THE EFFECT OF REFERENCE FRAMES ON VLBI EOP

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ABSTRACT

Only VLBI of the space geodesy techniques has the capability of directly linking the celestial and terrestrial reference frames while estimating all components of Earth orientation. The choice of frame definitions and the analysis configuration have significant effects on the EOP time series. In addition, VLBI solutions optimized for CRF or TRF or EOP do not produce the best results for the other aspects. An approach to an integrated analysis is outlined. Characteristics of the various space geodesy techniques and the IVS observing program for 2002 are described.

1. INTRODUCTION

The measurement of Earth orientation parameters (EOP) by VLBI has a history of two decades and is one of the principal reasons why VLBI was developed in as a space geodesy tool starting in the 1970s. The unique features of VLBI applicable to EOP monitoring are shown in table 1, but its actual use also depended on the development of instrumentation with sufficient precision of observation and modeling of sufficient completeness and accuracy as well as organizations and stations with a long term commitment to EOP. Changes in each of these factors and knowledge gained through experience and theoretical studies have paced the development and improvement of the EOP time series.

Table 1: Features of VLBI

Sensitivity to all Earth orientation parameters: x-pole, y-pole, UT1, $\Delta\varepsilon$, $\Delta\psi$
Direct access to quasi-inertial reference frame
Direct tie between celestial and terrestrial frames

2. REFERENCE FRAMES

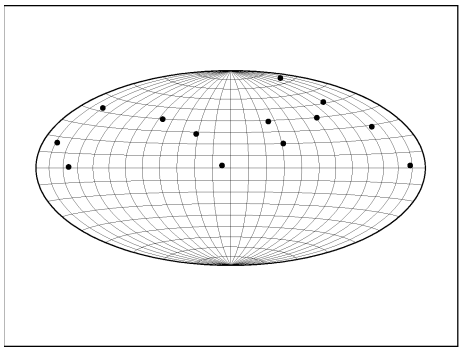
Since EOP is the relationship between the terrestrial reference frame (TRF) and the celestial reference frame (CRF), it is instructive to describe how these frames have been realized in practice in the context of VLBI.

The CRF is conceptually realized by the fixed positions of a defined set of extragalactic radio sources. However, the set of radio sources used in EOP monitoring by VLBI has evolved considerably over time as shown in Figures 1A through 1E. Each figure shows the sources used most frequently during a five-year interval in all the geodetic/astrometric VLBI observing sessions. Since EOP sessions are the most common and other geodetic sessions use generally the same sources, these sources are the actual CRF in the relevant time interval. It can be seen that the number of "geodetic" sources has increased substantially since the beginning. The number was limited to the strongest sources at the outset by instrumental sensitivity and increased both as sensitivity improved and as the need for higher temporal resolution, i.e., more observations per hour, and higher density on the sky became clearer for better estimation of troposphere variations. In addition, the use of a larger number of sources in a given observing session permits a more robust schedule, a practical consideration since stations and sources do not always behave as expected. It should be noted that the choice of sources and the sequence of their (repeated) observation, i.e., the scheduling of a VLBI session, require deliberation, and scheduling algorithms have evolved along with instrumental and analytical capability.

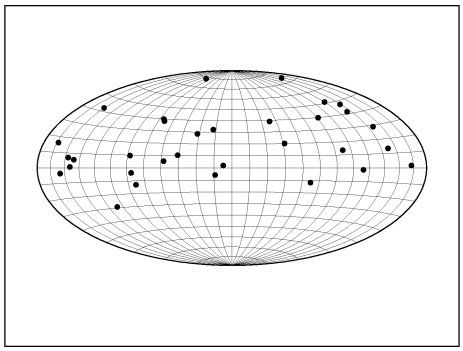
The geodetic sources are only a small subset of the sources included in the ICRF and ICRF-Ext.1 catalogues. The majority of sources in these catalogues were observed only in astrometric sessions. The geodetic sources were and continue to be chosen from the strongest compact sources distributed as uniformly as practical over the sky. They are not necessarily ICRF defining sources, and they may even have a degree of position instability undesirable for the realization of the CRF, especially in the earliest years. As all aspects of VLBI have continued to evolve, the proper EOP analysis to take into account position variation for some sources and understanding the effect of such variations as well as changes in the set of geodetic sources are subjects of current studies. Two approaches could be to estimate different source positions at each epoch for such "unstable" sources or to model apparent proper motions.

