ASTROMETRY AND GEODESY FROM VLBI

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ABSTRACT. Dual frequency Mark III VLBI observations acquired since 1979 by several geodetic and astrometric observing programs have been used to establish precise celestial and terrestrial reference frames. The program to establish a uniformly distributed celestial reference frame of ~400 compact radio sources with optical counterparts was begun in 1987. Some 700 sources have been considered as part of this effort and a preliminary list of ~400 has been observed. At present, 308 sources have formal 1σ errors less than 1 mas in right ascension and 308 have similar precision in declination. The astrometric results include some data acquired for geodetic purposes. The geodetic results using data to September, 1992 include the positions of 105 sites with formal 1σ horizontal errors generally less than 1 cm at 1992.6 and the velocities of 64 sites with formal 1σ horizontal errors generally better than 2 mm/yr.

1. INTRODUCTION

Compact extragalactic radio sources can be used to define a nearly inertial reference frame for measuring both celestial and terrestrial positions and motions. This paper describes the current astrometric and geodetic results of more than a decade of dual frequency Mark III VLBI (Very Long Baseline Interferometry) observations. The network of astrometric/geodetic VLBI stations now extends to all continents. Refinement of models and analysis methods has contributed to improvement of results using the entire data set while enhancements of instrumentation have continued to improve the intrinsic data quality. The astrometric program has made steady progress and will probably be significantly assisted in the northern hemisphere by observations using the VLBA (VLBI Array). Much work remains to be done in the southern hemisphere where the

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availability of VLBI observing time is more limited. Support for geodetic VLBI has been declining, however, and the quality of the terrestrial reference frame may eventually be degraded.

2. OBSERVING PROGRAMS

The current high precision VLBI data set includes nearly one million observations, of which ~95% were acquired primarily for geodetic purposes. The main geodetic programs are the National Aeronautics and Space Administration's Crustal Dynamics Project (which terminated at the end of 1991), its successor the Dynamics of the Solid Earth, the POLARIS and IRIS programs sponsored by the National Oceanic and Atmospheric Administration, and the Navnet program of the U.S. Naval Observatory. The first two programs have concentrated on establishing a global terrestrial reference frame and measuring crustal motions while the latter two have been regularly monitoring Earth orientation. Other smaller efforts include monthly Earth orientation sessions by the National Astronomical Observatory at Mizusawa and mobile observations by the Geographical Survey Institute in Japan and by various European agencies in Europe and the eastern Atlantic. The U.S. mobile activities have been in abeyance since 1991 and the positions of their mobile sites are beginning to degrade with time. The Japanese and European programs generally have insufficient data to usefully determine site velocities at this time. New permanent stations have been added to the international astrometic/geodetic network since 1991 in North America, South America, Antarctica, and eastern Russia, although the last two have not yet contributed useful any useful data. New stations are under construction in western Russia, western China, eastern Brazil and Spitsbergen.

The astrometric program for a global celestial reference frame was begun in 1987 (Johnston et al., 1988) as a joint effort of the Naval Research Laboratory, the U.S. Naval Observatory, and NASA with the cooperation of observatories in Australia, South Africa, and Japan. The purpose was to establish a link between the radio and optical reference frames based on 400 extragalactic radio sources. The sources were to be chosen to be compact, i.e., quasars or compact galaxies, flat spectrum, strong enough to be measured with available VLBI networks (>0.5 Jy) and from prime focus optical plates (m<19), and evenly distributed about the sky. The observations are scheduled regularly in the northern hemisphere and as time is available in the southern hemisphere.

3. DATA ANALYSIS

Our current analysis methods for geodesy are described in Ma et al. (1992) while the corresponding astrometric methods are described in Ma et al. (1990). The differences arise from the perceived need to generate and expand the radio source catalog without changing previously published precise positions as new sources are added or improved. While each new geodetic analysis is done with the most recent models and methods, the methodology for astrometric analysis has been frozen for the series of papers beginning with Ma et al. (1990). The differences include the relativistic formulation of the VLBI theoretical model, the tropospheric model, and the parametrization of the site clocks and tropospheres. Each new astrometric analysis is an incremental solution using the previous result as input, while each geodetic analysis re-uses the entire geodetic data set. The initial astrometric catalog was generated with both geodetic and astrometric data. Only astrometric data were added in subsequent incremental solutions. It should be noted that both geodetic and astrometric solutions adjust a correction to the nutation angles for each day except the reference day. We expect to re-analyze the complete astrometric and geodetic data using the best models to establish a state-of-the-art radio/optical catalog prior to the next IAU General Assembly.

