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MODEST: a Tool for Geodesy and Astrometry

Ojars J. Sovers [1], *Christopher S. Jacobs* [2], *Gabor E. Lanyi* [2]

[1] *RSA Systems/Jet Propulsion Laboratory*

[2] *Jet Propulsion Laboratory*

Contact author: Ojars J. Sovers, e-mail: `ojars@rsasys.com`

Abstract

Features of the JPL VLBI modeling and estimation software "MODEST" are reviewed. Its main advantages include thoroughly documented model physics, portability, and detailed error modeling. Two unique models are included: modeling of source structure and modeling of both spatial and temporal correlations in tropospheric delay noise. History of the code parallels the development of the astrometric and geodetic VLBI technique and the software retains many of the models implemented during its advancement. The code has been traceably maintained since the early 1980s, and will continue to be updated with recent IERS standards. Scripts are being developed to facilitate user-friendly data processing in the era of e-VLBI.

1. Introduction

The final step in analysis of radiometric Very Long Baseline Interferometric (VLBI) data is the determination of best estimates of physical parameters from the observables: the delays of wavefront arrival times and their time rates of change. Software for carrying out this procedure normally consists of two programs: modeling and parameter estimation. The code developed and used by the Jet Propulsion Laboratory combines these two functions and is known by the acronym "MODEST" (for MODel and ESTimate). This paper gives an overview of the features of MODEST that may be of interest to the general VLBI community. We include a brief history of the initial development and evolution since the 1970s, and enumerate some features that appear to be unique to its current version. During the past two decades, several detailed comparisons have been carried out with other analysis codes in order to validate correct implementation of commonly accepted modeling standards, as well as to determine the possible level of uncertainty introduced by alternate choices in analyses of identical data. Portability of the code to a wide range of computers using varied operating systems has been demonstrated. Finally, reasonably complete documentation of MODEST has been maintained over the years. This includes a user manual, periodic publication of a modeling algorithm description [6], and a 1998 review paper of the physics of VLBI modeling [5].

2. History

The JPL VLBI code originated in the 1970s when Fanselow, Thomas, Williams and collaborators set out to identify and code physical models pertinent to quantitative description of radiometric VLBI measurements. The time was ripe to take advantage of the potential of highly stable clocks and large antennas at gigahertz frequencies to provide unprecedented accuracy in determining an inertial celestial reference frame and positioning points on the Earth's surface. Initially the analysis code was developed for single baseline experiments using the Deep Space Network (DSN) antennas. Its first incarnation, named Masterfit, was on IBM System 360 computers at Caltech, using the Fortran-66 language with 9-track magnetic tapes and punch cards as storage devices and I/O media.

A major step forward was stimulated by the introduction of relatively small and inexpensive computing equipment in the late 1970s. Availability of individual VAX computers for small groups of researchers provided convenient platforms for data analyses. At this point the MODEST code already comprised several tens of thousands of source lines, and it was realized that maintainability and traceability would be indispensable requirements for its future evolution. For easier code readability, a structured Fortran preprocessor had been used in the IBM version, and was retained in the migration to VAXes. This facilitated code modularity and anticipated many features which are now available in standard Fortran. During this era, VLBI analyses were already complicated and voluminous enough to benefit from ever-increasing computer speed and storage capacity. Estimation of thousands of parameters from tens of thousands of observables demanded a large fraction of available disk storage and many hours of CPU time.

The next major step in the evolution of VLBI data analyses was the advent of ever cheaper personal computers with Unix-based operating systems in the 1990s. The consequence for MODEST was the development of portable code utilizing the advantages of the features of advanced Fortran compilers. Improvements in computer speed and storage capacity have paralleled the growth of the VLBI data base during the past two decades. Hundreds of thousands of parameters are now determined from millions of observations in elapsed times of order 24 hours on gigahertz-CPU machines.