The TRF is conceptually a set of station positions and velocities. As with the CRF, the actual stations used for EOP monitoring have changed as shown in Figures 2 and 3. ¿From the earliest one-baseline POLARIS network, the size of the individual networks, the number of active networks, and the temporal resolution of the EOP time series have fluctuated, sometimes increasing and sometimes decreasing. The changes were generally not for technical reasons but were related to the commitment and funding of the individual government agencies with interests in EOP for operational and scientific purposes. The U.S. National Geodetic Survey (NGS) and German Institut für Angewandte Geodäsie (IfAG) were early strong supporters of VLBI EOP monitoring, and the U.S. National Aeronautics and Space Administration (NASA) provided the initial and continuing technical expertise. The IRIS-A program, supported jointly by NGS and IfAG, was the primary source of VLBI EOP from 1984-1993. The U.S. Naval Observatory (USNO) initially began the NAVNET program to assure an EOP capability entirely under U.S. control but merged NAVNET with IRIS-A in 1993 under the U.S. National Earth Orientation Service (NEOS). Starting in 1997 the weekly NEOS program was complemented by several CORE networks to test the effects of varying the EOP network. VLBI EOP monitoring has been weakened in recent years by the withdrawal of NGS, which satisfies its statutory requirement for polar motion using GPS, and by decreased funding support at USNO and NASA. USNO fulfills its statutory responsibility for UT1 through weekly 24-hr sessions and daily 1-hr intensive sessions. The closure of the Richmond, Florida and Green Bank, West Virginia stations has been somewhat compensated by the addition of the Algonquin, Ontario station and regular participation of European stations, particularly Ny Ålesund in Spitsbergen.

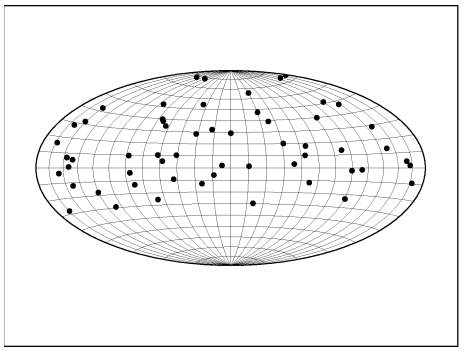
As with the ICRF, the EOP network stations are a small subset of the VLBI TRF and ITRF2000. Similar questions about the proper modeling of particular stations and the effect of network changes over time and between sessions are being actively addressed. How well the VLBI EOP networks represent the orientation changes of the entire globe is related to the



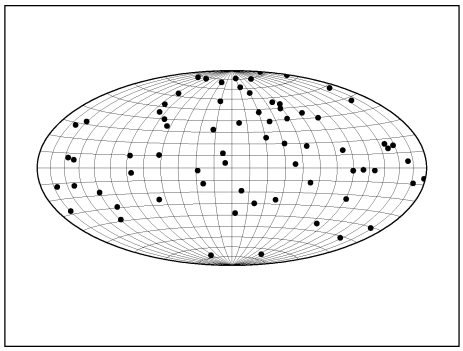
A. 13 sources, 1979–1983.



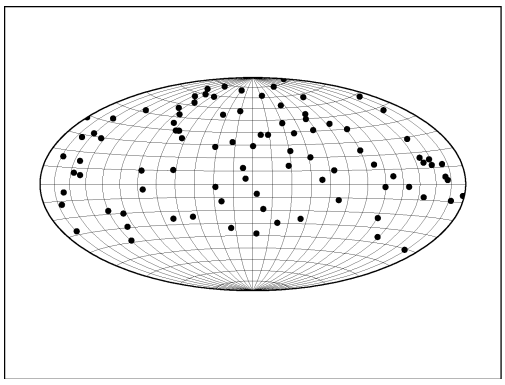
B. 32 sources, 1984–1988.



C. 57 sources, 1989–April 1993.



D. 70 sources, May 1993–1996.



E. 92 sources, 1997–2001.

Figure 1: Progression of most commonly observed sources, 1979–2001.

