Z_i d\Delta Z_i \qquad (3.2\text{-}28)$$

Substituting (3.2-24) into (3.2-28) yields

$$\begin{aligned}\frac{d\ell_i}{\ell_i} = {} & \Delta X_i(d\tau_i - \Delta Y_i d\alpha_1 + \Delta Z_i d\xi_1 + W_d \Delta Y_i d\kappa_1) \\ & + \Delta Y_i(d\varepsilon_i + \Delta X_i d\alpha_1 - \Delta Z_i d\eta_1 - W_d \Delta X_i d\kappa_1) \qquad (3.2\text{-}29) \\ & + \Delta Z_i(d\,\sigma_i - \Delta X_i d\xi_1 + \Delta Y_i d\eta_1)\end{aligned}$$

thus,

$$\frac{d\ell_i}{\ell_i} = \Delta X_i\, d\tau_i + \Delta Y_i d\varepsilon_i + \Delta Z_i d\sigma_i \qquad (3.2\text{-}30)$$

Comparing (3.2-28) and (3.2-30), it follows that ℓ_i is unaffected by errors in α_1, ξ_1, η_1 and κ_1 which is obvious since distance is invariant of coordinate system definition. However, baseline lengths as well as components will vary due to earth tides and geodynamic phenomena, and therefore these phenomena may be parameterized as will be discussed in section 3.2.7.

In VIP, the baseline length standard deviations are estimated by propagation of errors from the baseline "components" τ_i, ε_i, σ_i. The mathematical model is given by equation (3.2-27). The variance-covariance matrix for distances, $\Sigma\ell_i$ is given, using the notation by [Uotila, 1967] as

$$\Sigma_{\ell_i} = G\Sigma_{\tau_i,\varepsilon_i,\sigma_i} G^T \qquad (3.2\text{-}31)$$

where G is the matrix of partial derivatives of ℓ_i with respect to each component. $\Sigma_{\tau_i,\epsilon_i,\sigma_i}$ is the full covariance matrix of the baseline "components" retrieved from their corresponding elements in the variance-covariance matrix of estimated parameters.

It is appropriate to summarize the previous discussion by listing the estimable parameters recoverable from delay observations

$\tau_i,\epsilon_i,\sigma_i$	baseline "components" contaminated by errors in the reference orientation
ℓ_i	baseline distances
δ_k	source declinations
$\alpha_k-\alpha_1$	right ascension differences
$\Delta\xi_{1\ell},\Delta\eta_{1\ell}$	polar motion variation components
$\Delta\kappa_{1\ell}$	UT1-UTC variations
$\Delta c_{0i},\Delta c_{1i}$	relative clock offset and rate, respectively.

3.2.4 Time Delay Rate Model

The geometric delay rate was defined in section 2.2 as the time derivative of the geometric delay. Including the clock parameters the delay rate is modelled

$$\dot{d}_{ijk} = -\frac{d\bar{B}_i(t_j)}{dt}\cdot\bar{s}_k + c\Delta c_{1i} \qquad (3.2\text{-}32)$$

Differentiating (3.2-4) with respect to time

$$\begin{aligned}\dot{d}_{ijk} = \omega_e\cos\delta_k\ \{&\Delta X_i\sin(\theta_j-\alpha_k) + \Delta Y_i\cos(\theta_j-\alpha_k)\\ &- \Delta Z_i[\xi\sin(\theta_j-\alpha_k) - \eta\cos(\theta_j-\alpha_k)]\}\\ &+ c\Delta c_{1i}\end{aligned} \qquad (3.2\text{-}33)$$

where

$$\omega_e = \frac{d\theta}{dt} = |\overline{\Omega}|$$

is the spin rate of the earth, $\overline{\Omega}$ the instantaneous earth rotation vector. The magnitude of the terms containing ξ and η in (3.2-33) are negligible, indicating that the delay rate is effectively insensitive to the ΔZ component of the baseline. It follows that only the length of the equatorial projection of the baseline can be estimated. In addition, the delay rate is unaffected by clock offset variations, Δc_{0i}. Furthermore, examining (3.2-32)

$$\frac{d\overline{B}}{dt} = \overline{\Omega} \times \overline{B}$$

is orthogonal to $\overline{\Omega}$ and, thus, the origin of declination is undefined [Counselman, 1976] as well as the right ascension origin. The discussion of the parameters estimable from delay rate is identical to that of delays except that in this case $\Delta Z_i(\sigma_i)$ and Δc_{0i} are deleted, and declination differences $\delta_k - \delta_1$ replace δ_k. Thus, an expression similar to (3.2-23), corresponding to delay rates

$$\begin{aligned} d(\dot{d}_{ijk\ell}) = {} & A_{\tau_i}[d\Delta X_i - \Delta Z_i d\xi_1 + \Delta Y_i d\beta_1] \\ & + A_{\varepsilon_i}[d\Delta Y_i + \Delta Z_i d\eta_1 - \Delta X_i d\beta_1] \\ & (+ A_{\sigma_i}[d\Delta Z_i + \Delta X_i d\xi_1 - \Delta Y_i d\eta_1])^* \qquad (3.2\text{-}34) \\ & + A_{(\kappa_\ell - \kappa_1)} d(\kappa_\ell - \kappa_1) + A_{(\xi_\ell - \xi_1)} d(\xi_\ell - \xi_1) + A_{(\eta_\ell - \eta_1)} d(\eta_\ell - \eta_1) \\ & + A_{(\alpha_k - \alpha_1)} d(\alpha_k - \alpha_1) + A_{(\delta_k - \delta_1)} d(\delta_k - \delta_1) + A_{\Delta c_{1i}} d(\Delta c_{1i}) \end{aligned}$$

---

*Negligible.

where δ_1 is the declination implicitly constrained to its a priori value by not including it in the parameter set. All the other terms have been defined in section 3.2.3. The partial derivatives of the delay rate with respect to the subscripted parameters are

$$A_{\tau_i} = \omega_e \cos\delta_k \sin(\theta_{j\ell}-\alpha_k) \tag{3.2-35}$$

$$A_{\varepsilon_i} = \omega_e \cos\delta_k \cos(\theta_{j\ell}-\alpha_k) \tag{3.2-36}$$

$$(A_{\sigma_i} = -\omega_e \cos\delta_k [\xi_\ell \sin(\theta_{j\ell}-\alpha_k) - \eta_\ell \cos(\theta_{j\ell}-\alpha_k)])^*$$

$$A_{(\kappa_\ell-\kappa_1)} = \omega_e^2 \cos\delta_k \{\Delta X_i \cos(\theta_{j\ell}-\alpha_k) - \Delta Y_i \sin(\theta_{j\ell}-\alpha_k) - \Delta Z_i [\xi_\ell \cos(\theta_{j\ell}-\alpha_k) + \eta_\ell \sin(\theta_{j\ell}-\alpha_k)]\} \tag{3.2-37}$$

$$A_{(\xi_\ell-\xi_1)} = -\omega_e \cos\delta_k \Delta Z_i \sin(\theta_{j\ell}-\alpha_k) \tag{3.2-38}$$

$$A_{(\eta_\ell-\eta_1)} = \omega_e \cos\delta_k \Delta Z_i \cos(\theta_{j\ell}-\alpha_k) \tag{3.2-39}$$

$$A_{(\alpha_k-\alpha_1)} = -A_{(\kappa_\ell-\kappa_1)}/\omega_e \tag{3.2-40}$$

$$A_{(\delta_k-\delta_1)} = -\omega_e \sin\delta_k \{\Delta X_i \sin(\theta_{j\ell}-\alpha_k) + \Delta Y_i \cos(\theta_{j\ell}-\alpha_k) - \Delta Z_i [\xi_\ell \sin(\theta_{j\ell}-\alpha_k) - \eta_\ell \cos(\theta_{j\ell}-\alpha_k)]\} \tag{3.2-41}$$

$$A_{\Delta c_{ii}} = c \tag{3.2-42}$$

From (3.2-41) it is evident that the delay rate is insensitive to the declinations of sources near the equator.

The delay rates are less important than the delays because of their relatively lower accuracy and reduced estimable parameter set.

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*Negligible - not included in VIP as well as all other terms including ξ_ℓ and η_ℓ in (3.2-35) - (3.2-42) and similarly for the delay partials.

However, delay rate observations do have the advantage of being unambiguously estimated and, thus, may be estimated with relatively simple equipment. In addition, Fanselow [1978] states that the delay rates aid in reducing correlations between certain parameters.

3.2.5 Adjustment Algorithm

The adjustment algorithm used in VIP is the standard method of observation equations of the form [Uotila, 1967]

$$L_a = F(X_a)$$

where L_a is the theoretical value of the "observed" quantities, delay and delay rate, related functionally to the theoretical values of the parameters. The function F is given by equations (3.2-3) and (3.2-33) for delay and delay rate, respectively. The non-linear function F, in each case, is linearized by retaining the first-order term of the Taylor series expansion about the approximate values of the parameters, X_0, such that

$$\begin{aligned} L_a &= F(X_0) + \left.\frac{\partial F(X_a)}{\partial X_a}\right|_{X_a = X_0} (X_a - X_0) \\ &= L_0 + A\,X \end{aligned}$$

where $L_0 = F(X_0)$ is the vector of approximate values of the observed quantities based on the approximate parameter vector, X_0 and computed from equations (3.2-3) and (3.2-33). The design matrix of partial derivatives $A = \left.\frac{\partial F(X_a)}{\partial X_a}\right|_{X_a = X_0}$ includes the elements given by equations (3.2-6) - (3.2-15) and (3.2-35) - (3.2-42). $X = X_a - X_0$ is the vector of parameter corrections to be applied to the approximate parameter estimates, X_0, to yield X_a, the adjusted parameters. The theoretical observable, L_a can be separated into the actually observed quantity vector, L_b (in this case group delay and phase delay rate estimated from the cross correlation process) and the vector of residuals, V, resulting from observational errors. Then,

$$L_b + V = L_0 + A\,X$$

$$V = A\,X + L$$

where $L = L_0 - L_b$.

By minimizing the sum of the squares, V^TPV, the least squares estimate for the parameter correction vector, X is

$$X = -(A^TPA)^{-1}A^TPL = -N^{-1}U$$

where P is the inverse of the variance-covariance matrix for the observables, Σ_{L_b} scaled by σ_0^2, the a priori variance of unit weight.

The a priori covariance matrix of the parameters is given by,

$$\Sigma_{X_a} = \sigma_0^2(A^TPA)^{-1}$$

The Σ_{X_a} matrix is the basis of the VIP covariance analysis. The a posteriori covariance matrix is given by

$$\hat{\Sigma}_{X_a} = \hat{\sigma}_0^2(A^TPA)^{-1}$$

where

$$\hat{\sigma}_0^2 = \frac{V^TPV}{n-u}$$

$\hat{\sigma}_0^2$ is the a posteriori variance of unit weight, n is the number of observations and u, the number of parameters. The scalar V^TPV can be computed from

$$V^TPV = L^TPL + X^TU$$

therefore, there is no need to compute each residual. However, in practice the residuals usually contain information on systematic effects, especially errant clock behavior. Since VIP is mainly intended as a covariance analysis program, the residuals are not computed when the least squares solution option is specified.

The VIP least squares algorithm uses the equations listed above. The normal matrix, N is filled in a sequential manner and in upper triangular form in order to conserve on storage requirements. This is crucial on TSO where the limit is 256K. Triangular storage requires u(u+1)/2 storage locations as opposed to u^2 in the full case. No attempt is made to exploit normal matrix sparsity patterns although this may become necessary for larger parameter sets. VIP is dimensioned to accept a parameter set of size 62 although this could be increased up to the storage limit of 256K. In order to simplify dimensioning all matrices are stored in vector form using the SSP subroutine LOC for bookkeeping purposes [IBM, 1970]. The SSP routine, DSINV which handles matrices stored in upper triangular form is called to invert the normal matrix.

Since simultaneous observations from several stations to a given source at a particular epoch j are correlated (as described in the next section), the N and U matrices and part of V^TPV are filled epoch by epoch as follows

$$N = \sum_{j=1}^{E} A_j^T P_j A_j$$

$$U = \sum_{j=1}^{E} A_j^T P_j L_j$$

$$V^TPV = X^TU + \sum_{j=1}^{E} L_j^T P_j L_j$$

where E is the number of simultaneous observation sets, each set containing the observations of one epoch. The P_j portion of the weight matrix is block diagonal, each block having its dimension equal to the number of independent baselines observing simultaneously at that epoch. This will become clear in the next section. The above summations assume that observations at different epochs are uncorrelated which is in accordance with the VIP mathematical model. In practice, such observations may be correlated but only as a result of unmodelled systematic effects such as those resulting from the propagation medium.

After inversion of the normal matrix, and multiplication by the variance of unit weight, the estimated standard deviations of the parameters are computed by taking the square root of the diagonal elements of the resulting variance-covariance matrix of parameters. In addition, the correlation matrix of parameters is computed from

$$\rho_{X_i X_j} = \frac{\sigma_{X_i X_j}}{\sigma_{X_i}\sigma_{X_j}}$$

where $\sigma_{X_i X_j}$ is the covariance of parameters X_i and X_j and σ_{X_i} and σ_{X_j} are their respective standard deviations. The correlation matrix describes the interrelationships among the parameters. A value of $|\rho_{X_i X_j}|$ close to unity indicates that the parameters are highly dependent while a value of unity indicates a singularity and complete linear dependence. High correlations may result in ill-conditioned matrices and thus unstable systems whose solutions are circumspect.

Ill conditioning of the normal matrix is reflected by the ratio of the largest and smallest eigenvalues. They are computed in VIP using the SSP routine, DEIGEN, which outputs the eigenvalues in descending order of magnitude. A relatively large ratio will indicate ill-conditioning possibly resulting from a critical geometric configuration (see Section 3.3.3).

3.2.6 Weighting of Observations

VLBI observations are usually performed simultaneously from all participating stations unless mutual source visibility makes this impossible. In accordance with the VIP mathematical model, simultaneous observations to a particular source at a given epoch are correlated. A simple model, suitable for covariance analyses, for computing these correlations will be described below. This formulation assumes that the delays are all observed with equal precision, a reasonable assumption for covariance analyses. Typical precisions are 0.1 ns (3 cm) for delay and 0.1 ps/s (0.108 m/hr) for delay rate.

The following discussion will address a triangle of stations for the sake of description but can be extended to any closed configuration. As described in Chapter 2, the raw observables are the bits recorded on magnetic tapes at the three sites. The delay (and delay rate) is estimated by cross-correlation of the tapes. Denoting the time delay between stations i, j as τ_{ij} it follows from the mathematical model that,

$$\tau_{12} + \tau_{23} + \tau_{31} = 0 \ . \qquad (3.2\text{-}43)$$

Thus, any one of the delays is linearly dependent on the other two. In other words, if two delays have been estimated then, theoretically, the third one is completely determined (Shapiro, private communication) and does not provide independent information. In this example, there are three possible combinations of two independent delays. Regardless of the chosen combination, the parameter estimates should be identical since all three sets of tapes, containing the same information in any case, are required. If the correlations between the observables, at each epoch, are neglected, there will be three different sets of parameter estimates, one for each combination.

The delay, conceptually, is the difference in times of arrival of a given portion of a wavefront at two antennas. Therefore, in triangle 1-2-3 the delays for one epoch can be written as

$$\begin{aligned} \tau_{12} &= t_2 - t_1 \\ \tau_{23} &= t_3 - t_2 \\ \tau_{31} &= t_1 - t_3 \end{aligned} \qquad (3.2\text{-}44)$$

In matrix form

$$\begin{bmatrix} \tau_{12} \\ \tau_{23} \\ \tau_{31} \end{bmatrix} = \begin{bmatrix} -1 & 1 & 0 \\ 0 & -1 & 1 \\ 1 & 0 & -1 \end{bmatrix} \begin{bmatrix} t_1 \\ t_2 \\ t_3 \end{bmatrix}$$

$$= \quad G \quad T \tag{3.2-45}$$

Assume that Σ_T, the variance-covariance matrix of the "observed" times is a diagonal, i.e., that all observations are of equal precision. Let us further assume that it is the identity matrix since at this point we are interested solely in the correlations between delays. By propagation of errors, the variance-covariance matrix of observed delays for one epoch of observation is

$$\Sigma_\tau = G\Sigma_T G^T = GG^T$$
$$= \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \tag{3.2-46}$$

However, the determinant of this matrix (of rank 2) is zero and thus cannot be inverted. This is just a restatement in mathematical terms of the fact that the three delays are dependent. Clearly, parameter estimation is impossible in this case and one delay must be eliminated. It makes no difference which one since, using this model, the parameter estimates and their variances will be identical using any two of the time delays. Let us choose τ_{12} and τ_{23}. Then, for one epoch of simultaneous observations

$$\Sigma_\tau = \begin{bmatrix} 2 & -1 \\ -1 & 2 \end{bmatrix} \equiv \begin{bmatrix} 1 & -\frac{1}{2} \\ -\frac{1}{2} & 1 \end{bmatrix}$$

disregarding the scale factor for the moment. Scaling this matrix to 3 cm precision in units of distance (equivalent to 0.1 nanosecond) and thus replacing τ by d

$$\Sigma_d = \begin{bmatrix} 0.0009 & -0.00045 \\ -0.00045 & 0.0009 \end{bmatrix}$$

This matrix is then inverted and the first element (upper left-hand corner) is scaled to unity, the scaling factor being the a priori variance of unit weight, σ_0^2. The complete weight matrix in this example is 2 × 2 block diagonal

$$P = \sigma_0^2 \Sigma_d^{-1} = \begin{bmatrix} 1 & -\frac{1}{2} & & & & 0 \\ -\frac{1}{2} & 1 & & & & \\ & & \ddots & & & \\ & & & & 1 & -\frac{1}{2} \\ & 0 & & & -\frac{1}{2} & 1 \end{bmatrix} \qquad (3.2\text{-}47)$$

where $\sigma_0^2 = 0.000675$. As with all other arrays, the weight matrix is stored in upper triangular vector form.

Correlations between simultaneously observed delay rates are computed in the same manner. In analyses involving both observables it is assumed that delay and delay rates are uncorrelated. As mentioned earlier delays at different epochs are assumed to be uncorrelated, and similarly for delay rates.

The above discussion indicates the importance of including the proper correlations among simultaneous observations. Otherwise, parameter estimation is not unique and it is meaningless to perform a covariance analysis. Using a diagonal weight matrix (neglecting the correlations) with all three time delays will yield a unique set but with parameter precision estimates that are overly optimistic. This may not be significant in the triangular configuration described above. In general, however, for an N-station configuration there are N(N-1)/2 possible baselines (tape combinations) but only N - 1 independent ones. For example, in a six station configuration there are 15 possible baselines, only 5 being independent.

The weighting procedure described above is highly simplified but appropriate for covariance analyses. In analyzing real data, the Σ_τ matrix is much more difficult to determine and the weight matrix is taken as diagonal. However, unless the true correlations are known, the least squares estimates may be quite misleading especially in larger networks.

3.2.7 Model Refinements

The mathematical models described in sections 3.2.3 and 3.2.4 are suitable for the type of applications for which VIP is intended. The parameter set chosen for VIP was influenced by studies of the Polaris triangle, i.e., monitoring of earth orientation variations. Other effects such as nutation, precession, crustal movements, earth tides and ocean loading were not included. In the handling of real data, though, these other phenomena must either be parameterized or compensated for by a priori information in order to correct for their influence on the observables. Otherwise, the estimated parameters would be contaminated by their effects.

Robertson [1975] has estimated the precession constant, the rate at which the Earth's spin axis rotates about the ecliptic pole, from VLBI observations spread over approximately four years. In simulation studies, Dermanis [1977] defined three rotation angles to model the total effects of precession and nutation. A step approach similar to that described in section 3.2.3 for earth orientation was used since only relative variations may be sensed by the observables.

Robertson [1975] was able to estimate the Love number, h, related to radial displacements caused by the tidal potential. Since a time delay can be estimated every few minutes, this provides ideal conditions from the point of view of earth tide analysis [Bonatz et al., 1978].

Geodynamic phenomena may be estimated from VLBI observations, by observing relative changes in the baseline components. When involved in a long observational campaign many data sets are generated. Although baseline components are non-estimable, the adoption of one reference baseline orientation for all the data sets at least will insure that the estimated τ, ϵ, σ parameters will refer to a consistent coordinate system. In this case, errors in reference orientation will cancel out. Otherwise, the differences in these parameters due to the varying reference orientation will look like time-like variations, although in reality they will only be due to inconsistent coordinate system definition.

3.3 Singularity Problems

3.3.1 Introduction

In the least squares process, when the normal matrix has rank less than its dimension it is singular and cannot be inverted, thereby preventing parameter estimation. In the VLBI case, more specifically using the models of VIP, singularity problems may occur for a variety of reasons. In this section we will review these problems. First, it should be noted that by defining the estimable parameters in 3.2.3 and 3.2.4, singularities due to coordinate system definition have been eliminated. As discussed previously, the origin of the terrestial system is arbitrary and the scale is inherent in the observations themselves. The reference orientation of the terrestial frame with respect to the true-of-data frame must be specified and this is done by parameterizing the earth orientation parameters as variations relative to the values assumed for the first step. In addition, the singularity due to lack of a reference direction for the true-of-date frame is eliminated by estimating right ascension differences relative to one fixed right ascension. For delay rate observations only, the origin of declinations must also be specified.

3.3.2 Observation Singularities

In least squares estimation the number of observations must, of course, exceed the number of parameters. In VLBI, these observations must be distributed correctly over a minimum of three sources, otherwise a singularity will occur. This can be seen from the following analysis that has been performed previously by Robertson [1975] and described very clearly by Shapiro [1978], both for a smaller parameter set than included in VIP.

Equation (3.2-4) can be rewritten as (dropping the subscripts)

$$d = K_1\cos(\theta-\alpha) + K_2\sin(\theta-\alpha) + K_3 + K_4 t \qquad (3.3\text{-}1)$$

where $K_1 = (-\Delta X + \Delta Z\xi)\cos\delta$

$K_2 = (\Delta Y + \Delta Z\eta)\cos\delta$

$K_3 = (-\Delta Z - \Delta X\xi + \Delta Y\eta)\sin\delta + c\Delta c_0$

$K_4 = c\Delta c_1$

For a given baseline the K terms are constants to a first approximation, but vary slowly with respect to time due to polar motion variations (as well as precession, nutation and earth tides). The terms $K_1\cos(\theta-\alpha)$ and $K_2\sin(\theta-\alpha)$ are both diurnal sinusoids, remembering though that θ is affected by UT1-UTC variations (the κ term). The amplitude of these sinusoids given by K_1 and K_2 are functions of the baseline vector, and the source declination. The two curves are shifted in phase by 90° since $\sin(\theta-\alpha) = \cos(\theta-\alpha-\frac{\pi}{2})$. The angular frequency of the sinusoids is given by the rotation rate of the earth. This can be seen by expressing

$$\theta = \theta_0 + \omega_e t$$

and, thus

$$\begin{aligned}\theta - \alpha &= (\theta_0-\alpha) + \omega_e t \\ &= \phi + \omega_e t\end{aligned} \qquad (3.3\text{-}2)$$

where ϕ is the phase of the sinusoids relative to some initial epoch, ω_e is the rotation rate of the earth, and θ is the Greenwich sidereal time. The sum of these two sinusoids is again a sinusoid of the general form

$$K\cos(\phi_0+\omega_e t)$$

where ϕ_0 is the resulting phase and K, the amplitude. Therefore,

$$d = K\cos(\phi_0+\omega_e t) + K_3 + K_4 t \qquad (3.3\text{-}3)$$

which represents a straight line added to a diurnal sinusoid.

Assume that delay observations are performed from one baseline to one source. From the discussion of section 3.2.3, over the first step the following parameters are estimable: τ_1, ε_1, σ_1, δ_1, Δc_{01}, Δc_{11}, a total of 6 parameters. An examination of (3.3-3) indicates, though, that only 4 independent parameters K, ϕ_0 (or ω_e), K_3 and K_4 can be estimated from at least 4 observations to one source. Three additional observations to a second source will enable 3 more independent parameters to be estimated, another set of K, ϕ_0, K_3--a total of 7. Note that K_4 is common to observations of all sources. Two new parameters, $\alpha_2-\alpha_1$ and δ_2 will be added to the set of interest--a total of 8 parameters. Thus, observations to two sources still yields a singular case with respect to the parameters of interest. In a similar manner, 3 additional observations to a third source will allow estimation of ten independent parameters. In this case $\alpha_3-\alpha_1$, δ_3 will be added to the set of interest--a total of 10 parameters. Thus, over the first (earth orientation) step we are able to estimate

$\tau_1, \epsilon_1, \sigma_1, \alpha_2-\alpha_1, \alpha_2-\alpha_1, \delta_1, \delta_2, \delta_3, \Delta c_{01}, \Delta c_{11}$

from at least 10 observations distributed as described above to 3 sources. For each subsequent step, we can estimate the 3 earth orientation variations $\Delta\xi_{1\ell}$, $\Delta\eta_{1\ell}$, $\Delta\kappa_{1\ell}$ as described in 3.2.3. As shown in the next section, only two of three of these parameters are estimable from observations from one baseline. In this case for each extra step, two more observations per step will be required to any of the three sources observed over the first step. In multi-baseline configurations all 3 earth orientation parameters may be estimated. In addition for each extra baseline the parameter set increases by five, τ_i, ϵ_i, σ_i, Δc_{0i}, Δc_{1i}. Thus, observations to the minimum 3 sources must be increased accordingly. Of course, for the sake of redundancy the number of observations always exceeds the minimum number required (increase in the degrees of freedom). In addition, for improvement of the geometric strength of the observations, more than the minimum three sources are observed.

For a similar analysis of delay rate observations, see [Robertson, 1975]. It is important to note that the addition of these observations do not add any independent information whereby the number and distribution of observations could be reduced. As mentioned earlier, delay rates have a reduced parameter set associated with them, though adding redundant information but of relatively lower quality.

3.3.3 Critical Configurations

There remains one additional category wherein the normal matrix is rank deficient and this can be classified as critical baseline configurations. Baseline orientation approaching these special cases will result in high correlations between certain parameters and ill-conditioning of the normal matrix.

It will be shown here that observations from a single baseline are sensitive to only two of the three earth orientation variation parameters, $\Delta\xi$, $\Delta\eta$, $\Delta\kappa$. To understand this let us first examine the possible critical configurations of the one baseline case. Consider a baseline parallel to the earth's axis of rotation observing a source at "infinity." Examining the partial derivative (3.2-11) it is evident that since $\Delta X_i = \Delta Y_i = 0$ (and neglecting the terms containing ξ and η)

$$A_{\Delta\kappa} = A_\kappa = 0$$

and, therefore, the delay (and rate, see (3.2-37)) is insensitive to the UT1-UTC parameters. Atte~~pting to estimate these parameters will result in a singular normal matrix. Consider a baseline parallel to the equator whose midpoint is situated on the Greenwich meridian or at 180° longitude. In this case $\Delta X_i = \Delta Z_i = 0$ implying from (3.2-9) that

$$A_{\Delta\xi} = A_\xi = 0$$

so that for this configuration the delay (and rate, see (3.2-38)) is insensitive to the $\Delta\xi$ parameters of polar motion variation. Similarly for a baseline parallel to the equator and whose midpoint is at 90°E or 270°E longitude from (3.2-10)

$$A_{\Delta\eta} = A_\eta = 0$$

and the delay (and rate, see (3.2-39)) is insensitive to the $\Delta\eta$ component of polar motion. For example, continental United States east-west baseline observations are hardly sensitive to the $\Delta\eta$ parameters. It is now evident that observations from one baseline can be used to estimate only two of three earth orientation parameters independently since a change in the orientation of one baseline is completely described by two distinct rotations. The choice of which two to choose will be dictated by the orientation of the baseline and examination of the magnitude of the partial derivatives of (3.2-9), (3.2-10) and (3.2-11). Note that the addition of any number of parallel baselines to any of the critical configurations listed above will not eliminate the rank deficiency. However, observations on any two non-parallel baselines will allow estimation of all three earth orientation variation parameters (over each step--except the first) since a change in orientation of a plane in space is fully described by three independent rotations. An exception to this is given in the next paragraph.

A baseline parallel to the equatorial plane (observing delays) constitutes another case of a critical configuration. In this case, $\Delta Z_i = 0$ and from the partial derivatives (3.2-6), (3.2-7), and (3.2-13) the following linear relationship is evident

$$A_{\delta_k} = -\tan\delta_k(\Delta X_i A_{\Delta X_i} + \Delta Y_i A_{\Delta Y_i}) \qquad (3.3\text{-}4)$$

assuming the terms containing ξ and η are negligible. This will result in a rank-deficient normal matrix. In geometric terms, the origin of declination is not sensed by the observations since the baseline is orthogonal to the instantaneous earth rotation vector, $\overline{\Omega}$. This is similar to case of delay rates described in 3.2.4. Therefore, for such a configuration, the parameter set must be modified by introducing declination differences as parameters instead of declinations. It should be noted that for any number of east-west baselines the configuration will be critical when estimating the regular delay parameter set described in 3.2.3. In practice, baselines parallel to the equatorial plane are not very common; however, observations from a baseline approaching this configuration may result in an all conditioned system and high correlations between certain parameters. The ratio of maximum to minimum normal matrix eigenvalues is a good indication of an ill-conditioned system. For typical "non-critical" VLBI baseline configurations this ratio is of the magnitude 10^5 or 10^6. For a near-critical configuration this ratio will be several orders of magnitude larger.

3.4 Source Visibility Equation

In planning an observation schedule the first factor to be considered is which sources are visible at a particular epoch and from which stations. This information is displayed in the visibility matrix computed for each source. The dimensions of each matrix are N × 24 where N is the number of stations and the columns refer to the epoch of observation at one-hour intervals. The elements of the matrix are output by VIP as zenith distances when the source is visible, a double asterisk when not. An example is given in Appendix B.

The source unit vector $\vec{s}$ in the inertial frame is given as

$$\vec{s} = \begin{bmatrix} \cos\delta \ \cos\alpha \\ \cos\delta \ \sin\alpha \\ \sin\delta \end{bmatrix}$$

The station unit vector $\vec{X}$ is given in the terrestial frame as

$$\vec{X} = \begin{bmatrix} \cos\phi \ \cos\lambda \\ \cos\phi \ \sin\lambda \\ \sin\phi \end{bmatrix}$$

ϕ and λ , the geodetic latitude and longitude of the station, respectively. The zenith distance is given by

$$z = \cos^{-1}(\vec{X}\cdot\vec{q}) \qquad (3.4\text{-}1)$$

where $\vec{q}$ corresponds to $\vec{s}$ rotated into the terrestial frame by $R_3(\theta)$, θ being the Greenwich sidereal time (see eq. (3.2-3)). Polar motion has been neglected. Any cutoff angle may be specified for the acceptable zenith distance which is usually taken as 80° (or less) because of the large refractivity effects for observations near the horizon.

4. CONCLUSIONS AND FUTURE RESEARCH

4.1 Summary and Conclusions

A VLBI covariance analysis Interactive Program (VIP) is presented in Appendix A as a tool for experiment planning, simulation studies and optimal design problems. Explanatory tables, figures and the necessary JCL are included for ease of adaptation and operation. The sample session included in Appendix B, consisting of two experiments, illustrates some of the capabilities of the program and the advantages of working in the interactive mode. The program itself is well documented in case the user wishes to incorporate his own modifications (e.g., expanding the parameter set). By an explanation of the theory on which the program is based and of the mathematical models which it incorporates, an overview of the VLBI process is given.

The introductory chapter touches upon the past, present and future aspects of VLBI as well as its applications to geodesy and the related fields of astronomy, geophysics and geodynamics.

Chapter 2 opens with a description of the basic VLBI geometry and of the quantities that are of primary interest--the time delay and time delay rate. Their estimation requires expensive and sophisticated instrumentation used for data collection and cross-correlation of the recorded tapes. The basic components of the system have been described (in broad terms) as well as their functions. The point is made that to arrive at geodetic parameter estimates, a two-stage estimation procedure is required. The first one results in maximum likelihood estimates of group delay and phase delay rate and their corresponding precision estimates from cross-correlation of the recorded tapes. The basic observables in this stage are the raw bits recorded on the various tapes. The second adjustment, by least squares, incorporates the above estimates as observables to estimate the relevant geodetic parameters. Of course, if the full covariance matrix of the "observables" (delay and delay rate) is available, there are no problems with this two-step procedure. However, in practice, this is not the case (see Section 4.3). In addition, unmodelled systematic effects further influence the estimation process and tend to reduce the reliability of the final estimated parameters. Clearly more research is needed to improve the mathematical models and for a more rigorous statistical treatment of the data.

In Chapter 3 the mathematical models used in VIP are described. The parameters estimable from delay measurements are derived. Except for baseline lengths and source declinations all estimable parameters are variational in nature, relative to the initial orientation of the inertial and terrestrial frames. These parameters include baseline components that are contaminated by errors in the reference orientation, polar motion and UT1-UTC variations. The importance of adhering to a standard reference orientation when combining several data sets is stressed so that all parameters will refer to a unique coordinate system. The delay rate model includes a reduced parameter set. The third "component" of the baseline is non-estimable and only declination differences may be estimated. Next, the VIP adjustment algorithm, the sequential observation equation method, is described. A model is presented for determining correlations between simultaneous observations used to formulate the variance-covariance matrix of the observables. It is suitable for covariance analyses and illustrates the importance of developing a model to handle real data. Next, possible model refinements are indicated including parameterization of precession and nutation, earth tides and geodynamic phenomena. Finally, singularity problems associated with the models described in this report are summarized. These occur from incorrect distribution and number of source observations, and from critical baseline configurations.

In the next two sections, two future areas of research will be discussed. Each one will make use of VIP and are actually the impetus for its development.

4.2 Optimal Design Problems

VIP is intended as an aid in VLBI simulations by providing a priori lower bounds on the expected variances of baseline and earth orientation parameters to be estimated from a given experiment. These simulations may include first- and second-order optimal design problems. Design problems, in general, may be approached from philosophically different but related points of view. In experiment planning, a parameter (or set of parameters) is required at a certain level of accuracy and the problem is to determine the conditions necessary for this requirement to be met, if it can be met at all. In experiment simulation, given a set of preliminary conditions we wish to determine the upper bounds on accuracy for a given parameter set. VIP can be of help in studying both approaches although it is more directly amenable to experiment simulation.

