3 VLBI Analysis Software (DG)

Several software packages have been developed over the years for VLBI processing and/or analysis. All have been developed independently by different groups. Four such software packages were used in studying the data included in ICRF2 and in generating preliminary and final solutions. In the following sections, we briefly describe each one.

3.1 Calc/Solve (DG)

The Calc/Solve analysis package has been under development and in use for over 30 years with most of the development work being done by the VLBI group at the GSFC. It is the oldest and most complete of the VLBI geodetic/astrometric analysis packages. It is composed of over one hundred different programs used for the creation and calibration of database session files, the analysis of individual sessions or mass analysis of multiple sessions, and many other assorted tasks. Calc/Solve was built around the original Mark III database handler which dates back to the late 1970's. Calc/Solve is the only analysis package which allows for single session editing and updating of individual VLBI sessions. As such, Calc/Solve provides the analyzed database versions which the other analysis packages depend on for their analysis.

Program Calc contains most of the geophysical models and computes a theoretical VLBI delay and delay rate for each observation in a session consistent with the IERS Conventions (2003) [McCarthy & Petit, 2004]. Calc also computes many of the partial derivatives of the delay and delay rates with respect to various parameters (such as nutation, polar motion, UT1, site positions, source coordinates, etc.) which are used in the analysis to solve for adjustments of those parameters. Calc also has an active role in the VLBI correlation process, as it is used at most of the world's VLBI geodetic and astronomical correlators (the three Mark IV correlators, the VLBA correlator, the JIVE correlator, the ATNF correlator, and the DiFX software correlator) to compute the correlator model delays for offsetting the bit streams from the different antennas.

Solve is made up of a large family of programs for both single session analysis and multiple session analysis. It performs a least-squares fit and parameter adjustments using the Calc theoretical delays and partial derivatives, the observed delays, and additional models and partials. Solve has two modes: an interactive single session analysis mode and a non-interactive global analysis mode. In the single session analysis mode, the analyst reads in the Calc'ed and calibrated X-band and S-band databases. They then perform ambiguity resolution (either automatically or manually); perform the ionosphere calibration; set the clock, atmosphere, and other parametrization; edit the data on each baseline (either automatically or manually); and update the X-band database. The analyzed, updated session version can then be used in the global analysis mode. In the non-interactive, global analysis mode, Solve is used to analyze large groups of sessions. It uses the arc-parameter elimination method described in Ma et al. [1990]. It can solve for various arc parameters (adjusted for each session) and global parameters (adjusted once for the entire data set). The use of Solve for generation of the ICRF2 solution is described in §7.

Calc/Solve was originally written in Fortran 77 and ran on a variety of HP machines for many years. Several years ago, it was converted to Fortran 90 and Linux. It is now most commonly used on Linux PC's under a variety of Linux operating systems.

3.2 SteelBreeze (SLB)

Software SteelBreeze was developed from scratch as a tool for geodetic VLBI data analysis at the Main Astronomical Observatory of the National Academy of Sciences of Ukraine. It performs a least-squares estimation of various geodynamical parameters using the Square Root Information Filter (SRIF) algorithm [Biermann, 1977]. SRIF allows the introduction of stochastic models for parameter estimation.

The software imports geodetic VLBI observations in known formats (NGS cards and Mark III databases). It stores observations as well as catalogs of radio sources, stations, EOP, ephemerides, and some other data sets in its own inner binary formats.

SteelBreeze analyzes VLBI data (group delays) of single and multiple sets of sessions. The time delay is modeled according to the IERS Conventions (2003) [McCarthy & Petit, 2004], and other additional models (tectonic plate motions, nutation models, wet and hydrostatic zenith delay, mapping function, etc.). The software makes estimations of the following parameters: Earth orientation parameters, coordinates and velocities of selected sets of stations, coordinates of selected sets of radio sources, clock functions and wet zenith delays and gradients, axis offsets, Love numbers, etc.

