Memo:1 The Processing of VLBA Spacecraft Data

Draft: January 3, 2005

ABSTRACT

The VLBA routinely measures the angular separation of close quasars in the sky with an accuracy of < 0.5 nrad (0.1 mas), and the same technique can be used to measure the separation between a quasar and a spacecraft. This memo describes the procedures which have been implemented at NRAO in order to obtain the spacecraft position from less than one hour of VLBA observations. In §1 we discuss the basic interferometric equations and define the gain, phase and delay quantities that will be used throughout this and other memos. In §2 we describe the phase referencing technique and reduction methods used to determine the spacecraft positions, obtained from the position of the peak intensity of the image, or by analysis of the total delay of the spacecraft. In §3, we summarize the reductions steps used in the AIPS software package, and in the appendix, an annotated AIPS script for complete reduction of spacecraft-quasar data is listed.

1. The Response of an Interferometer

This memo outlines the observations, processing, imaging and calculation of the total delays of spacecraft data. The analysis and discussion of the 15 spacecraft observing sessions are given in three additional reports: Memo 2 is *Analysis of the MER-B VLBA Observations*; Memo 3 is *Analysis of the Cassini Oct 2004 Experiments*; Memo 4 is *Recommendations for VLBA Observations of Spacecraft at 32 GHz*.

1.1. The Total Phase Delay

The response of a two-element interferometer, $R(t) = A(t)\cos\ \phi(t)$, is a quasi-sinusoidal response, called fringes. The phase $\phi(t)$ of the fringes is related to the properties of the emitter (quasar or spacecraft), the location of the telescopes, the Earth orientation and rotation, the location of the planets and sun, and the propagation and amplification of the quasar signals through the two telescope systems. By adding a phase of $\pi/2$ to the signal from one telescope, the quadrature component of the fringes can be obtained, and the complex fringe response, $F(t)$, is defined as

$$F(t) = A(t)\ (\cos\ \phi(t)) + i\sin\ \phi(t)) = A(t)\ \exp(i\ \phi(t)) \tag{1}$$

The response is also frequency ν dependent. The amplitude and phase parts of the complex fringe response that will be discussed in this memo are:

$$A(t,\nu) = S\ a(t)\ G(t)\ H(\nu) \tag{2}$$

where S is the flux density of the quasar, $a(t)$ is the normalized visibility amplitude which depends on the quasar angular structure, and $G(t)$ and $H(\nu)$ are the amplification factors associated with the telescope electronic and propagation lossed of the incident radio waves. To a good approximation, the time and frequency dependence are separable, and the dependence of S and $a(t)$ over the relatively narrow frequency range of the experiments is insignificant.

The phase part of the complex fringe response can be split into the following components:

$$\phi(t,\nu) = \psi(t) + P(t) + Q(\nu) + 2\pi\nu D_t(t,\nu) + N2\pi \tag{3}$$

where $\psi(t)$ depends on the quasar angular structure, $P(t)$ and $Q(\nu)$ are the phase changes in the telescope electronics (again separable between time and frequency). The term D_t is called the total phase delay and contains the astrometric information inherent in the interferometer response. The last term represents the phase ambiguity in the array response. Only the phase difference between the two telescope signals is measured; hence there can be an arbitrary number, N, of 2π radians added to the phase delay quantities on the right side of the equation. Since the experimental parameters are generally well-known, the estimate of the total delay is accurate enough so that N is usually zero, or at most a small positive or negative integer.

The total delay contains the following parts:

$$D_t(t,\nu) = D_g(t) + D_s(t) + D_a(t) + D_c(t) + D_i(t)\nu^{-2} \tag{4}$$

where D_g is the uncorrupted geometric delay and represents the delay of the quasar signals between the two telescopes. By uncorrupted we mean the delay that would be obtained between the two telescopes if they were transported outside of the solar system. The pure delay terms are D_s from the gravitational delay of the planets and sun, D_a is the delay from the troposphere, D_c is the delay between the clock and propagation properties within each telescope, and D_i is the delay produced by a plasma in the propagation paths—the ionosphere or solar corona—with the known frequency dependence included. The largest term by far is $D_g(t)$. For two telescopes separated by 5000 km and observing with $\nu = 8$ GHz, the phase rate is 10^3 Hz. The other terms produce a phase rate which is generally $< 10^{-2}$ Hz.

1.2. The Residual Response and the Delay Model

Using precise astrometric information from the NASA/GSFC Calc software package, from GPS and ground measurements of tropospheric and ionospheric refraction, and by monitoring many system electronic properties, an accurate model, D_m, of the fringe response can be estimated. The residual delay is simply the difference between the total delay and the model

$$D_t(t,\nu) - D_m(t,\nu) = d_p(t) + d_b(t) + d_s(t) + d_a(t), + d_c(t) + d_i(t)\nu^{-2} \tag{5}$$

where the small "d" correspond to the residual delays after removal of the model. The residual geometric delay has been split into two parts: $d_p(t)$ is associated with the position offset and

$d_b(t)$ is associated with the telescope location offset that includes the Earth orientation and other astrometric errors. The residual fringe response, $f(t,\nu)$, after removal of the model delay, is a slowly varying function and is split into the visibility amplitude, V and visibility phase θ

$$f(t,\nu) = V(t,\nu)\ \exp\ i\ (\theta(t,\nu)) \tag{6}$$

with the visibility amplitude

$$V(t,\nu) = S\ a(t)\ g(t)\ h(\nu) \tag{7}$$

The visibility phase will be of main concern in this memo, and is given by

$$\begin{aligned} \theta(t,\nu) &= \psi(t) + p(t) + q(\nu) \\ &+2\pi\nu(d_p(t) + d_b(t) + d_s(t) + d_a(t) + d_i(t)\nu^{-2}) + N2\pi \end{aligned} \tag{8}$$

where

$\theta(t,\nu)$ is the visibility phase

$\psi(t)$ is the visibility phase from the quasar structure

$p(t)$ is the temporal phase variations (plus clock) of the interferometer

$q(\nu)$ is the bandpass phase across the frequency band

$d_p(t)$ is the residual geometric delay, associated with the position offset

$d_b(t)$ is the residual geometric delay, associated with the telescope offset

$d_s(t)$ is the residual solar system delay related to gravitational bending

$d_a(t)$ is the residual tropospheric delay

$d_i(t)$ is the residual ionospheric, coronal delay

$d_c(t)$ is the residual clock offset

The group delay $g(t,\nu)$ is another quantity that can be measured with an interferometer that spans a wide frequency range. When the residual fringe fringe response is measured at two or more frequencies, the group delay is defined as the derivative of the visibility phase with frequency

$$2\pi g(t,\nu) = \frac{d\theta}{d\nu} = d_p(t) + d_b(t) + d_a(t) - d_i(t)\nu^{-2} + \quad \text{small terms} \tag{9}$$