VIP was developed while studying the proposed Polaris triangle (Westford-Ft. Davis-Richmond) of NGS to be dedicated to the monitoring of earth orientation variations. Therefore, the description of first- and second-order design problems will use this network for explanatory purposes. First-order design may be defined, generally, as the selection of station sites for the "optimal" estimation of a given geodetic parameter set. The criterion for optimality (in any sort of design) may vary, one example being the minimization of the trace (or partial trace) of the variance-covariance matrix of parameters. First-order design may be approached according to one of the viewpoints described above, for example:

1) Suppose we wish to determine 24-hour averages of polar motion and earth rotation variations to the 10 cm and 1 ms level respectively. What are the minimal conditions necessary, e.g., number and choice of stations (given a source catalogue) for those accuracies to be met? Or alternatively,

2) Suppose there are five available stations for the Polaris network but only three may be chosen. Which three would allow the

"best" overall determinations of earth orientation variations? Obviously, the first question is more difficult because of its absolute nature, while the second one requires only a relative answer. The presence of unmodelled systematic effects in the actual measurement process (particularly at the present VLBI state-of-the-art) may make good a priori accuracy estimates (via covariance analyses) difficult to obtain, especially for question 1 above.

Ma [1978] studied the first-order Polaris network design problem from an experiment simulation point of view. He introduced the effects of typical systematic errors by including model error parameters in the covariance analysis. The first-order design problem has not been of primary importance since antenna availability in conjunction with economic and political considerations have almost totally constrained its solution. However, with the development of portable antennas and allocation of greater resources, this problem assumes greater relevance. Dermanis [1977] derived parameter sensitivity vectors in studying first-order design for earth orientation and baseline parameter estimation.

The second-order design problem may be defined as follows: Given a network of stations, a radio-source catalogue, and an interval of time of antenna availability, optimize an observation schedule for the estimation of, for example, baseline and earth orientation parameters. This problem can also be approached in two ways. It can be asked whether required earth orientation variation accuracies mentioned above can be resolved in an eight-hour daily shift or whether continuous observations are needed, the answer being of obvious economic significance. In a similar vein, Mollinder [1978] reported on a method to compute required antenna time to achieve a given baseline accuracy. Alternatively, Ma [1978] searched for a scheduling strategy to minimize the baseline component variances. The second-order design problem has been somewhat constrained in the past by the low number of sources acceptable for geodetic applications (up to 20 with the Mark I system). The new Mark III system will enable more sources to be observed resulting in a better sky distribution.

Hints to a possible solution of the design problem are presented below. The partial derivatives of the observable with respect to a particular parameter constitute the elements of the design matrix A that forms the normal matrix $N = A^T PA$, whose inverse yields the a priori covariance matrix of parameters. In VLBI, the partials are diurnal sinusoids, the baseline vector and source declination determining the amplitude, the source right ascension and epoch of observation, the phase with respect to 0^hUT (for example). For second-order design, the station locations are given which leaves variable the choice of sources and their epochs of observation. The magnitude of a particular partial which reflects the sensitivity of an observation to a particular parameter determines its numerical contribution to the normal matrix. Assuming no correlations between parameters (and observations) a diagonal normal matrix would result, and in this case the larger the diagonal elements, the smaller the parameter variances. In this ideal case, the solution to the design problem would be to observe the sources when they would maximize the partials with respect to the different parameters. However, the parameters are correlated, and Ma [1978] found that this approach does not yield optimal results for baseline length recovery. Therefore, a particular source must be observed not only at the epochs at which the partial derivative sinusoids attain their maxima. How then should the observations be distributed? Since the partials enter the normal equations squared, the sinusoids are composed of two equivalent 12-hour half-cycles, it is reasonable to assume (although correlations between parameters may invalidate this assumption) that observations on both half-cycles are unnecessary from the point of view of added sensitivity (though they do add redundancy--on the other hand from a systematic error modelling viewpoint, Shapiro [1978] suggests observing high declination sources ("clock stars") over a large fraction of the diurnal cycle to correct for the effects of long-term drifts in the clock behavior). Observational constraints (described below) may limit the availability of a particular source to the quarter-cycle. It will be tested by simulations whether the sensitivity of the observable to a particular parameter can be adequately exploited by observing sources throughout a half (or quarter cycle) of the corresponding parameter partial, in such a way that the sinusoid is adequately represented. In this way, the sensitivity of the observable to a particular parameter may be fully exploited. [Ma, 1978] found that the strategy of maximum sources is not optimal. According to the above hypothesis this is due to inadequate sampling of the sinusoids since less observations are available to a particular source while at the same time antenna slew time is increased. Therefore, it would be advantageous to observe less sources; Ma suggests ten for geodetic purposes.

Until further results are available, the following two-stage procedure is suggested. In the first stage, the sources to be observed are selected from the available source list as follows. Suppose we are interested in the optimal estimation of earth orientation parameters. By an examination of the partial derivatives it can be seen that for a particular station configuration, estimation of the elements of the parameter set are sensitive to either low, medium or high declination sources [Bock, 1980]. Further suppose that it has been decided to observe twelve sources over a 24-hour period. Thus, for each parameter we can choose four sources whose right ascensions are distributed fairly evenly over 24 hours. These sources can be chosen by sorting through the available source list and choosing for each group those sources that provide the largest partial derivative values (a function of source declination). Once the sources are selected, the second stage will involve choosing the corresponding epochs of observation according to the hypothesis suggested in the previous paragraph.

There are problems with the above procedure. In a multi-baseline experiment there are several baselines to consider. The source sort is then performed according to the "best" baseline for the estimation of a particular parameter determined by comparing the sensitivities of the corresponding partial derivatives. In addition, low declination sources are visible for shorter periods of time which will require their more judicious selection. Finally, and most important, this procedure does not consider the correlations between parameters. Clearly, more research is required into this problem area to translate the above suggestions into mathematical form, or to search for other more rigorous optimization techniques. Observation scheduling is quite a tiresome chore and an efficient algorithm that could provide an "optimal" schedule is needed.

In developing an optimal schedule algorithm several constraints must be considered. A source must be observable from all participating stations at a particular epoch of observation. VIP contains a routine that outputs visibility matrices for each source over a 24-hour period as described in Section 3.4. An example is given in Appendix B.

The slew rates of the station antennas are other factors to be considered. Slew rate is a function of the size, steering mechanism and mount geometry of a particular antenna. With equatorial mounts, slew time between any two sources is constant over the entire day, although high declination sources are difficult to track. The equatorially mounted Ft. Davis antenna has an hour angle constraint of 5-1/2 hours on each side of the meridian. For az-el mounts the slew time between any two sources is a function of the epoch of observation. In addition, there is a blind spot at the zenith as well as cable wrap problems. Robertson [private communication] has suggested a function that would weigh cost, corresponding to slew time, against benefit to the objective function of some optimization technique.

Another constraint is dead time which is the time required for nonobservational matters such as the switching of tapes and water vapor radiometry. Economic constraints may include the availability of only one eight-hour shift per day.

4.3 Observation Correlations

In Section 3.2.6 a model suitable for covariance analyses was developed for determining the correlations between simultaneously observed time delays (and time delay rates) in an N station network. The model is a formulation of the theoretical time delay definition--the difference in times of arrival of a given segment of a wavefront at two antennas. However, since delays are not measured in this manner, rather by the cross-correlation procedure described in Section 2.3, this model needs to be modified for application to real data. Neglect of the real observation correlations (or a suitable approximation to them) in the second adjustment mentioned in Section 4.1 may alter significantly the geodetic parameter estimates.

In this context, an experiment was performed at the Goddard Space Flight Center with the aid of Jim Ryan and Chopo Ma. Two good data sets were edited to retain all good simultaneous observations from the Haystack, OVRO (Owens Valley) and NRAO (Greenbank) stations. Least squares estimates of baseline and earth orientation parameters using all three baseline observation sets (a dependent set, see Section 3.2.6) were compared to the results of each of the three two-baseline independent combinations. Theoretically, the two-baseline combinations should yield identical estimates when the true observation correlations are considered [Shapiro, private communication]. The three-baseline case includes only two independent baselines and therefore will yield overly optimistic estimates. In practice, due to inadequate knowledge of observation correlations, a diagonal variance-covariance matrix of observables is assumed. Since the NASA software cannot accommodate off-diagonal elements for the variance-covariance matrix of observables, the experiments were performed with a diagonal matrix.

The data sets were divided into three intervals of time. The first set makes up the first interval of observations of approximately 25-hour duration. This entire interval is used for the first earth orientation step, thereby providing reference orientation for the polar motion and earth rotation parameters of the subsequent steps, as described in Section 3.2.3. The second data set is divided into two approximately 20-hour steps. For each of these two steps, three earth orientation variation parameters are estimated relative to the initial orientation provided by the first step.

The experiments were run in the "unweighted" and "weighted" observation modes. The unweighted mode involves the original time delay observations with their estimated standard deviations as they are recovered from cross-correlation of the tapes. The weighted mode uses observations that have been scaled after an initial adjustment to reduce the a posteriori variance of unit weight to unity. Each baseline is scaled differently, the scale factors computed by a numerical procedure [Robertson, 1975]. It is felt by those involved that this scaling tends to compensate for unmodelled systematic effects as well as for the neglected observation correlations. This writer is not aware of any statistical justification for this scaling.

The results are presented in Tables 4.1 and 4.2. It can be seen in both tables that the baseline "components" τ, ϵ and σ may differ by as much as 50 cm from one solution to the next, and in some cases these

TABLE 4.1 COMPARING SIMULTANEOUS 3-STATION OBSERVATIONS USING ALL 3 BASELINES WITH 2-BASELINE COMBINATIONS (DIAGONAL WEIGHT MATRIX - UNWEIGHTED MODE)

		Configurations / Parameters	HAY-OVRO-NRAO Adjusted Value	HAY-OVRO-NRAO Standard Error	NRAO-HAY HAY-OVRO Adjusted Value	NRAO-HAY HAY-OVRO Standard Error	NRAO-OVRO HAY-OVRO Adjusted Value	NRAO-OVRO HAY-OVRO Standard Error	NRAO-OVRO HAY NRAO Adjusted Value	NRAO-OVRO HAY NRAO Standard Error	Maximum Estimate Difference[1]
Baseline Components	HAY-NRAO	τ_1 (m)	- 609 524.267	0.011	4.256[2]	0.013	4.277	0.017	4.270	0.017	2.1 (cm)
		ϵ_1	- 467 216.782	0.048	6.815	0.600	6.708	0.064	6.791	0.059	10.8
		σ_1	- 352 750.988	0.068	0.962	0.084	1.089	0.088	1.017	0.079	12.5
	HAY-OVRO	τ_2 (m)	-3902 005.464	0.034	5.490	0.047	5.480	0.034	5.479	0.052	3.0 (cm)
		ϵ_2	- 21 088.162	0.130	8.185	0.156	8.392	0.092	8.050	0.241	34.2
		σ_2	- 458 279.311	0.133	9.263	0.163	9.056	0.097	9.481	0.230	42.4
	NRAO-OVRO	τ_3 (m)	-3292 481.197	0.036	1.235	0.049	1.203	0.026	1.209	0.056	3.8 (cm)
		ϵ_3	446 128.620	0.128	8.630	0.156	8.316	0.105	8.741	0.221	42.5
		σ_3	- 105 528.323	0.136	8.301	0.168	7.970	0.119	8.464	0.214	49.4
Baseline Lengths		ℓ_1 (m)	845 129.939	0.012	9.938	0.015	9.946	0.017	9.958	0.016	2.0 (cm)
		ℓ_2	3928 881.683	0.027	1.704	0.039	1.670	0.020	1.717	0.040	4.7
		ℓ_3	3324 244.185	0.026	4.223	0.037	4.140	0.019	4.218	0.036	3.8
Earth Orientation Variations	Step 2	$\Delta\xi_{12}$ [3]	14.390	5.001	16.540	6.022	19.715	3.728	9.737	9.953	9.9
		$\Delta\eta_{12}$ [3]	-187.118	28.292	-174.120	34.861	-145.340	38.159	-192.090	30.730	46.8
		Δx_{12} (ms)	- 1.811	0.434	- 1.339	0.518	- 1.456	0.397	- 2.114	0.804	0.8
	Step 3	$\Delta\xi_{13}$ [3]	9.967	4.495	14.222	5.867	13.564	3.669	4.539	9.937	5.4
		$\Delta\eta_{13}$ [3]	-169.331	28.364	-158.277	34.896	-124.477	38.061	-174.718	30.764	50.2
		Δx_{13} (ms)	- 2.006	0.430	- 1.791	0.507	- 1.271	0.395	- 2.384	0.806	1.1

[1] Among two-baseline combinations [2] Significant portion retained [3] milli-arcseconds

TABLE 4.2 COMPARING SIMULTANEOUS 3-STATION OBSERVATIONS USING ALL 3 BASELINES WITH 2-BASELINE COMBINATIONS (DIAGONAL WEIGHT MATRIX - WEIGHTED MODE)

		Configurations / Parameters	HAY-OVRO-NRAO Adjusted Value	HAY-OVRO-NRAO Standard Error	NRAO-HAY HAY-OVRO Adjusted Value	NRAO-HAY HAY-OVRO Standard Error	NRAO-OVRO HAY-OVRO Adjusted Value	NRAO-OVRO HAY-OVRO Standard Error	NRAO-OVRO HAY-NRAO Adjusted Value	NRAO-OVRO HAY-NRAO Standard Error	Maximum Estimate Difference[1]
Baseline Components	HAY-NRAO	r_1 (m)	- 609 524.275	0.015	4.277[2]	0.017	4.254	0.019	4.292	0.018	3.8 (cm)
		ϵ_1	- 467 216.696	0.050	6.662	0.062	6.738	0.065	6.644	0.058	9.1
		σ_1	- 352 751.030	0.058	1.048	0.068	0.997	0.075	1.081	0.070	8.3
	HAY-OVRO	r_2 (m)	-3902 005.461	0.033	5.468	0.040	5.470	0.026	5.479	0.051	1.7 (cm)
		ϵ_2	- 21 038.022	0.137	7.962	0.157	8.318	0.112	7.797	0.215	52.1
		σ_2	- 158 279.484	0.143	9.488	0.166	9.198	0.118	9.706	0.221	50.1
	NRAO-OVRO	r_3 (m)	-3292 481.187	0.035	1.191	0.044	1.215	0.030	1.186	0.054	2.9 (cm)
		ϵ_3	446 128.674	0.133	8.701	0.157	8.420	0.117	8.847	0.200	28.1
		σ_3	- 105 528.454	0.135	8.440	0.160	8.201	0.121	8.625	0.199	42.4
Baseline Lengths		ℓ_1 (m)	845 129.914	0.017	9.905	0.020	9.969	0.021	9.917	0.022	1.5 (cm)
		ℓ_2	3928 881.700	0.028	1.707	0.034	1.676	0.024	1.742	0.043	6.6
		ℓ_3	3324 244.187	0.027	4.194	0.036	4.173	0.024	4.215	0.038	4.2
Earth Orientation Variations	Step 2	$\Delta\xi_{12}$[3]	3.440	4.858	- 2.077	5.350	13.550	4.204	- 3.004	8.202	16.5
		$\Delta\eta_{12}$[3]	-199.549	23.340	-179.439	27.120	-199.521	32.400	-192.023	25.497	20.1
		$\Delta\chi_{12}$ (ms)	- 2.711	0.401	- 2.929	0.447	- 2.068	0.388	- 3.214	0.639	1.1
	Step 3	$\Delta\xi_{13}$[3]	- 2.204	4.739	- 5.618	5.715	7.712	4.119	- 11.605	8.046	19.3
		$\Delta\eta_{13}$[3]	-165.824	23.319	-149.445	27.060	-168.582	32.316	-156.134	25.467	19.1
		$\Delta\chi_{13}$ (ms)	- 2.708	0.404	- 3.062	0.446	- 1.919	0.391	- 3.231	0.646	1.3

[1] Among two-baseline combinations [2] Significant portion retained [3] milli-arcseconds

discrepancies do not fall within the estimated noise levels. Baseline distance estimates, on the other hand, are well behaved differing by not more than 6.6 cm and are within the noise levels. The polar motion variation parameter estimates, $\Delta\varepsilon_{1\ell}$ and $\Delta\eta_{1\ell}$ are very erratic, while $\Delta\kappa_{1\ell}$ variations are well behaved. Of course, in the three baseline configuration, the standard deviation estimates are lower than in the two-baseline combination cases, but not significantly. However, these differences should become more pronounced as the number of stations is increased. Finally, there seems to be little difference compared to the discrepancies of the weighted mode, some increase and some decrease. Therefore, at least in this experiment, the "weighting" procedure is ineffective in generally reducing the discrepancies.

It is planned to study the effect of including observation correlations using these data sets. It is hoped to be able to reduce the discrepancies in this manner. However, systematic errors may be a more important factor in causing these differences than the random nature of the observations. In order to test whether correlation neglect is significant, the simplified model of Section 3.2.6 must be at least expanded to handle time delays of varying precision. A substantial reduction in the discrepancies will indicate a good correlation model, while remaining differences will be due to unmodelled systematic effects. The latter need to be reduced by better instrument calibration and by improved mathematical models.

APPENDIX A

VLBI COVARIANCE ANALYSIS INTERACTIVE PROGRAM (VIP)

JCL, Explanatory Tables and Figures, Documented Listing

A.1 Introduction

In this appendix a documented listing of VIP is presented, as well as the JCL and explanatory tables and figures for the user's ease of adaptation and operation. The program, written in FORTRAN, must be loaded with the FORTRAN Library (FORTLIB), the IBM FORTRAN Scientific Subroutine Package (FORTSSP) and the Tektronix Graphics 2 package (TXGRAPH2) to achieve its full capability. The FORTSSP is called for normal matrix inversion (DSINV) and calculation of the normal matrix eigenvalues (DEIGEN). Thus, any other routine that performs the same functions may be substituted, though it must be able to handle matrices whose upper triangular elements are stored in vector format. The graphics portion of VIP may be skipped so that TXGRAPH2 is optional. Consequently, the program may be run on any Time Sharing Option (TSO) compatible interactive terminal.

VIP is mainly intended as a covariance analysis program as explained in Chapter 3. However, it is also possible to perform a standard least squares estimation of the parameters and their standard deviations (a posteriori) but only for simulation purposes. An example is given in Appendix B. The program is not equipped to handle real data.

A.2 Job Control Language (JCL)

All the VIP JCL listed in Figure A.1 is given in the form of a command procedure (CLIST) of the IBM OS/VS2 TSO Command Language [IBM, 1978]. In this case, the program is stored in a sequential data set called BOCK.FORT. The CLIST, stored in BOCKLIB.CLIST, allocates the necessary files, compiles BOCK.FORT and loads BOCK.OBJ with SYS2.TXGRAPH2, SYS1.FORTLIB and SYS2.FORTSSP described earlier. The contents of each file are listed in Table A.1. The entire procedure is initiated by the following sequence of commands:

enter:	EXEC BOCKLIB.CLIST
terminal response:	ENTER POSITIONAL PARAMETERS DSNAME
enter:	BOCK.FORT

It may taken from a few seconds up to a few minutes until the program is compiled and loaded depending on the system status. The first program prompt to the user will be

DO YOU WISH TO DRAW MAP?

At the end of the session, the object module, BOCK.OBJ is deleted. The program (2770 card records) and the other necessary data files occupy approximately 35 tracks of disk space.

```
BOCKLIB.CLIST
PROC 1 DSNAME
WRITE
WRITE ALLOCATING FILES
WRITE WAITING FOR COMPILATION
FREE F(FT03F001,FT04F001,FT05F001)
FREE F(FT06F001,FT07F001,FT08F001)
FREE F(FT09F001,FT10F001,FT11F001)
FREE F(FT12F001,FT13F001,FT14F001)
FREE F(FT15F001)
FREE ATTRLIST(XX)
ATTR XX RECFM(F,B,A) BLKSIZE(133) LRECL(133)
ALLOC F(FT03F001) DA(BOCKLIB.DATA)
ALLOC F(FT04F001) DA(DATAQ.DATA)
ALLOC F(FT05F001) DA(*)
ALLOC F(FT06F001) DA(*)
ALLOC F(FT07F001) SYSOUT(A) USING(XX)
ALLOC F(FT08F001) SYSOUT(B)
ALLOC F(FT09F001) DA(YEHUDA.DATA)
ALLOC F(FT10F001) DA(OBSERV.DATA1.DATA)
ALLOC F(FT11F001) DA(OBSERV.DATA2.DATA)
ALLOC F(FT12F001) DA(OBSERV.DATA3.DATA)
ALLOC F(FT13F001) DA(OBSERV.DATA4.DATA)
ALLOC F(FT14F001) DA(OBSERV.DATA5.DATA)
ALLOC F(FT15F001) DA(OBSERV.DATA6.DATA)
FORT &DSNAME
LOAD (BOCK.OBJ) LIB('SYS2.TXGRAPH2','SYS1.FORTLIB','SYS2.FORTSSP')
DELETE BOCK.OBJ
PEND
```

Figure A.1 VIP CLIST

Table A.1. VIP File Allocation

File No.	Content	Format
3	Station file followed by Radio Source file	
	first record -	
	ellipsoid equatorial radius	(unformatted)
	inverse flattening	
	for each station record -	
	station number	I2
	station name	3A4
	latitude (D.M.S.)	I3,I2,F6.3
	longitude (east) (D.M.S.)	I4,I2,F6.3
	ellipsoidal height (m)	F10.2
	for each source record -	
	source number	I2
	source name	3A4
	right ascension (H.M.S.)	I3,I2,F6.3
	declination (D.M.S.)	I4,I2,F6.3
4 (optional)	Digitized map coordinates Format: standard digitizer card format 6 points per card (8X, 12F6.3)	
5	TSO terminal input file	
6	TSO terminal output file	
7	Line printer output file (may be VERSATEC)	
8	Card punch file (not used in program)	
9 (optional)	Planned observation schedule (filled prior to run) Format: Source number - one per record unformatted - to be used only for simultaneous observations from all participating stations at even intervals of time or Format: Source number, hour and minute of observation - one set record unformatted - to be used only for simultaneous observations from all participating stations at uneven intervals of time.	

Table A.1 (continued)

10-15 (optional)	Simulated observation files - one per baseline - filled in order of baseline selection, e.g., 10 - first baseline, 11 - second baseline, etc.	
		Format
	each record -	
	baseline number	I5
	source number	I5
		Format
	hour of observation relative to 0^h UT of initial day	I5
	minute of observation	I5
	delay (m) (zero if interested in covariance analysis only)	F20.10
	delay rate (m/hr) (zero if interested in covariance analysis only or delay observations only)	F20.10
	index - only for nonsimultaneous observations (when not all participating stations observe at each epoch) 0 - next baseline observation at same epoch 1 - next baseline observation at next epoch	I2
	Use these files for the following cases: when entering observation prior to program run, and/or when entering a schedule of non-simultaneous observation	

A.3 Explanatory Information

Table A.2 provides, for easy reference, an index of the various subroutines and their respective purpose. Figure A.2 illustrates the flow of the program and the interconnections among the subroutines.

Table A.3 contains a listing of all data that needs to be input by the operator at the terminal (and, optionally, prior to the program run). The operator is prompted to supply the information by messages on the screen. Some of the input may not be requested depending on the program options as indicated in the table. In Table A.4, the VIP program options are listed. These are chosen by the operator interactively in response to program prompts.

There are certain program parameters that may need to be modified depending on the user's needs. These are indicated at the appropriate locations in the program and are summarized here. In the main program, the variables NSTAT and NQUAS refer to the number of stations and number of sources respectively, stored on file 3 (see Table A.1). The values specified in the program are 6 and 47 respectively (see VP 112, in the listing). A greater number will necessitate increasing the dimensions of the appropriate arrays (see VP 520 - VP 980). Remember that the maximum available storage on TSO is normally 256K (default value - 192K).

Subroutines MAPDRW and BSLN assume that the coordinates of the United States are digitized, at a scale of approximately 1 : 10,000,000, as well as the station locations of Westford, Owens Valley, Goldstone, Ft. Davis, Greenbank and Richmond. Any deviation from these assumptions will necessitate minor modifications in these routines (see the listing).

Of course, the user must supply a set of digitized map coordinates of his area of interest and may need to redefine the screen and virtual windows (see VP 1740 - VP 1790) to take into account the map scale. However, the graphics portion of the program is optional so that digitized map coordinates are not a necessity.

In the interactive mode the user inputs data at the terminal when prompted to do so by the program. All input is accepted after the RETURN key is hit. If an error is made before RETURN, simply hit the BREAK key and re-enter. If RETURN has been specified, the program will usually provide additional chances, immediately or at a later stage, until an acceptable response is made. However, certain erroneous responses will cause the program to abnormally terminate. Therefore, it is good practice to examine your responses before hitting RETURN and to follow directions carefully.

Table A.2 VIP Subroutine Index

Name	Purpose
Main Program	Administers the following: MAIN 1: Baseline configuration display MAIN 2: Mutual visibility outliner MAIN 3: Schedule simulator MAIN 4: Least squares estimation
MAPDRW (optional)	Plots digitized map coordinates, station locations and station symbol selection menu.
BSLN	Inputs station and baseline selections and displays them on map.
SIDTIM	Inputs time information and outputs GST of initial epoch and chosen interval of observations.
GRESID[1]	Calculates GST of initial epoch.
JULIA[1]	Converts Universal Time to Julian date.
STATNS	Inputs station information and computes baseline coordinate differences and baseline lengths.
QUASAR	Sources are displayed and selected. Computes mutual visibility matrix[1] (optional).
SIMULT	Simulates observations for chosen schedules.
FLAGS	Inputs experiment flags.
WEIGHT	Inputs observation weighting information and computes weight matrix of observables.
PARTDR	Calculates partial derivatives of observables with respect to parameters.
AMATR	Fills design matrix (A) with calculated partial derivatives for delay and combination of delay and delay rate observations.
FAMTR	Fills design matrix (A) with calculated partial derivatives for delay rate observations.

[1]Adapted from [Dermanis, 1977].

Table A.2 (Continued)

Name	Purpose
FILL	Fills normal matrix (A^TPA) and U matrix (A^TPL) sequentially.
SOLVE	Computes variance-covariance matrix of parameters (a priori and a posteriori), parameter correlation matrix and normal matrix eigenvalues.
STDLST	Computes and outputs estimated standard deviations of parameters (a priori and a posteriori) and outputs corrections to approximate parameters.
	AUXILIARY ROUTINES
RAD	Converts angle in degrees, minutes, seconds, to radians.
DEGMS	Performs opposite function of RAD.
MATPV	Performs matrix multiplication for matrices stored in general or triangular storage.
LOC	IBM SSP routine-matrix storage manipulator.
	PLOTTING ROUTINES
FRAME	Frames a screen window.
UNITS	Converts centimeters to virtual coordinates.
RECT	Plots a square.
EQUITR	Plots an equilateral triangle.
CIRCLE	Plots a circle.

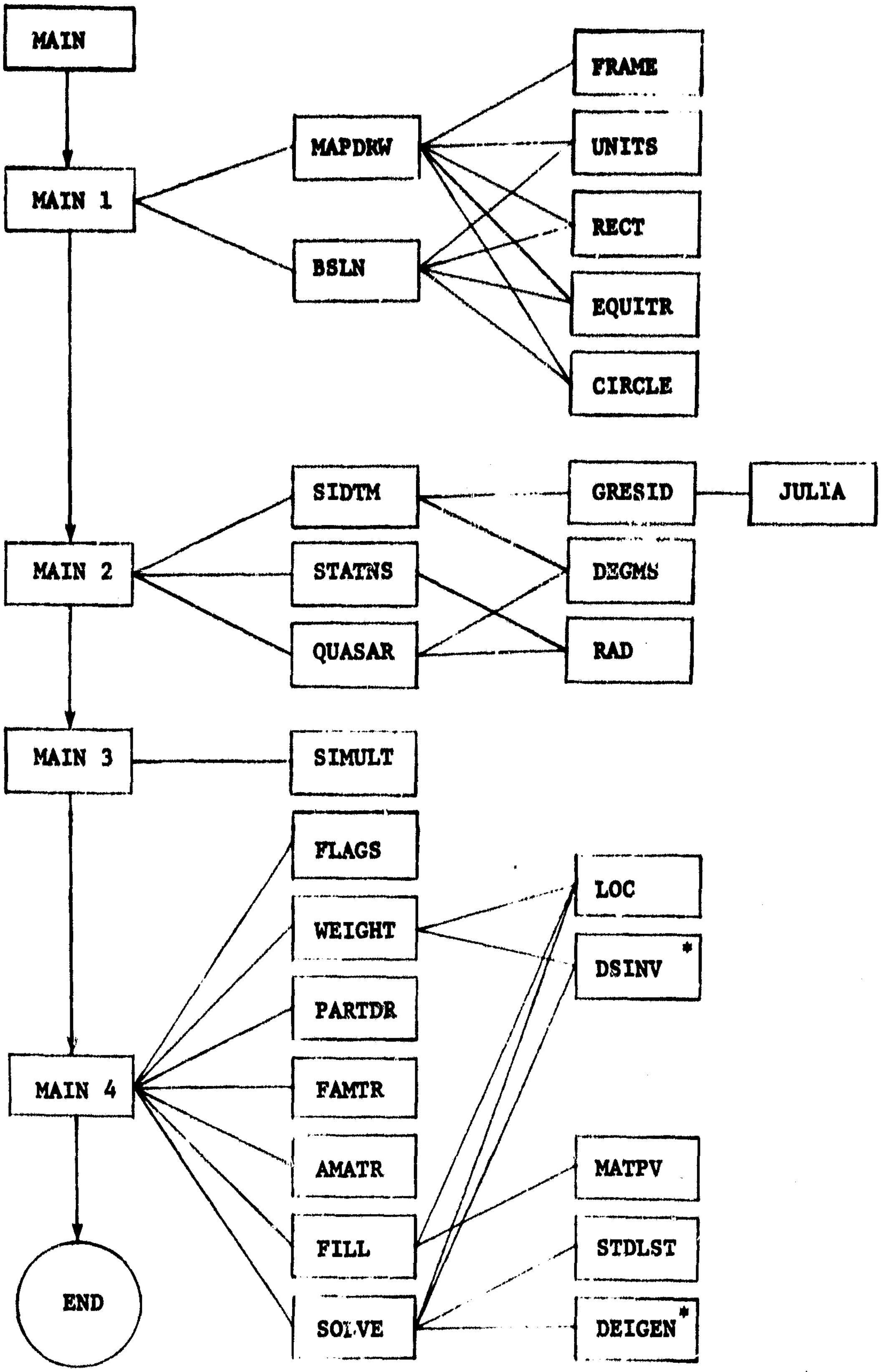


Figure A.2 Program flow.

*SSP

Table A.3. VIP Input Parameters

Variable Name	Description	Subroutine
IN	Number of stations	BSLN
TNB	Number of baselines	
IST[1]	Station selection	
NEX	Experiment number	
Symbol Selection[2]	Operator moves cursor to choose station symbol.	
IYEAR, IMO, IDAY IHOUR, IMIN, SEC	Initial epoch of observations (UT)	SIDTM
JYEAR, JMO, JDAY JHOUR, JMIN, SECJ	Final epoch of observations (UT)	
IQUAS[1]	Chosen source numbers	QUASAR
ZNTMAX[2]	Maximum source zenith distance	
IPFIX	Reference right ascension source number	
ISTT	Number of steps for earth orientation	MAIN 3
SFNC[1]	Final epochs of earth orientation steps	
PMX[1,2]	Approximate step values - first component of polar motion (ξ)	SIMULT
PMY[1,2]	Approximate step values - second component of polar motion (η)	
PMZ[1,2]	Approximate step values (UTC-UT1)	
DT	Time interval between observations	
IFILE[1]	Storage files for observations - one per baseline	(or MAIN 3)

Table A.3 (Continued)

Variable Name	Description	Subroutine
K[2]	Scheduled Observations - source number (when DT is specified)	
K,IHOUR,MIN[2]	Scheduled observations - source number, hour (relative to initial epoch), minute (when DT not specified)	
FLAG1, FLAG2 FLAG3, FLAG4	Program flags (see Table A.4 for details)	FLAGS
SIG1	Delay standard error (m)	WEIGHT
SIG2	Delay rate standard error (m/hr)	
P1[1]	Covariance matrix of observations - upper triangular and diagonal elements scaled to unity (one N x N block - see Section 3.2.6)	
	Prior to Program Run[2]	
K	Source number - see Table A.1, file 9 for details	
or		
K, IHOUR, MIN	Source number, hour and minute of observation	
NB, IP, IHOUR, IMIN, DS[3], FRNG[3], IEND[2]	Baseline number, source number, hour of observation (UT), minute of observation, delay, delay rate, end of observacion index - see Table A.1, files 10-15 for details	

[1] Array.

[2] Optional.

[3] May be set to zero for covariance analysis.