4. ASTROMETRIC RESULTS

Using VLBI we have so far obtained observations of 417 sources and have published positions for 287 of them (Ma et al. 1990, Russell et al. 1991, Russell et al. 1992, Fey et al. 1992). The next three publications are in progress and will add 117 new sources as well as improved positions for 122 of those already published. The distribution of all of these sources is shown on an Aitoff projection plot in Figure 1 and the distribution of 1σ formal errors is shown in Figures 2 and 3. These results do not include the 1992 observations. Optical observations are more difficult to obtain but have progressed far enough for us to recommend the list of extraglactic sources which should replace the original radio/optical list of the IAU working group (Argue et al. 1984). The breakdown of the 301 best sources is given below.

N	Description	Total
187	Quasars, m < 20	187
17	Quasars, 23 > m > 20	204
40	BL Lac, 39: m < 20	244
17	Galaxies, 15: m < 20	261
9	Empty fields, strong radio	270
31	Misc	301

The 187 quasars with optical counterparts brighter than 20th magnitude are the ideal sources for linking the radio and optical reference frames. The other sources in the list are exceptions and additions to the list to fill in where ideal sources are not available. In some cases we are taking advantage of geodetic sources with extensive VLBI observations to strengthen the radio reference frame. The miscellaneous sources are those which have incomplete or conflicting information in our data base and we are working to complete or correct data for those entries. Of the 404 positions which have been published, or which are in preparation for publication, 308 have errors less than 1 mas in right ascension and 308 in declination. Fifty-two sources have errors in either coordinate greater than 4 mas; 46 of these have been observed only on short baselines (and are not included in Figures 2 and 3) but have been scheduled for

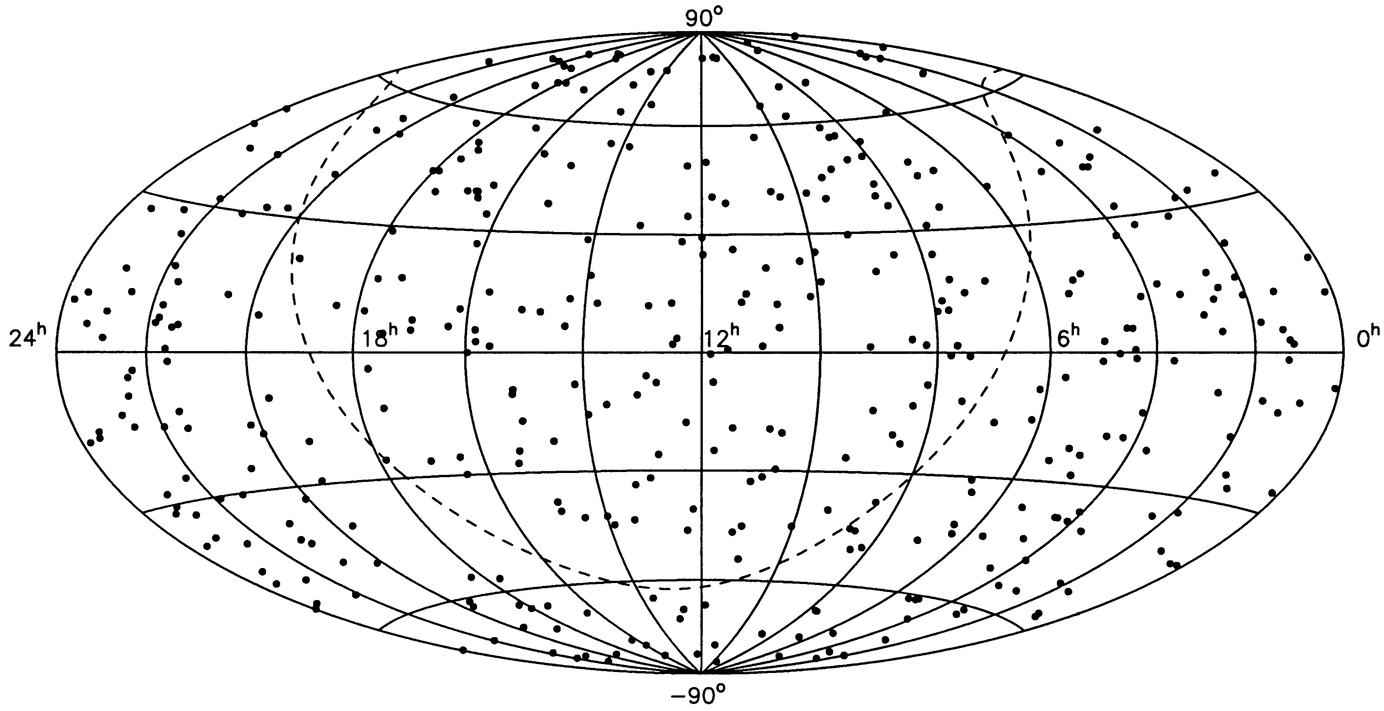

Figure 1. Radio sources observed with VLBI for the celestial reference frame. Dashed line is the galactic plane.