We have assumed that any residual clock delay is small, and the structure term $\psi(t)$ and residual bandpass $q(\nu)$ are negligible functions of frequency. Notice the change of sign of d_i compared with the phase delay. This is the quantity that is measured using the Delta-Dor measurements used by JPL interferometry for spacecraft tracking. The phase ambiguity term, $N2\pi$, is not in the group delay equation, so that the total delay can be unambiguously measured using the group delay. This is the main advantage for the use of the group delay for astrometric measurements, and most all-sky astrometric observations by NASA GSFC, USNO and JPL use this method because N can be large and difficult to obtain, especially for all-sky observations. However, the angular sensitivity of the group delay is much less than that using the phase delay (the relative sensitivity is the spanned bandwidth divided by the observing frequency) and it cannot be measured for relatively weak sources. In addition, spacecraft telemetry signals are narrow band, so that the group delay cannot be accurately measured unless the spacecraft can transmit signals at widely-spaced frequencies.

1.3. The Time Systems

The time system, UTC, is generally used. However the time-tag definition differs between the JPL navigation and interferometric applications. The VLBA time-tag convention for all quantities is the time associated with the uncontaminated wavefront passing through the Earth center, t_0. This wavefront passed by one telescopes at $t_0 - D_1$ where D_1 is related to the distance that the telescope is from the Earth center, its clock error and any retardation caused by the troposphere, ionosphere and gravitational bending. Similarly $t_0 - D_2$ is the time when the wavefront arrived at the second telescope. Other time-tag conventions are used. The geodetic groups (USNO, GSFC, JPL) use a time-tag which corresponds to the time when the wavefront passes by one of the telescopes. The JPL navigation group uses an independent time-tag for each telescope; when the wavefront (from a quasar or tone from a spacecraft) arrives at each telescope. Conversion from one time-tag system to the other can be done since the relevant delay contributions are accurately known.

2. Phase Referencing

2.1. The Phase Difference

Some of the terms in the visibility phase, shown in Eq. 8, are related to the source structure and position, $\psi(t), d_p(t), d_s(t)$[1]; some are purely temporal changes unrelated to the source position in the sky, $p(t),\ q(\nu)$; and some are functions of the source direction as well as time, $d_b(t),\ d_a(t),\ d_i(t)$. If two quasars or a quasar and a spacecraft that are close in the sky could be observed simultaneously, then the approximate phase difference, $\Delta\theta(t)$, between the two sources, s and q and positions σ^s and σ^q in the sky is

$$\Delta\theta(t) = \theta(t)^s - \theta(t)^q = \psi^s - \psi^q + 2\pi\nu(d_p^s - d_p^q) + (\sigma^{\mathbf{s}} - \sigma^{\mathbf{q}}) \cdot \mathbf{G}) + \mathbf{2N}\pi \qquad (10)$$

[1]For the remainder of the memo, we will assume that the delay model accurately determines the gravitational bending of solar system objects. Thus, $d_s(t) = 0$. An error in this calculation for a spacecraft in the solar system in the VLBA correlator model was fixed in July 2004

All of these quantities are functions of time and are associated with each baseline of an array. The first four terms on the right are related to the structure and position offset between the two sources. The next term is a generalized phase contribution associated with a delay gradient $\mathbf{G}$ in the sky between the two sources. This is the approximate sky dependence of the delay terms, d_a, d_i, and d_b, and produces the phase-gradient error, $d_r = (\sigma^{\mathbf{s}} - \sigma^{\mathbf{q}}) \cdot \mathbf{G}$.

The last term is the phase-ambiguity term of the phase difference. It will be non-zero when the position offset $(d_p^s - d_p^q)$ is large (say more than 20 nrad at 8 GHz). However, when the sources displacements are determined by imaging techniques, the magnitude of d_r and $\psi(t)^q$ are generally small so that $N = 0$. This problem will be discussed below.

The quasar and spacecraft all observed over a different range of frequencies (the spacecraft signal is usually confined to < 0.1 MHz, but the quasars are observed over many MHz bandwidth to give better signal to noise). Thus, the bandpass phase, $q(\nu)$, must be determined before making the phase difference between the quasar and spacecraft. The bandpass is stable with time and can be determined by observing any strong quasar for a few minutes. The frequency dependence of d_i can be ignored for the relatively narrow bandwidths of the observations.

2.2. Source Nodding

Unless the quasar (q) and spacecraft (s) are closer than about $5'$, they cannot be observed simultaneously with the VLBA. (For example, observations of two spacecrafts orbiting Mars can be observed simultaneously so the d_r term in Eq. 10 is virtually zero.) But, if the residual phase, $\psi(t)$, is slowly varying, then simultaneous observations of the two sources are not needed to obtain an accurate different phase. In the technique of *phase referencing*, the observations alternative quickly between the two sources so that residual phase between successive scans of one of the sources can be interpolating accurately to the scans of the other source. In other words, the variations of $\psi(t)$ between calibrator scans should be less than about 1 rad.