Table A.4. VIP Program Options
(Specified by User Interactively)

Variable	Option	Subroutine
MAP = 0	Baseline configuration map is not displayed - subroutine MAPDRW is skipped - graphics display terminal not required - file 4 is empty	MAIN1
MAP = 1	Digitized map coordinates from file 4 are plotted on graphics screen + baseline configuration - option to terminate program if only map is desired	
GG = YES[1]	Change time input from previous run	MAIN2
GG = NO	Keep same time input as in previous run	
IFY = 0	Skip source mutual visibility outliner - choose sources directly	QUASAR
IFY = 1	Compute visibility matrix - plotted source by source on screen until specified number of sources chosen - can generate complete visibility matrix by specifying last source on list as last chosen source - may terminate program at this point if only visibility matrix is desired	
FG = XES[1]	Keep same earth orientation step input from previous run	MAIN3
FG = XO	Change earth orientation step input	
GG = XES	Skip subroutine SIMULT - store schedule information (and optional observations) on files 10-15 prior to program run (see Table A.1) - one baseline per file	MAIN3
GG = XO	Call subroutine SIMULT - either store schedule information on file 9 previous to run or input schedule interactively (see Table A.1)	
IFLAG = 1	Enter observation schedule at terminal	SIMULT
IFLAG = 2	Input observation schedule from file 9	
DT = 0	Time interval between observations is variable	SIMULT
DT = X	Time interval between observations is X minutes	
IPASS = 0	Observations scheduled ever DT minutes,	SIMULT
IPASS = 1	Observations scheduled at uneven intervals	

Table A.4 (Continued)

Variable	Option	Subroutine
IFRNG = 0	Simulate delay observations only	SIMULT
IFRNG = 1	Simulate delay rate observations, too	
ISIM = 0	All observations are performed simultaneously from all participating stations	MAIN4
ISIM = 1	Opposite of ISIM = 0, when mutual visibility makes observations from all stations at a particular epoch impossible	
FG = XES[1]	Keep same flag input as in previous run	MAIN4
FG = XO	Reinitialize program flags	
FLAG1 = 1	Delay observations only	FLAGS
FLAG1 = 2	Delay + delay rate observations	
FLAG1 = 3	Delay rate only	
FLAG2 = 1	Multi-baseline configuration	FLAGS
FLAG2 = 2	One baseline - estimate first component of polar motion variations (ξ)	
FLAG2 = 3	One baseline - estimate second component of polar motion variations (η)	
FLAG3 = 1	Covariance analysis only	FLAGS
FLAG3 = 2	Complete least squares estimation	
FLAG4 = 1	Estimate all parameters	FLAGS
FLAG4 = 2	Delete clock parameters from parameter list	
FG = XES[1]	Keep same observation weight input as in previous run	MAIN4
FG = XO	Input new observation weight data	
GG = XES	Rerun program with new data input (see ICODE)	MAIN4
GG = XO	Terminate session	
ICODE = 1[1]	Change station input (but not source)	MAIN4
ICODE = 2	Change source input data (but not station)	
ICODE = 3	Change both station and source input data	
ICODE = 4	Change other input data (but not source or station)	

[1]For program rerun only

C-2

A.4 VIP Documented Listing

Most of the information presented in the tables and figures are also described in the program documentation. The VIP documentation consists of a heading at the beginning of each subroutine and other comment cards interspersed throughout the program for added detail. Each heading includes the following information when relevant:

1. Subroutine function (title)
2. INPUT parameters - passes to the routine through the parameter list or via common blocks
3. READ parameters - read within the subroutine using file number 5
4. WRITE parameters - written from within subroutine using file number 6 or 7
5. OUTPUT parameters - output for use in other parts of program by the parameter list or via common blocks
6. OPTIONS - subroutine options
7. SUBROUTINES - called by routine