Recent important applications of MODEST have included updates of the celestial and terrestrial reference frames (source positions and DSN station locations). These results were used in VLBI-assisted navigation of the Mars '03 landers. Anticipated future developments include software correlation and post-processing VLBI data, feeding automated scripts for MODEST analyses.

3. Portability

As mentioned in the previous section, MODEST code was reworked to make it compliant with modern Fortran compilers during the 1990s. It was subsequently found to be fully portable to many computers then in common use. The VMS operating system, however, requires platform-specific compilation to provide for the specification of record sizes in units of 4-byte words rather than bytes. By early 2004 the platforms on which MODEST has been successfully implemented include a variety of Intel PCs with Linux systems, Hewlett-Packard, Sun, and Digital Unix systems, as well as the venerable Alpha running under VMS. MODEST also currently compiles on Macintoshes with OS X operating systems. After some minor linking problems are resolved, it will be functional on all current versions of Unix-like operating systems.

Future improvements are expected to focus on making the code more readable and therefore more easily maintainable. The advanced features of Fortran 90/95 should improve program modularity and dynamic memory allocation. The resulting code is expected to remain fully portable as various Fortran compilers become more standardized.

4. Unique Features

While VLBI analysis packages are generally quite similar in their capabilities, several features appear to be implemented only in MODEST code. These may be categorized in two general classes: observable weighting and modeling. Most simply, weighting is employed in the presence of unidentified systematic errors in VLBI observables that are manifested as normalized χ^2 values which depart from 1. Traditionally, added noise σ_{CON} is introduced in order to force $\chi^2_\nu \approx 1$. This uniform white noise is the same for all observations in a given subset. MODEST has three additional categories of added noise, applied to different data subsets in order to discriminate between different systematic errors. They target varied error sources: σ_{STN} is particular to the observing station and accounts for instrumental errors; σ_{SRC} is particular to the source and accounts for source structure problems; and σ_{TRP} is particular to the tropospheric delay and downweights observations at low elevation angles. Such added noise contributions may be either empirically adjusted, or chosen on general principles for a conjectured model of the particular hypothetical systematic error.

Another aspect of observable weighting goes beyond the above-mentioned noise sources to address one of the presently dominant VLBI error sources, namely the troposphere. The standard troposphere model maps zenith delays to the elevation of each observation and estimates them at frequent intervals. A MODEST option employs a parameterized turbulent atmospheric flow model [8] to calculate an observable covariance matrix for all observations within an experiment. This matrix is based on physical parameters such as troposphere height, wind velocity, and saturation scale describing the turbulent flow. In contrast to Kalman filtering, it accounts for spatial as well as temporal correlations between observations. If desired, this covariance matrix can supplement the customary troposphere model. For single-baseline DSN data the troposphere covariance formulation is found to reduce baseline length scatter substantially.

In the unique model category, maps may be available for the spatial structure of a source's radio emission. MODEST is capable of accepting models of such extended distributions, parameterized as Gaussian components. Delay corrections based on such maps [1] can replace the standard point-source model, and have been demonstrated to produce modeling improvements amounting to several mm [4].

A final non-standard capability of the MODEST code is to "restart" parameter estimation runs. If details of the least-squares parameter estimation have been saved for a given fit, more data may be added to resume the least squares estimates starting with the previous results. This may facilitate operational aspects of large fits, and is especially useful in combining raw observables from different space geodetic techniques. For example, it was used in an early determination of the precession constant from a combination of VLBI and lunar laser ranging measurements [2].

Finally, it should be mentioned that MODEST has a plethora of modeling options. For example the current version offers a choice of nine tropospheric mapping functions and 13 nutation models, to name but two categories. Such versatility makes it a very powerful tool.

5. Operational Characteristics

To illustrate some practical aspects of maintaining and running MODEST code, we summarize some pertinent measures of size, time, and storage space requirements. The source code consists of approximately 50000 lines, 30000 of which are non-comment. Internal memory requirements of the executable are less than 1 Gbyte. With the exception of the Solar System ephemeris, all auxiliary input files (*e.g.* UT1 and polar motion, ocean loading, etc.) are in ASCII format. The observable ("FIT") file can be either ASCII or binary (to save space for global data sets). Its contents are limited to information required for analyses; all other post-correlation results are archived separately.