The question arises as to how big a gap in time can the measured phases for one source be accurately interpolated? After years of experience on the VLBA and EVN, the following criterion for interpolating over a time gaps of t_{gap} is[2]

$$t_{gap}(min) = \frac{30}{\nu(GHz)\ \sec(z)} : \quad \nu > 5\text{GHz} \tag{11}$$

where z is the zenith angle of the observations. Thus, alternating observations with 2-min integrations at 8 GHz or 0.5-min integrations at 32 GHz are sufficient for interpolation of the measured phases. However, in order to determine the phase accurately, approximately $4\times$ SNR (signal to noise) is needed. The ramification of this sensitivity is discussed more in the 32-GHz

[2]http://www.aoc.nrao.edu/vlba/html/MEMOS/SCI/sci24memo.ps, Table 1

report, Memo 3 An example of the phase versus time for a typical VLBA observations is shown in Fig. 1.

The observing strategy for phase referencing is, thus, straight-forward: observations are alternated between the quasar and spacecraft with cycle times of a few minutes at most. As long as the temporal phase, $p(t)$, can be easily connected (interpolated) between successive scans, the small errors of interpolation that tend to be random will not add much error compared with simultaneous observations. If ambiguities of 2π radians, when connecting the phase between two successive scans is a serious problem, the time range associated with this data and telescope should not be included in the analysis.

In obtaining the phase difference, shown in Eq. 10, one of the sources is chosen as the reference. which means that either $\theta(t)^q$ or $\theta(t)^s$ is used to define the phase zero as a function of time. This is equivalent to removing all phase errors associated with the reference source. The choice is often arbitrary, but it is better to pick the source for which the phase interpolation with time is more accurately defined. Since the spacecraft is often stronger than the quasar and it is a point source ($\psi^s = 0$), it has usually be chosen as the reference source. If the quasar is used, then its structure phase ψ^q should be determined from self-calibration techniques before processing.

The d_r term is the main error term in the determination of the relative source positions since it depends on the angular separation between the sources. Because the magnitude of the error is roughly proportional to the angular separation between the quasar and spacecraft, finding quasars which are near in the sky to the spacecraft are important in obtaining accurate positions. The observed effect of this term will be discussed in other memos. By observing several quasars near the spacecraft, this term can be approximately evaluated, and removed.

3. The Spacecraft−Quasar Separation:

After using one source as the phase reference, the visibility phases from all baselines and times for the other sources can be Fourier-transformed to produce an image (for a better image quality, the amplitudes should also be calibrated). The image should be dominated by a small-diameter component with a well-defined peak. The image is distorted because of the relatively poor point-spread function (psf=dirty beam), especially for short observations. A deconvolution technique called CLEAN is used to approximate the true structure of the quasar. The offset of the peak intensity from the (0,0) point in the image is related to the difference of the assumed−true delay model for the quasar and the spacecraft. With an accurate model of the observations, the major contributor to the position offset of the peak is, in fact, the (true−apriori) angular separation between the quasar and spacecraft. But, some model errors can displace the image position (incorrect gravitational bending and especially errors in the modeling of the spacecraft orbit), while other unmodeled angular errors (d_r-related terms) can displace and distort the image.

The combination of the point-spread function (psf) properties and the phase gradient term, d_r, can distort the image so that the source position may be somewhat in error. A very distorted image may be composed of several *components* which are well-separated (15 nrad apart) and nearly equal in intensity; hence the position of the object is ambiguous. This situation must be avoided in order to obtain reliable spacecraft positions. An discussion of this problem, which could be important for 32 GHz observations, is given in the 32-GHz report, Memo 4. This problem can be alleviated in two ways; the quasar target separation must be made as small as possible, and the psf must not have high sidelobes. The latter can be alleviated by observing with as many telescopes as possible, and by lengthening the observation time.

Hence, the image position is clearly tied to the properties of the delay model. But, what is model insensitive is a sum of the observed residual phase and the assumed model delay. The difference in the total delay for the quasar and spacecraft, based on Eqs. 5 and 10, is given in Eq. 12.

$$\begin{aligned} \text{Quasar ref:}\ \ D_t^q = D_m^q; \quad D_t^s &= D_m^s + d_p^s - d_p^q + \frac{\Delta\theta^q}{2\pi\nu} \\ \text{Sp Cr ref:}\ \ D_t^s = D_m^s: \quad D_t^q &= D_m^q + d_p^q - d_p^s + \frac{\Delta\theta^s}{2\pi\nu} \\ (D_t^s - D_t^q) &= D_m^s - D_m^q + d_p^s - d_p^m + \frac{\Delta\theta^q}{2\pi\nu} \end{aligned} \tag{12}$$

In the first line of the equation we have used the quasar as the reference. Its total delay is simply the model delay since we have defined its residual phase to be zero. For the spacecraft, the total delay is its model delay, plus any the delay associated with any position shifts, plus any residual phase converted into a delay. These residual phases should be near zero. The second line is similar except the spacecraft has been used as the reference. The third line give the total delay difference between the two sources. It is the same regardless of which object was chosen as the reference since the relationship between the residual phases, $\Delta\theta^q = -\Delta\theta^s$.

The caveats associated with the image quality and the determination of the source position is still applicable when determining the total delays, since the correct positional delay contribution, d_p, must be added to the rest of the delay model. However, if the model used in incorrect (for whatever reason) and, therefore, changes the apparent position of the source, the total delay (incorrect model plus incorrect source position) will be unchanged. This delay difference can then be reanalyzed using different models of the experiment parameters and the spacecraft properties and more easily incorporated into the navigation Doppler data base which contains other spacecraft data, usually in a form similar to total delays.

4. The Data Processing Steps

The observations and calibration procedure is as follows.

Setting up the Observations

Set-up the observation parameters. For the spacecraft, the transmission frequency band and polarization are needed. The apriori orbit to an accuracy of < 250 nrad is required.

Find one or more suitable quasars, using the various VLBI calibrator catalogs, that are $< 3°$ from the spacecraft. At least one calibrator should have a position on the ICRF-grid more accurate than 2.0 nrad.

The typical frequency set-up is as follows: one frequency setting (IF) is centered on the spacecraft frequency, with a width of 8 MHz and individual frequency channels of 31 kHz. Three other frequency settings can be used for the quasars in order to increase the SNR of the quasar observations and for the determination of group delays as a backup for the position determination.