VIP is listed on the following pages.

```
C     ***********************************************************************
C     **                                                                  **
C     **              VIP - A VLBI INTERACTIVE PROGRAM                    **
C     **              --------------------------------                    **
C     **                                                                  **
C     **                                                                  **
C     **    PURPOSE : TO AID IN THE SIMULATION AND DESIGN OF VLBI         **
C     **       EXPERIMENTS.                                               **
C     **                                                                  **
C     **    DESCRIPTION : VIP IS INTENDED PRIMARILY AS A MULTI-           **
C     **       OPTIONAL COVARIANCE ANALYSIS PROGRAM ALTHOUGH IT           **
C     **       IS POSSIBLE TO PERFORM A LEAST SQUARES ADJUSTMENT          **
C     **       ON SIMULATED DATA. THE PARAMETER SET INCLUDES              **
C     **       BASELINE VECTOR PARAMETERS,VARIATIONS IN POLAR MOTION      **
C     **       AND EARTH ROTATION AVERAGED OVER EARTH ORIENTATION         **
C     **       STEPS,SOURCE PARAMETERS AND CLOCK PARAMETERS (SEE          **
C     **       CHAPTER 3 FOR AN EXPLANATION OF THE ESTIMABLE PARA-        **
C     **       METER SET). THE ANALYSIS MAY INCLUDE DELAY AND/OR          **
C     **       DELAY RATE OBSERVATIONS.                                   **
C     **                  VIP IS RUN IN THE INTERACTIVE MODE ON ANY       **
C     **       TSO COMPATIBLE INTERACTIVE TERMINAL ALTHOUGH THE           **
C     **       OPTIONAL GRAPHICS CAPABILITIES ARE DESIGNED FOR            **
C     **       TEKTRONIX TERMINALS (E.G.TEKTRONIX 4012).IN THIS MODE      **
C     **       THE USER IS ABLE TO SIMULATE AN EXPERIMENT,VIEW THE        **
C     **       RESULTS IN REAL TIME AND RERUN THROUGH THE PROGRAM         **
C     **       WITH THE OPTION OF CHANGING ANY OR ALL OF THE PREVIOUS     **
C     **       INPUT PARAMETERS.THIS PROCESS MAY BE REPEATED AS MANY      **
C     **       TIMES AS DESIRED WITH ONE LOADING OF THE PROGRAM. VIP      **
C     **       PROVIDES EASE OF OPERATION AS WELL AS SAVINGS IN TIME      **
C     **       AND COST RELATIVE TO THE BATCH MODE. VIP MUST BE           **
C     **       LOADED WITH FORTLIB,FORTSSP AND TXGRAPH2.                  **
C     **       VIP IS DIVIDED INTO FOUR SECTIONS :                        **
C     **                                                                  **
C     **              1. BASELINE CONFIGURATION DISPLAY                   **
C     **              2. MUTUAL VISIBILITY OUTLINER                       **
C     **              3. SCHEDULE SIMULATOR                               **
C     **              4. LEAST SQUARES ESTIMATION                         **
C     **                                                                  **
C     **                                                                  **
C     **       WRITTEN BY YEHUDA BOCK  DEPT GEODETIC SCIENCE  1979        **
C     **                                                                  **
C     ***********************************************************************
C
C      MAIN PROGRAM
C      ------------
C
      IMPLICIT REAL*8(A-H,O-Z)
      REAL*4 XX,YY,ARAY
      INTEGER*2 INDEX
      INTEGER TNB,FLAG1,FLAG2,FLAG3,FLAG4
C
C     MAXIMUM NUMBER OF PARAMETERS ALLOWED BY DIMENSIONS
C        1.  6 BASELINES
C        2. 12 QUASARS
C        3.  4 EARTH ORIENTATION STEPS
C        4.  6 CLOCK RATE PARAMETERS
C        5.  6 CLOCK OFFSET PARAMETERS
C     THE TOTAL NUMBER OF PARAMETERS SHOULD NOT EXCEED 62
C     INCREASE DIMENSIONS FOR A LARGER PARAMETER SET
C     NOTE:MAXIMUM STORAGE AVAILABLE ON TSO-256K
C
C     ARRAY                FUNCTION                     SUBROUTINES
C
C     ARAY        TERMINAL STATUS ARRAY                 MAPDRW,BSLN
C     XX,YY       DIGITIZED MAP COORDINATES             MAPDRW,BSLN
C     IS,JS,IST   INDICES FOR CHOSEN STATIONS           BSLN,STATNS
```

```
C       X,Y,Z            CARTESIAN STATION COORDINATES       STATNS
C       XT,YT,ZT         STATION UNIT VECTOR COMPONENTS      STATNS
C       DIST             BASELINE DISTANCES                  STATNS,SOLVE
C       XC,YC,ZC         BASELINE COORDINATE DIFFERENCES     STATNS,SIMULT,PART
C       XTP,YTP,ZTP      CHOSEN STATION UNIT VECTOR COMPON.  STATNS,QUASAR
C       RAR,DECR         QUASAR COORDINATES ON FILE          QUASAR
C       E1,E2,E3         QUASAR UNIT VECTOR COMPONENTS       QUASAR
C       KEEP             TITLE FOR OBSERVABILITY OUTLINER    QUASAR
C       INDEX            OBSERVABILITY MATRIX                QUASAR
C       IQUAS            INDICES FOR CHOSEN QUASARS          QUASAR
C       RA,D             CHOSEN QUASAR COORDINATES           QUASAR,SIMULT,PART
C       IFILE            OUTPUT FILES FOR OBSERVATIONS       SIMULT
C       PMX,PMY,PMZ      APPROX VALUES EARTH ORIENTATION     SIMULT
C       AL               MISCLOSURE VECTOR                   PARTDR,FILL
C       P,P1,PB          WEIGHT MATRIX MANIPULATORS          WEIGHT,FILL
C       PART,G           PARTIAL DERIVATIVES DELAY & RATE    PARTDR,AMATR
C       AM,AC            DESIGN MATRIX MANIPULATORS          AMATR,FILL
C       BC               WORK MATRIX (BC=ATP)                FILL
C       W                NORMAL MATRIX AND ITS INVERSE       FILL,SOLVE
C       U                U=ATPA VECTOR                       FILL,SOLVE
C       XA               CORRECTIONS TO APPROX PARAMETERS    SOLVE
C       B,DM,EM          PROPAGATION OF BASELINE DISTANCE    SOLVE
C       CORR             CORRELATION MATRIX MANIPULATION     SOLVE
C       SFNC             STEP FINAL EPOCHS                   MAIN3
C
      DIMENSION RA(12), D(12), KEEP(24), IQUAS(12), INDEX(6,24), ARAY(60
     1), X(6), Y(6), Z(6), IS(6), JS(6), IST(6), IFILE(6), RAR(47), DECR
     2(47), E1(47), E2(47), E3(47), XT(6), YT(6), ZT(6), PMX(4), PMY(4),
     3 PMZ(4), XC(6), YC(6), ZC(6), DIST(6), W(1953), U(62), XA(62), PAR
     4T(10), G(10), AM(124), CORR(63), B(108), DM(36), EM(108), XTP(6),
     5YTP(6), ZTP(6), AC(744), BC(744), P(78), PB(21), XX(6), YY(6), P1(
     642), AL(12), SFNC(4)
C
      COMMON /DRAW1/ XX/DRAW2/YY/DRAW3/ARAY/CRD1/XTP/CRD2/YTP/CRD3/ZTP/C
     1RD4/XC/CRD5/YC/CRD6/ZC/TIME/IMO,IDAY,IYEAR/DEX1/IS/DEX2/JS/DEX3/IS
     2T/DEX4/NEX/SOU1/RA/SOU2/D/FLG/FLAG1,FLAG2,FLAG3,FLAG4/PDR1/PART/PD
     3R2/G/ATRX/AM/NTRX/W/UTRX/U/BS/TNB,KK
C
C     DEFINE TERMINAL RESPONSES
      DATA XO,XES,XERM,XILE/'NO','YES','TERM','FILE'/
C
C     DEFINE PROGRAM CONSTANTS :
C     NSTAT - TOTAL NUMBER OF STATIONS ON FILE (CHANGE IF NECESSARY)
C     NQUAS - NUMBER OF QUASARS ON FILE (CHANGE IF NECESSARY)
C     IF INCREASING NSTAT AND/OR NQUAS CHANGE APPROPRIATE DIMENSIONS
      DATA NSTAT/6/,NQUAS/47/
C     CONV - CONVERSION FACTOR UNIVERSAL TO SIDEREAL TIME
C     ERAD - APPROXIMATE EARTH RADIUS
C     C - THE SPEED OF LIGHT IN METERS/NSEC
      DATA CONV/1.002737909265D0/,ERAD/6371000.D0/,C/0.2997D0/
      PI=4.D0*DATAN(1.D0)
C     RO : CONVERSION FACTOR FROM RADIANS TO SECONDS OF ARC
      CALL RAD (0,0,1.0,P,PI)
      RO=1.D0/DSIN(P)
C     OMEGA IS THE ROTATION RATE OF THE EARTH IN RADIANS/HOUR
      OMG=PI*CONV/12.D0
C
C     INITIALIZE TERMINAL CONTROL SYSTEM
      CALL INITT (120)
C
C     MAIN1 : BASELINE CONFIGURATION DISPLAY
C     -----------------------------------------------
C
C     CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C        PURPOSE : CHOOSE PARTICIPATING STATIONS AND PROVIDE
C                  GRAPHICAL DISPLAY (MAP) OF EACH EXPERIMENT.
C                  MAP IS OPTIONAL SO THAT THIS SECTION MAY
```

```
C                       BE RUN ON ANY INTERACTIVE SCREEN OR TERMINAL
C                       AT IRCC AND NOT NECESSARILY A TERMINAL WITH
C                       GRAPHICS CAPABILITY.
C                       OPTION TO TERMINATE PROGRAM AT END OF SECTION
C                       WHEN MAP DISPLAY IS ONLY DESIRED OBJECTIVE.
C                       SEE INDIVIDUAL SUBROUTINES FOR MORE INFO.
C
C                   CALLS SUBROUTINES MAPDRW,BSLN
C
C     CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C     ICODE=0 DENOTES INITIAL PROGRAM RUN (OTHER ICODES ARE PROGRAM
C       RERUN OPTIONS - EXPLAINED AT END OF MAIN PROGRAM)
      ICODE=0
C
C     OPTION : MAP=0,MAP IS NOT DRAWN
C              MAP=1,MAP IS DRAWN
 1    MAP=0
C     ERASE SCREEN
      CALL ERASE
C     MOVE CURSOR TO UPPER LEFT-HAND CORNER OF SCREEN
      CALL HOME
C     SAVE CURRENT STATUS OF TERMINAL CONTROL AREA
      CALL SVSTAT (ARAY)
C     SWITCH TO ALPHANUMERIC MODE
      CALL ANMODE
 2    WRITE (6,3)
 3    FORMAT (' DO YOU WISH TO DRAW MAP')
      READ (5,4) F
      IF(F.NE.XES.AND.F.NE.XO) GO TO 2
 4    FORMAT (A4)
      CALL ERASE
      CALL HOME
      IF(F.EQ.XO) GO TO 5
C     FILE 4 CONTAINS DIGITIZED MAP COORDINATES-MAY BE EMPTY IF MAP=0
      IF(ICODE.NE.0) REWIND 4
      MAP=1
C
      CALL RESTAT (ARAY)
C     DEFINE SCREEN AND VIRTUAL WINDOWS
      CALL SWINDO (350,560,270,505)
C     VIRTUAL MAPS TO SCREEN IN A 2:1 RATIO - DIGITIZED MAP TO SCREEN
C      SCALE CAN BE CHANGED TO SUIT PARTICULAR MAP SO IT FALLS IN
C      SCREEN WINDOW BY SUITABLE CHOICE OF VIRTUAL WINDOW
      CALL VWINDO (0.0,1320.,0.0,1010.)
C
C     CALL MAP HANDLER
      CALL MAPDRW (NSTAT)
C
C     CALL BASELINE HANDLER
 5    CALL BSLN (IN,MAP,NSTAT,ICODE)
C
      CALL ERASE
      CALL HOME
      CALL ANMODE
 6    WRITE (6,7)
 7    FORMAT (' DO YOU WISH TO RUN OR RE-RUN MAP DRAWING SESSION'/'
     1OR STATION AND BASELINE SELECTION')
      READ (5,4) GG
      IF(GG.NE.XES.AND.GG.NE.XO) GO TO 6
      IF(GG.EQ.XO) GO TO 8
      CALL ERASE
      REWIND 4
      GO TO 1
C
 8    WRITE (6,9)
 9    FORMAT (' DO YOU WISH TO TERMINATE SESSION')
      READ (5,4) GG
```

```
      IF(GG.NE.XES.AND.GG.NE.XO) GO TO 8
      IF(GG.EQ.XES) GO TO 76
C
C     MAIN2 : MUTUAL VISIBILITY OUTLINER
C     ----------------------------------
C
C     CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C        PURPOSE : INPUT PARAMETERS FOR CALCULATION OF MUTUAL
C                  VISIBILITY OF QUASAR FROM ALL PARTICIPATING
C                  STATIONS.VISIBILITY MATRIX OPTIONAL BUT INPUT
C                  PARAMETERS NECESSARY FOR REMAINDER OF RUN.
C                  IF VISIBILITY MATRIX THE ONLY OBJECTIVE THERE
C                  IS OPTION OF TERMINATING PROGRAM.
C                  SEE INDIVIDUAL SUBROUTINES FOR MORE INFO.
C
C                CALLS SUBROUTINES SIDTM,STATNS,QUASAR
C
C     CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      CALL ERASE
      CALL HOME
      CALL ANMODE
C
C     OPTION TO RETAIN SAME TIME INPUT FOR PROGRAM RE-RUN
      IF(ICODE.EQ.0) GO TO 12
 10   WRITE (6,11)
 11   FORMAT (' DO YOU WISH TO CHANGE INTERVAL OF OBSERVATIONS')
      READ (5,4) GG
      IF(GG.NE.XES.AND.GG.NE.XO) GO TO 10
      IF(GG.EQ.XO) GO TO 13
C     CALL TIME HANDLER
 12   CALL SIDTM (THO,PI,TF)
C
C     CALL STATION HANDLER
 13   CALL STATNS (X,Y,Z,XT,YT,ZT,DIST,PI,ICODE,NSTAT)
C
C     OPTION TO SKIP QUASAR SELECTION FOR PROGRAM RE-RUN
      IF(ICODE.EQ.1) GO TO 16
 14   CALL ERASE
      CALL HOME
C
C     CALL QUASAR HANDLER
      CALL QUASAR (XO,DECR,RAR,E1,E2,E3,OMG,PI,IQUAS,KEEP,INDEX,ICODE,IM
     1,IPFIX,NQUAS,THO,TF,IN)
C
C     OPTION TO TERMINATE SESSION IF ONLY INTERESTED
C      IN VISIBILITY OUTLINER
 15   WRITE (6,9)
      READ (5,4) GG
      IF(GG.NE.XES.AND.GG.NE.XO) GO TO 15
      IF(GG.EQ.XES) GO TO 76
C
C     MAIN3 : SCHEDULE SIMULATION
C     ---------------------------
C
C     CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C        PURPOSE : SIMULATE CHOSEN VLBI OBSERVATION SCHEDULES
C                  TIME DELAY AND/OR TIME DELAY RATES MAY BE SIMULATED
C                  VARIOUS OPTIONS AVAILABLE- SEE SUBROUTINE
C                  SIMULT FOR DETAILS. OPTION TO SKIP OBSERVATION
C                  SIMULATION IF WORKING WITH SIMULATED DATA - IN THAT
C                  CASE OBSERVATION FILES FILLED PRIOR TO RUN.
C
C        INPUT   : ISTT  # STEPS EARTH ORIENTATION STEP FUNCTION
C                  SFNC  FINAL EPOCHS OF EARTH ORIENTATION STEPS
C
```

```
C         WRITE    :  ISTT,SFNC
C
C                   CALLS SUBROUTINE SIMULT
C
C      CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
 16    CALL ERASE
       CALL HOME
       CALL ANMODE
C
C      OPTION TO SKIP STEP INPUT - FOR PROGRAM RE-RUN
       IF(ICODE.EQ.0) GO TO 20
 17    WRITE (6,18)
 18    FORMAT (' DO YOU WISH TO SKIP STEP INPUT')
       READ (5,4) FG
       IF(FG.NE.XES.AND.FG.NE.XO) GO TO 17
       IF(FG.EQ.XO) GO TO 20
       WRITE (7,19)
 19    FORMAT (1H1)
       GO TO 27
C
C      INPUT #STEPS AND FINAL EPOCHS FOR EARTH ORIENTATION STEP FUNCTION
 20    WRITE (6,21)
C      CHANGE FORMAT IF MAXIMUM STEP #(4) HAS BEEN INCREASED
 21    FORMAT (/,' ENTER #STEPS FOR EARTH ORIENTATION',/,' MAXIMUM NUMBER
     1 OF STEPS IS 4')
       READ (5,*) ISTT
C      CHANGE IF MAXIMUM STEP #(4) HAS BEEN INCREASED
       IF(ISTT.GT.4) GO TO 20
       WRITE (6,22)
 22    FORMAT (/,' ENTER END OF STEP EPOCH FOR EACH STEP'/,' FORMAT : HOU
     1R,MINUTE  (INTEGERS)'/,'  PRESS RETURN THEN ENTER NEXT FINAL EPOCH
     2'/,' NOTE: HOUR RELATIVE TO INITIAL EPOCH'/,'        (MAY BE GREATE
     3R THAN 24)')
       WRITE (7,23) ISTT
 23    FORMAT (1H1,8X,'NUMBER STEPS FOR EARTH ORIENTATION PARAMETERS =',I
     12)
       WRITE (7,24)
 24    FORMAT (//,8X,' STEP FINAL EPOCHS - RELATIVE TO INITIAL EPOCH')
       DO 26  I=1,ISTT
       READ (6,*) IHOUR,IMIN
       WRITE (7,25) I,IHOUR,IMIN
 25    FORMAT (/,10X,'STEP #',I2,4X,I3,2X,'HOURS',5X,I3,2X,'MINUTES')
       SFNC(I)=DFLOAT(IHOUR)+IMIN/60.D0
 26    CONTINUE
C
C      OPTION TO SKIP SCHEDULE SIMULATION
 27    WRITE (6,28)
 28    FORMAT (' DO YOU WISH TO SKIP SCHEDULE SIMULATION ?   '/' ANSWER Y
     1ES OR NO')
       READ (5,4) GG
       IF(GG.NE.XES.AND.GG.NE.XO) GO TO 27
       IF(GG.EQ.XES) GO TO 29
C
C      CALL SCHEDULE SIMULATOR
       CALL SIMULT (XERM,XILE,XES,ERAD,PMX,PMY,PMZ,OMG,TF,THO,IFILE,ISTT,
     1SFNC,ICODE,CONV)
       GO TO 32
C
 29    WRITE (6,30)
 30    FORMAT (' ENTER OBSERVATION FILE NUMBERS'/' AVAILABLE FILE NUMBERS
     1  10-15')
       READ (5,*) (IFILE(J),J=1,TNB)
       DO 31 J=1,TNB
       IF(IFILE(J).LT.10.OR.IFILE(J).GT.15) GO TO 29
 31    CONTINUE
       IF(ICODE.EQ.0) GO TO 34
C
```

```
C       REWIND OBSERVATION FILES IF RE-RUNNING PROGRAM
  32    DO 33 I=1,TNB
        NUM=IFILE(I)
        REWIND NUM
  33    CONTINUE
C
C       MAIN4 : LEAST SQUARES ESTIMATION HANDLER
C       ---------------------------------------
C
C       CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C          PURPOSE : A) COMPUTES NUMBER OF PARAMETERS FOR ADJUSTMENT
C                    B) ZEROS OUT WORK VECTORS
C                    C) INPUTS OBSERVATIONS FROM STORAGE FILES
C                    D) CALLS LEAST SQUARES ROUTINES
C                    E) PRESENTS PROGRAM RERUN OPTIONS
C
C                 CALLS SUBROUTINES FLAGS,WEIGHT,PARTDR,FAMTR,
C                                   AMATR,FILL,SOLVE
C
C       CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
  34    CALL ERASE
        CALL HOME
        CALL ANMODE
C
C       SIMULTANEOUS OBSERVATIONS FROM ALL STATIONS OPTION
C          ISIM=0  : SIMULTANEOUS OBSERVATIONS
C          ISIM=1  : NON-SIMULTANEOUS
        ISIM=0
  35    WRITE (6,36)
  36    FORMAT (' ARE ALL STATIONS INVOLVED AT EACH EPOCH OF OBSERVATION')
        READ (5,4) FG
        IF(FG.NE.XES.AND.FG.NE.XO) GO TO 35
        IF(FG.EQ.XO) ISIM=1
C
C       OPTION TO SKIP FLAG HANDLER - FOR PROGRAM RERUN
        IF(ICODE.EQ.0) GO TO 39
  37    WRITE (6,38)
  38    FORMAT (' DO YOU WISH TO SKIP FLAG HANDLER')
        READ (5,4) FG
        IF(FG.NE.XES.AND.FG.NE.XO) GO TO 37
        IF(FG.EQ.XES) GO TO 40
C
C       CALL PROGRAM FLAGS HANDLER
  39    CALL FLAGS (JK)
C
C       OPTION TO SKIP WEIGHT HANDLER - FOR PROGRAM RERUN
  40    IF(ICODE.EQ.0) GO TO 43
  41    WRITE (6,42)
  42    FORMAT (' DO YOU WISH TO SKIP WEIGHT HANDLER')
        READ (5,4) FG
        IF(FG.NE.XES.AND.FG.NE.XO) GO TO 41
        IF(FG.EQ.XES) GO TO 44
C
C       CALL OBSERVATION WEIGHT HANDLER
  43    CALL WEIGHT (P,PB,SIG,P1)
C
C       COMPUTE THE NUMBER OF PARAMETERS TO BE ADJUSTED
C       KK IS THE NUMBER OF PARAMETERS
  44    KK=5*TNB+2*IM+(3-JK)*(ISTT-1)-1
C       IF DELAY RATES ONLY CHANGE NUMBER OF PARAMETERS
        IF(FLAG1.EQ.3) KK=3*TNB+2*IM+(3-JK)*(ISTT-1)-2
C       IF NO CLOCK PARAMETERS CHANGE NUMBER OF PARAMETERS
        IF(FLAG1.NE.3.AND.FLAG4.EQ.2) KK=KK-2*TNB
        IF(FLAG1.EQ.3.AND.FLAG4.EQ.2) KK=KK-TNB
        KK2=KK*2
        K2=KK*(KK+1)/2
```

```
      KS=KK
      IF(FLAG1.EQ.2) KS=KK2
C
C     ZERO OUT WORK VECTORS
      DO 45 J=1,K2
      W(J)=0.D0
   45 CONTINUE
      DO 46 J=1,KK
      U(J)=0.D0
      XA(J)=0.D0
   46 CONTINUE
      DO 47 I=1,KK2
   47 AM(I)=0.D0
      DO 48 J=1,10
      AL(J)=0.D0
      G(J)=0.D0
   48 PART(J)=0.D0
      VTPV1=0.D0
      ICOUNT=0
      IEND=0
      L=1
C
      IF(ICODE.EQ.4) GO TO 51
      WRITE (7,49)
   49 FORMAT (1H1,12X,'OBSERVATION SCHEDULE'/)
      WRITE (7,50) L
   50 FORMAT (/,9X,'STEP   ',I2/6X,'BSLN',1X,'QUAS',2X,'HR',2X,'MIN',5X,'
     1DELAY (M)  ',8X,'DELAY RATE (M/HR)'/)
C
C     INPUT OBSERVATIONS
C     L : BASELINE COUNTER
C     IJ : EARTH ORIENTATION STEP NUMBER COUNTER
   51 IJ=0
   52 IJ=IJ+1
C     UPDATE END OF STEP EPOCH
      ST=SFNC(IJ)
      IF(IJ.GT.1) GO TO 61
C     READ OBSERVATIONS-BASELINE BY BASELINE,EPOCH BY EPOCH
   53 NUM=IFILE(L)
C     NB : BASELINE NUMBER
C     IP : QUASAR NUMBER
C     IHOUR,IMIN : EPOCH OF OBSERVATION
C     DS : DELAY OBSERVABLE (PATH DIFFERENCE)
C     FRNG : DELAY RATE OBSERVABLE (PATH DIFFERENCE RATE)
      IF(ISIM.EQ.1) GO TO 55
      READ (NUM,54,END=69) NB,IP,IHOUR,IMIN,DS,FRNG
   54 FORMAT (4I5,2F20.10)
      GO TO 57
C     IEND : END OF EPOCH INDEX (NON-SIMULTANEOUS OBSERVATIONS)
   55 READ (NUM,56,END=69) NB,IP,IHOUR,IMIN,DS,FRNG,IEND
   56 FORMAT (4I5,2F20.10,I2)
C     INCREASE OBSERVATION COUNTER BY 1
   57 ICOUNT=ICOUNT+1
      TK=DFLOAT(IHOUR)+IMIN/60.D0
      IF(ICODE.EQ.4) GO TO 60
      IF(TK.LE.ST) GO TO 58
      IJK=IJ+1
      WRITE (7,50) IJK
   58 WRITE (7,59) NB,IP,IHOUR,IMIN,DS,FRNG
   59 FORMAT (4X,4I5,2F20.10)
C     UPDATE STEP NUMBER IF NECESSARY
   60 IF(TK.GT.ST) GO TO 52
C
C     CALCULATE PARTIAL DERIVATIVES FOR PRESENT OBSERVATION
   61 CALL PARTDR (IP,TK,XC(NB),YC(NB),ZC(NB),TH0,OMG,C,RO,DS,FRNG,CONV,
     1ERAD,AL,JK,IJ,NB)
C
C     FILL DESIGN MATRIX WITH PRESENT OBSERVATION PARTIALS
```

```
      IF(FLAG1.NE.3) GO TO 62
C     FILL DELAY RATE DESIGN MATRIX
      CALL FAMTR (NB,IP,IM,IJ,ISTT,JK,IPFIX)
      GO TO 63
C     FILL DELAY OR DELAY-DELAY RATE DESIGN MATRIX
 62   CALL AMATR (NB,IP,IM,IJ,ISTT,JK,IPFIX)
 63   DO 64 IZ=1,KS
C     FILL PRESENT EPOCH PORTION OF "A" MATRIX WITH ONE BASELINE
C      CONTRIBUTION AT A TIME
      JZ=(NB-1)*KS+IZ
      AC(JZ)=AM(IZ)
 64   CONTINUE
      DO 65 KN=1,KK2
 65   AM(KN)=0.D0
C
C     CHECK FOR NEXT EPOCH OF OBSERVATION
      IF(IEND.EQ.1) GO TO 66
      L=L+1
      IF(L.LE.TNB) GO TO 53
C     RE-INITIALIZE BASELINE COUNTER
 66   L=1
C
C     ADD CONTRIBUTION OF AN EPOCH OF OBSERVATIONS TO NORMAL MATRIX
      CALL FILL (AC,P,VTPV1,AL,BC)
      KZ=TNB*KK
      DO 67 KN=1,KZ
 67   AC(KN)=0.D0
      DO 68 KN=1,TNB
 68   AL(KN)=0.D0
C     CONTINUE TO NEXT EPOCH OF OBSERVATIONS
      GO TO 53
C
C     CALL SOLUTION SUBROUTINE
 69   CALL SOLVE (SIG,CORR,XA,IM,ISTT,DIST,B,DM,EM,VTPV1,ICOUNT)
C
      CALL ERASE
      CALL HOME
      CALL ANMODE
C
C      PROGRAM RERUN OPTION
C       1.  ICODE=1 CHANGE BASELINE CONFIGURATION (OR TIME INPUT)
C       2.  ICODE=2 CHANGE QUASAR SELECTION
C       3.  ICODE=3 CHANGE BOTH OF THE ABOVE
C       4.  ICODE=4 CHANGE OTHER INPUT PARAMETERS
 70   WRITE (6,71)
 71   FORMAT (/' DO YOU WISH TO RUN THE PROGRAM AGAIN')
      READ (5,4) GG
      IF(GG.NE.XES.AND.GG.NE.XO) GO TO 70
      IF(GG.EQ.XO) GO TO 76
 72   WRITE (6,73)
 73   FORMAT (//' DO YOU WISH TO CHANGE THE BASELINE CONFIGURATION')
      READ (5,4) GG
      IF(GG.NE.XES.AND.GG.NE.XO) GO TO 72
      IF(GG.EQ.XO) GO TO 74
      ICODE=1
 74   WRITE (6,75)
 75   FORMAT (//' DO YOU WISH TO CHANGE QUASAR SELECTION')
      READ (5,4) HH
      IF(HH.NE.XES.AND.HH.NE.XO) GO TO 74
      IF(HH.EQ.XES) ICODE=2
      IF(HH.EQ.XES.AND.GG.EQ.XES) ICODE=3
      IF(HH.EQ.XO.AND.GG.EQ.XO) ICODE=4
      IF(ICODE.EQ.1.OR.ICODE.EQ.3) GO TO 1
      IF(ICODE.EQ.4) GO TO 16
      GO TO 14
C
C     CALL TERMINATION ROUTINE
 76   CALL FINITT (0,70)
      STOP
      END
```

```
      SUBROUTINE MAPDRW (NSTAT)
C     ******************************************************************
C     **                                                              **
C     **                  PLOT DIGITIZED MAP AND MENU                 **
C     **                                                              **
C     **     INPUT  : XO       TERMINAL "NO" RESPONSE                 **
C     **              NSTAT    NUMBER OF STATIONS ON FILE             **
C     **              ARAY     TERMINAL STATUS ARRAY                  **
C     **                                                              **
C     **     OUTPUT : MAP OF UNITED STATES,STATION LOCATIONS,         **
C     **              MENU (SYMBOL SELECTION)                         **
C     **                                                              **
C     **            CALLS SUBROUTINES FRAME,UNITS,RECT,               **
C     **                              EQUITR,CIRCLE                   **
C     **                                                              **
C     ******************************************************************
C
C     NOTE : MAPDRW MUST BE MODIFIED TO ACCOMODATE OTHER MAPS -
C            AREAS OF POSSIBLE CHANGE INDICATED IN PROGRAM
C     MAPDRW WILL NOT BE CALLED IF MAP DRAW OPTION NOT SET
C
      DIMENSION X(12)
      COMMON /DRAW1/ XX(1)/DRAW2/YY(1)/DRAW3/ARAY(1)
      DATA ZO/'NO'/
C
C     DRAW SCREEN WINDOW
      CALL FRAME (350,660,270,505)
C
C     READ DIGITIZED COODINATES OF UNITED STATES BORDER FROM UNIT 4
C     KR : NUMBER OF DIGITIZED MAP RECORDS (CHANGE IF NECESSARY)
      KR=77
      DO 4 J=1,KR
      READ (4,1) (X(K),K=1,12)
    1 FORMAT (8X,12F6.3)
C     PLOT THESE COORDINATES
      DO 3 I=1,11,2
C     SK,TK : TRANSLATION COMPONENTS (CHANGE IF NECESSARY)
      SK=11.03
      TK=0.92
      X(I)=X(I)-SK
      X(I+1)=X(I+1)-TK
C     CONVERT TO VIRTUAL UNITS FROM CENTIMETERS
      CALL UNITS (X(I),X(I+1),DX,DY)
C     "PEN UP" FOR FIRST POINT OF FIRST RECORD
      IF(I.EQ.1.AND.J.EQ.1) GO TO 2
C     DRAW TO COORDINATE DX,DY
      CALL DRAWA (DX,DY)
      GO TO 3
C     MOVE TO COORDINATE DX,DY
    2 CALL MOVEA (DX,DY)
    3 CONTINUE
    4 CONTINUE
C
C     READ DIGITIZED STATION COORDINATES
C     DRAW THE STATION NUMBERS IN ALPHANUMERIC MODE
      DO 12 J=1,NSTAT
      READ (4,5) (X(K),K=1,2)
    5 FORMAT (8X,2F6.3)
      X(1)=X(1)-SK
      X(2)=X(2)-TK
      XX(J)=X(1)
      YY(J)=X(2)
      CALL UNITS (X(1),X(2),DX,DY)
C     DRAW A POINT AT STATION LOCATION
      CALL POINTA (DX,DY)
C     POSITION STATION NUMBERS ON MAP (CHANGE IF NECESSARY)
```

```
      IF(J.EQ.3) DY=DY-60.
      IF(J.EQ.4) DY=DY-15.
      IF(J.EQ.5) DY=DY-25.
      IF(J.EQ.1.OR.J.EQ.2.OR.J.EQ.4) DX=DX-55.
      IF(J.EQ.[illegible]) DX=DX+15.
      IF(J.EQ.[illegible]) DX=DX-80.
      IF(J.EQ.6) DX=DX+40.
      CALL MOVEA (DX,DY)
      CALL SVSTAT (ARAY)
      CALL ANMODE
      IF(J.EQ.1) WRITE (6,6)
      IF(J.EQ.2) WRITE (6,7)
      IF(J.EQ.3) WRITE (6,10)
      IF(J.EQ.4) WRITE (6,8)
      IF(J.EQ.5) WRITE (6,9)
      IF(J.EQ.6) WRITE (6,11)
    6 FORMAT (' WS')
    7 FORMAT (' OV')
    8 FORMAT (' CS')
    9 FORMAT (' FD')
   10 FORMAT (' GB')
   11 FORMAT (' RM')
      CALL RESTAT (ARAY)
   12 CONTINUE
C
C     DRAW STATION SYMBOL MENU
C     OPTION TO CHOOSE FROM 3 STATION SYMBOLS
C        1. RECTANGLE
C        2. TRIANGLE
C        3. CIRCLE
      CALL MOVABS (KCM(13.5),KCM(4.4))
      CALL SVSTAT (ARAY)
      CALL ANMODE
      WRITE (6,13)
   13 FORMAT (' SYMBOL SELECTION')
      CALL RESTAT (ARAY)
C     DEFINE NEW WINDOWS FOR SYMBOL DRAWING
      CALL SWINDO (KCM(12.0),KCM(7.0),KCM(2.8),KCM(2.0))
      CALL UNITS (7.0,2.0,S,T)
      CALL VWINDO (0.0,S,0.0,T)
      CALL FRAME (KCM(12.0),KCM(7.0),KCM(2.8),KCM(2.0))
C     DRAW RECTANGLE
      CALL RECT (1.0,1.0,1.0)
C     DRAW EQUILATERAL TRIANGLE
      CALL EQUITR (3.2,1.0,1.0)
C     DRAW CIRCLE
      CALL CIRCLE (5.7,1.0,0.5)
C
      RETURN
      END
```

```
      SUBROUTINE BSLN (IN,MAP,NSTAT,ICODE)
C     ******************************************************************
C     **                                                              **
C     **                  SELECT AND MAP BASELINES                    **
C     **                                                              **
C     **      INPUT  : MAP     MAP DRAWING OPTION INDEX               **
C     **               ICODE   INITIAL PROGRAM RUN INDEX              **
C     **               NSTAT   NUMBER OF STATIONS ON FILE             **
C     **                                                              **
C     **      OUTPUT : IN      NUMBER OF STATIONS CHOSEN              **
C     **               TNB     NUMBER OF BASELINES CHOSEN             **
C     **               IS,JS   SELECTED BASELINES INDEX               **
C     **               IST     SELECTED STATION INDEX                 **
C     **               NEX     EXPERIMENT NUMBER                      **
C     **                                                              **
C     **    OPTIONS : STATION SYMBOL SELECTION                        **
C     **                                                              **
C     **                                                              **
C     **          CALLS SUBROUTINES UNITS,RECT,EQUITR,CIRCLE          **
C     **                                                              **
C     ******************************************************************
C
C     NOTE : IF CHANGING STATIONS MODIFY FORMATS 182
C
      INTEGER TNB
      DIMENSION IS(1), JS(1), IST(1)
      COMMON /DRAW1/ XX(1)/DRAW2/YY(1)/DRAW3/ARAY(1)/DEX1/IS/DEX2/JS/DEX
     13/IST/DEX4/NEX/BS/TNB,JUST
      PI=3.14
C
C     LIST AVAILABLE VLBI STATIONS
      CALL HOME
      CALL ANMODE
      WRITE (6,1)
C     CHANGE STATION NAMES IF NECESSARY
 1    FORMAT (' STATION SELECTION'/'     1. WESTFORD'/'     2. OWENS VAL
     1LEY'/'     3. GREENBANK'/'     4. GOLDSTONE'/'     5. FT. DAVIS'/'
     2     6. RICHMOND')
C
C     STATION AND BASELINE SELECTION
      WRITE (6,2)
C     CHANGE NUMBER OF STATIONS AND BASELINES IF NECESSARY
 2    FORMAT (' ENTER #STATIONS,#BSLNS'/' STATION 1 2 3 4 5 6'/' PUT 0 I
     1F NOT OBSERVING'/' MAXIMUM #BSLNS=6')
      DO 3 I=1,NSTAT
 3    IST(I)=0
      READ (5,*) IN,TNB,(IST(I),I=1,NSTAT)
      DO 6 IJ=1,TNB
      CALL RESTAT (ARAY)
      CALL MOVABS (1,KCM(8.9))
      CALL SVSTAT (ARAY)
      CALL ANMODE
      WRITE (6,4) IJ
 4    FORMAT (' CHOOSE BASELINE #',I3/' ENTER I J OF BASELINE')
      READ (5,*) IS(IJ),JS(IJ)
C
C     MAP DISPLAY IS SKIPPED IF MAP DRAW OPTION NOT SET
      IF(MAP.EQ.0) GO TO 6
      CALL RESTAT (ARAY)
      CALL MOVABS (1,KCM(7.2))
      CALL SVSTAT (ARAY)
      CALL ANMODE
C
C     SYMBOL SELECTION
      WRITE (6,5) IJ
 5    FORMAT (' SELECT SYMBOLS #',I1,' BSLINE'/' PRESS 1-RETURN,MOVE'/
```

```
     1CURSOR INSIDE SYM-PRESS P')
      READ (5,*) MOM
      CALL RESTAT (ARAY)
C
C     REDEFINE MENU WINDOW
      CALL SWINDO (KCM(12.0),KCM(7.0),KCM(2.8),KCM(2.0))
      CALL UNITS (7.,2.,S,T)
      CALL VWINDO (0.,S,0.,T)
C     FIND CURSOR LOCATION IN VIRTUAL WINDOW
      CALL VCURSR (I1,XI,YI)
C     SELECT SYMBOL ACCORDING TO CURSOR LOCATION
      IF(XI.GT.FLOAT(KCM(0.5)).AND.XI.LT.FLOAT(KCM(1.5))) ISYM=1
      IF(XI.GT.FLOAT(KCM(2.5)).AND.XI.LT.FLOAT(KCM(3.5))) ISYM=2
      IF(XI.GT.FLOAT(KCM(5.2)).AND.XI.LT.FLOAT(KCM(6.2))) ISYM=3
C
C
C     REDEFINE MAP WINDOW
      CALL SWINDO (350,660,270,505)
      CALL VWINDO (0.,1320.,0.,1010.)
C     DRAW APPROPRIATE SYMBOL
C     DRAW CHOSEN SYMBOL
      IF(ISYM.EQ.1) CALL RECT (XX(IS(IJ)),YY(IS(IJ)),1.0)
      IF(ISYM.EQ.2) CALL EQUITR (XX(IS(IJ)),YY(IS(IJ)),1.0)
      IF(ISYM.EQ.3) CALL CIRCLE (XX(IS(IJ)),YY(IS(IJ)),.5)
      IF(ISYM.EQ.1) CALL RECT (XX(JS(IJ)),YY(JS(IJ)),1.0)
      IF(ISYM.EQ.2) CALL EQUITR (XX(JS(IJ)),YY(JS(IJ)),1.0)
      IF(ISYM.EQ.3) CALL CIRCLE (XX(JS(IJ)),YY(JS(IJ)),.5)
C
C     DRAW BASELINE
      CALL UNITS (XX(IS(IJ)),YY(IS(IJ)),DX,DY)
      CALL MOVEA (DX,DY)
      CALL UNITS (XX(JS(IJ)),YY(JS(IJ)),DX,DY)
      CALL DRAWA (DX,DY)
      IF(IJ.EQ.TNB) CALL MOVABS (1,KCM(9.8))
      CALL SVSTAT (ARAY)
    6 CONTINUE
C
C     DRAW EXPERIMENT NUMBER
      CALL MOVABS (1,KCM(4.4),DX,DY)
      CALL SVSTAT (ARAY)
      CALL ANMODE
      WRITE (6,7)
    7 FORMAT (' ENTER EXPERIMENT #')
      READ (5,*) NEX
      IF(MAP.EQ.0) GO TO 8
      CALL RESTAT (ARAY)
      CALL UNITS (9.0,16.5,DX,DY)
      CALL MOVEA (DX,DY)
      GO TO 9
    8 CALL MOVABS (1,KCM(2.5),DX,DY)
    9 CALL SVSTAT (ARAY)
      CALL ANMODE
      WRITE (6,10) NEX
   10 FORMAT (' EXPERIMENT #',1X,I3)
C     SKIP TO NEW PAGE ON LINE PRINTER IF REPEATING PROGRAM
      IF(ICODE.GT.0) WRITE (7,11)
   11 FORMAT (1H1)
      WRITE (7,12) NEX
   12 FORMAT (10X,'EXPERIMENT #',I3)
C
      CALL MOVABS (KCM(6.3),KCM(3.4),DX,DY)
      CALL ANMODE
      WRITE (6,13)
   13 FORMAT (' PRESS 1 THEN RETURN')
      READ (5,*) MOM
C
      RETURN
      END
```

```
      SUBROUTINE SIDTM (TH0,PI,TF)
C     ******************************************************************
C     **                                                              **
C     **                      TIME HANDLER                            **
C     **                                                              **
C     **      INPUT  : PI                                             **
C     **                                                              **
C     **      READ   : IYEAR... INITIAL EPOCH OF OBSERVATIONS (UT)    **
C     **               JYEAR... FINAL EPOCH OF OBSERVATIONS   (UT)    **
C     **                                                              **
C     **      WRITE  : TH0      GST AT INITIAL EPOCH                  **
C     **                                                              **
C     **      OUTPUT : TH0                                            **
C     **               TF       TOTAL INTERVAL OF OBSERVATIONS        **
C     **                                                              **
C     **             CALLS SUBROUTINE GRESID,DEGMS                    **
C     **                                                              **
C     ******************************************************************
C
      IMPLICIT REAL*8(A-H,L-Z)
      COMMON /TIME/ IMO,IDAY,IYEAR
C
C     READ INITIAL EPOCH IN UNIVERSAL TIME
    1 WRITE (6,2)
    2 FORMAT (' ENTER INITIAL EPOCH IN UNIVERSAL TIME'/' FORMAT: YEAR,MO
     1NTH,DAY,HOUR,MIN,SEC'/' PRESS RETURN THEN ENTER FINAL EPOCH IN SIM
     2ILAR MANNER'//' IF INITIAL&FINAL EPOCH IN DIFFERENT MONTHS OR YEAR
     3S'/' EXPRESS FINAL EPOCH IN SAME MONTH OR YEAR AS INITIAL EPOCH'/'
     4 E.G. IF INITIAL EPOCH DEC 30, 1979 FINAL EPOCH JAN 1,1980'/' ENTE
     5R FINAL EPOCH AS DEC 32,1979'//' ENTER FOR INITIAL EPOCH 0 HOURS U
     6T OF INITIAL DAY')
      READ (5,*) IYEAR,IMO,IDAY,IHOUR,IMIN,SEC
      READ (5,*) JYEAR,JMO,JDAY,JHOUR,JMIN,SECJ
      WRITE (6,3)
      WRITE (7,3)
    3 FORMAT (//,15X,'INITIAL EPOCH',2X,'(UT)')
      WRITE (6,4)
      WRITE (7,4)
    4 FORMAT (/10X,'YEAR',1X,'MONTH',1X,'DAY',1X,'HOUR',2X,'MIN',2X,'SEC
     1',/)
      WRITE (6,5) IYEAR,IMO,IDAY,IHOUR,IMIN,SEC
      WRITE (7,5) IYEAR,IMO,IDAY,IHOUR,IMIN,SEC
    5 FORMAT (10X,I4,4I5,F5.1)
      WRITE (6,6)
      WRITE (7,6)
    6 FORMAT (/,15X,'FINAL EPOCH',2X,'(UT)'/)
      WRITE (6,5) JYEAR,JMO,JDAY,JHOUR,JMIN,SECJ
      WRITE (7,5) JYEAR,JMO,JDAY,JHOUR,JMIN,SECJ
C
      IF(JYEAR.NE.IYEAR.OR.JMO.NE.IMO) GO TO 9
C
C     TF : TOTAL INTERVAL OF OBSERVATIONS
      TF=DFLOAT(JDAY-IDAY)*24.D0+DFLOAT(JHOUR-IHOUR)+DFLOAT(JMIN-IMIN)/6
     10.D0+(SECJ-SEC)/3600.D0
C
C     CALCULATE GREENWICH SIDEREAL TIME AT EPOCH T0
      CALL GRESID (IYEAR,IMO,IDAY,IHOUR,IMIN,SEC,TH0)
      PI2=2.D0*PI
C     CHECK FOR NEGATIVE VALUE OF GST
      IF(TH0.GT.-PI2.AND.TH0.LT.0.D0) TH0=TH0+PI2
      THOT=TH0/15.D0
      CALL DEGMS (THOT,PI,IDEG,IMIN,SEC)
      WRITE (6,7) IDEG,IMIN,SEC
      WRITE (7,7) IDEG,IMIN,SEC
    7 FORMAT (//10X,'GREENWICH SIDEREAL TIME AT INITIAL EPOCH =',2I4,2X,
     1F6.3)
```

```
      WRITE (6,8)
 8    FORMAT (///,' PRESS 1 - THEN RETURN')
      READ (5,*) MOM
      GO TO 11
C
 9    WRITE (6,10)
