THE APPLICATIONS OF VLBI IN GEODESY AND GEODYNAMICS

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The applications of VLBI in geodesy and geodynamics arise from its ability to construct a terrestrial reference frame and a celestial reference frame from geometrical measurements and to determine the relationship between these frames without recourse to other information. VLBI contributes directly to the ITRF, defines the ICRF and provides stable, consistent EOP time series with decadal to subdiurnal resolution. The results derived from VLBI include refinement of plate tectonic and deformation zone models and detection of variations in geophysical fluid motions.

INTRODUCTION

VLBI is a geometrical technique that measures the difference in time of arrival of a wave front at two widely separated antennas with precision of 10–15 picoseconds. The radio emitters observed for geodesy are extragalactic objects, generally quasars, so the wave fronts are planar. A 24-hour geodetic session may observe up to 80 radio sources around the entire sky and include up to 20 stations worldwide. The limitation on the number of sources is related to the sensitivity and slewing speed of the antennas available for VLBI geodesy while the limit on stations in a single observing network is imposed by the size of existing VLBI correlators. Using the set of time differences (delays) from a session the relative positions of the sources and of the stations can be estimated with high precision and accuracy, taking into account such effects as relativity, orbital and diurnal velocity, ground motions from solid Earth and ocean tides, propagation medium delays including tropospheric gradients, atmospheric loading, and station clock behavior. The data from the entire span of dual-frequency geodetic VLBI observations can be analyzed uniformly and concatenated to derive station velocities or time series of station positions and baseline components. While the celestial reference frame of extragalactic radio sources is conceptually fixed in a kinematic sense, in actuality there is some amount of noise and pseudosystematic behavior in the source positions because of changes in source structure. The limit of accuracy of individual source positions is estimated to be 0.25 milliarcsecounds [1], so the celestial reference frame is not the limiting factor for current VLBI applications in geodesy and geodynamics. The reference frame of extragalactic objects measure by VLBI was adopted by the IAU as the ICRF (International Celestial Reference Frame) effective 1 January 1998.

GEODYNAMICAL RESULTS FROM VLBI

The measurements of station positions from VLBI are intrinsically relative to each other since the VLBI delay observable is derived from a baseline connecting two stations. Likewise relative velocities can be derived from the two decades of VLBI data, but for geodynamical interpretation individual station velocities are useful. By suitable no-net-translation and no-net-rotation conditions relative to an *a priori* velocity model, the set of relative velocities can be separated into individual station velocities. In practice the velocity frame of NUVEL-1A NNR is conventionally used with the conditions applied to stations whose relative velocities agree with NUVEL-1A. It should be noted that no vertical velocity condition need be applied, but the applicability of such no-net-translation/rotation conditions requires a global distribution of the specified stations. Figure 1 shows the velocities of selected VLBI stations in the NUVEL-1A reference frame. Since NUVEL-1A NNR is defined geometrically rather than geophysically, all stations show motion arising from their respective plate motion. Figure 2 shows the difference between the VLBI horizontal velocities and the underlying plate velocities. The stations without vectors in Europe, North America and Australia show that these parts of the plates are essentially rigid. In contrast the large vector on the west coast of South America indicates substantial deformation caused by the subduction of the Nazca plate. The differing vector magnitudes and directions in western North America show a more complex pattern: slight deformation in the interior, marked deformation nearer the coast where the North American and Pacific plates interact, a small discrepancy at the coast (this point is modeled as being on the Pacific plate), and a northward deformation near the U.S.-Canada border.