The observing schedule is made using the VLBA program SCHED which incorporates parameters for spacecraft observing. Minimum session times are about one hour, although observations over five hours have been made in order to determine the quality of the solutions. The spacecraft is observed for alternate a one-minute scans. The interleaving scans are scheduled for the quasars in turn. Hence, the spacecraft is observed about 40% of the time, regardless of the number of quasars.

Correlating the Data

The data tapes from each telescopes are shipped to the AOC in Socorro. Typical shipping times are seven days.

The data are processed in the VLBA correlator which runs the GSFC/CALC version 9.1. The model is calculated every two minutes for each telescope and source, with sufficiently higher order terms for interpolation to any time to an accuracy of 0.1 psec.

The correlator output is placed in a data base which contains time-tags and residual visibility amplitude and phases. Other observing parameters are also included. A typical sampling time is 2 seconds and the time-tag is UTC associated with the wavefront passage at the Earth center.

Apply Calibrations

The apriori gain calibrations using the measured telescope gains and system temperatures and correlation statistics are applied. This determines the visibility amplitude, $G(t)$ to approximately 10% accuracy.

The parallactic angle phase dependence for all sources is removed. This is a phase term in $P(t)$ which is associated with the VLBA right and left circular feeds as the source is tracked in the sky.

Using measurements of the ionospheric content from a GPS data base (ftp cddisa.gsfc.nasa.gov), an apriori ionospheric delay model, D_i is determined.

Determine the relative amplitude $H(\nu)$ and phase $Q(\nu)$ over the bandpass using an observations of a strong quasar anywhere in the sky. This calibration ties the phase of the calibrator, made over a wide bandwidth, to that of the spacecraft made over a narrow bandwidth to an accuracy of $3^\circ = 1$ psec at 8 GHz.

Determine the average residual clock delay d_c over the experiment for each telescope, generally using the bandpass observations. The apriori clock delay in Calc D_c is several μsec of time, whereas the residual clock errors of tens of nsec remain and are removed.

The spacecraft is then used as the phase reference source which determines its residual phase as a function of time, $\theta(t)$. The spacecraft is a point source and is generally stronger over its transmitting bandpass than the quasars. The quasar can be used as the phase reference, but any significant structure phase should be removed using self-calibration techniques before this step.

The spacecraft temporal phase variation is interpolated and applied to all of the calibrator observations. Data for some telescopes at some times may be flagged if the interpolation is uncertain. It is better to delete periods of unstable phase stability (usually bad weather or low elevation observations) than keep the data.

Produce the Image and Determine the offset position:

After applying the phase calibration from the spacecraft, image all of the quasars.

The offset of the image peak from the center of the image is equal to (quasar true position - quasar apriori position) - (spacecraft true position - spacecraft apriori position). This difference does depend on some parameters in the correlator model; however, the above offsets can be accurately determined to 1.0 nrad.

The quality (not the position!) of the quasar images is an indication of errors which are primarily associated with the angular dependence of the phase between the spacecraft and the quasars.

The true quasar structure can be determined by self-calibrating the quasars. If the peak intensity of the original image is less than about 60% of that of the self-calibrated image, significant decorrelation has occurred. See the Cassini memo (Memo 3) for more details and the use of multiple calibrators for estimating a better value of d_a with improved image accuracy and quality.

Obtaining the Total Delay

The position offset of the source is removed and the corresponding delay component is added to the total delay model

Reimage the quasar to make sure that they now lie near the center of the image.

The residual phases for the quasar should be near zero for each baseline, and this should be checked. Excursions larger than about 120° indicate a possibility of phase ambiguities, and these are caused by the d_r term. Flag data for which this ambiguity is possible.

An AIPS program, CLJPL, will then make the appropriate sum for each scan, source and baseline to obtain the total delay. The time-tag is also changed from Earth-centered to reference telescope. The total delay for the reference source (spacecraft or quasar) is simply the total delay model, D_m. The total delay for the other source equals $D_m + d_p + \theta/2\pi\nu$.

The total delays and put in an ascii format for delivery to JPL for further analysis and incorporation into the navigation data base.