Single-experiment analyses are essentially instantaneous on GHz-speed machines. Logistical considerations are only important for large global solutions. A solution estimating 700 source coordinate pairs and 400000 other parameters from 3.3 million observation pairs (EST step) requires approximately 36 hours on a 2.2-GHz dual processor XEON machine. It uses a 64-MB solution specifications file (2.4 million lines), an 8-GB regress file, 25 GB scratch space, and produces 12 GB of output. Modeling the observations (MOD step) requires 9 hours to produce the regress data set from a 300-MB raw observable file.

Numerous auxiliary programs are associated with MODEST processing. They include codes to generate the complex solution specification file for large fits, to optimize parameters for troposphere covariance matrices, to print and plot various classes of estimated parameters, and to perform comparisons of radio source catalogs. The total lines of code in such software exceed the size of MODEST itself by approximately a factor of 2.

6. Traceability, Documentation, and Verification

Starting in the early VAX days, automated procedures were developed to keep track of software changes at each new version of the code. Differences of program modules are archived along with narratives of the reasons for the changes. Much of this history is also preserved in the code itself in the form of comment lines. In principle, any of the hundreds of versions of MODEST and Masterfit that were operational during the past quarter century can be reinstated, and any particular data processing run can be reproduced, given availability of the raw input data. In late 2003 numbered versions reached 417. Together with several hundred versions of the predecessor Masterfit, there is a long archived history of traceable, time-stamped changes of the code over the past two decades. Many outdated models (*e.g.* Woolard nutation) remain available for historical purposes.

It appears that the MODEST software is perhaps the most thoroughly documented VLBI analysis program in common use today. This documentation consists of two parts: an "operator manual", and algorithm definition. The operator manual is a 50-page long description of the contents of all input and output files required to run MODEST. It is embedded in the main module, and is thus never separated from the code itself. Algorithm documentation includes periodically updated modeling descriptions in the form of a JPL Report, initially published in 1983 and now in its 7th (1996) version [6], which is now somewhat outdated. These practically oriented reports have a more intimate connection to the software than does the 60-page 1998 review paper describing the detailed physics of the VLBI model [5].

In order to gain assurance that VLBI modeling and parameter estimation are performed correctly, several detailed comparisons with other software were carried out over the years. On the modeling side, the first was a comparison with the Goddard Space Flight Center software CALC in 1982 [7] and again in 1997. Comparisons with the Paris Observatory's GLORIA and the satellite geodetic code GINS [3] were done in 1997 and 2000, respectively. It was concluded that the codes agree to close to a picosecond for the important aspects of the model. Stronger conclusions were prohibited only by the inability to make models exactly equivalent. Parameter estimates present a more difficult problem, but recent comparisons of global source position results between MODEST and CALC/SOLVE were found to agree at the 100 microarc second (15-ps) level. This is most likely a consequence of editing and parameterization choices by different analysts.

7. Conclusion

The JPL VLBI analysis software MODEST has evolved during the past three decades to keep pace with improvements of physical models as well as with advances in computing hardware. It offers several unique options for data weighting and modeling, and retains all models used during its evolution. Documentation is currently probably the most complete among contemporary VLBI analysis packages. Discrepancies with independent software are at the picosecond level for model details. Comparisons of the results of parameter estimates (which also test effects of editing choices by different analysts) similarly show agreement at the 15-ps level. In this era of easily available, cheap and fast computing power, MODEST has proved to be portable to numerous platforms.

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Masterfit and MODEST development over the years profited from the efforts of people (too many to name individually) in the Tracking Systems and Applications section at JPL. They analyzed, coded, and tested the numerous parts of the VLBI model, as well as exposed deficiencies and improved the efficiency of the code.

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