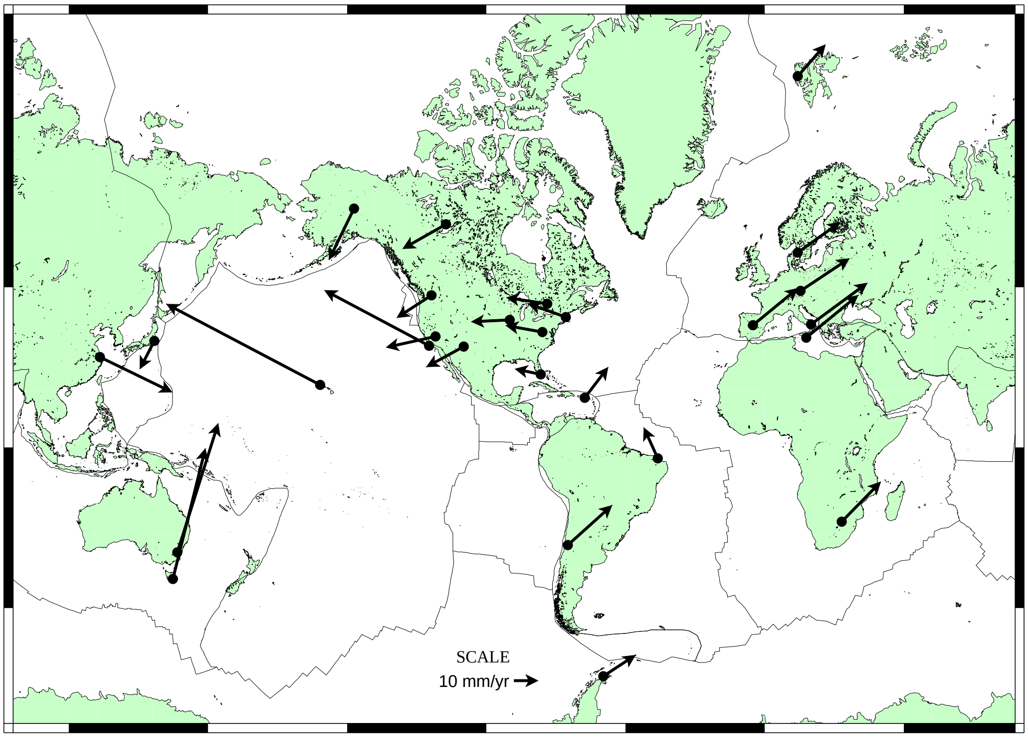

Figure 1: Selected VLBI velocities in the NUVEL-1A NNR reference frame

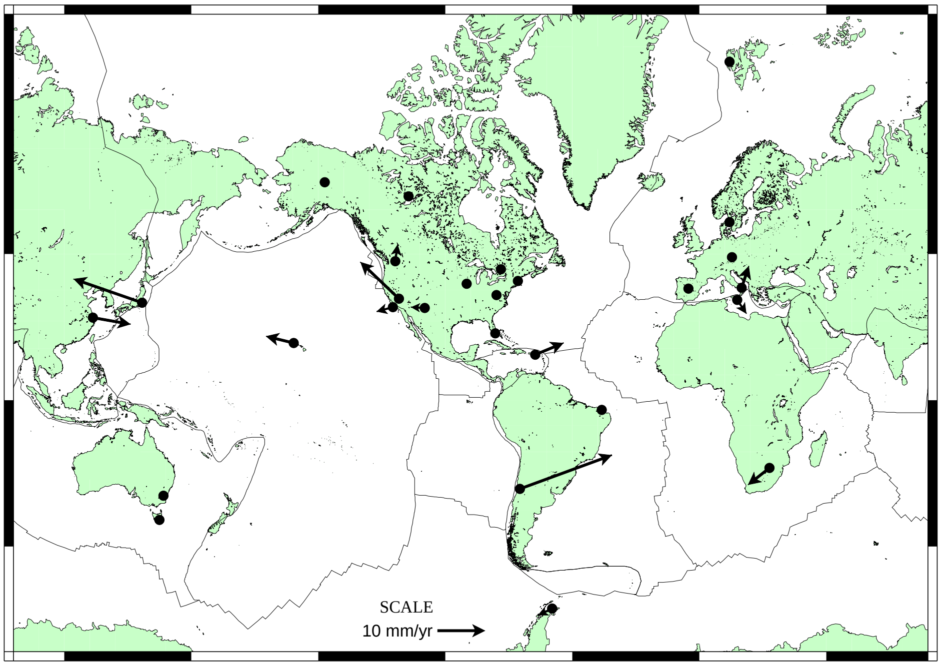

Figure 2: Differences between VLBI velocities and their corresponding plate models. The reference frame is NUVEL-1A NNR. Velocity residuals less than 2 mm/yr are not displayed