APPENDIX: The AIPS Reduction Script

The following is a verbatim listing of an AIPS script which we have used to analyze the October 17, 2004 Cassini observation.

```
$  AIPS RUN FILE FOR CASSINI OBSERVATIONS ON OCT 17, 2004

     SOURCES                   OFFSET       POSITION ERR           SKY  MAP
                             RA    DEC       RA    DEC
     J0555+3948 is BP cal                                              1
     J0756+2040 is scname(C)                                                  3
     J0748+2400 is   ocal(1) -1.9  +3.2       0.25, 0.25
     J0750+1823 is   ocal(2) -1.4  -2.1       0.6,  0.6 PT          C
     J0743+2328 is   ocal(3) -4.0  +2.9       5.0   5.0 PT
     J0802+1809 is   ocal(4) +1.5  -2.2       0.4   0.4 SR
                                                             4        2

                                                               |----3 deg----|

                 PART 1. SET IMAGING PARAMETERS ******

RESTORE 0
PROC DDUM
  STRING*12 DNAME, SCNAME, BCAL, OCAL(5)
  STRING*6  DCLAS
  STRING*1  ZZ
  SCALAR    DSEQ, DDISK, NCAL
  SCALAR    NRCHAN, ORCHAN, XREF, XCHAN, YCHAN
  SCALAR    SCXOFF, SCYOFF, TSCXOFF, TSCYOFF
  ARRAY     XPOFF(5), YPOFF(5), TXPOFF(5), TYPOFF(5)
  FINISH

  DDUM

$  Initialize and set input parameters

  DNAME = 'CASS_OCT17';DCLAS='UVCOP'; DSEQ=1;DDISK=1 $ File name
  SCNAME = 'CASSINI'         $ spacecraft name
  BCAL =  'J0555+3948'       $ bandpass name
  NCAL = 4                   $ number of other calibrators
       OCAL(1) = 'J0748+2400'  $ICRF catalog source
       OCAL(2) = 'J0750+1823'
       OCAL(3) = 'J0743+2328'
       OCAL(4) = 'J0802+1809'
  ORCHAN = 1; NRCHAN = 150;  $ Orig ref chan, true ref chan
  XCHAN=140; YCHAN=160       $ Spacecraft channels
```

```
  XREF = 5                   $ Reference Telescope
  ZZ = 'C'                   $ Experiment Code

$
$----------------------------------------------------------
$  REMOVE ALL CL, SN, BP, NX tables                      |
$                                                        |
$  MAKE A LOGICAL DATA AREA:  egs. export XXX=`pwd`      |
$  Put IONOSPHERE FILE in XXX:jplg2930.04i               |
$   ftp  cddisa.gsfc.nasa.gov                            |
$   cd /gps/products/ionex/YYYY/DDD                      |
$                  (YYYY-year; DDD-day number)           |
$   mget                                                 |
$                                                        |
$----------------------------------------------------------

$ Change the reference frequency to the middle of the spacecraft spectrum

  inname  dname; incl dclas; ins dseq; ind ddisk

  keyw 'cdelt3'; geth; I=keyv(1)+keyv(2)      $ get channel sep
  keyw 'crval3'; geth; keyv(1)=keyv(1) + I*(NRCHAN-ORCHAN)
  puth                                        $ freq at NRCHAN
  inext 'an'; keyword 'freq'
  putth                                       $ put freq in AN file
  keyw 'crpix3'; keyv = NRCHAN,0
  puth                                        $ New ref pixel

$ END OF REFERENCE PIXEL ASSIGNMENT


                PART 2. APPLY APRIORI CALIBRATIONS-----

$ Remake CL1 table.  This table include D_g, D_a, D_c

  TASK 'INDXR'
  default
  inname  dname; incl dclas; ins dseq; ind ddisk
  cparm 2,4,0.25,1,1
  go; wait

$ Put in Apriori Amplitude Calibrations
$ SN1->CL2 accor; SN2->CL3 tsys.  This table calculated G(t).

  RUN MERGECAL
  inname  dname; incl dclas; ins dseq; ind ddisk
```

```
  MERGECAL
  RUN VLBAUTIL
  inname  dname; incl dclas; ins dseq; ind ddisk
  VLBACALA

$ Check corrections

  TASK 'SNPLT'
  tvinit
  default
  inname  dname; incl dclas; ins dseq; ind ddisk
  inext 'cl'; inver 3
  nplots 10; optype 'amp'; opcode 'alsi'; do3col 1
  dotv 1
  go; wait

$
$--------------------------------------------------------
$  SNPLT SHOWS APRIORI AMPLITUDES.  VALUES SHOULD        |
$    BE NEAR 20 WITH NO LARGE DEVIATIONS                 |
$                                                        |
$  MAKE A LOGICAL DATA AREA:  egs export XXX=`pwd`       |
$  Put IONOSPHERE FILE in XXX                            |
$                                                        |
$--------------------------------------------------------

$ Put in the parallactic angle term  -> CL4
$   This is a source-dependent p(t) component.

  VLBAPANG

$ Apply Ionosphere    -> CL5
$   This calculates D_i

  TASK 'TECOR'
  default
  inname  dname; incl dclas; ins dseq; ind ddisk
  gainver 4;gainuse 5
  aparm 1 0
  nfiles 1;  infile 'XXX:jplg2910.04i
  go; wait

$ Copy SU files and flag spacecraft channels

  TASK 'TACOP'
  default
```

```
  inname dname; incl dclas; ins dseq; ind ddisk
  inext 'su'
  inver 1; ncount 1
  outn inn; outcl incl; outs ins; outd ind
  outver 2
  go; wait

$ Copy FG file

  TASK 'TACOP'
  default
  inname dname; incl dclas; ins dseq; ind ddisk
  inext 'fg'
  inver 1; outver 2; ncount 1
  go; wait

$  FG1 contains apriori flags, FG2 contains spacecraft and others

  TASK 'UVFLG'
  default
  inname dname; incl dclas; ins dseq; ind ddisk
  source(1) 'cassini'
  bchan 1; echan xchan -1
  go; wait
  bchan ychan +1; echan 256
  go; wait


                PART 3. GET BANDPASS and AVERAGE DELAY-------


  TASK 'UVCOP'
  default
  inname dname; incl dclas; ins dseq; ind ddisk
  outname = ZZ!!bcal; outcl 'bpass'; outs 0; outd ddisk
  flagv = -1
  source(1) = bcal
  go; wait

  TASK 'INDXR'
  default
  inname = ZZ!!bcal; incl 'bpass'; ins 0; ind ddisk
  cparm 2,4 0
  go; wait

  TASK 'FRING'
```

```
  default
  inname = ZZ!!bcal; incl 'bpass'; ins 0; ind ddisk
  cals(1) = bcal
  docal 1; flagver 0; doband -1
  smodel = 1, 0
  refant = XREF
  solint = 0
  aparm = 5,0,0,0,0,0,3
  dparm 3, 400, 30, 2
  go; wait

  TASK 'CLCAL'
  default
  inname = ZZ!!bcal; incl 'bpass'; ins 0; ind ddisk
  snver = 3; inver 0; gainv 5; gainuse 6
  refant = XREF
  go; wait

$  Image the bandpass calibrator after fringing

  TASK 'IMAGR'
  default
  inn = ZZ!!bcal; incl 'bpass'; ins 0; ind ddisk
  outn ZZ!!bcal; outs 0; outd ddisk; outv 1
  source(1) = bcal
  nchav=256
  cellsize 0.0001
  docal 1; gainuse 0
  doband -1; flagver 0
  imsize 512
  niter 2000
  docal 1; gainuse 0
  bmaj 0.002; bmin 0.0008; bpa 0
  factor 3
  refant xref
  dotv 1
  go; wait

$ Determine bandpass   H(nu) and Q(nu)
  TASK 'BPASS'
  default
  inname = ZZ!!bcal; incl 'bpass'; ins 0; ind ddisk
  in2n = ZZ!!bcal; in2cl 'icl001'; in2s 0; in2d ddisk; inv 1
  cals(1) = bcal
  refant xref
  docal 1; gainuse 0
```

```
  solint = -1
  bpassprm(5) = -1
  go; wait

  TASK 'BPLOT'
  tvinit
  default
  inname = ZZ!!bcal; incl 'bpass'; ins 0; ind ddisk
  bpver = 1; freqid = 0
  codetype 'amp'
  dotv 1
  go; wait
  codetype 'phas'
  go; wait

$    Copy BP and SN3 over to main data set

  TASK 'TACOP'
  default
  inname = ZZ!!bcal; incl 'bpass'; ins 0; ind ddisk
  outname dname; outcl dclas; outs dseq; outd ddisk