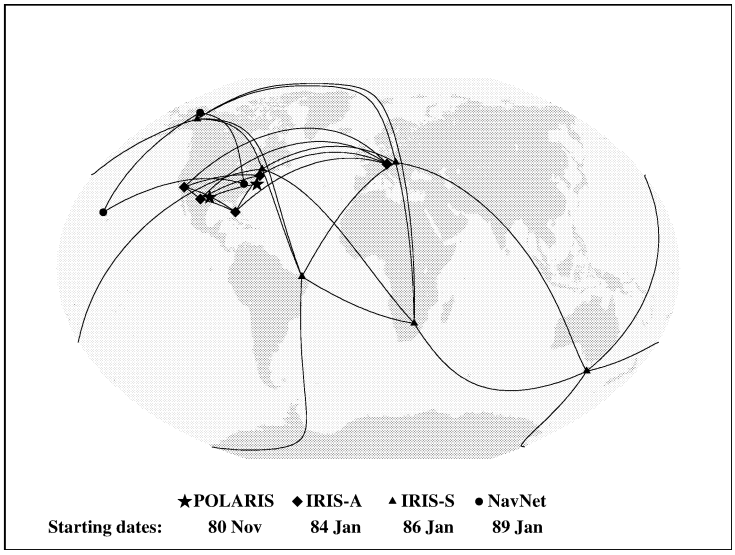


Figure 2: EOP networks–Polaris (1980-83), Iris-A (1984-93), Iris-S (1986-2001), Navnet (1989-93)

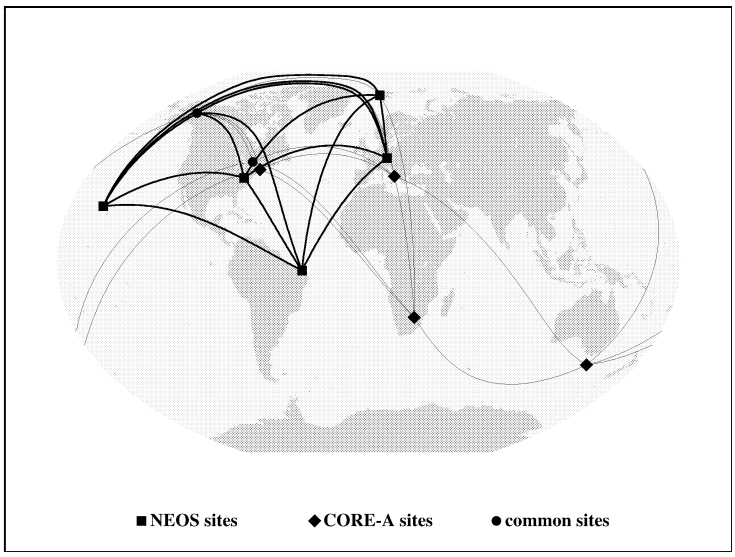


Figure 3: Neos and Core-A networks.

internal consistency and external datum of the TRF, but the results from the analysis of the VLBI EOP times series clearly show that considerable useful information is present.

It should be noted that there are some periods of exceptional quality, daily VLBI EOP measurements, particularly the fortnight of CONT94 in the beginning of 1994. Because of the personnel required at most VLBI stations, such extended periods of observation require a special effort. The stations also must be in the optimal operating condition, again requiring a special effort. Unfortunately the VLBI network performance has not been optimal recently because of lower funding in certain places. In addition, radio frequency interference from land and satellite transmissions is becoming a serious problem. While the Mark V recording system using PC disk drives will likely improve station reliability, interference may become a limiting factor in the dual-frequency ionosphere calibration.

3. OPTIMIZATION CONFLICTS

While the entire geodetic/astrometric VLBI data set can be used for analysis of the TRF, CRF and EOP, the reference frames for each and hence the analysis required have different individual purposes. A summary and some specific characteristics are shown in Table 2.

The ITRF2000 is a set of station position and velocities from various space geodetic techniques including VLBI. Such a construct is best served by using the longest time span to maximize the precision of the velocities and by treating all sites as moving linearly. Of particular interest are sites with collocated techniques to allow the integration of the TRF results from SLR, VLBI, GPS and DORIS. In reality some of the VLBI points show evidence of nonlinear movement, at least in some directions. Because of the temporal resolution from the EOP monitoring programs, these motions are most easily seen in the stations of the EOP networks, particularly Fort Davis, Texas and Green Bank, West Virginia. There may also be seasonal variations elsewhere that are not modeled. It should be mentioned that ITRF2000 was derived from analyses done in 2000, so the VLBI analysis configurations were state of the art for 2000.