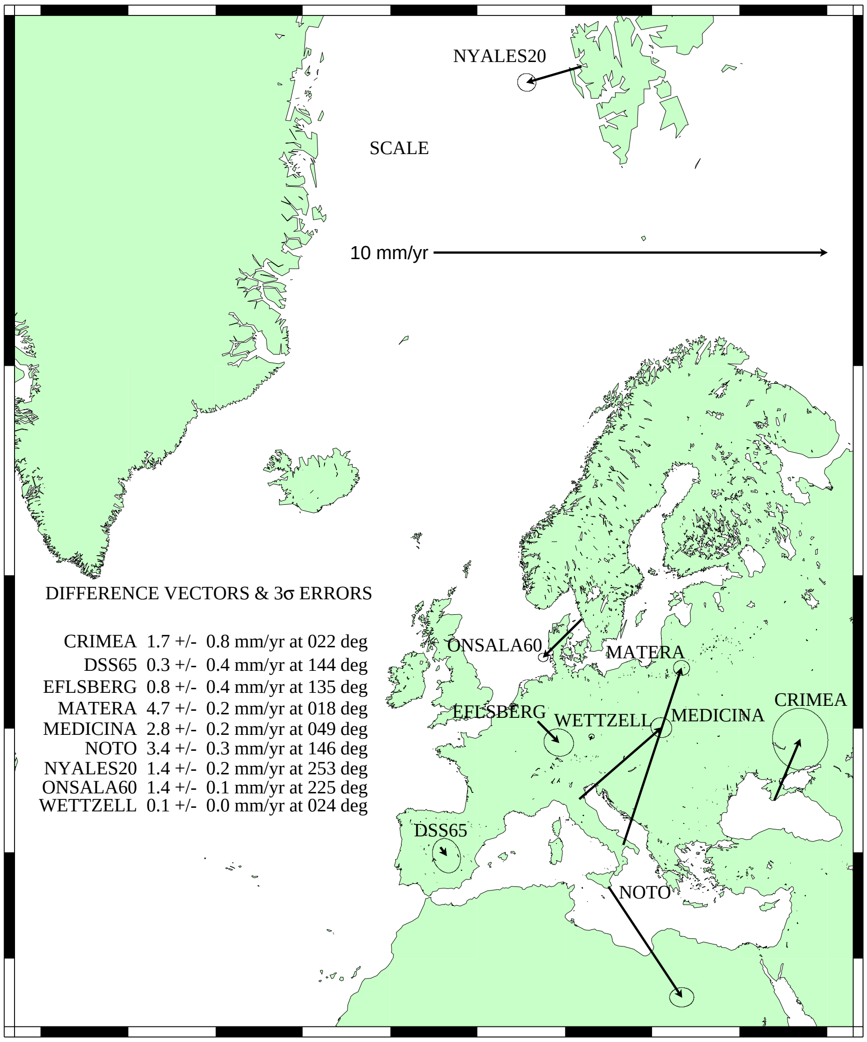

Figure 3: Horizontal velocity adjustments at selected European sites. Differences are from the rigid plate model. The reference frame is NUVEL-1A NNR. Error ellipses are 3σ

The vector in Japan shows the deformation caused by the Pacific plate while the vector on the coast of China is a result of the Indian-Eurasian collision. The vector in the middle of the Pacific probably indicates an overall error in the NUVEL-1A model rather than a midplate deformation, but the vector in South Africa is indicative of intraplate rifting.

Figure 3 shows more details of horizontal motions in Europe. It can be seen that Spain, Germany, Sweden and Spitsbergen are relatively rigid. In Italy the interaction of the Eurasian and African plates causes larger, significant deformations. The station Noto is modeled as being on the African plate. It should be noted that the error related to the reference frame definition, *i.e.*, the choice of stations in the no-net-translation/rotation conditions, is estimated to be 0.4 mm/yr and must be kept in mind in interpreting the velocity of an single station in isolation.

Figure 4 illustrates the ability of VLBI to measure vertical motions. Vertical motions are inherently more difficult than horizontal because of asymmetry; antennas do not point into the ground. In addition, an elevation cutoff around 7 degrees is usually imposed in analysis because of difficulties in properly modeling the troposphere at lower elevations. Formal errors of vertical rates are generally two to three times greater than the corresponding horizontal errors. Nonetheless it can be seen that significant vertical rates are found at Onsala (from post-glacial rebound), at Medicina (probably from ground water withdrawal) and at Ny Alesund (of as yet unknown cause for such a high value).