 10   FORMAT (//' WRONG INITIAL AND FINAL DATA - RE-ENTER')
      WRITE (6,8)
      READ (5,*) MOM
      CALL ERASE
      CALL HOME
      CALL ANMODE
      GO TO 1
C
 11   RETURN
      END
      SUBROUTINE GRESID (IYEAR,IMO,IDAY,IHOUR,IMIN,SEC,TH0)
C     ********************************************************************
C     **                                                               **
C     **          CALCULATES THE GREENWICH SIDEREAL TIME               **
C     **             AT INITIAL EPOCH OF OBSERVATIONS                  **
C     **                                                               **
C     **    INPUT  : IYEAR...  INITIAL EPOCH OF OBSERVATIONS           **
C     **                                                               **
C     **    OUTPUT : TH0       GST AT INITIAL EPOCH                    **
C     **                                                               **
C     **             CALLS SUBROUTINE JULIA                            **
C     **                                                               **
C     ********************************************************************
C
      IMPLICIT REAL*8(A-H,L-Z)
      PI=4.D0*DATAN(1.D0)
C
      CALL JULIA (IYEAR,IMO,IDAY,IHOUR,IMIN,SEC,MJD)
      T=(MJD-2415020.D0)/36525.D0
      T2=T*T
      AT=6.6460656610D0
      BT=(8640184.628D0/3600.D0)*T
      BT=DMOD(BT,24.D0)
      CT=(0.0929D0/3600.D0)*T2
      TH0=AT+BT+CT
      DT=DFLOAT(IHOUR)+DFLOAT(IMIN)/60.D0+SEC/3600.D0
      TH0=TH0+DT
      IF(TH0.GE.24.D0) TH0=TH0-24.D0
      TH0=TH0*15.D0*PI/180.D0
C
      RETURN
      END
      SUBROUTINE JULIA (IYEAR,IM,IDAY,IHHH,IMMM,S,MJD)
C     ********************************************************************
C     **                                                               **
C     **          CONVERTS UNIVERSAL TIME TO JULIAN DATE               **
C     **                                                               **
C     **    INPUT  : IYEAR...  INITIAL EPOCH OF OBSERVATIONS           **
C     **                                                               **
C     **    OUTPUT : MJD       JULIAN DATE OF INITIAL EPOCH            **
C     **                                                               **
C     ********************************************************************
C
      IMPLICIT REAL*8(A-H,L-Z)
      DIMENSION IMONTH(12)
      DATA IMONTH/0,31,59,90,120,151,181,212,243,273,304,334/
C
      H=DFLOAT(IHHH)
      M=DFLOAT(IMMM)
      ICOD=0
      IDIS=(IYEAR-1897)/4
      IF(IYEAR.GT.1900) IDIS=IDIS-1
```

```
      ICH=4*(IYEAR/4)
      IF(IYEAR.EQ.ICH.AND.IM.GT.2) ICOD=1
      IF(IYEAR.EQ.1900) ICOD=0
      MJD=2415020+(IYEAR-1900)*365.D0+IDIS+IMONTH(IM)+ICOD-0.5D0+IDAY+H/
     124.D0+M/1440.D0+S/86400.D0
C
      RETURN
      END
```

```
      SUBROUTINE STATNS (X,Y,Z,XT,YT,ZT,DIST,PI,ICODE,NSTAT)
C     *****************************************************************
C     **                                                             **
C     **                       STATION HANDLER                       **
C     **                                                             **
C     **      INPUT  : L1,L2,L3 STATION NAME                         **
C     **               IDEG1... LATITUDE OF STATION                  **
C     **               IDEG2... LONGITUDE OF STATION                 **
C     **               H        HEIGHT OF STATION ABOVE ELLIPSOID    **
C     **               IS,JS    STATION INDICES                      **
C     **               IST      BASELINE INDEX                       **
C     **               NEX      EXPERIMENT NUMBER                    **
C     **               TNB      TOTAL NUMBER OF BASELINES            **
C     **               NSTAT    NUMBER OF STATIONS ON FILE           **
C     **               ICODE    INITIAL PROGRAM RUN INDEX            **
C     **               PI                                            **
C     **               A,FI     ELLIPSOIDAL PARAMETERS               **
C     **                                                             **
C     **      WRITE  : X,Y,Z    CARTESIAN STATION COORDINATES (APPROX) **
C     **               XC,YC,ZC COORDINATE DIFFERENCES               **
C     **               DIST     BASELINE DISTANCES                   **
C     **               IDEG1...                                      **
C     **               IDEG2...                                      **
C     **               H                                             **
C     **               L1,L2,L3                                      **
C     **               IS,JS                                         **
C     **                                                             **
C     **      OUTPUT : XTP,YTP  BASELINE UNIT VECTOR COMPONENTS      **
C     **                 ZTP                                         **
C     **               XC,YC,ZC                                      **
C     **               DIST                                          **
C     **                                                             **
C     **                                                             **
C     **             CALLS SUBROUTINE RAD                            **
C     **                                                             **
C     *****************************************************************
C
      IMPLICIT REAL*8(A-H,O-Z)
      INTEGER TNB
      DIMENSION XT(1), YT(1), ZT(1), X(1), Y(1), Z(1), XTP(1), YTP(1), Z
     1TP(1), XC(1), YC(1), ZC(1), DIST(1), IS(1), JS(1), IST(1)
      COMMON /CRD1/ XTP/CRD2/YTP/CRD3/ZTP/CRD4/XC/CRD5/YC/CRD6/ZC/DEX1/I
     1S/DEX2/JS/DEX3/IST/DEX4/NEX/BS/TNB,JUST
C
C     READ ELLIPSOIDAL PARAMETERS FROM FILE 3
      IF(ICODE.NE.0) REWIND 3
      READ (3,*) A,FI
      WRITE (7,1)
    1 FORMAT (//,10X,'PARAMETERS OF REFERENCE ELLIPSOID')
      WRITE (7,2) A,FI
    2 FORMAT (/,9X,'EQUATORIAL RADIUS = ',F11.2,3X,'METERS',/9X,'INVERSE
     1 FLATTENING = ',F7.2/)
C     COMPUTE ELLIPSOID FLATTENING AND ECCENTRICITY
      FLAT=1.D0/FI
      EE=2.D0*FLAT-FLAT*FLAT
C
      CALL ERASE
      CALL HOME
      CALL ANMODE
C
C     READ CHOSEN STATION COORDINATES FROM FILE 3
      WRITE (6,3)
      WRITE (7,3)
    3 FORMAT (/,15X,'APPROXIMATE STATION COORDINATES')
      WRITE (6,4)
      WRITE (7,4)
```

```
4     FORMAT (/,35X,'    LATITUDE     ',4X,'LONGITUDE   ',8X,'HEIGHT',//,27
     1X,'DG',1X,'MIN',1X,'SEC',6X,'DEG',1X,'MIN',1X,'SEC',9X,'METERS')
      INDX=0
      DO 10 I=1,NSTAT
      READ (3,5) IDUM,L1,L2,L3,IDEG1,MIN1,SEC1,IDEG2,MIN2,SEC2,H
5     FORMAT (I2,3A4,I3,I2,F6.3,I4,I2,F6.3,3X,F10.2)
      IF(IST(I).NE.I) GO TO 7
      INDX=INDX+1
      WRITE (6,6) IDUM,L1,L2,L3,IDEG1,MIN1,SEC1,IDEG2,MIN2,SEC2,H
      WRITE (7,6) IDUM,L1,L2,L3,IDEG1,MIN1,SEC1,IDEG2,MIN2,SEC2,H
6     FORMAT (6X,I2,2X,3A4,4X,I3,1X,I2,1X,F6.3,4X,I3,1X,I2,1X,F6.3,3X,F1
     10.2)
C     CONVERT LATITUDE AND LONGITUDE TO RADIANS
7     CALL RAD (IDEG1,MIN1,SEC1,PHI,PI)
      CALL RAD (IDEG2,MIN2,SEC2,ALONG,PI)
C     COMPUTE RADIUS IN PRIME VERTICAL
      AN=A/DSQRT(1.D0-EE*DSIN(PHI)**2)
C     COMPUTE CARTESIAN COORDINATES OF STATIONS
C     BASELINE UNIT VECTOR
      XT(I)=DCOS(PHI)*DCOS(ALONG)
      YT(I)=DCOS(PHI)*DSIN(ALONG)
      ZT(I)=DSIN(PHI)
      X(I)=(AN+H)*XT(I)
      Y(I)=(AN+H)*YT(I)
      Z(I)=(AN*(1.D0-EE)+H)*ZT(I)
C     STORE CHOSEN BASELINE UNIT VECTORS
      IF(IST(I).NE.I) GO TO 10
      XTP(INDX)=XT(I)
      YTP(INDX)=YT(I)
      ZTP(INDX)=ZT(I)
      WRITE (6,8) X(I),Y(I),Z(I)
8     FORMAT (10X,'X =',F14.3,2X,'Y =',F14.3,2X,'Z =',F14.3,2X)
      WRITE (7,9) X(I),Y(I),Z(I)
9     FORMAT (/,10X,'X =',F14.3,2X,'Y =',F14.3,2X,'Z =',F14.3,2X)
10    CONTINUE
C
C     COMPUTE COORDINATE DIFFERENCES AND BASELINE LENGTHS
      WRITE (6,11)
      WRITE (7,11)
11    FORMAT (//,6X,'BASELINE',6X,'DELX',10X,'DELY',10X,'DELZ',8X,'DISTA
     1NCE',2X,'(M)'/)
      DO 13 K=1,TNB
      XC(K)=X(JS(K))-X(IS(K))
      YC(K)=Y(JS(K))-Y(IS(K))
      ZC(K)=Z(JS(K))-Z(IS(K))
      DIST(K)=DSQRT(XC(K)**2+YC(K)**2+ZC(K)**2)
      WRITE (6,12) IS(K),JS(K),XC(K),YC(K),ZC(K),DIST(K)
      WRITE (7,12) IS(K),JS(K),XC(K),YC(K),ZC(K),DIST(K)
12    FORMAT (7X,I2,2X,I2,4F14.3)
13    CONTINUE
C
      WRITE (6,14) NEX
14    FORMAT (///,' THESE ARE THE STATION COORDINATES FOR EXPERIMENT #',
     1I2/' PRESS 1 THEN RETURN')
      READ (5,*) MOM
C
      RETURN
      END
```

```
      SUBROUTINE QUASAR (XO,DECR,RAR,E1,E2,E3,OMG,PI,IQUAS,KEEP,INDEX,IC
     1ODE,IM,IPFIX,NQUAS,TH0,TF,IN)
C     ******************************************************************
C     **                                                              **
C     **                       QUASAR HANDLER                         **
C     **                                                              **
C     **    INPUT  :  XTP,YTP,ZTP       BASELINE UNIT VECTOR           **
C     **              IMO,IDAY,IYEAR    DATE OF START OF OBSERVATIONS  **
C     **              NQUAS             NUMBER OF QUASARS ON FILE      **
C     **              ICODE             INITIAL PROGRAM RUN INDEX      **
C     **              TH0,TF            GST0,INTERVAL OF OBSERVATIONS  **
C     **              IN                TOTAL NUMBER OF STATIONS       **
C     **              PI,OMG            PROGRAM CONSTANTS              **
C     **                                                              **
C     **    READ   :  IM                NUMBER OF QUASARS OBSERVED     **
C     **              IQUAS             CHOSEN QUASAR NUMBERS          **
C     **              ZNTMAX            MAXIMUM ZENITH DISTANCE        **
C     **              IPFIX             REFERENCE R.A. QUASAR          **
C     **                                                              **
C     **    WRITE  :  INDEX             VISIBILITY MATRIX              **
C     **              I                 QUASAR NUMBER                  **
C     **              L1,L2,L3          QUASAR NAME                    **
C     **              IDEG1...          QUASAR RIGHT ASCENSION         **
C     **              IDEG2...          QUASAR DECLINATION             **
C     **              KEEP              VISIBILITY MATRIX HEADING      **
C     **                                                              **
C     **    OUTPUT :  RA,D              CHOSEN QUASAR COORDINATES      **
C     **              E1,E2,E3          QUASAR UNIT VECTOR COMPONENTS  **
C     **                                                              **
C     **  OPTIONS : MUTUAL VISIBILITY OUTLINER                        **
C     **                                                              **
C     **            CALLS SUBROUTINE DEGMS,RAD                        **
C     **                                                              **
C     ******************************************************************
C
      IMPLICIT REAL*8(A-H,O-Z)
      INTEGER*2 INDEX
      DIMENSION XTP(1), YTP(1), ZTP(1), DECR(1), RAR(1), E1(1), E2(1), E
     13(1), RA(1), D(1), IQUAS(1), KEEP(1), INDEX(6,24)
      COMMON /CRD1/ XTP/CRD2/YTP/CRD3/ZTP/TIME/IMO,IDAY,IYEAR/SOU1/RA/SO
     1U2/D
      CALL ANMODE
C
C     IF PROGRAM RE-RUN DO NOT LIST QUASAR FILE
      IF(ICODE.EQ.2.OR.ICODE.EQ.3) GO TO 8
      WRITE (6,1)
    1 FORMAT (' QUASAR SELECTION')
      WRITE (6,2)
      WRITE (7,2)
    2 FORMAT (1H1,15X,'APPROXIMATE SOURCE COORDINATES'/)
      WRITE (6,3)
      WRITE (7,3)
    3 FORMAT (26X,'RIGHT ASCENSION',3X,'DECLINATION',//,7X,'#',2X,'NAME'
     1,13X,'HR ','MIN ','SEC',6X,'DEG ','MIN ','SEC'/)
C
C      READ QUASAR COORDINATES
C     KM - PAGE COUNTER
C     KN - NUMBER OF QUASARS DISPLAYED PER PAGE OF SCREEN DISPLAY
      KM=1
      KN=26
      DO 7 I=1,NQUAS
      READ (3,4) IDUM,L1,L2,L3,IDEG1,MIN1,SEC1,IDEG2,MIN2,SEC2
    4 FORMAT (I2,3A4,I3,I2,F6.3,I4,I2,F6.3)
      IF(I.NE.KN) GO TO 5
      KM=KM+1
      KN=KN*KM
```

```
      WRITE (6,42)
      READ (5,*) MOM
      CALL ERASE
      CALL HOME
      CALL ANMODE
  5   WRITE (6,6) I,L1,L2,L3,IDEG1,MIN1,SEC1,IDEG2,MIN2,SEC2
      WRITE (7,6) I,L1,L2,L3,IDEG1,MIN1,SEC1,IDEG2,MIN2,SEC2
  6   FORMAT (6X,I2,2X,3A4,4X,I3,1X,I2,1X,F6.3,4X,I3,1X,I2,1X,F6.3,3X,F1
     10.2)
C     CONVERT RA AND DEC TO RADIANS
      CALL RAD (IDEG1,MIN1,SEC1,RAR(I),PI)
      RAR(I)=RAR(I)*15.D0
      CALL RAD (IDEG2,MIN2,SEC2,DECR(I),PI)
      CD=DCOS(DECR(I))
      SD=DSIN(DECR(I))
      CA=DCOS(RAR(I))
      SA=DSIN(RAR(I))
C     COMPUTE COMPONENTS OF QUASAR UNIT VECTOR
      E1(I)=CD*CA
      E2(I)=CD*SA
      E3(I)=SD
  7   CONTINUE
C
      WRITE (6,42)
      READ (5,*) MOM
  8   CALL ERASE
      CALL HOME
      CALL ANMODE
C
      DO 9 J=1,12
      RA(J)=0.D0
      D(J)=0.D0
  9   CONTINUE
C
 10   WRITE (6,11)
C     CHANGE FORMAT IF MAXIMUM #(12) OF QUASARS INCREASED
 11   FORMAT (//,' HOW MANY QUASARS DO YOU WISH TO OBSERVE',/,' MAXIMUM
     1NUMBER IS 12')
      READ (5,*) IM
C     CHANGE IF MAXIMUM #(12) OF QUASARS INCREASED
      IF(IM.GT.12) GO TO 10
C
C     OPTION TO CHOOSE QUASARS WITHOUT VISIBILITY OUTLINER
C     IF IFY=0 SKIP VISIBILITY OUTLINER
      IFY=0
      WRITE (6,12)
 12   FORMAT (5X,'DO YOU WISH TO CHOOSE QUASARS BEFORE VISIBILITY OUTLIN
     1ER ?')
      READ (5,13) GG
 13   FORMAT (A4)
      IF(GG.EQ.XO) GO TO 18
 14   WRITE (6,15)
 15   FORMAT (/5X,'ENTER CHOSEN QUASARS'/5X,'E.G. 1 3 5 7')
      READ (5,*) (IQUAS(K),K=1,IM)
      DO 16 K=1,IM
C     CHANGE IF NUMBER OF QUASARS (47) IN FILE CHANGED
      IF(IQUAS(K).GT.47) GO TO 14
 16   CONTINUE
C
C     INDX : CHOSEN QUASARS INDEX
      INDX=0
      IFY=1
      KL=0
 17   KL=KL+1
      IND=IQUAS(KL)
      IF(KL.LE.IM) GO TO 31
      GO TO 35
C
```

```
   18 CALL ERASE
      CALL HOME
      CALL ANMODE
C
C      MUTUAL VISIBILITY OUTLINER
C     DRAW TITLE FOR VISIBILITY OUTLINER
      WRITE (6,19)
   19 FORMAT (' MUTUAL VISIBILITY OUTLINER'//,' INPUT MAXIMUM ZENITH DIS
     1TANCE')
      WRITE (7,20)
   20 FORMAT (1H1,10X,'MUTUAL VISIBILITY OUTLINER'/)
      WRITE (7,25) IMO,IDAY,IYEAR
C
C     INPUT MAXIMUM OBSERVABLE ZENITH DISTANCE
      READ (5,*) ZNTMAX
      WRITE (7,21) ZNTMAX
   21 FORMAT (//,5X,'MAXIMUM ZENITH DISTANCE =',F6.2/)
C
C     COMPUTE VISIBILITY MATRIX QUASAR BY QUASAR
      DO 22 IJ=1,24
   22 KEEP(IJ)=IJ-1
      T0=0.D0
      IND=0
      INDX=0
      DO 34 I=1,NQUAS
      IND=IND+1
      DO 24 K=1,24
      T=T0+(K-1)
C     TRANSFORM QUASAR UNIT VECTOR TO EARTH FIXED SYSTEM AT EPOCH T
      ANGLE=OMG*(T-T0)+TH0
      CA=DCOS(ANGLE)
      SA=DSIN(ANGLE)
      Q1=CA*E1(I)+SA*E2(I)
      Q2=-SA*E1(I)+CA*E2(I)
      Q3=E3(I)
C     CALCULATE ZENITH DISTANCE
      DO 23 J=1,IN
      ARGU=XTP(J)*Q1+YTP(J)*Q2+ZTP(J)*Q3
      IF(ARGU.LT.-1.D0) ARGU=-1.D0
      IF(ARGU.GT.1.D0) ARGU=1.D0
      ZNT=DARCOS(ARGU)
      ZNT=DABS(ZNT)*180.D0/PI
C     IF ZNT.GT.ZNTMAX CAUSE TWO STARS TO BE PLACED
C      IN APPROPRIATE LOCATION OF VISIBILITY MATRIX
      IF(ZNT.GT.ZNTMAX) ZNT=1000.D0
C      FILL VISIBILITY MATRIX
      INDEX(J,K)=ZNT
   23 CONTINUE
   24 CONTINUE
C     DRAW TITLE FOR VISIBILITY MATRIX
      WRITE (6,25) IMO,IDAY,IYEAR
   25 FORMAT (///1X,I2,'/',I3,'/',I5,1X,'ZENITH DISTANCES (** DENOTES NO
     1INVISIBILITY)')
      WRITE (6,26) (KEEP(IL),IL=1,24)
      WRITE (7,26) (KEEP(IL),IL=1,24)
   26 FORMAT (//,2X,'QS ST',24(1X,I2))
      DO 28 IK=1,IN
      WRITE (6,27) IND,IK,(INDEX(IK,KI),KI=1,24)
      WRITE (7,27) IND,IK,(INDEX(IK,KI),KI=1,24)
   27 FORMAT (1X,I3,1X,I2,24(1X,I2))
   28 CONTINUE
      WRITE (7,29)
   29 FORMAT (/)
C     CHOOSE QUASAR IF APPROPRIATE
      WRITE (6,30)
   30 FORMAT (/' DO YOU WISH TO OBSERVE THIS QUASAR'/' ANSWER YES OR NO'
     1/)
      READ (5,13) CC
```

```
      IF(GC.EQ.XO) GO TO 33
C     ADD CHOSEN QUASAR
 31   INDX=INDX+1
      RA(INDX)=RAR(IND)
      D(INDX)=DECR(IND)
      IQUAS(INDX)=IND
      IF(IFY.EQ.1) GO TO 17
      WRITE (6,32) INDX,IM
 32   FORMAT (' YOU HAVE CHOSEN',I2,' QUASARS  OUT OF ',I2,' QUASARS')
      WRITE (6,42)
      READ (5,*) MOM
      IF(INDX.EQ.IM) GO TO 35
 33   CALL ERASE
      CALL HOME
      CALL ANMODE
 34   CONTINUE
C
 35   CALL ERASE
      CALL HOME
      CALL ANMODE
C
C     LIST CHOSEN QUASARS
      WRITE (6,36)
      WRITE (7,36)
 36   FORMAT (1H1,//,20X,'THESE ARE THE SOURCES CHOSEN'/,25X,'RIGHT ASCE
     1NSION',3X,'DECLINATION',//,20X,'# ',4X,'HR ','MIN ','SEC',7X,'DEG
     2','MIN ','SEC'/)
      DO 38 I=1,INDX
      RQ=RA(I)/15.D0
      CALL DEGMS (RQ,PI,IDEG1,MIN1,SEC1)
      CALL DEGMS (D(I),PI,IDEG2,MIN2,SEC2)
      WRITE (6,37) I,IQUAS(I),IDEG1,MIN1,SEC1,IDEG2,MIN2,SEC2
      WRITE (7,37) I,IQUAS(I),IDEG1,MIN1,SEC1,IDEG2,MIN2,SEC2
 37   FORMAT (13X,I2,'.    ',I2,3X,2(I3,1X,I3,1X,F7.3,4X))
 38   CONTINUE
C
 39   WRITE (6,40)
 40   FORMAT (/,19X,'ENTER THE REFERENCE SOURCE'/,19X,'USE SEQUENTIAL NU
     1MBER (LEFT-MOST COLUMN ABOVE)')
      READ (5,*) IPFIX
C     CHANGE IF MAXIMUM #(12) OF QUASARS INCREASED
      IF(IPFIX.GT.12) GO TO 39
      WRITE (7,41) IPFIX
 41   FORMAT (/21X,'SOURCE',I4,'  IS THE REFERENCE SOURCE')
 42   FORMAT (//' PRESS 1 - THEN RETURN')
C
      RETURN
      END
```

```
      SUBROUTINE SIMULT (XERM,XILE,XES,ERAD,PMX,PMY,PMZ,OMG,TF,THO,IFILE
     1,ISTT,STSZ,ICODE,CONV)
C     *******************************************************************
C     **                                                              **
C     **                      SCHEDULE SIMULATOR                      **
C     **                                                              **
C     **   INPUT  :  OMG          EARTH ROTATION RATE                 **
C     **             ERAD         MEAN EARTH RADIUS                   **
C     **             THO,TF       GST0,INTERVAL OF OBSERVATIONS       **
C     **             ICODE        INITIAL PROGRAM RUN INDEX           **
C     **             TNB          TOTAL NUMBER OF BASELINES           **
C     **             ISTT         NUMBER OF EARTH ORIENTATION STEPS   **
C     **             STSZ         END OF STEPS EPOCH                  **
C     **             XC,YC,ZC     BASELINE COORDINATE DIFFERENCES     **
C     **             RA,D         QUASAR COORDINATES                  **
C     **             CONV         CONVERT UNIVERSAL TO SIDEREAL TIME  **
C     **                                                              **
C     **   READ   :  PMX,PMY,PMZ  APPROX. VALUES EARTH ORIENTATION    **
C     **             DT           TIME INTERVAL BETWEEN OBSERVATIONS  **
C     **             IFILE        OBSERVATION STORAGE FILE NUMBERS    **
C     **                                                              **
C     **   WRITE  :  PMX,PMY,PMZ                                      **
C     **                                                              **
C     **   OUTPUT :  SIMULATED OBSERVATIONS ON FILES 10-15            **
C     **             L            BASELINE NUMBER                     **
C     **             K            QUASAR NUMBER                       **
C     **             IHOUR,IMIN   EPOCH OF OBSERVATION                **
C     **             DS,FRNG      OBSERVED DELAY & DELAY RATE         **
C     **                                                              **
C     ** OPTIONS : SIMULATE DELAY RATE OBSERVABLES                    **
C     **           READ OBSERVATION SCHEDULE FROM FILE 9              **
C     **           READ OBSERVATION SCHEDULE FROM TERMINAL            **
C     **           INPUT TIMES OF OBSERVATION (DT NOT CONSTANT)       **
C     **                                                              **
C     *******************************************************************
C
      IMPLICIT REAL*8(A-H,O-Z)
      INTEGER TNB
      DIMENSION D(1), RA(1), XC(1), YC(1), ZC(1), PMX(1), PMY(1), PMZ(1)
     1, IFILE(1), STSZ(1)
      COMMON /CRD4/ XC/CRD5/YC/CRD6/ZC/SOU1/RA/SOU2/D/BS/TNB,JUST
C
      WRITE (6,1)
    1 FORMAT (/,' READ IN APPROX VALUES FOR EARTH ORIENTATION '/'  THERE
     1 SHOULD BE 3*(#STEPS) OF PARAMETERS'/'  FORMAT : TWO POLAR MOTION
     2COMPONENTS IN METERS'/'  EARTH ROTATION IN SECONDS OF TIME')
      READ (5,*) (PMX(J),J=1,ISTT),(PMY(J),J=1,ISTT),(PMZ(J),J=1,ISTT)
      WRITE (7,2) (PMX(J),J=1,ISTT)
    2 FORMAT (//9X,'APPROXIMATE VALUES FOR EARTH ORIENTATION'//28X,'STEP
     11',5X,'STEP2',5X,'STEP3',5X,'STEP4'/11X,'PMX',1X,'(METERS)',3X,4(F
     28.3,2X))
      WRITE (7,3) (PMY(J),J=1,ISTT)
    3 FORMAT (/11X,'PMY',1X,'(METERS)',3X,4(F8.3,2X))
      WRITE (7,4) (PMZ(J),J=1,ISTT)
    4 FORMAT (/11X,'PMZ',1X,'(SECONDS)',2X,4(F8.3,2X))
C
      WRITE (6,5)
    5 FORMAT (//' ENTER TIME INTERVAL BETWEEN OBSERVATIONS (IN MINUTES)'
     1/' INPUT 0 IF TIME INTERVALS NOT REGULAR')
      READ (5,*) DT
      DT=DT/60.D0
      WRITE (6,6)
    6 FORMAT (//' PRESS 1 - THEN RETURN')
      READ (5,*) MOM
C
      IF(ICODE.EQ.0) GO TO 7
```

```
C      REWIND INPUT FILES IF RE-RUNNING PROGRAM
       REWIND 9
 7     CALL ERASE
       CALL HOME
C
       WRITE (6,8)
C      CHANGE FORMAT IF MAXIMUM #(6) OF BASELINES INCREASED
 8     FORMAT (/' CHOOSE ONE FILE PER BASELINE'/' AVAILABLE FILE NUMBERS
      1: 10-15  START WITH 10')
 9     WRITE (6,10)
 10    FORMAT (/'  ENTER OUTPUT FILES')
       READ (5,*) (IFILE(J),J=1,TNB)
       DO 11 J=1,TNB
C      CHANGE IF MAXIMUM #(6) OF BASELINES INCREASED
       IF(IFILE(J).LT.10.OR.IFILE(J).GT.15) GO TO 9
 11    CONTINUE
C
       IF(ICODE.EQ.0) GO TO 13
       DO 12 I=1,TNB
       NUM=IFILE(I)
       REWIND NUM
 12    CONTINUE
C
C      OPTION TO ENTER OBSERVATIONS AT TERMINAL OR FROM FILE
C       1. IFLAG=1 : FROM TERMINAL
C       2. IFLAG=2 : FROM FILE 9
 13    WRITE (6,14)
 14    FORMAT (/' IF YOU WISH TO ENTER DATA AT TERMINAL,INPUT TERM'/' IF
      1YOU HAVE STORED OBSERVATION SCHEDULE DATA ON FILE,INPUT FILE')
       READ (5,17) GG
       IF(GG.NE.XERM.AND.GG.NE.XILE) GO TO 13
       IF(GG.EQ.XERM) IFLAG=1
       IF(GG.EQ.XILE) IFLAG=2
C
C      OPTION : IPASS=0 SIMULATE OBSERVATIONS EVERY DT MINUTES
C               IPASS=1 SIMULATE OBSERVATIONS AT UNEVEN INTERVALS
       IPASS=0
       WRITE (6,15)
 15    FORMAT (' ARE OBSERVATIONS AT UNEVEN INTERVALS OF TIME')
       READ (5,17) GG
C       LAST OBSERVATION SHOULD BE GREATER THAN TF IF IPASS=1
       IF(GG.EQ.XES) IPASS=1
C
C      OPTION : IFRNG=0 - SIMULATE DELAYS ONLY
C               IFRNG=1 - SIMULATE DELAY RATES TOO
       IFRNG=0
       FRNG=0.D0
       WRITE (6,16)
 16    FORMAT (/' DO YOU WISH TO SIMULATE DELAY RATES')
       READ (5,17) F
 17    FORMAT (A4)
       IF(F.EQ.XES) IFRNG=1
C
C      T : TIME COUNTER
C      IJ : STEP COUNTER
C      L : BASELINE COUNTER
       T=0.D0
       IJ=0
       L=0
       CALL ERASE
       CALL HOME
       CALL ANMODE
C
C      UPDATE EARTH ORIENTATION STEP
 18    IJ=IJ+1
C      CHANGE UNITS OF EARTH ORIENTATION VALUES FOR THE IJ TH STEP
       PM1=PMX(IJ)/ERAD
       PM2=PMY(IJ)/ERAD
```

```
      PM3=PMZ(IJ)*15.D0/206265.D0
      ST=STWZ(IJ)
 19   IF(T.GT.TF) GO TO 37
      IF(IPASS.EQ.1.AND.IJ.GT.1) GO TO 31
C     INCREASE BASELINE COUNTER
 20   L=L+1
      IF(L.GT.TNB) GO TO 36
      IF(L.GT.1) GO TO 32
      IF(T.EQ.0.D0.OR.IFLAG.EQ.2) GO TO 22
      CALL ERASE
      CALL HOME
      CALL ANMODE
C
C     WRITE PREVIOUS OBSERVATION ON SCREEN
      WRITE (6,21) K,IHOUR,MIN
 21   FORMAT (' THE PREVIOUS OBSERVATION WAS :'/' QUASAR =',I3,2X,' HOUR
     1 =',I3,2X,' MIN =',I3//)
C
 22   IF(IPASS.EQ.1) GO TO 26
      IF(IFLAG.EQ.2) GO TO 25
C
C     ENTER QUASAR NUMBER
 23   WRITE (6,24)
 24   FORMAT (5X,'CHOOSE NEXT OBSERVATION'/5X,'INPUT #QUASAR')
      READ (5,*) K
C     CHANGE IF MAXIMUM #(12) OF QUASARS INCREASED
      IF(K.GT.12) GO TO 23
      GO TO 31
 25   READ (9,*) K
      GO TO 31
C
 26   IF(IFLAG.EQ.2) GO TO 29
C     ENTER QUASAR AND EPOCH OF OBSERVATION
 27   WRITE (6,28)
 28   FORMAT (5X,'CHOOSE OBSERVATION SCHEDULE'/5X,' INPUT #QUASAR HOUR M
     1INUTE')
      READ (5,*) K,IHOUR,MIN
C     CHANGE IF MAXIMUM #(12) OF QUASARS INCREASED
      IF(K.GT.12) GO TO 27
      GO TO 30
 29   IF(T.GE.TF) GO TO 37
      READ (9,*) K,IHOUR,MIN
 30   T=DFLOAT(IHOUR)+MIN/60.D0
      IF(T.GT.ST) GO TO 18
C
C     CALCULATE TRIGONOMETRIC MEMBERS OF OBSERVATIONS
 31   CD=DCOS(D(K))
      SD=DSIN(D(K))
      Y1=OMG*T+TH0+PM3*CONV
      Y2=Y1-RA(K)
      CKP=DCOS(Y2)
      SKP=DSIN(Y2)
C
C     DELAY OBSERVABLE SIMULATION
 32   DS=-XC(L)*(CD*CKP+PM1*SD)+YC(L)*(CD*SKP+PM2*SD)-ZC(L)*(SD-PM1*CD*C
     1KP-PM2*CD*SKP)
      IF(IFRNG.NE.1) GO TO 33
C
C     DELAY RATE OBSERVABLE SIMULATION
C     FRNG IS DERIVATIVE OF DELAY W.R.T. TIME (METERS/HOUR)
      FRNG=OMG*CD*(XC(L)*SKP+YC(L)*CKP-ZC(L)*(PM1*SKP-PM2*CKP))
C
C     STORE SIMULATED OBSERVATIONS ON UNITS 10-14
 33   IF(IPASS.EQ.1) GO TO 34
      IHOUR=IDINT(T)
      TMIN=T-IHOUR
      TMIN=TMIN*60.D0+0.00001D0
      MIN=IDINT(TMIN)
```

```
      IF(MIN.NE.60) GO TO 34
      MIN=MIN-60
      IHOUR=IHOUR+1
   34 NUM=IFILE(L)
      WRITE (NUM,35) L,K,IHOUR,MIN,DS,FRNC
   35 FORMAT (4I5,2F20.10)
      GO TO 20
   36 L=0
      IF(IPASS.EQ.1) GO TO 20
      T=T+DT
C     CHECK FOR STEP UPDATE
      IF(T.GE.ST) GO TO 18
      GO TO 19
C
   37 RETURN
      END
```

```
      SUBROUTINE FLAGS (JK)
C     ****************************************************************
C     **                                                            **
C     **                 EXPERIMENT FLAG HANDLER                    **
C     **                                                            **
C     **  READ    :    FLAG1=1:DELAY IS ONLY OBSERVABLE             **
C     **               FLAG1=2:OBSERVABLES ARE DELAY AND DELAY RATE **
C     **               FLAG1=3:DELAY RATE IS ONLY OBSERVABLE        **
C     **                                                            **
C     **               FLAG2=1:MULTI-BASELINE CONFIGURATION         **
C     **               FLAG2=2:ESTIMATE KSI COMPONENT OF POLAR MOTION **
C     **               FLAG2=3:ESTIMATE ETA COMPONENT OF POLAR MOTION **
C     **                                                            **
C     **               FLAG3=1:COVARIANCE ANALYSIS ONLY             **
C     **               FLAG3=2:COMPLETE LEAST SQUARES ESTIMATION    **
C     **                                                            **
C     **               FLAG4=1:ESTIMATE ALL PARAMETERS              **
C     **               FLAG4=2:DELETE CLOCK PARAMETERS              **
C     **                                                            **
C     **  WRITE   :    FLAG MESSAGES                                **
C     **                                                            **
C     **  OUTPUT  :    JK - ONE BASELINE CASE INDEX                 **
C     **                                                            **
C     ****************************************************************
C
      INTEGER FLAG1,FLAG2,FLAG3,FLAG4
C
      COMMON /FLG/ FLAG1,FLAG2,FLAG3,FLAG4
C
    1 WRITE (6,2)
    2 FORMAT (5X,'CHOOSE EXPERIMENT FLAGS'/' FLAG1=1 : DELAY IS ONLY OBS
     1ERVABLE'/' FLAG1=2 : DELAY RATE OBSERVABLE INCLUDED'/' FLAG1=3 : D
     2ELAY RATE IS ONLY OBSERVABLE'//' FLAG2=1 : MULTI-BASELINE EXPERIME
     3NT'/' FLAG2=2 : ONLY ETA COMPONENT OF POLAR MOTION'/' FLAG2=3 : ON
     4LY KSI COMPONENT OF POLAR MOTION'//' FLAG3=1 : COVARIANCE ANALYSIS
     5 ONLY'/' FLAG3=2 : COMPLETE LEAST SQUARES SOLUTION'//' FLAG4=1 : A
     6LL      PARAMETERS'/' FLAG4=2 : NO CLOCK PARAMETERS'//' INPUT FLAG1
     7,FLAG2,FLAG3,FLAG4')
C
C     READ PROGRAM FLAGS
      READ (5,*) FLAG1,FLAG2,FLAG3,FLAG4
      IF(FLAG1.GT.3.OR.FLAG2.GT.3.OR.FLAG3.GT.2.OR.FLAG4.GT.2) GO TO 1
      WRITE (7,3)
    3 FORMAT (//,12X,'PROGRAM FLAGS')
      WRITE (7,4) FLAG1,FLAG2,FLAG3,FLAG4
    4 FORMAT (/,9X,'FLAG1 = ',I2/9X,'FLAG2 = ',I2/9X,'FLAG3 = ',I2/9X,'F
     1LAG4 = ',I2//)
C
C     IF ONE BASELINE OMIT ONE POLAR MOTION PARAMETER(JK=1)
      JK=0
      IF(FLAG2.EQ.2.OR.FLAG2.EQ.3) JK=1
C
C     WRITE FLAG MESSAGES
      IF(FLAG1.EQ.1) WRITE (7,5)
      IF(FLAG1.EQ.2) WRITE (7,6)
      IF(FLAG1.EQ.3) WRITE (7,7)
      IF(FLAG3.EQ.1) WRITE (7,8)
      IF(FLAG3.EQ.2) WRITE (7,9)
    5 FORMAT (9X,'ANALYSIS INCLUDES ONLY THE TIME DELAY OBSERVABLE')
    6 FORMAT (9X,'ANALYSIS INCLUDES TIME DELAY&TIME DELAY RATE')
    7 FORMAT (9X,'ANALYSIS INCUDES ONLY DELAY RATE OBSERVABLE')
    8 FORMAT (/,9X,'COVARIANCE ANALYSIS ONLY')
    9 FORMAT (/,9X,'COMPLETE LEAST SQUARES SOLUTION')
C
      WRITE (6,10)
   10 FORMAT (//' PRESS 1 - THEN RETURN')
      READ (5,*) MOM
      RETURN
      END
```

```
      SUBROUTINE WEIGHT (P,PB,SIG,P1)
C     ******************************************************************
C     **                                                              **
C     **                 OBSERVATION WEIGHTING HANDLER                **
C     **                                                              **
C     **    INPUT   :   TNB           TOTAL NUMBER OF BASELINES       **
C     **                F1            FLAG FOR OBSERVABLES            **
C     **    READ    :   SIG1,SIG2     PRECISION OF DELAY & DELAY RATE **
C     **                P1            COVARIANCE MATRIX OF OBSERVABLES**
C     **                                                              **
C     **    WRITE   :   SIG           A PRIORI VARIANCE OF UNIT WEIGHT**
C     **                PB,P          WEIGHT MATRIX OF OBSERVABLES    **
C     **                SIG1,SIG2                                     **
C     **                                                              **
C     **    OUTPUT  :   P,SIG                                         **
C     **                                                              **
C     **   OPTIONS  :   DELAYS ONLY                                   **
C     **                DELAY RATES ONLY                              **
C     **                DELAY AND DELAY RATES                         **
C     **                                                              **
C     **          CALLS SSP SUBROUTINES LOC,DSINV                     **
C     **                                                              **
C     ******************************************************************
C
      IMPLICIT REAL*8(A-H,O-Z)
      INTEGER TNB,F1
      DIMENSION P(1), PB(1), P1(1)
      COMMON /FLG/ F1,IDUM2,IDUM3,IDUM4/BS/TNB,JUST
C
C     INPUT WEIGHTING INFORMATION
C     SIG1 IS THE PRECISION OF TIME DELAY (METERS)
C     SIG2 IS THE PRECISION OF TIME DELAY RATE (METERS/HOUR)
    1 CALL ERASE
      CALL HOME
      CALL ANMODE
      WRITE (6,2)
    2 FORMAT (5X,'INPUT WEIGHTING INFORMATION'//' SIG1 : PRECISION OF TI
     1ME DELAY IN METERS'/' SIG2 : PRECISION OF TIME DELAY RATE',' IN M
     2ETERS/HOUR',/,' E.G. 0.03 0.108(CORRESPONDS TO 0.1 NS,0.1 PS/S)')
      READ (5,*) SIG1,SIG2
C
      KS=TNB
C     IF DELAY RATE INCLUDED DOUBLE DIMENSIONS OF WEIGHT MATRIX
      IF(F1.EQ.2) KS=KS*2
C     COMPUTE # OF ELEMENTS IN UPPER TRIANGULAR WEIGHT MATRIX
      KR=TNB*(TNB+1)/2
      WRITE (6,3)
    3 FORMAT (/' INPUT COVARIANCE MATRIX OF OBSERVATIONS'/' ENTER IN UPP
     1ER TRIANGULAR FORM COLUMNWISE - DIAGONAL ELEMENTS SCALED TO UNITY'
     2)
      READ (5,*) (P1(I),I=1,KR)
      IF(F1.EQ.2) GO TO 7
      IF(F1.EQ.3) GO TO 5
C
C     SCALE FOR DELAY NOISE
      DO 4 KG=1,KR
    4 P(KG)=P1(KG)*SIG1**2
      GO TO 11
C
C     SCALE FOR DELAY RATE NOISE
    5 DO 6 KG=1,KR
    6 P(KG)=P1(KG)*SIG2**2
      GO TO 11
C
C     DEVELOP COVARIANCE MATRIX FOR DELAY&DELAY RATES
    7 KR=KS*(KS+1)/2
```

```
      DO 8 I=1,KR
      P(I)=0.D0
    8 CONTINUE
      II=0
      DO 10 I=1,TNB
      II=II+1
      DO 9 J=1,II
      CALL LOC (J,I,IT,TNB,TNB,1)
      KA=2*J-1
      KB=2*I-1
      KC=2*J
      KD=2*I
      CALL LOC (KA,KB,IU,KS,KS,1)
      CALL LOC (KC,KD,IV,KS,KS,1)
      P(IU)=P1(IT)*SIG1**2
      P(IV)=P1(IT)*SIG2**2
    9 CONTINUE
   10 CONTINUE
C
C     INVERT COVARIANCE MATRIX TO GET WEIGHT MATRIX
   11 CALL DSINV (P,KS,0.0001,IER)
C
C     SIG IS THE A PRIORI VARIANCE OF UNIT WEIGHT
      SIG=1.D0/P(1)
C     SCALE WEIGHT MATRIX
      DO 12 KC=1,KR
   12 P(KC)=P(KC)*SIG
C
C     PRINTOUT WEIGHTING INFORMATION
      IF(TNB.LE.5) GO TO 13
      CALL ERASE
      CALL HOME
      CALL ANMODE
   13 WRITE (7,14)
      WRITE (6,14)
   14 FORMAT (//12X,'WEIGHTING OF OBSERVATIONS')
      WRITE (6,15)
      WRITE (7,15)
   15 FORMAT (//9X,'WEIGHT MATRIX - SCALED TO FIRST ELEMENT UNITY')
      II=0
      DO 20 J=1,KS
      II=II+1
      DO 16 I=1,II
      CALL LOC (J,I,IT,TNB,TNB,1)
      PB(I)=P(IT)
   16 CONTINUE
      IF(F1.NE.2) WRITE (6,17) (PB(K),K=1,II)
      IF(F1.EQ.2) WRITE (6,18) (PB(K),K=1,II)
      WRITE (7,19) (PB(K),K=1,II)
   17 FORMAT (/,9X,6F7.4)
   18 FORMAT (9X,6F10.7)
   19 FORMAT (9X,12F7.4)
   20 CONTINUE
      WRITE (6,21) SIG
   21 FORMAT (/9X,'A PRIORI VARIANCE OF UNIT WEIGHT =',F10.6)
      WRITE (7,22) SIG1,SIG2,SIG
   22 FORMAT (//,9X,'TIME DELAY',5X,F10.5,5X,'(METERS)'/9X,'DELAY RATE',
     15X,F10.5,5X,'(METERS/HOUR)'/9X,'A PRIORI VARIANCE OF UNIT WEIGHT',