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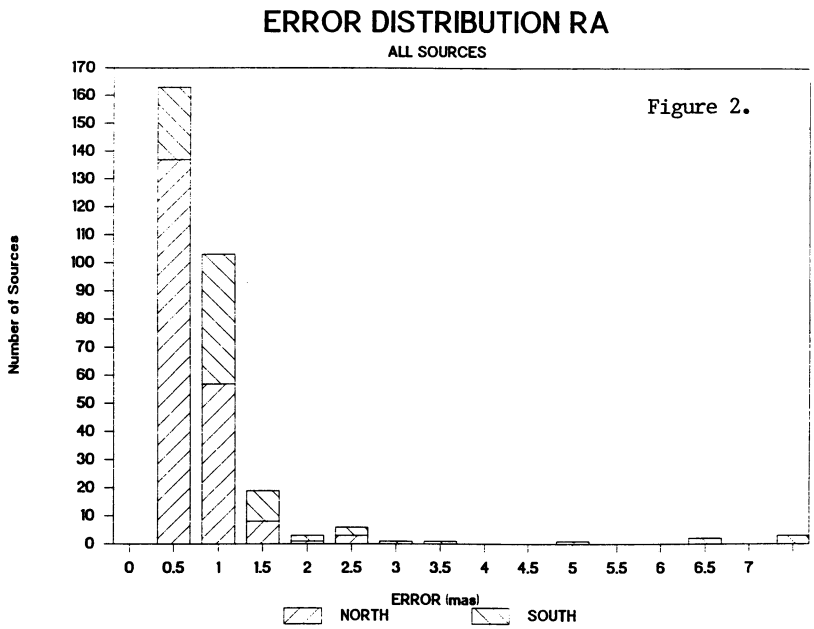

Figure 2.

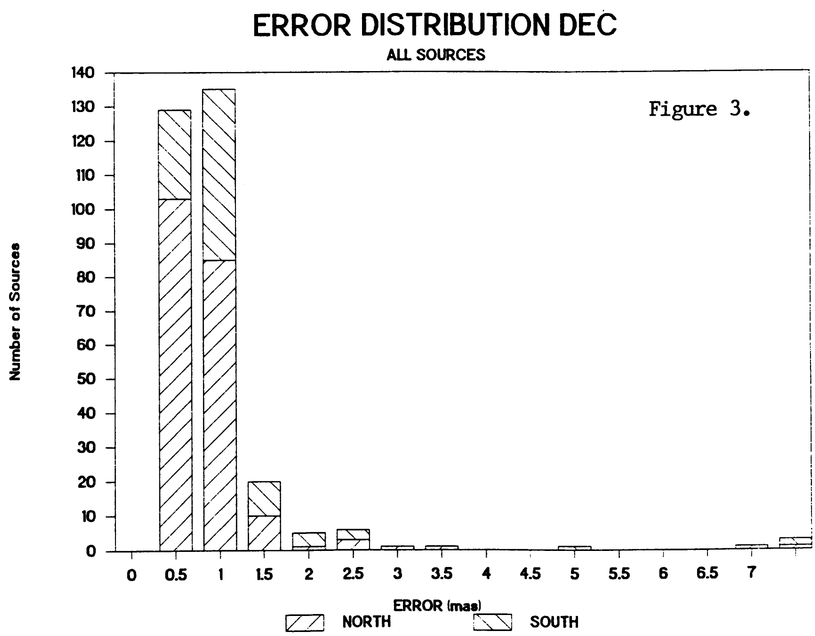

Figure 3.