The SRIF algorithm allows estimations of unbiased parameters as well as stochastic ones. In SteelBreeze, each estimated parameter can be one of the following types:

- Global parameter: unbiased estimation for an entire set of selected sessions (typically applied for source and station coordinates estimation, etc.).
- Local parameter: unbiased estimation at each session. The estimates on different sessions are considered to be independent (e.g., EOP).
- Local parameter with time propagation: unbiased estimation at each session, the estimates on adjacent sessions are dependent according to a given rule.
- Stochastic parameter: the behavior of the estimated parameter is assumed to be varying with time with a given rule (implemented: white noise, 2^{nd} order Markov process, random walk). This type is useful for estimation of clock parameters and wet zenith delays.
- Stochastic parameter with time propagation: the same as above, but adjacent estimations for different sessions are tied with the same rule.

SteelBreeze is written in C++, uses the Qt user interface library and runs on Linux/GNU system.

3.3 OCCAM (OAT)

The OCCAM software package [Titov et al., 2004a] analyzes VLBI data by the least-squares collocation method (LSCM) [Titov et al., 2004b]. The LSCM minimizes a function similar to the conventional least-squares method and, additionally, it takes into account intra-day correlations between observations. These correlations are calculated from external data, in the case of VLBI, from the data about stochastic behavior of hydrogen maser clocks and wet components of troposphere delays and gradients. All estimated parameters are split into three groups based on their properties: stochastic, estimated for every epoch (clock functions and wet troposphere delays); daily or 'arc' parameters to be approximately constant within a 24-hour session; and so-called 'global' parameters, which are constant over the total period of observations.

3.4 QUASAR (SK)

QUASAR [Gubanov et al., 2004; Kurdubov, 2007] is the VLBI analysis software package developed by the Institute of Applied Astronomy of the Russian Academy of Sciences. It uses the least-squares collocation technique. Most of the reduction calculations are implemented according to the IERS Conventions (2003) [McCarthy & Petit, 2004]. QUASAR software supports both single and multi-session adjustment. There is a wide list of parameters which have partials and can be estimated. Every parameter can be estimated as a global, arc, or stochastic parameter. Every parameter can be represented as a polynomial function over the span of one session or the entire observation period. The Vienna Mapping Function (VMF1) [Böhm, Werl, & Schuh, 2006] is used for the tropospheric delay. QUASAR has two options for atmospheric loading: a one-dimensional regression model and a three dimensional numerical model. Antenna and axis offset thermal deformation are also accounted for. Celestial Intermediate Pole (CIP) formalism is used for Celestial pole coordinates and derivations. For nutation adjustments, QUASAR estimates the new CIP-X and CIP-Y instead of $d\psi$, $d\epsilon$.

For the iaa008c catalogue, VLBI observations from 1980 to 2009 March 30 (mostly from the GSFC list) were used. There were a total of 6353387 group delays. The celestial reference frame was defined by No-Net-Rotation (NNR) constraints on the coordinates of 203 sources from the ICRF1 "defining" list. The VTRF2008 catalog was used for *a priori* station positions. No-net-translation and no-net-rotation constraints were applied for the coordinates and velocities of 11 stations: MATERA, KOKEE, WETTZELL, FORTLEZA, WESTFORD, ALGOPARK, NYALES20, NOTO, ONSALA60, LA-VLBA, MK-VLBA. Coordinates of all radio sources, and positions and velocities of all stations were estimated as global parameters. EOP's were estimated as local parameters. Clock functions were estimated as the sum of a quadratic polynomial and a stochastic function. Tropospheric wet zenith delays were estimated as the sums of linear and stochastic parts. Total tropospheric gradients were estimated as local parameters with no constraints and no *a priori* model applied. For coordinates of sources that were observed fewer than 5 times, a soft 10 cm constraint was applied. For velocities of stations participating in fewer than 5 session or time spans less than one year, a soft 10 cm constraint was applied. Atmospheric pressure loading was applied using the Petrov & Boy [2004] 3-D model and the Vienna Mapping Function (VMF1) [Böhm, Werl, & Schuh, 2006] was used.