     25X,F10.6)
C
      WRITE (6,23)
   23 FORMAT (//' PRESS 1 - THEN RETURN')
      READ (5,*) MOM
C
      CALL ERASE
      CALL HOME
      CALL ANMODE
      WRITE (6,24)
```

```
 24     FORMAT (//,' IF YOU WISH TO REENTER WEIGHTING DATA ENTER 2 - ',/,'
       1 OTHERWISE ENTER ANY OTHER NUMBER')
        READ (5,*) MOM
        IF(MOM.EQ.2) GO TO 1
C
        RETURN
        END
```

```
      SUBROUTINE FILL (A,P,VTPV1,AL,B)
C     ******************************************************************
C     **                                                              **
C     **                  NORMAL MATRIX HANDLER                       **
C     **                                                              **
C     **        FILL NORMAL MATRIX IN A SEQUENTIAL MANNER             **
C     **          IN TRIANGULAR STORAGE                               **
C     **                                                              **
C     **   INPUT  : A       CONTRIBUTION TO NORMAL MATRIX AT GIVEN    **
C     **                      EPOCH OF ALL OBSERVING STATIONS         **
C     **            P       WEIGHT MATRIX OF OBSERVABLES              **
C     **            KK      TOTAL NUMBER OF PARAMETERS                **
C     **            F1,F2   PROGRAM FLAGS                             **
C     **            AL      MISCLOSURE VECTOR                         **
C     **            TNB     TOTAL NUMBER OF BASELINES                 **
C     **                                                              **
C     **   OUTPUT : W       CONTRIBUTION TO NORMAL MATRIX             **
C     **            U       CONTRIBUTION TO U=ATPL VECTOR             **
C     **            VTPV    CONTRIBUTION TO SUM OF RESIDUALS SQUARED  **
C     **                                                              **
C     **          CALLS SUBROUTINE MATPV,LOC(SSP)                     **
C     **                                                              **
C     ******************************************************************
C
      IMPLICIT REAL*8(A-H,O-Z)
      INTEGER F1,F3,TNB
      DIMENSION A(1), W(1), U(1), P(1), B(1), VTPV(1), AL1(12), AL(1)
      COMMON /FLG/ F1,IDUM2,F3,IDUM4/NTRX/W/UTRX/U/BS/TNB,KK
C
      KS=TNB
      IF(F1.EQ.2) KS=KS*2
C     CALCULATE ATP
      CALL MATPV (A,P,B,KK,KS,KS,0,1)
      II=0
      IND=1
      DO 5 J=1,KK
      II=II+1
      IF(F3.EQ.1) GO TO 2
      DO 1 JK=1,KS
      CALL LOC (J,JK,IY,KK,KS,0)
C     ADD CONTRIBUTION TO U=ATPL VECTOR
      U(J)=U(J)-B(IY)*AL(JK)
    1 CONTINUE
    2 DO 4 I=1,II
      DO 3 K=1,KS
      KZ=(K-1)*KK
C     ADD CONTRIBUTION TO NORMAL MATRIX
      W(IND)=W(IND)+B(I+KZ)*A(J+KZ)
    3 CONTINUE
      IND=IND+1
    4 CONTINUE
    5 CONTINUE
      IF(F3.EQ.1) GO TO 6
C
C     ADD CONTRIBUTION TO SUM OF RESIDUALS SQUARED
C     VTPV=LTPL+XTU
C     CALCULATE LTPL IN THIS ROUTINE
      CALL MATPV (AL,P,AL1,1,KS,KS,0,1)
      CALL MATPV (AL1,AL,VTPV,1,KS,1,0,0)
      VTPV1=VTPV1+VTPV(1)
C
    6 RETURN
      END
```

```
      SUBROUTINE PARTDR (IP,TK,DX,DY,DZ,TH,OMG,C,RO,DS,FRNG,CONV,ERAD,AL
     1,JK,IJ,NB)
C     ******************************************************************
C     **                                                              **
C     **               CALCULATES PARTIAL DERIVATIVES                 **
C     **                                                              **
C     **   INPUT  : OMG        EARTH ROTATION RATE                    **
C     **            C          SPEED OF LIGHT                         **
C     **            ERAD       MEAN EARTH RADIUS                      **
C     **            CONV       CONVERTS UNIVERSAL TO SIDEREAL TIME    **
C     **            DX,DY,DZ   STATION COORDINATE DIFFERENCES         **
C     **            RA,D       QUASAR COORDINATES                     **
C     **            IP         QUASAR NUMBER                          **
C     **            DS,FRNG    OBSERVED DELAY & DELAY RATE            **
C     **            JK         ONE BASELINE CASE INDEX                **
C     **            IJ         STEP NUMBER                            **
C     **            NB         BASELINE NUMBER                        **
C     **            F1,F2,...  PROGRAM FLAGS                          **
C     **            TH         GST AT INITIAL EPOCH                   **
C     **            TK         EPOCH OF OBSERVATION                   **
C     **                                                              **
C     **   OUTPUT : DS0,FRNG0  THEORETICAL PARTIALS                   **
C     **            AL         MISCLOSURE VECTOR                      **
C     **            PART,G     DELAY & DELAY RATE PARTIALS            **
C     **                                                              **
C     ** OPTIONS  : DELAYS ONLY                                       **
C     **            DELAY RATES ONLY                                  **
C     **            DELAY AND DELAY RATES                             **
C     **                                                              **
C     ******************************************************************
C
      IMPLICIT REAL*8(A-H,O-Z)
      INTEGER F1,F2,F3,F4
      DIMENSION F(1), G(1), X(1), Y(1), Z(1), RA(1), D(1), AL(1)
      COMMON /FLG/ F1,F2,F3,F4/PDR1/F/PDR2/G/SOU1/RA/SOU2/D
C
C     COMPUTE TRIGONOMETRIC MEMBERS OF PARTIAL DERIVATIVES
      CD=DCOS(D(IP))
      SD=DSIN(D(IP))
      Y1=OMG*TK+TH
      Y2=Y1-RA(IP)
      CKP=DCOS(Y2)
      SKP=DSIN(Y2)
C
      IF(F1.EQ.3) GO TO 5
C
C     COMPUTE PARTIAL DERIVATIVES
C
C     TAU PARTIAL DERIVATIVE
      F(1)=-CD*CKP
C     EPSILON PARTIAL DERIVATIVE
      F(2)=CD*SKP
C     SIGMA PARTIAL DERIVATIVE
      F(3)=-SD
      EXP=(DX*SKP+DY*CKP)*CD
      IF(IJ.EQ.1) GO TO 3
C
C     SKIP EARTH ORIENTATION PARAMETERS FOR FIRST STEP
C       TO PROVIDE INITIAL ORIENTATION OF BASELINE
C     POLAR MOTION DIFFERENCES PARTIAL DERIVATIVES
C     SKIP ETA IF F2=3
      IF(F2.EQ.3) GO TO 1
C      KSI COMPONENT
      F(4)=-DX*SD+DZ*CD*CKP
      F(4)=F(4)/ERAD
C     SKIP KSI IF F2=2
```

```
      IF(F2.EQ.2) GO TO 2
C      ETA COMPONENT
 1    F(5)=DY*SD+DZ*CD*SKP
      F(5-JK)=F(5)/ERAD
C     UT1-UTC PARTIAL DERIVATIVE
 2    F(6)=CONV*EXP
C     CHANGE UNITS TO MILLISECONDS
      F(6-JK)=15.D0*F(6)/(1000.D0*RO)
C
C     DECLINATIONS
 3    F(7)=(DX*CKP-DY*SKP)*SD-DZ*CD
      F(7-JK)=F(7)/RO
C     RIGHT ASCENSION DIFFERENCES
      F(8)=-EXP
      F(8-JK)=F(8)/RO
C
C     SKIP CLOCK PARAMETERS IF F4=2
      IF(F4.EQ.2) GO TO 4
C     CLOCK OFFSET PARTIAL DERIVATIVE
      F(9-JK)=C
C     CLOCK RATE PARTIAL DERIVATIVE
      F(10-JK)=C*TK
C
C     SKIP DELAY RATES IF F1=1
 4    IF(F1.EQ.1) GO TO 9
C
C     DELAY RATE PARTIALS
 5    OMC=OMG*CD
C     TAU
      G(1)=OMC*SKP
C     EPSILON
      G(2)=OMC*CKP
C     SIGMA
      G(3)=0.D0
      EXT=(DX*CKP-DY*SKP)*OMC
      IF(IJ.EQ.1) GO TO 8
      IF(F2.EQ.3) GO TO 6
C
C     POLAR MOTION DIFFERENCES
C     KSI COMPONENT
      G(4)=-OMC*DZ*SKP
      G(4)=G(4)/ERAD
      IF(F2.EQ.2) GO TO 7
C     ETA COMPONENT
 6    G(5)=OMC*DZ*CKP
      G(5-JK)=G(5)/ERAD
C     UT1-UTC DIFFERENCES
 7    G(6)=CONV*EXT*OMG
C     CHANGE UNITS TO MILLISECONDS
      G(6-JK)=G(6)/(3600.D0*1000.D0)
C
C     DECLINATIONS
 8    G(7)=-OMG*SD*(DX*SKP+DY*CKP)
      G(7-JK)=G(7)/RO
C     RIGHT ASCENSION DIFFERENCES
      G(8)=-EXT
      G(8-JK)=G(8)/RO
      IF(F4.EQ.2) GO TO 9
C
C     CLOCK OFFSET DIFFERENCES
      G(9-JK)=0.D0
C     CLOCK RATE DIFFERENCES
      G(10-JK)=C
C
C     RETURN IF COVARIANCE ANALYSIS ONLY
 9    IF(F3.EQ.1) GO TO 12
C
C     COMPUTE APPROXIMATE VALUE OF OBSERVATION
```

```
      NC=NB
      IF(F1.EQ.1.OR.F1.EQ.2) GO TO 10
      NC=NC-1
      GO TO 11
   10 DS0=-DX*CD*CKP+DY*CD*SKP-DZ*SD
C
C      CALCULATE MISCLOSURES
      IF(F1.EQ.2) NC=2*NB-1
      AL(NC)=DS0-DS
      IF(F1.EQ.1) GO TO 12
   11 FRNG0=OMC*(DX*SKP+DY*CKP)
      AL(NC+1)=FRNG0-FRNG
C
   12 RETURN
      END
```

```
      SUBROUTINE AMATR (NB,IP,IM,STEP,NSTEPS,JK,IPFIX)
C     ****************** ***************************************************
C     **                                                                  **
C     **                      DESIGN MATRIX HANDLER                       **
C     **                                                                  **
C     **   INPUT  : NB         NUMBER OF BASELINE                         **
C     **              TNB        TOTAL NUMBER OF BASELINES                  **
C     **              IP         QUASAR NUMBER                              **
C     **              KK         TOTAL NUMBER OF PARAMETERS                 **
C     **              IM         TOTAL NUMBER OF QUASARS                    **
C     **              STEP       EARTH ORIENTATION STEP NUMBER              **
C     **              NSTEPS     TOTAL NUMBER OF STEPS                      **
C     **              JK         ONE BASELINE CASE INDEX                    **
C     **              IPFIX      QUASAR OF FIXED RIGHT ASCENSION            **
C     **              F1,F2,F4   PROGRAM FLAGS                              **
C     **              F,G        PARTIALS OF DELAY & DELAY RATE             **
C     **                                                                  **
C     **   OUTPUT : A          OBSERVATION CONTRIBUTION TO A - MATRIX     **
C     **                                                                  **
C     ** OPTIONS : DELAYS ONLY                                            **
C     **              DELAY AND DELAY RATES                               **
C     **                                                                  **
C     **********************************************************************
C
      IMPLICIT REAL*8(A-H,O-Z)
      INTEGER TNB,F1.F2,F4,STEP
      DIMENSION F(1), G(1), A(1)
      COMMON /FLG/ F1,F2,IDUM3,F4/PDR1/F/PDR2/G/ATRX/A/BS/TNB,KK
C
C     DELAYS
C     TAU EPSILON SIGMA
      J1=3*(NB-1)+1
      DO 1 IJ=1,3
      A(J1)=F(IJ)
      J1=J1+1
    1 CONTINUE
      J2=3*TNB
C     SKIP EARTH ORIENTATION PARAMETERS FOR FIRST STEP
C      TO PROVIDE REFERENCE ORIENTATION
      IF(STEP.EQ.1) GO TO 3
C     POLAR MOTION COMPONENT DIFFERENCES
      J3=J2+STEP-1
      A(J3)=F(4)
      IF(F2.EQ.2.OR.F2.EQ.3) GO TO 2
      A(J3+NSTEPS-1)=F(5)
    2 J4=J2+(2-JK)*NSTEPS+STEP-(3-JK)
C     UT1 DIFFERENCE
      A(J4)=F(6-JK)
C     DECLINATIONS
    3 J5=J2+(3-JK)*(NSTEPS-1)+IP
      A(J5)=F(7-JK)
C     IF REFERENCE QUASAR DO NOT FILL DESIGN MATRIX
C      TO PROVIDE RIGHT ASCENSION ORIGIN
      IF(IP.EQ.IPFIX) GO TO 4
      J6=J5+IM
      IF(IP.GT.IPFIX) J6=J6-1
C     RIGHT ASCENSION DIFFERENCES
      A(J6)=F(8-JK)
    4 IF(F4.EQ.2) GO TO 5
      J7=J2+(3-JK)*(NSTEPS-1)+2*IM+2*(NB-1)
      J8=J7+1
C     CLOCK OFFSET DIFFERENCES
      A(J7)=F(9-JK)
C     CLOCK RATE DIFFERENCES
      A(J8)=F(10-JK)
    5 IF(F1.EQ.1) GO TO 10
```

```
C
C       DELAY RATES
        J1=3*(NB-1)+1
        DO 6 IJ=1,3
        A(J1+KK)=G(IJ)
        J1=J1+1
  6     CONTINUE
        IF(STEP.EQ.1) GO TO 8
        A(J3+KK)=G(4)
        IF(F2.EQ.2.OR.F2.EQ.3) GO TO 7
        A(J3+NSTEPS-1+KK)=G(5)
  7     A(J4+KK)=G(6-JK)
  8     A(J5+KK)=G(7-JK)
        IF(IP.EQ.IPFIX) GO TO 9
        A(J6+KK)=G(8-JK)
  9     IF(F4.EQ.2) GO TO 10
        A(J7+KK)=G(9-JK)
        A(J8+KK)=G(10-JK)
C
 10     RETURN
        END
```

```
      SUBROUTINE FAMTR (NB,IP,IM,STEP,NSTEPS,JK,IPFIX)
C     *****************************************************************
C     **                                                             **
C     **        DESIGN MATRIX HANDLER FOR DELAY RATE PARTIALS        **
C     **                                                             **
C     **                SEE SUBROUTINE AMATR FOR DETAILS             **
C     **                                                             **
C     *****************************************************************
C
      IMPLICIT REAL*8(A-H,O-Z)
      INTEGER TNB,F2,F4,STEP
      DIMENSION G(1), A(1)
      COMMON /FLG/ IDUM1,F2,IDUM3,F4/PDR1/DUM(1)/PDR2/G/ATRX/A/BS/TNB,KK
C
C     SIGMA,CLOCK OFFSET PARAMETERS NOT ESTIMABLE
C
C     TAU EPSILON
      J1=2*(NB-1)+1
      DO 1 IJ=1,2
      A(J1)=G(IJ)
      J1=J1+1
    1 CONTINUE
      J2=2*TNB
C     EARTH ORIENTATION PARAMETERS
      IF(STEP.EQ.1) GO TO 3
      J3=J2+STEP-1
C     KSI COMPONENT
      A(J3)=G(4)
      IF(F2.EQ.2.OR.F2.EQ.3) GO TO 2
C     ETA COMPONENT
      A(J3+NSTEPS-1)=G(5)
    2 J4=J2+(2-JK)*NSTEPS+STEP-(3-JK)
C     UTC-UT1
      A(J4)=G(6-JK)
    3 IF(IP.EQ.IPFIX) GO TO 4
      J5=J2+(3-JK)*(NSTEPS-1)+IP
      IF(IP.GT.IPFIX) J5=J5-1
C     DECLINATION DIFFERENCES
      A(J5)=G(7-JK)
      J6=J5+IM-1
C     RIGHT ASCENSION DIFFERENCES
      A(J6)=G(8-JK)
    4 IF(F4.EQ.2) GO TO 5
C     CLOCK RATE DIFFERENCES
      J7=J2+(3-JK)*(NSTEPS-1)+2*(IM-1)+NB
      A(J7)=G(10-JK)
C
    5 RETURN
      END
```

```
      SUBROUTINE SOLVE (SIG2,CORR,XX,IM,NSTEPS,DIST,B,DM,EM,VTPV1,ICOUNT
     1)
C     ******************************************************************
C     **                                                              **
C     **               LEAST SQUARES ESTIMATION HANDLER               **
C     **                                                              **
C     **   INPUT  :  XC,YC,ZC  BASELINE COMPONENTS                    **
C     **             N         COMPLETE NORMAL MATRIX                 **
C     **             U         COMPLETE ATPL VECTOR                   **
C     **             VTPV1     LTPL CONTRIBUTION TO VTPV              **
C     **             SIG2      A PRIORI VARIANCE OF UNIT WEIGHT       **
C     **             DIST      BASELINE DISTANCES                     **
C     **             KK        TOTAL NUMBER OF PARAMETERS             **
C     **             IM        TOTAL NUMBER OF QUASARS                **
C     **             TNB       TOTAL NUMBER OF BASELINES              **
C     **             NSTEPS    TOTAL NUMBER OF STEPS                  **
C     **             F1...     PROGRAM FLAGS                          **
C     **             ICOUNT    TOTAL NUMBER OF OBSERVATIONS           **
C     **                                                              **
C     **   WRITE  :  N         NORMAL & COVARIANCE MATRIX             **
C     **             DM        BASELINE VARIANCE & COVARIANCES        **
C     **             CORR      CORRELATION MATRIX OF PARAMETRS        **
C     **             VTPV      SUM OF RESIDUALS SQUARED               **
C     **             SIG2H     A POSTERIORI VARIANCE OF UNIT WEIGHT   **
C     **             XX        CORRECTION TO APPROXIMATE PARAMETERS   **
C     **             EIG       EIGENVALUES OF COVARIANCE MATRIX       **
C     **                                                              **
C     **        CALLS SSP ROUTINES : DSINV,DEIGEN,LOC                 **
C     **        CALLS SUBROUTINES STDLST                              **
C     **                                                              **
C     ******************************************************************
C
      IMPLICIT REAL*8(A-H,L-Z)
      INTEGER TNB,F1,F2,F3,F4,NSTEPS
      DIMENSION XC(1), YC(1), ZC(1), DIST(1), EM(1), DM(1), B(1), N(1),
     1CORR(1), U(1), XX(1)
      COMMON /FLG/ F1,F2,F3,F4/CRD4/XC/CRD5/YC/CRD6/ZC/NTRX/N/UTRX/U/BS/
     1TNB,KK
C
C     PRINT NUMBER OF OBSERVATIONS
C     DOUBLE OBSERVATIONS IF DELAY RATE INCLUDED
      IF(F1.EQ.2) ICOUNT=ICOUNT*2
      WRITE (7,1) ICOUNT
    1 FORMAT (//12X,'THE NUMBER OF OBSERVATIONS =',I4)
C
C     PRINTOUT NORMAL MATRIX
      WRITE (7,2)
    2 FORMAT (1H1,12X,'NORMAL MATRIX')
      II=0
      DO 5 J=1,KK
      II=II+1
      DO 3 I=1,II
      CALL LOC (J,I,IT,KK,KK,1)
      CORR(I)=N(IT)
    3 CONTINUE
      WRITE (7,4) J,(CORR(K),K=1,II)
    4 FORMAT (/,5X,I2,', ',(T10,12F9.2))
    5 CONTINUE
C
C     INVERT NORMAL MATRIX
C     ONLY UPPER TRIANGULAR PART IS NEEDED
      CALL DSINV (N,KK,0.0001,IER)
C     PRINTOUT VARIANCE-COVARIANCE MATRIX (UNSCALED)
      WRITE (7,6)
    6 FORMAT (1H1,12X,'VARIANCE-COVARIANCE MATRIX (UNSCALED)')
      II=0
```

```
      DO 9 J=1,KK
      II=II+1
      DO 7 I=1,II
      CALL LOC (J,I,IT,KK,KK,1)
      CORR(I)=N(IT)
    7 CONTINUE
      WRITE (7,8) J,(CORR(K),K=1,II)
    8 FORMAT (/,5X,I2,'. ',(T10,12F9.5))
    9 CONTINUE
C
C     COMPUTE AND LIST STANDARD DEVIATIONS (A PRIORI)
      CALL STDLST (SIG2,NSTEPS,IM,XX,1)
C
C     IF DELAY RATE-DISTANCE NOT ESTIMABLE
      IF(FI.EQ.3) GO TO 31
C
C     COMPUTE DISTANCE COVARIANCE MATRIX
      J=3*TNB*TNB
      DO 10 I=1,J
      EM(I)=0.D0
   10 B(I)=0.D0
      JL=3*TNB
      DO 11 K=1,TNB
      JK=3*(K-1)*(TNB+1)+1
C     COMPUTE ERROR PROPAGATION PARTIALS
      B(JK)=XC(K)/DIST(K)
      B(JK+1)=YC(K)/DIST(K)
      B(JK+2)=ZC(K)/DIST(K)
   11 CONTINUE
      IB2=TNB*TNB
      DO 12 I=1,IB2
   12 DM(I)=0.D0
      DO 15 I=1,TNB
      I3=(I-1)*JL
      DO 14 K=1,JL
      I2=I3+K
      DO 13 J=1,JL
      CALL LOC (J,K,IR,KK,KK,1)
      I4=I3+J
      EM(I2)=EM(I2)+B(I4)*N(IR)*SIG2
   13 CONTINUE
   14 CONTINUE
   15 CONTINUE
      K3=0
      DO 18 I=1,TNB
      I3=(I-1)*JL
      DO 17 K=1,TNB
      K2=(K-1)*JL
      K3=K3+1
      DO 16 J=1,JL
      J1=I3+J
      J2=K2+J
      DM(K3)=DM(K3)+EM(J1)*B(J2)
   16 CONTINUE
   17 CONTINUE
   18 CONTINUE
      CALL ERASE
      CALL HOME
      CALL ANMODE
      WRITE (7,19)
   19 FORMAT (1H1,///,12X,'DISTANCE COVARIANCE MATRIX'/)
      DO 22 I=1,TNB
      DO 20 J=1,TNB
      CALL LOC (I,J,IR,TNB,TNB,0)
C     CHANGE UNITS TO CENTIMETERS SQUARED
      CORR(J)=DM(IR)*10000.D0
   20 CONTINUE
      WRITE (7,21) (CORR(K),K=1,TNB)
```

```
 21     FORMAT (15X,6F10.8)
 22     CONTINUE
C       PRINT BASELINE STANDARD DEVIATIONS
        WRITE (6,23)
        WRITE (7,23)
 23     FORMAT (//12X,'BASELINE STANDARD DEVIATIONS  (CM)')
        DO 25 I=1,TNB
        CALL LOC (I,I,IR,TNB,TNB,0)
C       CHANGE UNITS TO CENTIMETERS
        BSTD=DSQRT(DM(IR))*100.D0
        WRITE (6,24) I,BSTD
        WRITE (7,24) I,BSTD
 24     FORMAT (/,12X,I2,'.',1X,F9.3)
 25     CONTINUE
C       COMPUTE BASELINE CORRELATION MATRIX
        WRITE (6,26)
        WRITE (7,26)
 26     FORMAT (///,12X,'BASELINE CORRELATION MATRIX')
        II=1
        DO 29 I=1,TNB
        DO 27 J=1,II
        CALL LOC (I,I,IR,TNB,TNB,0)
        CALL LOC (J,J,IS,TNB,TNB,0)
        CALL LOC (I,J,IT,TNB,TNB,0)
        CORR(J)=DM(IT)/DSQRT(DM(IR)*DM(IS))
 27     CONTINUE
        WRITE (6,28) I,(CORR(K),K=1,II)
        WRITE (7,28) I,(CORR(K),K=1,II)
 28     FORMAT (/,12X,I2,'. ',6F5.2)
        II=II+1
 29     CONTINUE
C
        WRITE (6,30)
 30     FORMAT (//,6X,'PRESS 1 THEN RETURN')
        READ (5,*) MOM
C
C       COMPUTE PARAMETER CORRELATION MATRIX
 31     WRITE (7,32)
 32     FORMAT (1H1,10X,'PARAMETER CORRELATION MATRIX'//)
        II=1
        DO 35 I=1,KK
        DO 33 J=1,II
        CALL LOC (I,I,IR,KK,KK,1)
        CALL LOC (J,J,IS,KK,KK,1)
        CALL LOC (I,J,IT,KK,KK,1)
        CORR(J)=N(IT)/DSQRT(N(IR)*N(IS))
 33     CONTINUE
        WRITE (7,34) I,(CORR(K),K=1,II)
 34     FORMAT (/,1X,I2,'. ',(T6,25F5.2))
        II=II+1
 35     CONTINUE
C
C       SKIP SOLUTION IF INTERESTED ONLY IN COVARIANCE ANALYSIS
        IF(F3.EQ.1) GO TO 41
C
        CALL ERASE
        CALL HOME
        CALL ANMODE
C
C       COMPUTE CORRECTIONS TO APPROXIMATE PARAMETERS
        DO 36 I=1,KK
        DO 36 J=1,KK
        CALL LOC (I,J,IR,KK,KK,1)
        XX(I)=XX(I)+N(IR)*U(J)
 36     CONTINUE
C
C       CALCULATE VTPV
        VTPV2=0.D0
```

```
      DO 37 I=1,KK
      VTPV2=VTPV2-XX(I)*U(I)
 37   CONTINUE
      VTPVF=VTPV1+VTPV2
C
C     CALCULATE THE A POSTERIORI VARIANCE OF UNIT WEIGHT
      SIG2H=VTPVF/(ICOUNT-KK)
C     CALCULATE A POSTERIORI/A PRIORI
      SIGR=SIG2H/SIG2
C
C
C     COMPUTE & LIST STANDARD DEVIATIONS - A POSTERIORI
      CALL STDLST (SIG2H,NSTEPS,IM,XX,2)
C
      CALL ERASE
      CALL HOME
      CALL ANMODE
C
      WRITE (6,38) VTPVF
      WRITE (7,38) VTPVF
 38   FORMAT (//,12X,'VTPV =',D15.8)
      WRITE (6,39) SIG2H
      WRITE (7,39) SIG2H
 39   FORMAT (/,12X,'A POSTERIORI VARIANCE OF UNIT WEIGHT =',D15.8)
      WRITE (6,40) SIGR
      WRITE (7,40) SIGR
 40   FORMAT (/,12X,'A POSTERIORI/A PRIORI =',D15.8)
C
      WRITE (6,30)
      READ (5,*) MOM
C
C     COMPUTE EIGENVALUES OF COVARIANCE MATRIX
 41   WRITE (7,42)
 42   FORMAT (1H1,18X,'EIGENVALUES'/)
      CALL DEIGEN (N,R,KK,1)
      DO 44 I=1,KK
      CALL LOC (I,I,IND,KK,KK,1)
      EIG=N(IND)
      WRITE (7,43) EIG
 43   FORMAT (15X,D14.3)
 44   CONTINUE
C
      CALL ERASE
      CALL HOME
      CALL ANMODE
      RETURN
      END
```

```
      SUBROUTINE STDLST (SIG2,NSTEPS,IM,XX,ISTD)
C     ****************************************************************
C     **                                                            **
C     **      COMPUTE & OUTPUT ESTIMATED STANDARD DEVIATIONS        **
C     **                                                            **
C     **   INPUT  : N          COVARIANCE MATRIX OF PARAMETERS      **
C     **              SIG2       VARIANCE OF UNIT WEIGHT            **
C     **              F1...      PROGRAM FLAGS                      **
C     **              NSTEPS     TOTAL NUMBER OF STEPS              **
C     **              TNB        TOTAL NUMBER OF BASELINES          **
C     **              KK         TOTAL NUMBER OF PARAMETERS         **
C     **              IM         TOTAL NUMBER OF QUASARS            **
C     **              XX         PARAMETER CORRECTIONS VECTOR       **
C     **              ISTD       INDEX - A PRIORI OR A POSTERIORI STD'S **
C     **                                                            **
C     **   WRITE  : SIGMA      STANDARD DEVIATIONS OF PARAMETERS    **
C     **                                                            **
C     ** OPTIONS : OUTPUT A PRIORI OR A POSTERIORI STANDARD DEV.    **
C     **             OUTPUT CORRECTIONS TO APPROXIMATE PARAMETERS   **
C     **                                                            **
C     ****************************************************************
C
      IMPLICIT REAL*8(A-H,L-Z)
      INTEGER NPARM,TNB,F1,F2,F3,F4,NSTEPS,TNP
      DIMENSION N(1), XX(1)
      COMMON /NTRX/ N/BS/TNB,KK/FLG/F1,F2,F3,F4
C
C     STANDARD DEVIATION FUNCTION
      S(A)=DSQRT(A*SIG2)
C
C      NPARM IS THE NUMBER OF PARAMETERS COUNTER
      NPARM=0
C
      IFLOW=0
      IF(SIG2.GT.1.D-10) GO TO 1
      SIGMA=0.D0
      IFLOW=1
C
    1 CALL ERASE
      CALL HOME
      CALL ANMODE
C
C     COMPUTE STANDARD DEVIATIONS
      IF(ISTD.EQ.2) GO TO 3
      WRITE (6,2)
      WRITE (7,2)
    2 FORMAT (1H1,5X,'STANDARD DEVIATIONS - A PRIORI')
      GO TO 5
    3 WRITE (6,4)
      WRITE (7,4)
    4 FORMAT (1H1,5X,'STANDARD DEVIATIONS - A POSTERIORI',/,5X,'+ PARAME
     1TER CORRECTIONS')
C
    5 IF(F1.EQ.3) GO TO 7
      WRITE (6,6)
      WRITE (7,6)
    6 FORMAT (/,7X,'TAU EPSILON SIGMA  (CM)')
      IT=TNB*3
      TNP=3
      GO TO 9
    7 WRITE (6,8)
      WRITE (7,8)
    8 FORMAT (/,7X,'TAU EPSILON  (CM)')
      IT=TNB*2
      TNP=2
    9 IC=0
```

```
      DO 15 I=1,TNB
      WRITE (6,10) I
      WRITE (7,10) I
   10 FORMAT (9X,'BASELINE # ',I2)
      DO 14 J=1,TNP
      IC=IC+1
      NPARM=NPARM+1
      IF(IFLOW.EQ.1) GO TO 12
      CALL LOC (IC,IC,IQ,KK,KK,1)
      SIGMA=S(N(IQ))
C     CHANGE UNITS TO CENTIMETERS
      SIGMA=SIGMA*100.D0
      IF(ISTD.EQ.2) GO TO 12
      WRITE (6,11) NPARM,SIGMA
      WRITE (7,11) NPARM,SIGMA
   11 FORMAT (4X,I3,'.',1X,F8.3)
      GO TO 14
   12 XIC=XX(IC)*100.D0
      WRITE (6,13) NPARM,SIGMA,XIC
      WRITE (7,13) NPARM,SIGMA,XIC
   13 FORMAT (4X,I3,'.',1X,F8.3,3X,F12.4)
   14 CONTINUE
   15 CONTINUE
C
      WRITE (6,16)
      WRITE (7,16)
   16 FORMAT (/,7X,'POLAR MOTION VARIATIONS (CM)')
      IF(F2.EQ.2) WRITE (6,17)
      IF(F2.EQ.2) WRITE (7,17)
   17 FORMAT (/,9X,'FIRST COMPONENT ONLY')
      IF(F2.EQ.3) WRITE (6,18)
      IF(F2.EQ.3) WRITE (7,18)
   18 FORMAT (/,9X,'SECOND COMPONENT ONLY')
      IT=IT+1
      ITM=IT+2*(NSTEPS-1)-1
      IZ=IT+(ITM-IT)/2+1
      IF(F2.EQ.2.OR.F2.EQ.3) ITM=IT+NSTEPS-2
      DO 22 I=IT,ITM
      IF(F2.EQ.1.AND.I.EQ.IT) WRITE (6,19)
      IF(F2.EQ.1.AND.I.EQ.IT) WRITE (7,19)
   19 FORMAT (9X,'FIRST COMPONENT')
      IF(F2.EQ.1.AND.I.EQ.IZ) WRITE (6,20)
      IF(F2.EQ.1.AND.I.EQ.IZ) WRITE (7,20)
   20 FORMAT (9X,'SECOND COMPONENT')
      NPARM=NPARM+1
      IF(IFLOW.EQ.1) GO TO 21
      CALL LOC (I,I,IQ,KK,KK,1)
      SIGMA=S(N(IQ))
C     CHANGE UNITS TO CENTIMETERS
      SIGMA=SIGMA*100.D0
      IF(ISTD.EQ.2) GO TO 21
      WRITE (6,11) NPARM,SIGMA
      WRITE (7,11) NPARM,SIGMA
      GO TO 22
   21 XIC=XX(I)*100.D0
      WRITE (6,13) NPARM,SIGMA,XIC
      WRITE (7,13) NPARM,SIGMA,XIC
   22 CONTINUE
C
      WRITE (6,23)
      WRITE (7,23)
   23 FORMAT (/,7X,'UT1-UTC VARIATIONS (10**2 MICROSECS)')
      IT=ITM+1
      ITM=IT+NSTEPS-2
      DO 25 I=IT,ITM
      NPARM=NPARM+1
      IF(IFLOW.EQ.1) GO TO 24
      CALL LOC (I,I,IQ,KK,KK,1)
```

```
      SIGMA=S(N(IQ))
C     CHANGE UNITS TO 10**2 MICROSECONDS
      SIGMA=SIGMA*10.D0
      IF(ISTD.EQ.2) GO TO 24
      WRITE (6,11) NPARM,SIGMA
      WRITE (7,11) NPARM,SIGMA
      GO TO 25
 24   XIC=XX(I)*10.D0
      WRITE (6,13) NPARM,SIGMA,XIC
      WRITE (7,13) NPARM,SIGMA,XIC
 25   CONTINUE
C
      IF(F1.EQ.3) GO TO 27
      WRITE (6,26)
      WRITE (7,26)
 26   FORMAT (/,7X,'DECLINATIONS  (MILLIARCSECS)')
      GO TO 29
 27   WRITE (6,28)
      WRITE (7,28)
 28   FORMAT (/,7X,'DECL. DIFFERENCES (MILLIARCSECS)')
 29   IT=ITM+1
      ITIM=IT+IM-1
      IF(F1.EQ.3) ITIM=ITIM-1
      DO 31 I=IT,ITIM
      NPARM=NPARM+1
      IF(IFLOW.EQ.1) GO TO 30
      CALL LOC (I,I,IQ,KK,KK,1)
      SIGMA=S(N(IQ))
C     CHANGE UNITS TO MILLISECONDS
      SIGMA=SIGMA*1000.D0
      IF(ISTD.EQ.2) GO TO 30
      WRITE (6,11) NPARM,SIGMA
      WRITE (7,11) NPARM,SIGMA
      GO TO 31
 30   XIC=XX(I)*1000.D0
      WRITE (6,13) NPARM,SIGMA,XIC
      WRITE (7,13) NPARM,SIGMA,XIC
 31   CONTINUE
C
      WRITE (6,32)
      WRITE (7,32)
 32   FORMAT (/,7X,'R.A. DIFFERENCES (MILLIARCSECS)')
      ITM=ITIM+1
      ITN=ITIM+IM-1
      DO 34 I=ITM,ITN
      NPARM=NPARM+1
      IF(IFLOW.EQ.1) GO TO 33
      CALL LOC (I,I,IQ,KK,KK,1)
      SIGMA=S(N(IQ))
C     CHANGE UNITS TO MILLISECONDS
      SIGMA=SIGMA*1000.D0
      IF(ISTD.EQ.2) GO TO 33
      WRITE (6,11) NPARM,SIGMA
      WRITE (7,11) NPARM,SIGMA
      GO TO 34
 33   XIC=XX(I)*1000.D0
      WRITE (6,13) NPARM,SIGMA,XIC
      WRITE (7,13) NPARM,SIGMA,XIC
 34   CONTINUE
C
      IF(F4.EQ.2) GO TO 45
      IF(F1.EQ.3) GO TO 39
      IF(NPARM.LT.42) GO TO 35
      WRITE (6,46)
      READ (5,*) MOM
      CALL ERASE
      CALL HOME
      CALL ANMODE
```

```
C
 35     WRITE (6,36)
        WRITE (7,36)
 36     FORMAT (/,7X,'CLOCK OFFSET (NSECS)')
        ITM=3*TNB+3*(NSTEPS-1)+2*IM
        IF(F2.EQ.2.OR.F2.EQ.3) ITM=ITM-(NSTEPS-1)
        ITN=ITM+2*TNB-2
        DO 38 I=ITM,ITN,2
        NPARM=NPARM+1
        IF(IFLOW.EQ.1) GO TO 37
        CALL LOC (I,I,IQ,KK,KK,1)
        SIGMA=S(N(IQ))
        IF(ISTD.EQ.2) GO TO 37
        WRITE (6,11) NPARM,SIGMA
        WRITE (7,11) NPARM,SIGMA
        GO TO 38
 37     WRITE (6,13) NPARM,SIGMA,XX(I)
        WRITE (7,13) NPARM,SIGMA,XX(I)
 38     CONTINUE
C
 39     WRITE (6,40)
        WRITE (7,40)
 40     FORMAT (/,7X,'CLOCK RATE (PICOSECS/HR)')
        IF(F1.EQ.3) GO TO 41
        ITM1=ITM+1
        ITN1=ITN+1
        JJ=2
        GO TO 42
 41     ITM1=ITN+1
        ITN1=ITM1+TNB-1
        JJ=1
 42     DO 44 I=ITM1,ITN1,JJ
        NPARM=NPARM+1
        IF(IFLOW.EQ.1) GO TO 43
        CALL LOC (I,I,IQ,KK,KK,1)
C       CHANGE UNITS TO PICOSECS/HR
        SIGMA=S(N(IQ))*1000.D0
        IF(ISTD.EQ.2) GO TO 43
        WRITE (6,11) NPARM,SIGMA
        WRITE (7,11) NPARM,SIGMA
        GO TO 44
 43     XCI=XX(I)*1000.D0
        WRITE (6,13) NPARM,SIGMA,XIC
        WRITE (7,13) NPARM,SIGMA,XIC
 44     CONTINUE
C
 45     WRITE (6,46)
 46     FORMAT (//6X,'PRESS 1 THEN RETURN')
        READ (5,*) MOM
C
        RETURN
        END
```

```
      SUBROUTINE RAD (IDEG,MIN,SEC,ANGLE,PI)
C     ******************************************************************
C     **                                                              **
C     **      CONVERTS ANGLE IN DEGREES,MINUTES,SECONDS TO RADIANS    **
C     **                                                              **
C     ******************************************************************
C
      IMPLICIT REAL*8(A-H,O-Z)
      C=0.D0
      A=SEC/3600.D0
      B=MIN/60.D0
      IF(IDEG.LT.0) C=A+B-IDEG
      C=-C
      IF(IDEG.GE.0) C=A+B+IDEG
      ANGLE=C
      ANGLE=ANGLE*PI/180.D0
      RETURN
      END
      SUBROUTINE DEGMS (ANGLE,PI,IDEG,MIN,SEC)
C     ******************************************************************
C     **                                                              **
C     **     CONVERTS ANGLE IN RADIANS TO DEGREES,MINUTES,SECONDS     **
C     **                                                              **
C     ******************************************************************
C
      IMPLICIT REAL*8(A-H,O-Z)
      ANGLE=ANGLE*180.D0/PI
      IDEG=IDINT(ANGLE)
      A=DFLOAT(IDEG)
      C=ANGLE-A
      C=C*60.D0
      MIN=IDINT(C)
      B=DFLOAT(MIN)
      D=C-B
      SEC=D*60.D0
      DSEC=SEC-60.D0
      DABSEC=DABS(DSEC)
      IF(DABSEC.GT.1.D-9) GO TO 1
      SEC=0.D0
      MIN=MIN+1
    1 CONTINUE
      IF(MIN.LT.60) GO TO 2
      MIN=MIN-60
      IDEG=IDEG+1
    2 CONTINUE
      ANGLE=ANGLE*PI/180.D0
      RETURN
      END
```

```
      SUBROUTINE MATPV (A,B,C,NRA,NCA,NCB,MTA,MTB)
C     ****************************************************************
C     **                                                            **
C     **     MATRIX MULTIPLICATION - GENERAL OR TRIANGULAR STORAGE  **
C     **                                                            **
C     **              CALLS SUBROUTINE LOC(SSP)                     **
C     **                                                            **
C     ****************************************************************
C
C     MT=0 MATRIX IN GENERAL STORAGE
C     MT=1 MATRIX IN TRIANGULAR STORAGE (SYMMETRIC)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION A(1), B(1), C(1)
      DO 3 I=1,NRA
      DO 2 K=1,NCB
      CALL LOC (I,K,IT,NRA,NCB,0)
      C(IT)=0.D0
      DO 1 J=1,NCA
      CALL LOC (I,J,IR,NRA,NCA,MTA)
      CALL LOC (J,K,IS,NCA,NCB,MTB)
      C(IT)=C(IT)+A(IR)*B(IS)
    1 CONTINUE
    2 CONTINUE
    3 CONTINUE
      RETURN
      END
      SUBROUTINE LOC (I,J,IR,N,M,MS)
C     ****************************************************************
C     **                                                            **
C     **       SSP SUBROUTINE - MATRIX STORAGE MANIPULATOR          **
C     **                                                            **
C     ****************************************************************
C
      IMPLICIT REAL*8(A-H,O-Z)
      IX=I
      JX=J
      IF(MS-1) 1,2,5
    1 IRX=N*(JX-1)+IX
      GO TO 7
    2 IF(IX-JX) 3,4,4
    3 IRX=IX+(JX*JX-JX)/2
      GO TO 7
    4 IRX=JX+(IX*IX-IX)/2
      GO TO 7
    5 IRX=0
      IF(IX-JX) 7,6,7
    6 IRX=IX
    7 IR=IRX
      RETURN
      END
```

```
      SUBROUTINE FRAME (IX,ISX,IY,ISY)
C
C     FRAMES A SCREEN WINDOW
C
      CALL MOVABS (IX,IY)
      CALL DRWABS (IX,IY+ISY)
      CALL DRWABS (IX+ISX,IY+ISY)
      CALL DRWABS (IX+ISX,IY)
      CALL DRWABS (IX,IY)
C
      RETURN
      END
      SUBROUTINE UNITS (A,B,DX,DY)
C
C     CONVERTS CENTIMETERS TO VIRTUAL COORDINATES
C
      IX=KCM(A)
      IY=KCM(B)
      DX=FLOAT(IX)
      DY=FLOAT(IY)
C
      RETURN
      END
      SUBROUTINE RECT (DX,DY,D)
C
C     DRAW A SQUARE WITH CENTER AT DX,DY
C     CD - LENGTH OF SIDE
C
      DS=KCM(D)
      CALL UNITS (DX,DY,S,T)
      CALL MOVEA (S,T)
      S=DS/2.
      CALL MOVER (-S,-S)
      CALL DRAWR (DS,0.)
      CALL DRAWR (0.,DS)
      CALL DRAWR (-DS,0.)
      CALL DRAWR (0.,-DS)
C
      RETURN
      END
      SUBROUTINE EQUITR (DX,DY,D)
C
C     DRAW AN EQUILATERAL TRIANGLE WITH CENTROID AT DX,DY
C     CD - LENGTH OF TRIANGLE LEG
C
      PI=3.14
      DS=KCM(D)
      CALL UNITS (DX,DY,S,T)
      CALL MOVEA (S,T)
      SS=.433*DS
      CALL MOVER (0.,-SS)
      CALL MOVER (-DS/2.,0.)
      CALL DRAWR (DS,0.)
      ANGLE=PI/3.
      X=COS(ANGLE)*DS
      Y=SIN(ANGLE)*DS
      CALL DRAWR (-X,Y)
      CALL DRAWR (-X,-Y)
C
      RETURN
      END
      SUBROUTINE CIRCLE (DX,DY,RS)
C
C     DRAW A CIRCLE WITH CENTER AT DX,DY
C     RS - RADIUS OF CIRCLE
C
```

```
      PI=3.14
      R=KCM(RS)
      CALL UNITS (DX,DY,S,T)
      CALL MOVEA (S,T)
      CALL MOVER (0.,R)
      C=2.*PI*R+1
      J=C
      AA=1./R
      DO 1 I=1,J
      A=I*AA
      X=R*SIN(A)
      Y=R*COS(A)
      CALL DRAWA (S+X,T-Y)
    1 CONTINUE
C
      RETURN
      END
```