  inext 'bp'
  inver 1; ncount 1; outver 1
  go; wait
  inext 'sn'
  inver 3;ncount 1; outver 3
  go;wait

$ Smooth delays   SN3 --> SN4
$    This removed a constant d_c for each telescope.  It is
$    not included in the total since it is the same for all sources.

  TASK 'SNSMO'
  default
  inname  dname; incl dclas; ins dseq; ind ddisk
  bparm 0 0 0 20 0 0 0 0 20
  cparm 0 0 0 1 0 0 0 0 20 0
  doblank -1
  smotype 'dela'
  refa xref
  go; wait

$ Copy SN file for modification  SN4 -> SN5

  TASK 'TACOP
  default
```

```
  inname dname; incl dclas; ins dseq; ind ddisk
  outn  dname; outcl incl; outs dseq; outd ddisk
  inext 'sn'
  inver 0; ncount 1; outver 0
  go; wait
$
  TASK 'SNCOR'
  default
  inname dname; incl dclas; ins dseq; ind ddisk
  snver 5
  opcode 'zrat'
  go; wait
  opcode 'zphs'
  go; wait

$  CLCAL   CL5 + SN5 --> CL6

  TASK 'CLCAL'
  default
  inname dname; incl dclas; ins dseq; ind ddisk
  snver 5; inver 5; gainver 5; gainuse 6
  refant xref
  go; wait

$----------------------------------------------------------
$  BANDPASS AND DELAY OFFSET OBTAINED                     |
$                                                         |
$                                                         |
$----------------------------------------------------------
$


                 PART 4. CALIBRATE ON SPACECRAFT ************


$ Calibrate on spacecraft and image all sources
$   This determines psi(t) for the reference source

  TASK ='CALIB'    $ CL6 --> SN6
  default
  inname dname; incl dclas; ins dseq; ind ddisk
  docal 1; gainuse 6
  doband 1; bpver 1
  flagver 0
  cals(1) = scname
  refant XREF
```

```
  solint 0
  aparm 5 0 0 0 0 0 1
  bchan xchan; echan ychan
  solmode 'p'
  snver 0
  go; wait

$---------------------------------------------------------
$  SNPLT SHOWS PHASES.  MAKE SURE THAT PHASES            |
$    ARE STABLE AND EASILY INTERPOLATABLE                |
$                                                        |
$  MAY HAVE TO FLAG DATA                                 |
$---------------------------------------------------------

  TASK 'SNPLT'
  tvinit
  default
  inname dname; incl dclas; ins dseq; ind ddisk
  inext 'sn'; inver 0
  nplots 10; optype 'phas';
  pixr -180,180
  dotv 1
  go; wait

$  CLCAL   CL6 + SN6 --> CL7
$   psi(t) from reference source is interpolated to other source

  TASK 'CLCAL'
  default
  inname dname; incl dclas; ins dseq; ind ddisk
  snver 6; inver 6; gainver 6; gainuse 7
  refant xref
  go; wait


               PART 5. IMAGE ALL CALIBRATORS ----------------

$ Split each source

  TASK 'SPLIT'
  default
  inname dname; incl dclas; ins dseq; ind ddisk
  ind ddisk
  docal 1; gainuse 0
  doband 1; bpver 1
  sour scname, oc(1), oc(2), oc(3), oc(4)
```

```
  flagv 3
  outcl zz!!'split'; outs 0; outd ddisk
  aparm 2 4 0
  nchav 256
  go; wait

$ Image each in turn

  TASK 'IMAGR'
  default
  incl ZZ!!'split'; ins 0; ind ddisk
  outs 0; outd ddisk; outv 1
  nchav=256
  cellsize 0.0001
  imsize 512
  niter 200
  bmaj 0.002; bmin 0.0008; bpa 0
  factor 3
  refant xref
  dotv 1
  nbox 1

  inn scname
  outn ZZ!!inn
  go; wait

  inn oc(1)
  outn ZZ!!inn
  go; wait

  inn oc(2)
  outn ZZ!!inn
  go; wait

  inn oc(3)
  outn ZZ!!inn
  go; wait

  inn oc(4)
  outn ZZ!!inn
  go; wait

$  get offsets of peaks

  inn ZZ!!scname; incl 'icl001'; ins 0; ind ddisk
  blc 0; trc 0
```

```
  imstat; maxfit
  scalr1 = (256-pixxy(1)) /10
  scalr2 = (pixxy(2) - 257) /10
  type 'offset for-'!!scname, scalr1, scalr2
  scxoff = scalr1
  scyoff = scalr2

  inn ZZ!!ocal(1); incl 'icl001'; ins 0; ind ddisk
  blc 0; trc 0
  imstat; maxfit
  scalr1 = (256-pixxy(1)) /10
  scalr2 = (pixxy(2) - 257) /10
  type 'offset for-'!!ocal(1), scalr1, scalr2
  xpoff(1) = scalr1
  ypoff(1) = scalr2

  inn ZZ!!ocal(2); incl 'icl001'; ins 0; ind ddisk
  blc 0; trc 0
  imstat; maxfit
  scalr1 = (256-pixxy(1)) /10
  scalr2 = (pixxy(2) - 257) /10
  type 'offset for-'!!ocal(1), scalr1, scalr2
  xpoff(2) = scalr1
  ypoff(2) = scalr2

  inn ZZ!!ocal(3); incl 'icl001'; ins 0; ind ddisk
  blc 0; trc 0
  imstat; maxfit
  scalr1 = (256-pixxy(1)) /10
  scalr2 = (pixxy(2) - 257) /10
  type 'offset for-'!!ocal(1), scalr1, scalr2
  xpoff(3) = scalr1
  ypoff(3) = scalr2

  inn ZZ!!ocal(4); incl 'icl001'; ins 0; ind ddisk
  blc 0; trc 0
  imstat; maxfit
  scalr1 = (256-pixxy(1)) /10
  scalr2 = (pixxy(2) - 257) /10
  type 'offset for-'!!ocal(1), scalr1, scalr2
  xpoff(4) = scalr1
  ypoff(4) = scalr2

$ Print out offsets of all sources

   XPOFF(1), YPOFF(1) IS POSITION OF QUASAR wrt to SPACECRAFT
```

```
  PRINT  scname, scxoff, scyoff
  PRINT  oc(1), xpoff(1), ypoff(1)
  PRINT  oc(2), xpoff(2), ypoff(2)
  PRINT  oc(3), xpoff(3), ypoff(3)
  PRINT  oc(4), xpoff(4), ypoff(4)

==============================================================================
$ END OF NORMAL PHASE REFERENCING   CL7, SN6, FG2, BP1, FG2 Cal tables
==============================================================================


                 PART 6. PUT POSITION OFFSETS INTO DELAYS ------------


$   Place d_p in data base and change phases for each calibrator
$
  TASK 'CLCOR'
  default
  inname dname; incl dclas; ins dseq; ind ddisk
  opcode 'antc'
  gainver 7; gainuse 8
  source(1) = ocal(1)
  clcor = 0, 0, 0, 0, xpoff(1)/1000.0, ypoff(1)/1000.0
  go;wait

  gainver 8; gainuse 8
  source(1) = ocal(2)
  clcor = 0, 0, 0, 0, xpoff(2)/1000.0, ypoff(2)/1000.0
  go;wait
  source(1) = ocal(3)
  clcor = 0, 0, 0, 0, xpoff(3)/1000.0, ypoff(3)/1000.0
  go;wait
  source(1) = ocal(4)
  clcor = 0, 0, 0, 0, xpoff(4)/1000.0, ypoff(4)/1000.0
  go;wait

$  Recalibrate on spacecraft  CL8 --> SN7
$   Determine residual phases after moving sources to phase center.

  TASK ='CALIB'
  default
  inname dname; incl dclas; ins dseq; ind ddisk
  docal 1; gainuse 0
  doband 1; bpver 1
  flagver 0
```

```
  cals = scname, ocal(1), ocal(2), ocal(3), ocal(4)
  refant XREF
  solint 0
  aparm 5 0 0 0 0 0 1
  solmode 'p'
  snver 0
  go; wait


$----------------------------------------------------------
$  SNPLT SHOWS PHASES.  MAKE SURE THAT PHASES              |
$    ARE STABLE AND SMALL AND SHOULD BE EASILY            |
$    CONNECTED FOR ALL SOURCES                            |
$  MAY HAVE TO FLAG DATA                                  |
$----------------------------------------------------------

  TASK 'SNPLT'
  tvinit
  default
  inname dname; incl dclas; ins dseq; ind ddisk
  inext 'sn'; inver 0
  nplots 10; optype 'phas';
  pixr -180,180
  dotv 1
  go; wait

              PART 7. DETERMINE TOTAL DELAYS  ------------

$  CLJPL is a modification of the GSFC CL2HF

VERS 'MARS'
  TASK 'CLJPL'
  default
  indi disk
  GETN SCALR1
  invers 8; in2v 8
  snver 7
  outf 'MARS:DELAY_OCT17'
  go; wait
-----------------------------------------------------------------------------
```