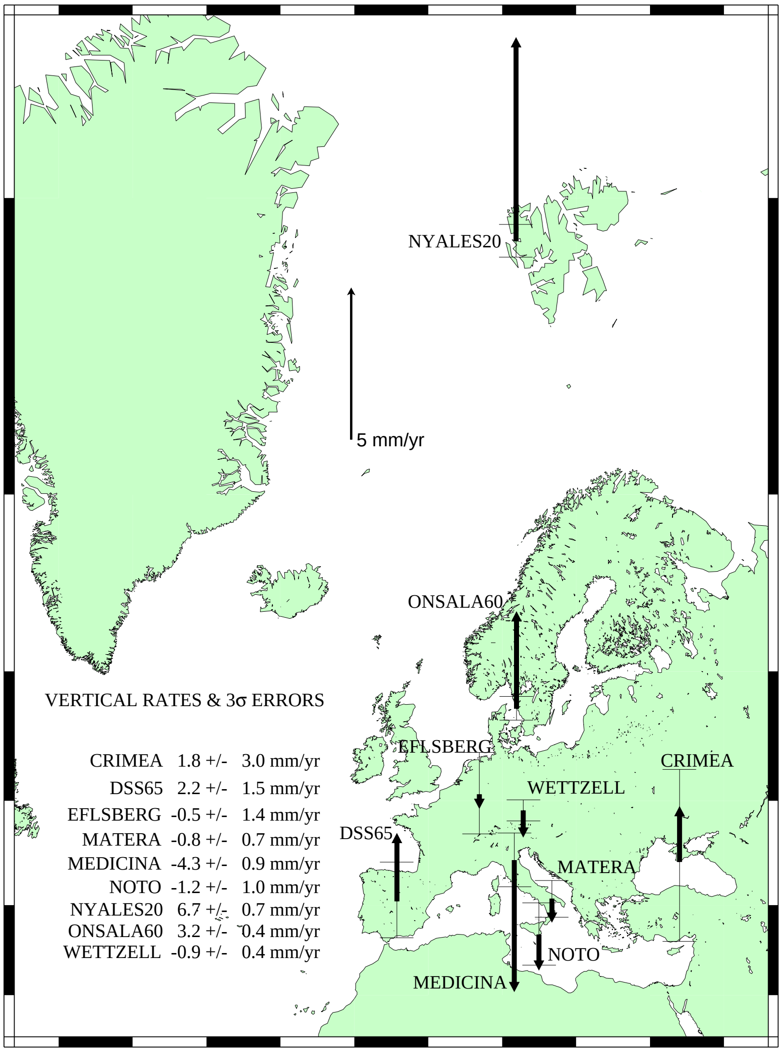

Figure 4: Vertical velocity adjustments at selected European sites. Error bars are 3σ

VLBI AND THE ITRF (INTERNATIONAL TERRESTRIAL REFERENCE FRAME)

Results from VLBI analysis are essential and significant inputs to the definition of the International Terrestrial Reference Frame. Although VLBI has no tie to the geocenter, it provides a self-consistent set of station positions and velocities that can be attached to a geocentric origin by suitable conditions. VLBI analysis centers have contributed regularly to the various realizations of the ITRF. For ITRF2000 three such submissions including 130 stations were used in the combination. The scale of the VLBI terrestrial reference frame depends on the accuracy and completeness of the theoretical delay model and the troposphere model. With recent improvements such as the consensus model in the 1996 IERS Conventions [2], the Niell mapping functions [3], and estimates of tropospheric gradients including *a priori* mean north-south values, the VLBI scale should be accurate at the 1 ppb level. Both VLBI and SLR values were used in defining the scale of ITRF2000.

The two-decade span of VLBI observations provides a long interval for accurate determination of station velocities. Figure 5 shows the precision of VLBI velocities. In general, the triangles (horizontal velocity formal errors less than 0.5 mm/yr) also correspond to currently active stations. The cluster of less precise velocities in Alaska and western U.S. are from measurement with mobile VLBI systems in the 1980s and early 1990s. When projected to the reference epoch of ITRF2000, these mobile positions as well as positions from other now inactive stations like Florida and Chile, have large errors, but some are still useful as collocations between different space geodetic techniques and ties between their respective reference frames.