The ICRF is a set of fixed source positions, formally only those for the 212 defining sources. (In the usual EOP analysis, the positions of all sources are held fixed at a priori values related to the ICRF or are treated as not changing with time.) For the CRF realization the most important considerations are to identify the sources whose positions are the most stable and reliable and to achieve the highest accuracy for their position estimates. An empirical test for stability is the time series of source positions, but generally only the geodetic sources have enough points for statistical analysis. The geodetic sources were not selected primarily for their CRF suitability, however. Astrometric sources are generally weaker radio emitters. Some of the astrometric sources may, in fact, be more stable in position, but with considerably fewer epochs of observation there may be insufficient data to decide. Since the relative positions of the sources in the sky are independent of the station positions, it is not necessary (and may even be deleterious) to estimate TRF positions and velocities in order get CRF information. Consequently, for example, it might be better to ignore the earliest VLBI data, which had a predominance of unstable sources (although this was not done in the ICRF and ICRF-Ext.1 analyses). If, however, TRF positions and velocities are not estimated, i.e., the station positions are estimated independently at each epoch, the terrestrial EOP components are not accessible. Finally, the ICRF analysis was done with the state of the art in 1995. Since the ICRF defining positions are now fixed, systematic modeling effects not included in the 1995 analyses are frozen. By 2000 and ITRF2000 the state of the art had progressed, particularly in modeling the troposphere, so there is a small degree of incompatibility between the ICRF and the VLBI analyses in ITRF2000 as well as an extended data set for the latter

The EOPs relate the CRF and TRF at a particular epoch. In reality the VLBI CRF and TRF at epoch are particular subsets of sources and stations, some of which may not be adequately

modeled by fixed source positions and linear station velocities, respectively. How to treat the imperfect sources and stations at epoch is now being discussed within and among the VLBI analysis groups.

More generally, the direct integration of TRF, CRF and EOP within a single VLBI solution requires a balancing of sometimes conflicting characteristics since the optimization of one aspect may weaken or discard another aspect. However, only VLBI among the space geodetic techniques has the potential of such an integrated solution independent of any other data. An integrated solution requires that at least some stations and sources be treated as moving linearly and fixed in space, respectively. Since there is a range of non-ideal behavior, it is not obvious that a clear distinction can be made that categorizes all sources and stations as ideal or non-ideal over the entire data span.

A conceivable approach, but rather laborious, might use several steps in creating the TRF and CRF followed by analysis of each session for non-ideal source or station behavior. The first step would be to define criteria for non-ideal behavior, perhaps from analyses of time series, to identify sources and stations that cannot be modeled by fixed positions and linear velocities, respectively. The next step would be to estimate TRF positions and velocities and CRF positions for the ideal stations and sources from independent optimized solutions while simultaneously estimating the positions of the non-ideal stations and sources at each relevant epoch. The third step would be to compute average station positions and velocities and average source positions for the non-ideal stations and sources from the resultant time series. Using the ideal and averaged TRF and CRF values, each session would be examined to determine which stations and sources deviated from their "correct" positions at that epoch by more than a specified amount, which might be epoch-dependent since the quality of the raw data has changed. Finally, in the integrated TRF/CRF/EOP solution, the TRF and CRF would be estimated for the ideal stations and sources while at each epoch EOP and the positions of any sources or stations behaving non-ideally at that epoch would be estimated.

Table 2: Desired Reference Frame for

TRF	CRF	EOP
maximum number of site positions and velocities	highest accuracy for positions of best sources	accurate TRF and/or CRF at observing epoch
long time span for precise velocity	minimize effects of network geometry and unstable sources	

4. DIFFERENCES BETWEEN SPACE GEODETIC TECHNIQUES

Table 3 shows characteristics of SLR, VLBI and GPS. The similarities and differences are rather heterogeneous. Certain particularities should be noted. While SLR is nominally continuous observing, most SLR stations do not observe all the time because of costs and weather. This also causes variation of the SLR network from day to day. The orbits of moving targets that define the celestial reference frame for satellite techniques must include VLBI UT1 for long

term stability. The huge number of GPS data effectively precludes frequent reanalysis of the entire data set with uniform modeling and elevation limits. Lower elevation limits permit better separation of troposphere and station vertical. At high latitudes, GPS observations also have a significant empty area at high elevations.