SAMPLE OF OUTFILE DELAYS IN FILE DELAY_OCT17

```
SCAN_NAME                  :: BR-HN-R00001
DATE            (yyyymmdd):: 20041017
TIME_T0                (s)::  44433.00
STATIONS                   ::   BR  HN
SOURCE_NAME                ::  J0748+2400 |
FRQ_WQ               (MHz)::   8430.72226
ELEV_CENTER          (deg)::   58.7333  63.7432
AZIM_CENTER          (deg)::  130.9597 231.5620
GEOMETRIC_DELAY_STN    (s)::      0.018150169153690     0.019053294948173
GEOMETRIC_RATE_STN   (s/s)::      0.000000406929089    -0.000000393876517
CLOCK_DELAY_STN        (s)::     -0.000000244785004     0.000000469455186
CLOCK_RATE_STN       (s/s)::      0.000000000000025    -0.000000000000060
ATMOSPHERE_DELAY_STN  (s)::      0.000000009158733     0.000000008307480
ATMOSPHERE_RATE_STN (s/s)::     -0.000000000000206     0.000000000000170
MODEL_DELAY_STN        (s)::      0.018149915209953     0.019053756095879
MODEL_RATE_STN       (s/s)::      0.000000406929319    -0.000000393876746
MODEL_ACCER_STN  (s/s**2)::      0.000000000062417     0.000000000070137
IONOSPHERE_DELAY_STN  (s)::      0.000000000129231     0.000000000247570
PHASE_DELAY_MODEL      (s)::     -0.000903840885927
PHASE_DELAY_ION        (s)::     -0.000000000118339
PHASE_RESIDUAL       (deg)::      -3.8
PHASE_RESIDUAL_DELAY  (s)::     -0.000000000001250
PHASE_TOTAL            (s)::     -0.000903841005516
GROUP_TOTAL            (s)::     -0.000903840768837
PHASE_RATE_TOTAL     (s/s)::      0.000000800805606


SCAN_NAME                  :: BR-KP-R00002
DATE            (yyyymmdd):: 20041017
TIME_T0                (s)::  44433.00
STATIONS                   ::   BR  KP
SOURCE_NAME                ::  J0748+2400 |
FRQ_WQ               (MHz)::   8430.72226
ELEV_CENTER          (deg)::   58.7333  72.8439
AZIM_CENTER          (deg)::  130.9597 112.6583
GEOMETRIC_DELAY_STN    (s)::      0.018150169153690     0.020313815995930
GEOMETRIC_RATE_STN   (s/s)::      0.000000406929089     0.000000359170037
CLOCK_DELAY_STN        (s)::     -0.000000244785004    -0.000002080000058
CLOCK_RATE_STN       (s/s)::      0.000000000000025     0.000000000000000
ATMOSPHERE_DELAY_STN  (s)::      0.000000009158733     0.000000006621429
ATMOSPHERE_RATE_STN (s/s)::     -0.000000000000206    -0.000000000000118
MODEL_DELAY_STN        (s)::      0.018149915209953     0.020311729374442
MODEL_RATE_STN       (s/s)::      0.000000406929319     0.000000359170154
MODEL_ACCER_STN  (s/s**2)::      0.000000000062417     0.000000000083800
```

```
IONOSPHERE_DELAY_STN  (s)::      0.000000000129231     0.000000000173475
PHASE_DELAY_MODEL     (s)::     -0.002161814164489
PHASE_DELAY_ION       (s)::     -0.000000000044244
PHASE_RESIDUAL      (deg)::       0.3
PHASE_RESIDUAL_DELAY  (s)::      0.000000000000109
PHASE_TOTAL           (s)::     -0.002161814208624
GROUP_TOTAL           (s)::     -0.002161814120136
PHASE_RATE_TOTAL    (s/s)::      0.000000047759053
```