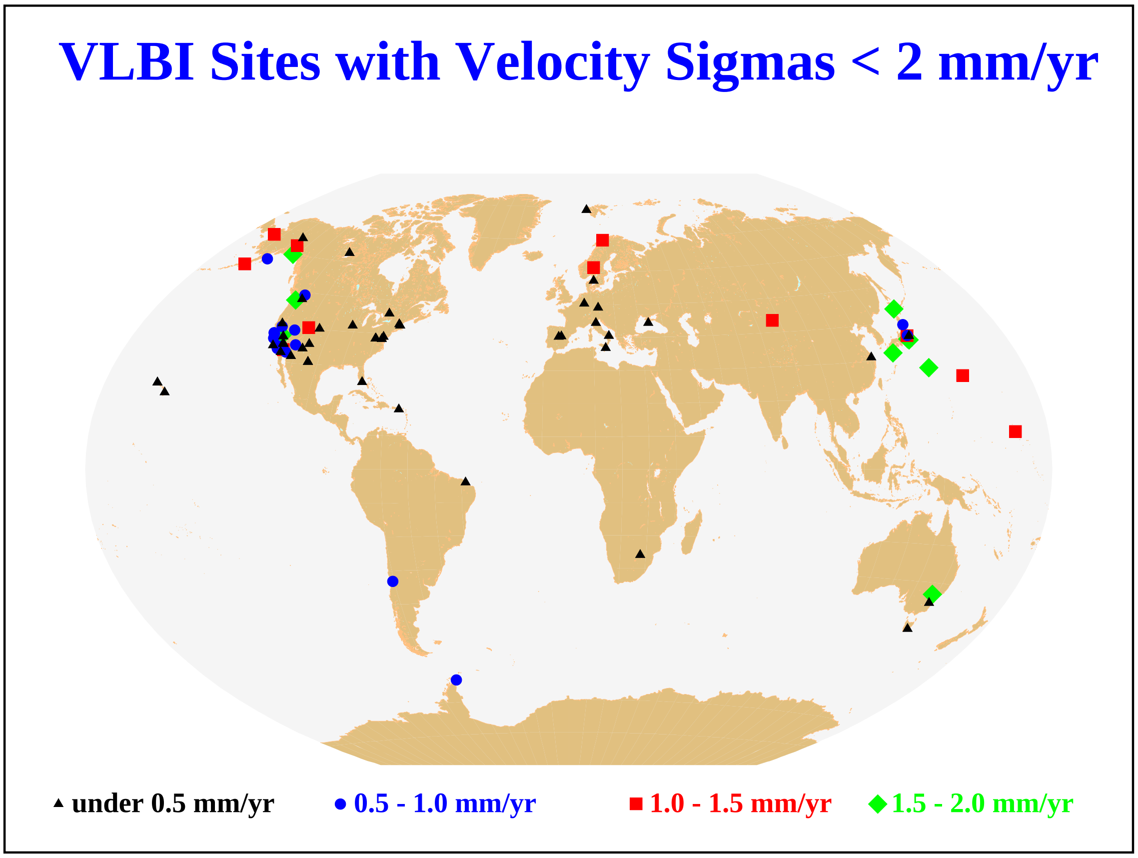

Figure 5: VLBI sites with horizontal velocity sigmas less than 2 mm/yr

VLBI AND EARTH ORIENTATION PARAMETERS

Of the space geodetic techniques only VLBI has direct access to the celestial reference frame. Consequently, any information about long term UT1 and nutation/precession, three of the five Earth orientation parameters, must come from VLBI measurements. Analysis of satellite data like SLR or GPS relies on UT1 from VLBI to align their celestial reference frames, which are the orbital planes. However, because of practical limitations in station availability and correlator capacity VLBI EOP measurements cannot be done continuously, unlike satellite measurements. At present there are between two and three 24-hour sessions per week on average, and increased observing is planned for the future. In addition, there are nearly daily, 2-hour, one-baseline observations for UT1 with reduced precision. Even with uneven temporal resolution VLBI EOP times series have been used to measure variations in atmospheric angular momentum related to seasonal weather and larger disturbances like El Nino/La Nina. The diurnal and semidiurnal bands in UT1, derived from spectral analysis of hourly VLBI time series or by direct estimation of harmonic coefficients, show the effects of ocean tides. The time series of deviations in longitude and obliquity from the 1980 IAU nutation/precision model provided information on the shape and coupling of the core-mantle boundary as well as constraints for the new nutation model adopted by the IAU in 2000.

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