Table 3: Differences between Techniques

item	SLR	VLBI	GPS
data span	25 yr	20 yr	10 yr
observing	continuous	few/week	continuous
network size	few tens	usual 5-6, up to 20	several hundred
network variation	moderate	considerable	minimal
targets	few	50-80/day	24
target stability	moving	fixed	moving
analysis	consistent	consistent	evolved
troposphere	dry	dry + wet	dry + wet
elevation limit	high	low	medium

5. IVS OBSERVATIONS FOR THE FUTURE

Table 4 shows the integrated IVS (International VLBI Service for Geodesy and Astrometry) observing program in 2002 most directly related to EOP and TRF. Of particular interest is the inauguration of two 24-hr sessions per week for EOP monitoring with rapid processing. The networks are shown in Figures 4 and 5. The operational goal is to have EOP values within 15 days of observation. The two days replace the single NEOS day. Two separate baselines for 1-hr intensive UT1 measurements will provide redundancy and robustness. The proposed continuous 15-day period should provide data on the remaining discrepancies of the high frequency EOP variations from oceanic and atmospheric tides. The other sessions will tie the TRF together and provide a limited set of EOP with precision better than the weekly data.

Table 4: Proposed IVS Observing 2002

Two 24-hr sessions per week with rapid processing (IVS-R1, IVS-R4)
15-day period of continuous 24-hr observing
Two baselines for 1-hr UT1 intensives
Six VLBA sessions with large networks
Semimonthly 7 and 8-station 24-hr sessions

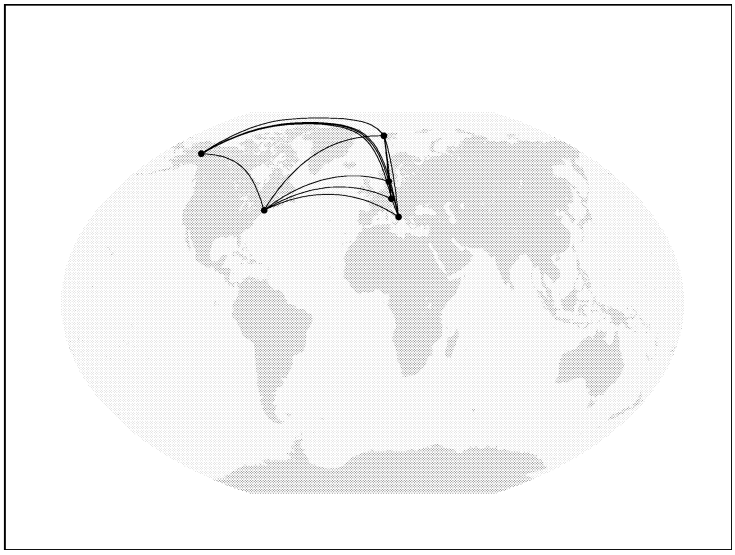


Figure 4: Sites in a representative IVS-R1 session.

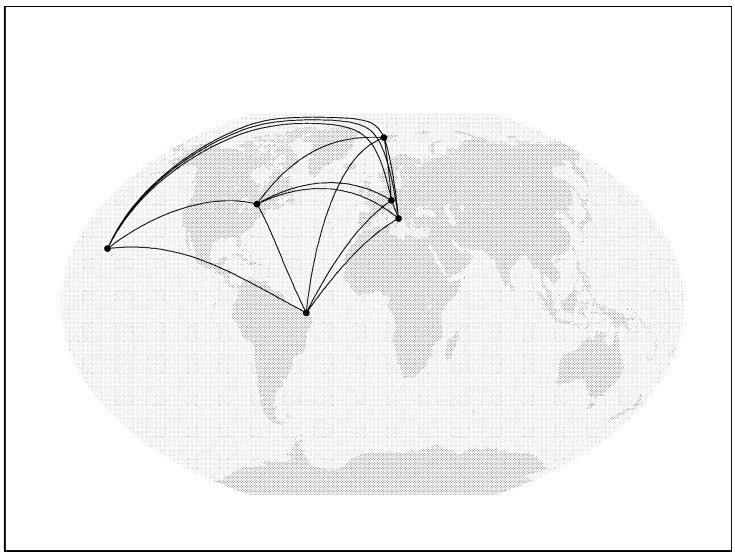


Figure 5: Sites in a representative IVS-R4 session.