APPENDIX B

VIP SAMPLE RUN

B.1 Introduction

A VIP sample run is presented in section B.2 to familiarize the user with the interactive mode of operation and to illustrate some of VIP's capabilities. This two-experiment session is listed screen by screen (some are combined on one page to conserve paper) as viewed by the user and reproduced by the Tektronix hard copy unit. The entire session is presented from LOGON to LOGOFF. Section B.3 includes additional output obtained by the user from the line printer (or VERSATEC) at the end of the session to serve as a record of that particular run.

Experiments 1 and 2 address the question of observation correlations as discussed in section 3.2.6 and 4.3. As mentioned there, in an N-station configuration there are (N)(N-1)/2 baselines (and thus the same number of possible delay observations) but of those only N-1 independent ones. In Experiment 1, a covariance analysis is performed on a 4-station network for the parameters described in section 3.2.3. Observations from 3 independent baselines are considered, their correlations determined according to the model of section 3.2.6. In Experiment 2, the same observation schedule is followed but all 6 possible baselines are included. In this case, though, a diagonal observation covariance matrix is introduced (recall that applying the correlations between all six simultaneous observations would result in a singular observation covariance matrix since the observations are linearly dependent). A comparison of the corresponding standard deviations of both experiments indicates a decrease in those of Experiment 2 ranging from 20-30%. The largest differences involve the earth orientation parameters since all baselines contribute to their estimation, in the global sense. It is apparent that as the number of stations increases and thus, the discrepancy between the total number of baselines and the number of independent baselines, the standard deviations become more optimistic when the correlations between simultaneous observations are neglected.

To illustrate the effects of errors in the initial orientation of the baseline on the baseline components as explained in Section 3.2.3, perfect observations are simulated in each experiment. As can be seen in B.2, errors of 10 cm are introduced into the initial orientation of the pole and 1 ms of time in earth rotation over the first step. Those errors cause subsequent corrections to the approximate baseline "components" of up to 29 cm in accordance with eqs. (3.2-24).

The observation schedule and the simulated observations are given in B.3. The analysis considers a combination of delay and delay rate observations. The option of storing the observation schedule on file 9 (see Table A.1) prior to the session was chosen. The schedule was guided by two considerations:

(1) that a source be observable simultaneously (maximum zenith distance of 80°) from all stations at a chosen epoch of observation,

(2) that the final source schedule, over the 24-hour period of the simulations, be evenly distributed in right ascensions and declinations to achieve a strong geometry, especially to provide good

recovery for low and high source declination-dependent parameters [Bock, 1980].

In addition, the schedule includes consideration of antenna slew time, cable wrap and tape constraints and was developed using a scheduling program written by Nancy Vandenberg at GSFC. The sources were selected from the source list obtained from the GSFC VLBI group and can be found in the sample run of B.2.

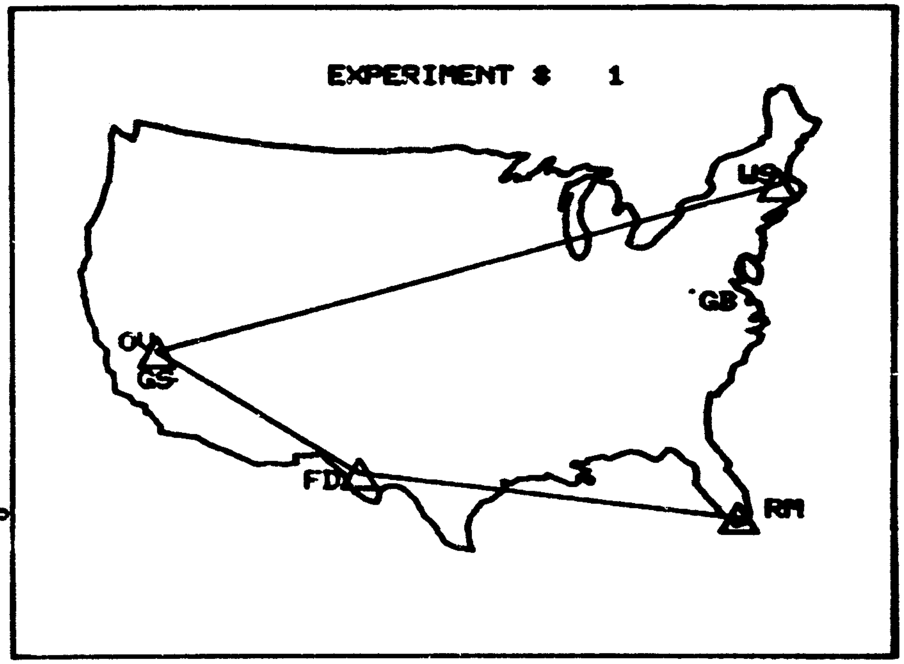
At the end of Experiment 2, a typical visibility matrix is displayed for the first five sources as viewed from the four participating stations.

B.2 A Typical Interactive Session

The following is a screen-by-screen display of Experiments 1 and 2 from LOGON to LOGOFF.

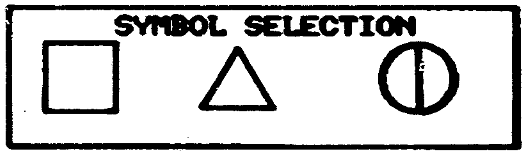
```
LOGON
USERID? TW0059 P(JEMUSER) SIZE(256)
PASSWORD? [redacted]
TERMINAL ID? SES1
UNIVERSITY ID? [redacted]
TW0059 LOGON IN PROGRESS AT 14:28:03 ON JANUARY 17, 1980
READY
EXEC BOCKLIB.CLIST
ENTER POSITIONAL PARAMETER DSNAME -
BOCK.FORT

ALLOCATING FILES
WAITING FOR COMPILATION


DO YOU WISH TO DRAW MAP
YES
```

```
STATION SELECTION
     1. WESTFORD
     2. OWENS VALLEY
     3. GREENBANK
     4. GOLDSTONE
     5. FT. DAVIS
     6. RICHMOND
ENTER #STATIONS,#BSLNS
STATION 1 2 3 4 5 6
PUT 0 IF NOT OBSERVING
?
4 3 1 2 0 0 5 6
CHOOSE BASELINE # 
ENTER I J OF BASELINE
?
1 2  2 5  5 6
SELECT SYMBOLS # BSLINE
PRESS 1-RETURN,MOVE
CURSOR INSIDE SYM-PRESS P
?
1
```




```
ENTER EXPERIMENT #
?
1
?
1
```

PRESS 1 THEN RETURN




```
DO YOU WISH TO RUN OR RE-RUN MAP DRAWING SESSION
   OR STATION AND BASELINE SELECTION
NO
DO YOU WISH TO TERMINATE SESSION
NO
```

```
ENTER INITIAL EPOCH IN UNIVERSAL TIME
FORMAT: YEAR,MONTH,DAY,HOUR,MIN,SEC
PRESS RETURN THEN ENTER FINAL EPOCH IN SIMILAR MANNER

IF INITIAL&FINAL EPOCH IN DIFFERENT MONTHS OR YEARS
EXPRESS FINAL EPOCH IN SAME MONTH OR YEAR AS INITIAL EPOCH
E.G. IF INITIAL EPOCH DEC 30, 1979 FINAL EPOCH JAN 1,1980
ENTER FINAL EPOCH AS DEC 32,1979

ENTER FOR INITIAL EPOCH 0 HOURS UT OF INITIAL DAY
?
1979 7 25 00 00 0.
?
1979 7 25 23 57 0.

            INITIAL EPOCH   (UT)

        YEAR MONTH DAY HOUR  MIN  SEC

        1979   7   25    0    0  0.0

            FINAL EPOCH   (UT)

        1979   7   25   23   57  0.0

        GREENWICH SIDEREAL TIME AT INITIAL EPOCH =  20   8  26.462


PRESS 1 - THEN RETURN
?
1
```

```
APPROXIMATE STATION COORDINATES

                        LATITUDE          LONGITUDE           HEIGHT

                       DG MIN SEC        DEG MIN SEC          METERS
1  WESTFORD            42 36 46.518      288 30 22.720          67.40
   X =   1492217.309  Y =  -4458135.436  Z =   4296022.998
2  OWENS VALLEY        37 13 53.287      241 43  2.441        1172.90
   X =  -2409595.429  Y =  -4478351.592  Z =   3838607.625
5  FORT DAVIS          30 38  0.0        256  3  0.0          1580.00
   X =  -1324514.629  Y =  -5332156.785  Z =   3231804.550
6  RICHMOND            25 36 47.130      279 37  4.200         100.00
   X =    961536.676  Y =  -5674205.114  Z =   2740531.287


BASELINE       DELX          DELY          DELZ        DISTANCE  (M)

 1   2   -3901812.738    -20216.156   -457415.372   3928585.007
 2   5    1085[illegible]0.800   -853805.193   -606803.075   1508175.594
 5   6    2286051.305   -342048.329   -491273.263   2363128.656


THESE ARE THE STATION COORDINATES FOR EXPERIMENT # 1
PRESS 1 THEN RETURN
?
1
```

QUASAR SELECTION

APPROXIMATE SOURCE COORDINATES

#	NAME	RIGHT ASCENSION HR	MIN	SEC	DECLINATION DEG	MIN	SEC
1	IIZW2	0	7	56.770	10	41	48.000
2	3C11.1	0	26	54.200	63	42	8.500
3	0048-09	0	48	10.000	-9	45	23.000
4	OC328	1	16	47.270	31	55	6.400
5	4C 67.05	2	24	42.900	67	8	6.000
6	0229+13	2	29	2.530	13	9	40.900
7	0234+283	2	34	55.620	28	35	11.900
8	3C84	3	16	29.500	41	19	51.700
9	NRAO150	3	55	45.200	50	49	20.100
10	3C119	4	29	7.880	41	32	8.600
11	3C 120	4	30	31.600	5	14	59.700
12	3C123	4	33	55.200	29	34	14.000
13	0605-08	6	5	36.026	-8	34	19.270
14	0607-15	6	7	25.600	-15	42	2.600
15	4C60.10	6	39	36.600	59	58	28.000
16	OH471	6	42	53.068	44	54	31.019
17	0735+17	7	35	14.170	17	49	9.400
18	4C55.16	8	31	4.350	55	44	41.800
19	OJ 287	8	51	57.229	20	17	58.500
20	4C39.25	9	23	55.300	39	15	23.700
21	3C236	10	3	5.400	35	8	48.100
22	1038+528	10	38	43.140	52	49	10.100
23	1055+01	10	55	55.290	1	50	2.700
24	1127-14	11	27	36.650	-14	32	54.800
25	1156+295	11	56	57.800	29	31	26.000

PRESS 1 - THEN RETURN

26	3C 273B	12	26	33.000	2	19	43.300
27	3C282	13	6	31.300	66	0	10.000
28	OQ 208	14	4	45.625	28	41	29.460
29	3C295	14	9	33.600	52	26	14.000
30	OQ172	14	42	50.496	10	11	12.606
31	1510-08	15	10	8.930	-8	54	50.900
32	1555+00	15	55	17.688	0	6	43.540
33	3C343	16	34	1.400	62	51	43.000
34	3C 345	16	41	17.600	39	54	11.000
35	NRAO530	17	30	13.538	-13	2	45.930
36	4C53.42	17	54	0.100	53	6	40.000
37	-20 431	18	5	5.000	22	14	0.0
38	OV-236	19	21	41.420	-29	20	25.300
39	OV080	19	47	40.160	7	59	35.000
40	2021+614	20	21	13.310	61	27	18.400
41	2048+31	20	48	47.450	31	16	11.300
42	2134+00	21	34	5.200	0	28	25.200
43	VR 422201	22	0	39.400	42	2	8.400
44	3C440	22	1	50.400	62	25	57.000
45	3C446	22	23	11.044	-5	12	18.247
46	3C 454.3	22	51	29.500	15	52	54.300
47	2345-16	23	45	27.691	-16	47	52.790

PRESS 1 - THEN RETURN
?

```
HOW MANY QUASARS DO YOU WISH TO OBSERVE
?
8
     DO YOU WISH TO CHOOSE QUASARS BEFORE VISIBILITY OUTLINER ?
YES

     ENTER CHOSEN QUASARS
     E.G. 1 3 5 7
?
5 8 19 26 28 34 43 46


                 THESE ARE THE SOURCES CHOSEN
                       RIGHT ASCENSION   DECLINATION

                 #      HR MIN SEC        DEG MIN SEC

         1.      5       2  24  42.900     67   8   6.000
         2.      8       3  16  29.500     41  19  51.700
         3.     19       8  51  57.229     20  17  58.500
         4.     26      12  26  33.000      2  19  43.300
         5.     28      14   4  45.625     28  41  29.400
         6.     34      16  41  17.600     39  54  11.900
         7.     43      22   0  39.400     42   2   8.400
         8.     46      22  51  29.500     15  52  54.300

                 ENTER THE REFERENCE SOURCE
                 USE SEQUENTIAL NUMBER (LEFT-MOST COLUMN ABOVE)
?
4
DO YOU WISH TO TERMINATE SESSION
NO
```

```
ENTER $STEPS FOR EARTH ORIENTATION
?
4

ENTER END OF STEP EPOCH FOR EACH STEP
FORMAT : HOUR,MINUTE  (INTEGERS)
 PRESS RETURN THEN ENTER NEXT FINAL EPOCH
NOTE: HOUR RELATIVE TO INITIAL EPOCH
      (MAY BE GREATER THAN 24)

6 0

12 0

18 0

24 0
DO YOU WISH TO SKIP SCHEDULE SIMULATION ?
ANSWER YES OR NO
NO

READ IN APPROX VALUES FOR EARTH ORIENTATION
 THERE SHOULD BE 3X($STEPS) OF PARAMETERS
 FORMAT : TWO POLAR MOTION COMPONENTS IN METERS
  EARTH ROTATION IN SECONDS OF TIME
?
0.1 0 0 0 0.1 0 0 0 0.001 0 0 0


ENTER TIME INTERVAL BETWEEN OBSERVATIONS (IN MINUTES)
INPUT 0 IF TIME INTERVALS NOT REGULAR
?
0
```

```
CHOOSE ONE FILE PER BASELINE
AVAILABLE FILE NUMBERS : 10-15  START WITH 10

 ENTER OUTPUT FILES
?
10 11 12

IF YOU WISH TO ENTER DATA AT TERMINAL,INPUT TERM
IF YOU HAVE STORED OBSERVATION SCHEDULE DATA ON FILE,INPUT FILE
file
ARE OBSERVATIONS AT UNEVEN INTERVALS OF TIME
yes

DO YOU WISH TO SIMULATE DELAY RATES
yes

ARE ALL STATIONS INVOLVED AT EACH EPOCH OF OBSERVATION
yes
    CHOOSE EXPERIMENT FLAGS
FLAG1=1 : DELAY IS ONLY OBSERVABLE
FLAG1=2 : DELAY RATE OBSERVABLE INCLUDED
FLAG1=3 : DELAY RATE IS ONLY OBSERVABLE

FLAG2=1 : MULTI-BASELINE EXPERIMENT
FLAG2=2 : ONLY ETA COMPONENT OF POLAR MOTION
FLAG2=3 : ONLY KSI COMPONENT OF POLAR MOTION

FLAG3=1 : COVARIANCE ANALYSIS ONLY
FLAG3=2 : COMPLETE LEAST SQUARES SOLUTION

FLAG4=1 : ALL      PARAMETERS
FLAG4=2 : NO CLOCK PARAMETERS

INPUT FLAG1,FLAG2,FLAG3,FLAG4
?
2 1 2 1


PRESS 1 - THEN RETURN
?
1
```

```
     INPUT WEIGHTING INFORMATION

SIG1 : PRECISION OF TIME DELAY IN METERS
SIG2 : PRECISION OF TIME DELAY RATE  IN METERS/HOUR
?
0.03 0.108

INPUT COVARIANCE MATRIX OF OBSERVATIONS
ENTER IN UPPER TRIANGULAR FORM COLUMNWISE - DIAGONAL ELEMENTS SCALED TO
UNITY
?
1. -.5 1. 0. -.5 1.


          WEIGHTING OF OBSERVATIONS


        WEIGHT MATRIX - SCALED TO FIRST ELEMENT UNITY
         1.0000000
         0.0       0.0771605
         0.6666667 0.0       1.3333333
         0.0       0.0514403 0.0       0.1028807
         0.3333333 0.0       0.6666667 0.0       1.0000000
         0.0       0.0257202 0.0       0.0514403 0.0       0.0771605

        A PRIORI VARIANCE OF UNIT WEIGHT =  0.000900


PRESS 1 - THEN RETURN
?
1
```

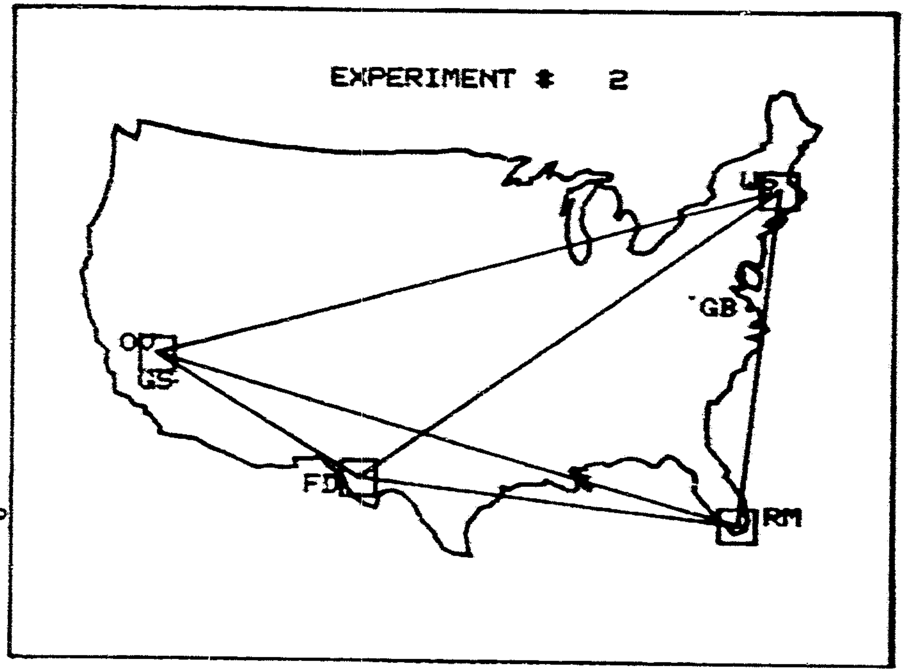
```
STANDARD DEVIATIONS - A PRIORI

 TAU EPSILON SIGMA  (CM)
   BASELINE # 1
1.     1.521
2.     2.708
3.     3.277
   BASELINE # 2
4.     0.786
5.     1.541
6.     2.022
   BASELINE # 3
7.     0.948
8.     1.966
9.     2.332

 POLAR MOTION VARIATIONS (CM)
   FIRST COMPONENT
10.    3.463
11.    3.944
12.    4.375
   SECOND COMPONENT
13.    4.193
14.    6.336
15.    8.896

 UT1-UTC VARIATIONS (10**2 MICROSECS)
16.    0.700
17.    0.769
18.    0.895

 DECLINATIONS  (MILLIARCSECS)
19.    0.783
20.    1.140
21.    2.276
22.    3.984
23.    1.789
24.    1.218
25.    1.090
26.    2.628

  R.A. DIFFERENCES (MILLIARCSECS)

27.    2.575
28.    1.398
29.    0.812
30.    0.966
31.    1.304
32.    1.343
33.    1.019

  CLOCK OFFSET (NSECS)
34.    0.084
35.    0.067
36.    0.069

  CLOCK RATE (PICOSECS/HR)
37.    3.949
38.    2.361
39.    2.595

 PRESS 1 THEN RETURN
?
1
```

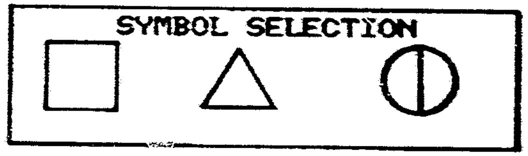
```
BASELINE STANDARD DEVIATIONS  (CM)

 1.     1.571

 2.     1.067

 3.     1.163

BASELINE CORRELATION MATRIX

 1.  1.00

 2.  0.75 1.00

 3.  0.77 0.67 1.00

PRESS 1 THEN RETURN
?
1
```

```
STANDARD DEVIATIONS - A POSTERIORI   21.    0.0          -0.0000
+ PARAMETER CORRECTIONS              22.    0.0           0.0000
                                     23.    0.0           0.0000
 TAU EPSILON SIGMA  (CM)             24.    0.0           0.0000
   BASELINE # 1                      25.    0.0          -0.0000
 1.     0.0          0.8654          26.    0.0          -0.0000
 2.     0.0        -29.1704
 3.     0.0         -6.0926           R.A. DIFFERENCES (MILLIARCSECS)
   BASELINE # 2
 4.     0.0          7.1785          27.    0.0           0.0000
 5.     0.0          6.9601          28.    0.0          -0.0000
 6.     0.0          3.0433          29.    0.0          -0.0000
   BASELINE # 3                      30.    0.0           0.0000
 7.     0.0          3.2654          31.    0.0           0.0000
 8.     0.0         15.8990          32.    0.0          -0.0000
 9.     0.0          4.1251          33.    0.0          -0.0000

 POLAR MOTION VARIATIONS (CM)         CLOCK OFFSET (NSECS)
   FIRST COMPONENT                   34.    0.0           0.0000
10.     0.0        -10.0000          35.    0.0          -0.0000
11.     0.0        -10.0000          36.    0.0          -0.0000
12.     0.0        -10.0000
   SECOND COMPONENT                   CLOCK RATE (PICOSECS/HR)
13.     0.0        -10.0000          37.    0.0          -0.0000
14.     0.0        -10.0000          38.    0.0          -0.0000
15.     0.0        -10.0000          39.    0.0          -0.0000

 UT1-UTC VARIATIONS (10**2 MICROSECS)
16.     0.0        -10.0000         PRESS 1 THEN RETURN
17.     0.0        -10.0000      ?
18.     0.0        -10.0000      1

 DECLINATIONS   (MILLIARCSECS)
19.     0.0         -0.0000
20.     0.0         -0.0000
```

```
UTPV = 0.17541524D-13

A POSTERIORI VARIANCE OF UNIT WEIGHT = 0.18681069D-16

A POSTERIORI/A PRIORI = 0.31135115D-13


DO YOU WISH TO RUN THE PROGRAM AGAIN
YES

DO YOU WISH TO CHANGE THE BASELINE CONFIGURATION
YES

DO YOU WISH TO CHANGE QUASAR SELECTION
NO
```

```
STATION SELECTION
     1. WESTFORD
     2. OWENS VALLEY
     3. GREENBANK
     4. GOLDSTONE
     5. FT. DAVIS
     6. RICHMOND
ENTER #STATIONS,#BSLNS
STATION 1 2 3 4 5 6
PUT 0 IF NOT OBSERVING
?
4 6 1 2 0 0 5 6
CHOOSE BASELINE # ■
ENTER I J OF BASELINE
?
1 2 1 5 1 6 2 5 2 6 5 6
SELECT SYMBOLS #■ BSLINE
PRESS 1-RETURN,MOVE
CURSOR INSIDE SYM-PRESS P
?
1
```






```
ENTER EXPERIMENT #
?
2
?
1
```

PRESS 1 THEN RETURN

```
DO YOU WISH TO CHANGE INTERVAL OF OBSERVATIONS
NO
```

```
APPROXIMATE STATION COORDINATES

                          LATITUDE          LONGITUDE            HEIGHT

                          DG MIN SEC        DEG MIN SEC
1  WESTFORD               42 36 46.518      288 30 22.720        METERS
   X =   1492217.309  Y =   -4458135.436  Z =   4296022.998     67.40
2  OWENS VALLEY           37 13 53.287      241 43  2.441
   X =  -2409595.429  Y =   -4478351.592  Z =   3838607.625    1172.90
5  FORT DAVIS             30 38  0.0        256  3  0.0
   X =  -1324514.629  Y =   -5332156.785  Z =   3231804.550    1580.00
6  RICHMOND               25 36 47.130      279 37  4.200
   X =    961536.676  Y =   -5674205.114  Z =   2740531.287     100.00

BASELINE      DELX           DELY           DELZ          DISTANCE  (M)

 1   2   -3901812.738     -20216.156    -457415.372    3928585.007
 1   5   -2816731.938    -874021.349   -1064218.448    3135355.328
 1   6    -530680.633   -1216069.678   -1555491.711    2044505.285
 2   5    1085080.800    -853805.193    -606803.075    1506175.594
 2   6    3371132.105   -1195853.522   -1098076.330    3741706.691
 5   6    2286051.305    -342048.329    -491273.263    2363128.656

THESE ARE THE STATION COORDINATES FOR EXPERIMENT # 2
PRESS 1 THEN RETURN
?
1
```

```
DO YOU WISH TO SKIP STEP INPUT
yes
DO YOU WISH TO SKIP SCHEDULE SIMULATION ?
ANSWER YES OR NO
no

READ IN APPROX VALUES FOR EARTH ORIENTATION
 THERE SHOULD BE 3*(#STEPS) OF PARAMETERS
 FORMAT : TWO POLAR MOTION COMPONENTS IN METERS
  EARTH ROTATION IN SECONDS OF TIME
?
0.1 0 0 0 0.1 0 0 0 0.001 0 0 0


ENTER TIME INTERVAL BETWEEN OBSERVATIONS (IN MINUTES)
INPUT 0 IF TIME INTERVALS NOT REGULAR
?
0


PRESS 1 - THEN RETURN
?
1
```

```
CHOOSE ONE FILE PER BASELINE
AVAILABLE FILE NUMBERS : 10-15  START WITH 10

 ENTER OUTPUT FILES
?
10 11 12 13 14 15

IF YOU WISH TO ENTER DATA AT TERMINAL,INPUT TERM
IF YOU HAVE STORED OBSERVATION SCHEDULE DATA ON FILE,INPUT FILE
file
ARE OBSERVATIONS AT UNEVEN INTERVALS OF TIME
yes

DO YOU WISH TO SIMULATE DELAY RATES
yes


ARE ALL STATIONS INVOLVED AT EACH EPOCH OF OBSERVATION
YES
DO YOU WISH TO SKIP FLAG HANDLER
YES
DO YOU WISH TO SKIP WEIGHT HANDLER
NO
```

```
     INPUT WEIGHTING INFORMATION

SIG1 : PRECISION OF TIME DELAY IN METERS
SIG2 : PRECISION OF TIME DELAY RATE  IN METERS/HOUR
?
0.03 0.108

INPUT COVARIANCE MATRIX OF OBSERVATIONS
ENTER IN UPPER TRIANGULAR FORM COLUMNWISE - DIAGONAL ELEMENTS SCALED TO
UNITY
?
1. 0. 1. 0. 0. 1. 0. 0. 0. 1. 0. 0. 0. 0. 1. 0. 0. 0. 0. 0. 1.


         WEIGHT MATRIX - SCALED TO FIRST ELEMENT UNITY
          1.0000000
          0.0          0.0771605
          0.0          0.0          1.0000000
          0.0          0.0          0.0          0.0771605
          0.0          0.0          0.0          0.0          1.0000000
          0.0          0.0          0.0          0.0          0.0          0.0771605
          0.0          0.0          0.0          0.0          0.0          0.0
          1.0000000
          0.0          0.0          0.0          0.0          0.0          0.0
          0.0          0.0771605
          0.0          0.0          0.0          0.0          0.0          0.0
          0.0          0.0          1.0000000
          0.0          0.0          0.0          0.0          0.0          0.0
          0.0          0.0          0.0          0.0771605
          0.0          0.0          0.0          0.0          0.0          0.0
          0.0          0.0          0.0          0.0          1.0000000
          0.0          0.0          0.0          0.0          0.0          0.0
          0.0          0.0          0.0          0.0          0.0          0.0771605

         A PRIORI VARIANCE OF UNIT WEIGHT =  0.000900

PRESS 1 - THEN RETURN
?
1
```


ORIGINAL PAGE IS
OF POOR QUALITY

```
STANDARD DEVIATIONS - A PRIORI

 TAU EPSILON SIGMA  (CM)
   BASELINE # 1
 1.     1.135
 2.     2.105
 3.     2.499
   BASELINE # 2
 4.     1.061
 5.     1.767
 6.     2.566
   BASELINE # 3
 7.     0.869
 8.     1.479
 9.     2.714
   BASELINE # 4
10.     0.663
11.     1.398
12.     1.708
   BASELINE # 5
13.     1.048
14.     2.106
15.     2.695
   BASELINE # 6
16.     0.762
17.     1.642
18.     1.896

 POLAR MOTION VARIATIONS (CM)
   FIRST COMPONENT
19.     2.449
20.     2.789
21.     3.093
   SECOND COMPONENT
22.     2.965
23.     4.480
24.     6.290

    UT1-UTC VARIATIONS (10**2 MICRO
SECS)
25.     0.496
26.     0.544
27.     0.633

    DECLINATIONS  (MILLIARCSECS)
28.     0.554
29.     0.806
30.     1.609
31.     2.817
32.     1.251
33.     0.861
34.     0.771
35.     1.858

    R.A. DIFFERENCES (MILLIARCSECS)

36.     1.821
37.     0.989
38.     0.574
39.     0.683
40.     0.922
41.     0.949
42.     0.721

   PRESS 1 THEN RETURN
?
1
```

```
  CLOCK OFFSET (NSECS)
43.     0.070
44.     0.075
45.     0.085
46.     0.059
47.     0.080
48.     0.061

  CLOCK RATE (PICOSECS/HR)
49.     2.914
50.     2.881
51.     2.858
52.     1.867
53.     3.177
[illegible]     2.016


 PRESS 1 THEN RETURN
?
1
```

1

BASELINE STANDARD DEVIATIONS (CM)

1.	1.164
2.	1.340
3.	2.026
4.	0.845
5.	1.423
6.	0.905

BASELINE CORRELATION MATRIX

1.	1.00					
2.	0.79	1.00				
3.	0.76	0.80	1.00			
4.	0.62	0.58	0.65	1.00		
5.	0.76	0.69	0.75	0.71	1.00	
6.	0.66	0.60	0.64	0.61	0.75	1.00

PRESS 1 THEN RETURN

?

```
STANDARD DEVIATIONS - A POSTERIORI
+ PARAMETER CORRECTIONS

 TAU EPSILON SIGMA  (CM)
    BASELINE #  1
 1.     0.0           0.8654
 2.     0.0         -29.1704
 3.     0.0          -6.0926
    BASELINE #  2
 4.     0.0           8.0439
 5.     0.0         -22.2103
 6.     0.0          -3.0493
    BASELINE #  3
 7.     0.0          11.3092
 8.     0.0          -6.3113
 9.     0.0           1.0758
    BASELINE #  4
10.     0.0           7.1785
11.     0.0           6.9631
12.     0.0           3.0433
    BASELINE #  5
13.     0.0          10.4438
14.     0.0          22.8591
15.     0.0           7.1684
    BASELINE #  6
16.     0.0           3.2854
17.     0.0          15.8990
18.     0.0           4.1251

 POLAR MOTION VARIATIONS (CM)
   FIRST COMPONENT
19.     0.0         -10.0000
20.     0.0         -10.0000
21.     0.0         -10.0000
   SECOND COMPONENT
22.     0.0         -10.0000
23.     0.0         -10.0000
24.     0.0         -10.0000

  UT1-UTC VARIATIONS (10**2 MICRO
SECS)
25.     0.0         -10.0000
26.     0.0         -10.0000
27.     0.0         -10.0000

  DECLINATIONS  (MILLIARCSECS)
28.     0.0          -0.0000
29.     0.0          -0.0000
30.     0.0          -0.0000
31.     0.0           0.0000
32.     0.0           0.0000
33.     0.0           0.0000
34.     0.0          -0.0000
35.     0.0          -0.0000

  R.A. DIFFERENCES (MILLIARCSECS)

36.     0.0           0.0000
37.     0.0          -0.0000
38.     0.0          -0.0000
39.     0.0           0.0000
40.     0.0           0.0000
41.     0.0          -0.0000
42.     0.0          -0.0000

 PRESS 1 THEN RETURN
?
1
```

CLOCK OFFSET (NSECS)

43.	0.0	0.0000
44.	0.0	0.0000
45.	0.0	0.0000
46.	0.0	-0.0000
47.	0.0	-0.0000
48.	0.0	-0.0000

CLOCK RATE (PICOSECS/HR)

49.	0.0	-0.0000
50.	0.0	-0.0000
51.	0.0	-0.0000
52.	0.0	-0.0000
53.	0.0	-0.0000
54.	0.0	-0.0000