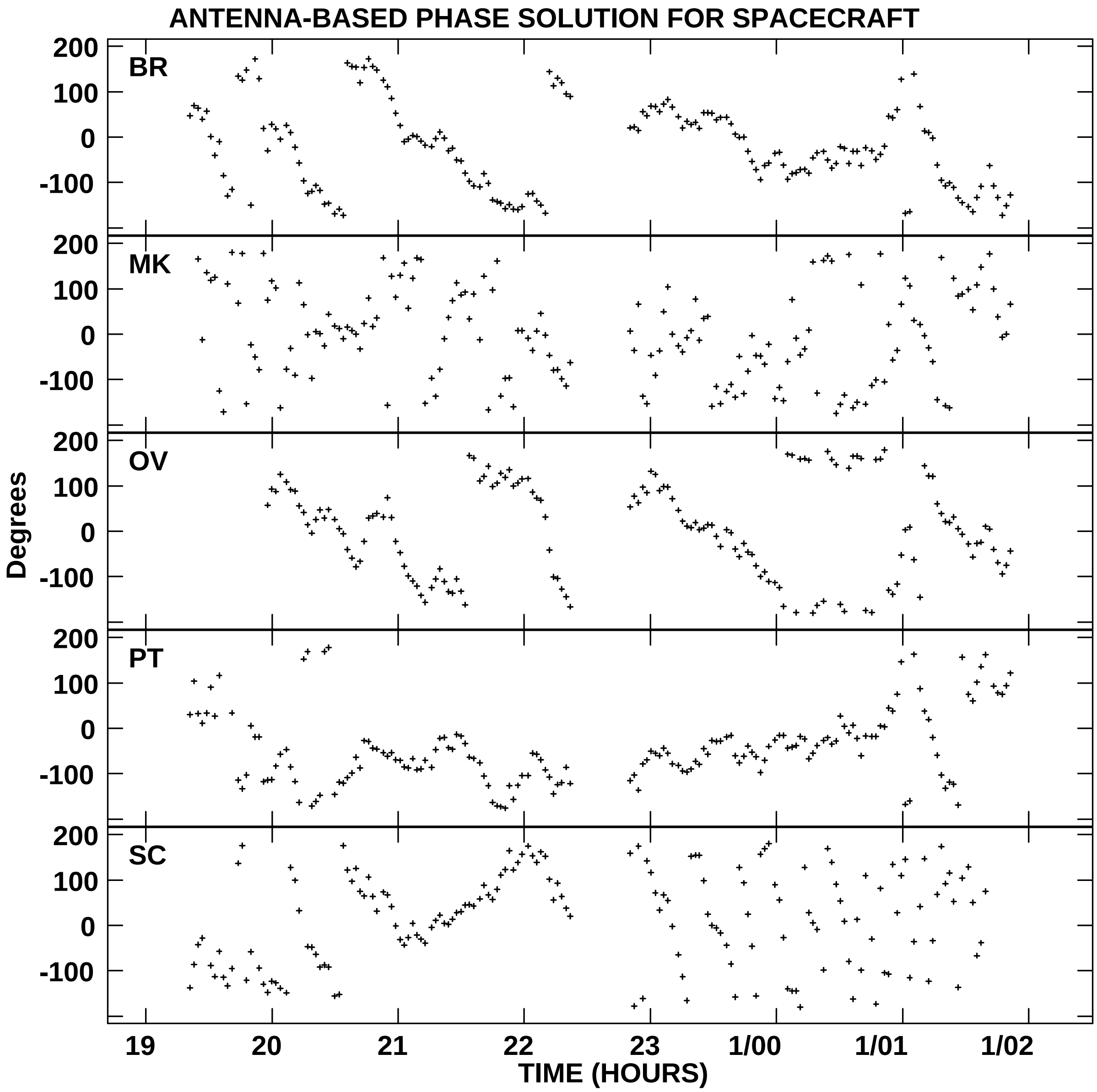

Fig. 1.— **The Spacecraft Phases $\theta(t)^s$:** The telescope-based phases for Mer-B spacecraft observations on January 19, 2004. Each point gives the scan average phase over a one-minute integration, with a scan each 2 minutes. The interpolation of the phases between observations is accurate for most times and telescopes. Exceptions are for MK with noisy phases (the weather was poor) and for SC after time 1/00.5 when the phase slope become excessive because of the low source elevation at this telescope.