PRESS 1 THEN RETURN

?
1

```
UTPU =-0.20878193D-12

A POSTERIORI VARIANCE OF UNIT WEIGHT =-0.10973813D-15

A POSTERIORI/A PRIORI =-0.12193126D-12


DO YOU WISH TO RUN THE PROGRAM AGAIN
YES

DO YOU WISH TO CHANGE THE BASELINE CONFIGURATION
NO

DO YOU WISH TO CHANGE QUASAR SELECTION
YES



HOW MANY QUASARS DO YOU WISH TO OBSERVE
?
5
     DO YOU WISH TO CHOOSE QUASARS BEFORE VISIBILITY OUTLINER ?
NO
```

```
MUTUAL VISIBILITY OUTLINER

INPUT MAXIMUM ZENITH DISTANCE
?
90


 7/ 25/ 1979 ZENITH DISTANCES (** DENOTES NONVISIBILITY)

 QS ST  0  1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21
 22 23
  1  1 ** ** ** ** 68 58 47 39 33 32 35 43 53 63 74 ** ** ** ** ** ** **
 ** **
  1  2 ** ** ** ** ** ** ** 69 58 46 36 28 28 30 39 50 61 73 ** ** ** **
 ** **
  1  3 ** ** ** ** ** ** 70 57 44 33 23 19 25 35 47 60 73 ** ** ** ** **
 ** **
  1  4 ** ** ** ** 76 63 49 36 24 15 17 28 40 54 67 ** ** ** ** ** ** **
 ** **

DO YOU WISH TO OBSERVE THIS QUASAR
ANSWER YES OR NO

YES
YOU HAVE CHOSEN 1 QUASARS  OUT OF  4 QUASARS

PRESS 1 - THEN RETURN
?
```

7/ 25/ 1979 ZENITH DISTANCES (** DENOTES NONVISIBILITY)

QS	ST	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
2	1	68	63	58	53	46	40	33	27	22	21	22	26	32	39	46	52	58	63	67	71	72	73	73	71
2	2	79	78	76	73	69	64	58	51	45	38	32	28	26	27	31	36	43	49	56	62	67	72	75	78
2	3	**	**	**	75	70	64	57	51	44	39	35	33	33	37	42	48	54	61	67	73	78	**	**	**
2	4	**	**	77	71	64	58	51	45	41	38	38	40	44	50	56	63	69	75	**	**	**	**	**	**

DO YOU WISH TO OBSERVE THIS QUASAR
ANSWER YES OR NO

NO

```
7/ 26/ 1979 ZENITH DISTANCES (** DENOTES NONVISIBILITY)

QS ST  0  1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21
22 23
 3  1 ** ** ** ** ** 79 70 61 55 52 53 56 63 71 ** ** ** ** ** ** ** **
** **
 3  2 ** ** ** ** ** ** ** ** 78 68 58 51 47 47 51 58 67 78 ** ** ** **
** **
 3  3 ** ** ** ** ** ** ** 77 65 54 46 41 40 45 53 63 75 ** ** ** ** **
** **
 3  4 ** ** ** ** ** ** 68 56 45 38 35 38 45 56 68 ** ** ** ** ** ** **
** **

DO YOU WISH TO OBSERVE THIS QUASAR
ANSWER YES OR NO

YES
YOU HAVE CHOSEN 2 QUASARS  OUT OF  4 QUASARS

PRESS 1 - THEN RETURN
?
```

```
7/ 25/ 1979 ZENITH DISTANCES (XX DENOTES NONVISIBILITY)

QS ST  0  1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21
22 23
 4  1 XX XX XX 77 67 57 46 35 24 14 10 17 27 38 49 60 70 79 XX XX XX XX
XX XX
 4  2 XX XX XX XX XX XX XX 71 60 48 37 25 13  5 13 25 37 49 60 71 XX XX
XX XX
 4  3 XX XX XX XX XX XX 74 63 51 38 26 13  1 12 25 37 50 62 74 XX XX XX
XX XX
 4  4 XX XX XX XX XX 70 58 45 32 20  8  9 21 33 46 59 71 XX XX XX XX XX
XX XX

DO YOU WISH TO OBSERVE THIS QUASAR
ANSWER YES OR NO

YES
YOU HAVE CHOSEN 3 QUASARS  OUT OF  4 QUASARS

PRESS 1 - THEN RETURN
?
```

```
7/ 25/ 1979 ZENITH DISTANCES (XX DENOTES NONVISIBILITY)

QS ST  0  1  2  3  4  5  6  7  8  9 10 11 12 13 14 15 16 17 18 19 20 21
22 23
 5  1 69 67 65 61 56 51 45 40 34 29 25 24 25 29 34 39 45 51 56 61 65 67
69 70
 5  2 72 74 75 75 73 70 66 62 56 51 45 39 34 31 29 30 33 38 43 49 55 60
65 69
 5  3 XX XX XX XX 77 73 68 63 57 51 45 41 37 36 37 40 44 49 55 61 66 71
75 79
 5  4 XX XX XX 79 75 69 64 58 52 47 44 41 41 43 47 51 57 63 68 74 79 XX
XX XX

DO YOU WISH TO OBSERVE THIS QUASAR
ANSWER YES OR NO

YES
YOU HAVE CHOSEN 4 QUASARS  OUT OF  4 QUASARS

PRESS 1 - THEN RETURN
?
```

```
                THESE ARE THE SOURCES CHOSEN
                     RIGHT ASCENSION   DECLINATION

                 #     HR MIN SEC         DEG MIN SEC

           1.    1     0   7  56.770       10  41  48.000
           2.    3     0  48  10.000       -9 -45 -23.000
           3.    4     1  16  47.270       31  55   6.400
           4.    5     2  24  48.900       67   8   6.000

               ENTER THE REFERENCE SOURCE
               USE SEQUENTIAL NUMBER (LEFT-MOST COLUMN ABOVE)
?
1
DO YOU WISH TO TERMINATE SESSION
YES




ENTRY (A) TW0059.BOCK.OBJ DELETED
READY
LOGOFF
```

B.3 Post-Session Output

The following information is output (on file 7) by the line printer (or Versatec) as a record of a particular session. It can be collected by the user after the termination of the session. It contains all the output given in B.2 and in addition includes for each experiment:

1. observation schedule (and optionally simulated observations)
2. the normal matrix
3. the variance-covariance matrix (unscaled)
4. the parameter correlation matrix
5. the normal matrix eigenvalues in descending order.

The observation schedule and simulated observations of Experiment 2 are presented on the following pages. The corresponding information for Experiment 1 is identical with those of baselines 1, 4 and 6 of Experiment 2 at each epoch of observation.

The parameter correlation matrix and normal matrix eigenvalues of Experiment 1 are also included.* Notice that the correlations are generally small indicating good separability of the parameters. The largest correlations (0.8 - 0.9) occur between the low-declination sources (also between each other) and the $\tau(\Delta X)$ component of the primarily east-west baseline. This follows from an examination of (3.3-4) (in this case the ΔY component of the Westford-Owens Valley baseline is relatively small).

---

*The numbering of the parameters correspond to those of the standard deviations list given in B.2

The ratio of maximum/minimum normal matrix eigenvalues is approximately 10^5 which is typical of multi-station configurations which are well-conditioned.

Items 2 and 3 above are not presented here.

OBSERVATION SCHEDULE

STEP 1

BSLN	QUAS	HR	MIN	DELAY (M)	DELAY RATE (M/HR)
1	5	0	0	146904.4973934824	-898333.2998355753
2	5	0	0	-295363.4335865788	-645331.5852673175
3	5	0	0	-327313.9867675398	-117694.1381293132
4	5	0	0	-442267.9308900612	253001.7145682577
5	5	0	0	-474218.4840710225	780639.1617062621
6	5	0	0	-31950.5531809613	527637.4471380043
1	5	0	6	57106.5333206206	-897522.8385814720
2	5	0	6	-359611.3705636806	-639353.3595960251
3	5	0	6	-338711.9649668636	-110252.3342284996
4	5	0	6	-416717.9038843012	257969.4769854468
5	5	0	6	-395818.4982874844	787270.5043530623
6	5	0	6	20899.4055968168	529301.0253676154
1	6	0	14	1984796.0731939126	-648301.6004753328
2	6	6	14	1361679.5566311344	-566547.9317728882
3	6	0	14	462674.8957803219	-227286.7182235109
4	6	0	14	-623116.5165597784	81753.6687024446
5	6	0	14	-1522121.1774105909	421014.8822518218
6	6	0	14	-899004.6608508126	339261.2135493772
1	6	0	20	1919390.5915453490	-659732.9082104620
2	6	0	20	1304797.3206252865	-571031.4538519761
3	6	0	20	440133.2253279620	-223520.7996370293
4	6	6	20	-614593.2709200627	88701.4543584859
5	6	0	20	-1479257.3662173871	436212.1085734327
6	6	0	20	-864664.0952973247	347510.6542149468
1	5	0	29	-285541.4293785914	-888696.7688417506
2	5	0	29	-599955.8407159744	-613359.4010382800
3	5	0	29	-375412.5009550083	-81067.1075400180
4	5	0	29	-314414.4111373830	275337.3678034705
5	5	0	29	-89871.0713764174	807629.6613017326
6	5	0	29	224543.3397609656	532292.2934982629
1	5	0	35	-374226.8502057996	-884909.7803208166
2	5	0	35	-660901.9779780164	-695493.3419452196
3	5	0	35	-383131.6242400868	-73306.4920368157
4	5	0	35	-286675.1277722168	279416.4383755910
5	5	0	35	-8904.7740342873	811603.2882839949
6	5	0	35	277770.3537379295	532186.8499084037
1	6	0	44	1647026.1333428083	-700837.8243953242
2	6	0	44	1073377.6072257953	-585003.7023936326
3	6	0	44	353960.9987333314	-296944.3581220704
4	6	0	44	-573648.5261130133	115834.1220016917
5	6	6	44	-1293065.1346094769	493893.4662732539
6	6	0	44	-719416.6084964640	378059.3442715622
1	6	0	50	1576484.0126584582	-709923.5651627150
2	6	0	50	1014749.3416980407	-587494.2682734931
3	6	0	50	333490.7884495550	-202436.3356297754
4	6	0	50	-561734.6709604178	122429.2968892220
5	6	6	50	-1242993.2242089033	507487.2295329395
6	6	0	50	-681258.5532484857	385057.9326437176
1	6	0	56	1505057.7278142923	-718520.0920475863
2	6	0	56	955892.2487816455	-589579.9872570906
3	5	0	56	313478.3817296155	-197788.8126749289
4	6	0	56	-549165.4790326471	128940.1047904956
5	6	0	56	-1191579.3460846769	520731.2793726573
6	6	0	56	-642413.8670520300	391791.1745821617
1	5	1	6	-824575.9167863987	-855703.5916061599
2	5	1	6	-962019.7188934790	-558336.2410524592
3	5	1	6	-410513.3756981168	-32524.8425244114
4	5	1	6	-137443.8021070803	297367.3505536916
5	5	1	6	414062.5410882817	823178.7490817395
6	5	1	6	551506.3431953621	525811.3985289478
1	5	1	12	-909776.6721886801	-848213.6555171474
2	5	1	12	-1017339.4215941751	-547994.2731829249
3	5	1	12	-413366.7358649938	-24539.0834659206
4	5	1	12	-107562.7494054948	300219.3823342224
5	5	1	12	496409.9363236866	823674.5720512266
6	5	1	12	603972.6857291814	523455.1897170042
1	4	1	23	-2812967.2905208911	-703510.1819954579
2	4	1	23	-2594360.4119881666	-344945.4522306023
3	4	1	23	-1159794.5956218254	134324.6142219502
4	4	1	23	218606.8785327245	358564.7297648556
5	4	1	23	1653172.6948990552	837834.7962174081
6	4	1	23	1434565.8163663407	479270.0664525524
1	4	1	29	-2882334.6059377685	-683756.4515852865
2	4	1	29	-2627942.1993096552	-326651.7224084857
3	4	1	29	-1145942.2883500288	142705.6205608276
4	4	1	29	254392.4066287135	357104.7291768012
5	4	1	29	1736392.3173876793	826462.0721461141
6	4	1	29	1481999.9109589658	469357.3429693128
1	5	1	38	-1269244.1171951268	-809077.3412844017
2	5	1	38	-1244414.0703343158	-498912.1329094572
3	5	1	38	-416478.9697617113	10190.4204962374
4	5	1	38	24830.0468608107	310165.2083749444
5	5	1	38	852765.1474334155	819267.7617806391
6	5	1	38	827935.1005726048	509102.5534056946
1	5	1	44	-1349629.5709183179	-798539.4030750042
2	5	1	44	-1293694.7446516389	-486644.7500393093
3	5	1	44	-415059.2387593894	18202.5688582607
4	5	1	44	55934.8262666792	311894.6530356948
5	5	1	44	934570.3321589287	816741.9719332648
6	5	1	44	878635.5058922497	504847.3188975700
1	4	1	53	-3139356.2369519665	-600170.6478326323
2	4	1	53	-2743649.7143037687	-251354.1579396602
3	4	1	53	-1082304.7720775981	175189.5361989004
4	4	1	53	395706.5226481978	348816.4898729721
5	4	1	53	2057051.4648743682	775360.1840315326
6	4	1	53	1661344.9422261703	426543.6941585605
1	4	1	59	-3198278.3272596786	-578203.4808688086
2	4	1	59	-2767822.0089174113	-232063.9792043[illegible]87
3	4	1	59	-1064393.1413797105	183622.5045997048
4	4	1	59	430456.3183422669	346139.5196644401
5	4	1	59	2133885.1858799676	76[illegible]7854685136
6	4	1	59	1703428.8675377008	4[illegible]4746040735
1	5	2	7	-1647281.1463942723	-75[illegible].3912957497
2	5	2	7	-1470797.5541801758	-43[illegible]0132231365
3	5	2	7	-492215.5497071237	4[illegible]38714494
4	5	2	7	176483.5922140969	316524[illegible]8726132
5	5	2	7	1245865.5966871488	801866.[illegible]1671992
6	5	2	7	1068582.0044730518	485341.4370945859
1	5	2	13	-1721940.7137357332	-739991.0021374169
2	5	2	13	-1513768.7310081166	-422784.1669775324
3	5	2	13	-396945.0757727774	56652.0011902733
4	5	2	13	208171.9827276165	317206.8351598845
5	5	2	13	1324995.6379629557	796643.0033276902
6	5	2	13	1116823.6552353390	479436.1681678057
1	5	2	19	-1795262.3486449951	-726357.4793905264
2	5	2	19	-1555344.6758900250	-408686.9768550034
3	5	2	19	-390886.4508102033	64513.5391718856
4	5	2	19	239917.6727549703	317670.5025355229
5	5	2	19	1404375.8978347920	790871.0185624120
6	5	2	19	1164458.2250798217	473200.5160268891
1	6	2	36	231234.6681648438	-785604.6501049014
2	6	2	36	-21424.2870338882	-564431.1379924728
3	6	2	36	58712.2375045568	-103037.9450830560
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6	6	4	56	1133376.4671245194	412978.7783280669
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6	5	5	10	2142739.6268326784	180986.3937217453
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2	5	5	16	-2654776.6010121065	87182.9526082333
3	5	5	16	105402.5566749219	254967.2659576407
4	5	5	16	1100803.3422582038	236515.5501262372
5	5	5	16	3260982.4999452319	404279.8625856445
6	5	5	16	2160179.1576370284	167784.3124494074
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2	7	5	39	1310226.3425222128	-553217.2087395452
3	7	5	39	499753.8514644534	-216094.4942755295
4	7	5	39	-564877.0927976316	86447.4442435289
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6	8	5	47	-1624302.0299954761	357035.7578052057
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3	8	5	53	-96512.3166116031	-305687.1856958293
4	8	5	53	-1143628.5249859064	57727.1297132115
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6	8	5	53	-1587996.5740422437	369031.6610962328
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2	7	6	0	1114351.7867257865	-565278.4355229003
3	7	6	0	426512.4633695647	-202133.2496536434
4	7	6	0	-530566.5113387883	109475.0723783477
5	7	6	0	-1218405.8346950097	472620.2582476045
6	7	6	0	-687839.3233562219	363145.1858692568

STEP 2

BSLN	QUAS	HR	MIN	DELAY (M)	DELAY RATE (M/HR)
1	7	6	6	1576989.6210613779	-683745.1114797807
2	7	6	6	1057692.1621111010	-567832.0514281687
3	7	6	6	406513.4508093006	-197825.6140018926
4	7	6	6	-519297.4589502770	115893.0600516119

5	7	6	6	-1170476.1622520771	485919.4974778880
6	7	6	6	-651178.7033018004	370026.4374262761
1	6	6	23	-2247637.4908229779	-415280.5408722734
2	6	6	23	-1503048.2060419391	-153238.9277241174
3	6	6	23	156225.3726139273	150278.0026786725
4	6	6	23	744589.2847810385	261941.6131481560
5	6	6	23	2403862.8634369050	565558.5435509460
6	6	6	23	1659273.5786558664	303616.9304027899
1	6	6	29	-2288285.2413206878	-397627.7813931161
2	6	6	29	-1517627.2343618777	-138224.8933165659
3	6	6	29	171541.4261563913	156025.4762711081
4	6	6	29	770658.0069588101	259462.8880765502
5	6	6	29	2459826.6674770790	553653.2576642243
6	6	6	29	1689168.6605182686	294250.3695876746
1	7	6	46	1104072.4191686567	-731383.4258502116
2	7	6	46	675782.1812761142	-574952.0386064733
3	7	6	46	285002.2697349478	-165777.0432408944
4	7	6	46	-428290.2378925427	156431.3872437383
5	7	6	46	-819070.1494337090	565606.3826093173
6	7	6	46	-390779.9115411663	409174.9953655789
1	7	6	52	1030667.5950597936	-736628.7441193079
2	7	6	52	618306.2643859009	-574500.2828084878
3	7	6	52	268687.1396970388	-160596.8189863313
4	7	6	52	-412361.3305738927	162128.4613108201
5	7	6	52	-761980.4553627546	576121.9260329766
6	7	6	52	-349619.1216888621	413993.4647221564
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3	8	7	0	-410719.1164050840	-253035.7297072819
4	8	7	0	-1024215.3276451031	154613.5028987686
5	8	7	0	-2132524.8786795740	635561.7555168698
6	8	7	0	-1108309.5516344769	483948.2524181285
1	8	7	6	1632106.1286679732	-982292.1708247594
2	8	7	6	628760.4872612581	-739586.1767558584
3	8	7	6	-435731.6058215880	-247185.2894780681
4	8	7	6	-1003345.6408058852	162761.9940889010
5	8	7	6	-2067837.7313786614	655196.8613496912
6	8	7	6	-1059492.0711328263	492844.8872697902
1	7	7	14	757634.6808559485	-751494.9235966745
2	7	7	14	408417.7582828379	-569442.0635668531
3	7	7	14	213503.0638307723	-149254.7903257513
4	7	7	14	-349216.5275736106	182032.8548298214
5	7	7	14	-544131.5169251696	611230.1358699232
6	7	7	14	-194914.6895515592	429197.2782401018
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6	7	7	20	-151319.3905040510	432659.2037860992
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3	6	7	43	493560.2507660770	216928.7756224708
4	6	7	43	1065211.4436715720	214071.4380549378
5	6	7	43	3039591.2626906461	378278.3269647636
6	6	7	43	1974379.8190190736	164206.8889693257
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6	1	7	58	-405093.7494545056	69914.9478367412
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6	1	8	4	-397897.5116606245	75891.4391250470
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4	7	8	13	-147165.2633531995	226633.8862535340
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3	1	9	57	1159957.6975118876	-114757.3057332578
4	1	9	57	47157.1690724245	42098.5462541389
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6	1	9	57	-158949.5042122878	172665.0352533742
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2	7	10	8	-1004039.9114383627	-357171.3909285989
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3	7	10	14	78656.60833[illegible]295	55068.6777980868
4	7	10	14	364594.80031[illegible]940	268987.1078783287
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5	8	10	44	965607.3293496933	886126.5805526383
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2	2	10	59	1260926.1942672154	-562662.2311365637
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5	2	10	59	-1372281.0813876844	410451.1993199232
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1	7	11	38	-2130268.3401803260	-411888.6887114916
2	7	11	38	-1394726.3828413577	-156929.6276880718
3	7	11	38	218339.6368473274	142213.1905319977
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5	7	11	38	2348607.9770276535	554101.8792434894
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2	1	11	51	753950.4454888141	-294888.5050087985
3	1	11	51	984145.8090654467	-66455.0946080452
4	1	11	51	186243.3717107773	101260.0441010569
5	1	11	51	416438.7352874100	329693.4545018102
6	1	11	51	230195.3635766327	228433.4104097533
1	1	11	57	528046.3832725093	-397019.7076412832
2	1	11	57	724543.0732652605	-293225.1628811744
3	1	11	57	977655.8088962980	-63337.4544114139
4	1	11	57	196496.6899927512	103794.5446571088
5	1	11	57	449609.4256237888	333682.2526298693
6	1	11	57	253112.7356310376	229887.7079727605

STEP 3

BSLN	QUAS	HR	MIN	DELAY (M)	DELAY RATE (M/HR)
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2	2	12	6	616909.8856067586	-580927.5557221594
3	2	12	6	248527.8273892019	-163145.6517101161
4	2	12	6	-429598.9636754320	162987.5900111403
5	2	12	6	-797981.0218929885	580769.4940231836
6	2	12	6	-368382.0582175567	417781.9940120433
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2	2	12	12	558853.4024729413	-580135.4237310127
3	2	12	12	232483.4511592895	-157723.4444428807
4	2	12	12	-413015.9808528799	168653.0193553248
5	2	12	12	-739385.9321665316	591064.9986434568
6	2	12	12	-326369.9513136517	422411.9792881319
1	8	12	31	-3050165.2619335542	-525017.1592516090
2	8	12	31	-2445404.3375847216	-195991.6178189453
3	8	12	31	-633257.8313523414	186976.6980819972
4	8	12	31	605060.9245488325	329025.5414026646
5	8	12	31	2417207.4305812123	711993.8573336062
6	8	12	31	1812146.5062323799	382968.3159309415
1	8	12	37	-3101866.7692350273	-502953.9474079541
2	8	12	37	-2464058.3314929272	-177066.8344834284
3	8	12	37	-614197.4531214126	194208.9739349839
4	8	12	37	637898.4377421002	325887.1129245257
5	8	12	37	2487669.3161136145	697162.9213429380
6	8	12	37	1849860.8783715141	371275.8084184123
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5	2	17	18	2579725.2990884455	510054.0233010154
6	2	17	18	1740819.3811227335	263380.4926459120
1	3	17	37	1143292.2105556922	-925260.2011263817
2	3	17	37	304802.4059707734	-725935.2556049402
3	3	17	37	-420840.6575171056	-207707.8776667971
4	3	17	37	-838489.8045849187	199324.9455214416
5	3	17	37	-1564132.8686727975	717552.3234595846
6	3	17	37	-725643.0634878791	518227.3779381430
1	3	17	43	1650437.5690782792	-931725.9763057252
2	3	17	43	232239.4092836139	-725241.3328168591
3	3	17	43	-441278.1206138837	-201017.9099582370
4	3	17	43	-818198.1597946655	206434.6434588660
5	3	17	43	-1491715.6396921627	730708.0663474881
6	3	17	43	-673517.5298974977	524223.4228886222
1	1	17	59	-1092151.9180118942	-22793.3985878734
2	1	17	59	-132947.3095808803	71038.9643216310
3	1	17	59	1197961.7140413669	120421.3966387788
4	1	17	59	959204.6084310141	93832.3629095044
5	1	17	59	2290113.6320532614	143214.7952266522
6	1	17	59	1330909.0236222474	49382.4323171478

STEP 4

BSLN	QUAS	HR	MIN	DELAY (M)	DELAY RATE (M/HR)
1	1	18	5	-1093909.4706881130	-12355.6362252295
2	1	18	5	-125460.5536020020	78687.5560264820
3	1	18	5	1210083.5455403223	122001.3102993276
4	1	18	5	968448.9170861112	91043.1922517026
5	1	18	5	2303993.0162284356	134356.9465245431
6	1	18	5	1335544.0991423244	43313.7542728456
1	2	18	13	-2555974.3694978650	-169327.2925049385
2	2	18	13	-1505752.5661737819	42824.9983206052
3	2	18	13	433363.5795611421	210002.1789264355
4	2	18	13	1650221.8033230831	212152.2908255436
5	2	18	13	2989337.9490590072	379329.4714313740
6	2	18	13	1939116.1457359239	167177.1806958303
1	2	18	19	-2571920.3998151785	-149574.9983554233
2	2	18	19	-1500709.5862976967	58028.8068937881
3	2	18	19	454566.0147635471	214022.1721701488
4	2	18	19	1071210.8135174818	207603.8052492114
5	2	18	19	3026486.4145787258	363597.1705255721
6	2	18	19	1955275.6010612438	155993.3652763607
1	1	18	27	-1091418.1327512611	25934.2584629347
2	1	18	27	-91533.0210288622	106228.8061634517
3	1	18	27	1255781.4295553819	127067.3908702174
4	1	18	27	999885.1117223991	80294.5477005170
5	1	18	27	2347199.5623068432	101133.1324072827
6	1	18	27	1347314.4505844445	20838.5847067657
1	1	18	33	-1088303.7322073318	36350.1752395126
2	1	18	33	-80541.9544901216	113579.9003581634
3	1	18	33	1268547.8621366736	128246.5973268496
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3	1	18	39	1281427.8030954960	129337.4280499846
4	1	18	39	1015329.2627184519	74111.6829296333
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6	1	18	39	1350247.4530725084	8484.7022949872
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2	2	18	47	-1457182.4464925665	128282.7126334424
3	2	18	47	558185.5388042613	230790.4653271417
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3	2	18	59	605268.3091725303	236959.1649529935
4	2	18	59	1198666.2137216113	173765.9461571981
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2	4	23	7	-1448420.407464[illegible]	-667146.3462677011
3	4	23	7	-1240724.0085075[illegible]	-62847.9181215645
4	4	23	7	-558938.169451[illegible]	328161.4265090404
5	4	23	7	-357241.7704948[illegible]	932459.8546551770
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THE NUMBER OF OBSERVATIONS =1956

PARAMETER CORRELATION MATRIX

1. 1.00

2. -0.08 1.00

3. 0.04-0.58 1.00

4. -0.39-0.53 0.11 1.00

5. 0.22-0.60 0.3[illegible] 0.42 1.00

6. 0.53 0.20-0.26-0.40-0.40 1.00

7. -0.71-0.07-0.12 0.28-0.18-0.39 1.00

8. 0.17-0.64 0.33 0.33 0.18 0.01 0.16 1.00

9. 0.47 0.24-0.47-0.22 0.14 0.35-0.45-0.42 1.00

10. -0.19-0.02 0.52-0.16-0.08-0.16-0.06-0.04-0.40 1.00

11. -0.28 0.19 0.39-0.26-0.16-0.19-0.06-0.15-0.38 0.66 1.00

12. -0.32 0.07 0.33-0.17-0.19-0.19 0.00-0.16-0.36 0.48 0.79 1.00

13. 0.06-0.09-0.12 0.25 0.33-0.24 0.11 0.32-0.00-0.21-0.40-0.39 1.00

14. 0.03-0.60-0.07 0.15 0.28-0.24 0.06 0.27-0.01-0.03-0.16-0.31 0.77 1.00

15. 0.02 0.06-0.01 0.07 0.21-0.21 0.01 0.20-0.03-0.02-0.04-0.14 0.63 0.85 1.00

16. -0.11 0.26 0.22-0.21-0.22-0.02-0.04-0.26-0.16 0.54 0.19 0.10-0.14-0.10-0.05 1.00

17. -0.10 0.41 0.09-0.30-0.23-0.01-0.04-0.35-0.09 0.17 0.17-0.07-0.13-0.02-0.01 0.60 1.00

18. -0.07 0.58-[illegible]-0.39-0.35 0.03-0.06-0.50-0.01 0.03-0.01-0.15-0.18-0.11-0.03 0.47 0.76 1.00

19. -0.28-0.27 0.19 0.41 0.10-0.16 0.39 0.22-0.24 0.21-0.30-0.26 0.28 0.15-0.03 0.13-0.08-0.17 1.00

20. -0.75-0.00-0.09 0.41-0.12-0.41 0.71-0.01-0.36 0.18-0.62-0.04 0.19 0.18 0.02 0.08 0.02-0.05 0.58 1.00

21. -0.86 0.16-0.20 0.28-0.25-0.54 0.72-0.17-0.44 0.14 0.23 0.17-0.01 0.05 0.01 0.04 0.06 0.09 0.23 0.74 1.00

22. -0.84 0.22-0.23 0.24-0.28-0.58 0.68-0.22-0.47 0.09 0.23 0.28-0.05-0.04 0.01 0.06 0.07 0.14 0.11 0.64 0.90 1.00

23. -0.86 0.23-0.06 0.17-0.34-0.47 0.63-0.26-0.47 0.21 0.36 0.43-0.21-0.13 0.00 0.18 0.16 0.19 0.09 0.57 0.80 0.85 1.00

24. -0.78 0.17-0.13 0.25-0.31-0.35 0.64-0.22-0.33-0.04 0.16 0.31-0.17-0.18-0.05 0.07 0.10 0.13 0.12 0.53 0.69 0.74 0.81 1.00

25. -0.74 0.04-0.23 0.44-0.17-0.36 0.74-0.07-0.27-0.16-0.19 0.02 0.16-0.02-0.05 0.00-0.05-0.04 0.44 0.71 0.67 0.67 0.63 0.69 1.00
26. -0.82 0.14-0.29 0.36-0.21-0.54 0.74-0.13-0.40-0.04 0.01 0.12 0.12 0.02-0.04 0.01-0.00 0.02 0.29 0.73 0.84 0.87 0.76 0.72 0.79
1.00

27. -0.01-0.51 0.54 0.38 0.22-0.24 0.14 0.40-0.42-0.09-0.15 0.07 0.09-0.10-0.03 0.08-0.01-0.13 0.23-0.01-0.11-0.04 0.02 0.10 0.16
0.03 1.00

28. 0.06-0.58 0.58 0.38 0.30-0.17 0.10 0.47-0.37 0.08-0.17-0.10 0.15 0.01-0.01 0.25 0.18-0.11 0.38 0.05-0.17-0.17-0.10-0.04 0.08
-0.07 0.74 1.00

29. 0.03-0.51 0.45 0.34 0.30-0.15 0.11 0.44-0.30 0.14-0.08-0.16 0.17 0.13 0.01 0.18 0.23-0.08 0.36 0.14-0.08-0.14-0.12-0.10 0.04
-0.05 0.49 0.70 1.00

30. 0.11-0.68 0.63 0.34 0.36-0.14 0.00 0.56-0.36 0.25 0.03-0.08 0.07 0.06 0.06 0.06-0.06-0.18 0.23-0.06-0.18-0.22-0.16-0.20-0.18
-0.22 0.52 0.64 0.58 1.00

31. 0.05-0.60 0.74 0.26 0.27-0.21-0.00 0.47-0.49 0.37 0.23 0.15-0.07-0.03 0.04 0.18 0.02-0.11 0.16-0.07-0.12-0.12-0.00-0.08-0.16
-0.17 0.57 0.64 0.52 0.79 1.00

32. 0.03-0.55 0.66 0.30 0.23-0.19 0.05 0.42-0.44 0.20 0.09 0.14-0.05-0.10-0.00 0.35 0.10-0.10 0.17-0.08-0.15-0.11 0.02 0.02-0.01
-0.11 0.73 0.76 0.56 0.69 0.76 1.00

33. 0.07-0.43 0.41 0.23 0.18-0.04 0.00 0.33-0.21 0.30 0.04 0.03-0.01-0.04-0.01 0.52 0.13-0.15 0.20-0.03-0.16-0.16-0.05-0.07-0.04
-0.12 0.46 0.64 0.53 0.57 0.59 0.72 1.00

34. 0.12-0.85 0.75 0.33 0.53-0.19-0.09 0.48-0.21 0.18 0.08 0.12 0.04-0.03-0.09-0.17-0.31-0.50 0.26-0.05-0.25-0.33-0.30-0.25-0.14
-0.26 0.44 0.48 0.41 0.47 0.46 0.43 0.26 1.00

35. 0.19 0.36-0.13-0.23-0.13 0.14-0.14-0.21 0.14-0.17-0.29-0.49 0.05 0.14 0.23 0.32 0.58 0.78-0.18-0.20-0.14-0.10-0.04-0.07-0.18
-0.16-0.05 0.02-0.01 0.08 0.05 0.03 0.02-0.52 1.00

36. 0.47 0.27-0.13-0.52-0.60 0.88-0.35 0.04 0.16 0.02-0.04-0.09-0.29-0.28-0.26 0.12 0.12 0.18-0.18-0.39-0.44-0.47-0.37-0.34-0.40
-0.49-0.19-0.13-0.12-0.04-0.07-0.09 0.00-0.26 0.24 1.00

37. -0.06-0.19 0.08 0.26 0.37-0.32 0.08 0.27-0.03-0.04 0.01 0.09 0.53 0.64 0.70-0.20-0.30-0.44 0.08 0.09 0.00-0.00 0.01 0.03 0.10
0.05 0.12 0.09 0.08 0.02 0.03 0.06 0.05 0.24-0.32-0.53 1.00

38. 0.39 0.31-0.18-0.32 0.12 0.22-0.55-0.69 0.80-0.08-0.09-0.15-0.23-0.19-0.15 0.14 0.20 0.31-0.29-0.40-0.38-0.38-0.30-0.28-0.37
-0.41-0.32-0.27-0.24-0.20-0.23-0.23-0.08-0.23 0.31 0.12-0.19 1.00

39. -0.11-0.28 0.07 0.25 0.18-0.13 0.14 0.40-0.19 0.06 0.17 0.32 0.33 0.36 0.35-0.32-0.52-0 73 0.14 0.16 0.06 0.03 0.01 0.04 0.15
0.10 0.09 0.03 0.05-0.03-0.02 0.01 0.01 0.33-0.66-0.20 0.53-0.54 1.00

EIGENVALUES

0.301D+02
0.213D+02
0.129D+02
0.792D+01
0.651D+01
0.605D+01
0.410D+01
0.242D+01
0.138D+01
0.933D+00
0.538D+00
0.349D+00
0.283D+00
0.224D+00
0.154D+00
0.118D+00
0.656D-01
0.635D-01
0.553D-01
0.176D-01
0.121D-01
0.263D-02
0.201D-02
0.125D-02
0.107D-02
0.860D-03
0.822D-03
0.490D-03
0.471D-03
0.445D-03
0.427D-03
0.370D-03
0.357D-03
0.334D-03
0.307D-03
0.271D-03
0.252D-03
0.225D-03
0.131D-03

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