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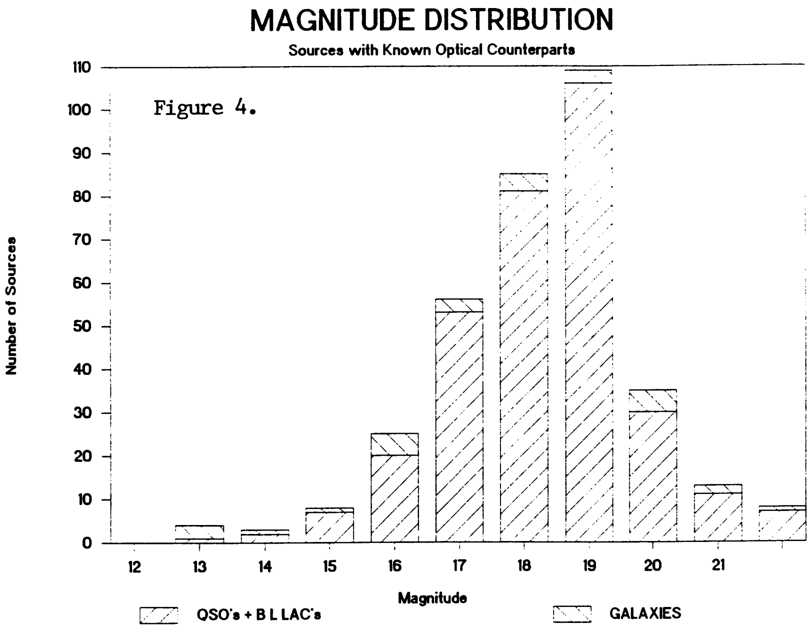

Figure 4.

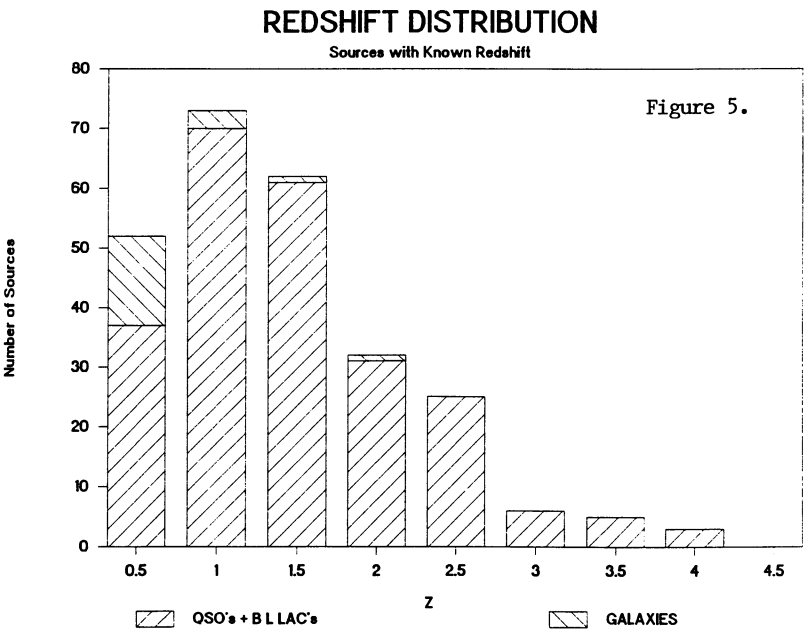

Figure 5.

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additional observations on longer baselines. We expect their position errors to approach those of the others with the analysis of the new observations. The magnitude and redshift distributions of the sources for which we have that information are shown in Figures 4 and 5, respectively.

5. GEODETIC RESULTS

The current topcentric precision of VLBI fixed and mobile site results is shown below. The fixed sites have permanent antennas from 9 m to 100 m in diameter with a preponderance in the 20-34 m range. The mobile sites were visited by smaller, self-contained VLBI systems with antennas between 3-5 m in diameter.

Error in mm and mm/yr (1σ)	<1	1-2	2-3	3-4	4-5	5-10	10-20	>20	tot
Fixed site error up :	0	3	4	3	5	15	9	5	44
Mobile site error up :	0	0	0	0	0	5	18	37	60
Fixed site error east :	5	12	8	4	1	9	4	1	44
Mobile site error east :	0	7	16	16	7	9	4	1	60
Fixed site error north :	4	8	5	6	5	11	4	1	44
Mobile site error north :	0	1	9	12	18	14	5	1	60
Fixed velocity error up :	11	7	3	4	4	0	1	0	30
Mobile velocity error up :	4	0	0	3	1	18	5	2	33
Fixed vel. error east :	23	5	3	0	0	0	0	0	31
Mobile vel. error east :	25	5	3	0	0	0	0	0	33
Fixed vel. error north :	21	7	2	1	0	0	0	0	31
Mobile vel. error north :	19	9	4	1	0	0	0	0	33

These formal 1σ position errors are at 1992.6, propagated using the site position/velocity covariance from VLBI if available, or at the mean observation epoch if there are insufficient VLBI data to determine velocity. The reference frame is defined by a fixed position for Westford, Massachusetts and a fixed vector direction between Westford and Richmond, Florida. The vertical rate of Kauai, Hawaii is also constrained to be zero. Figures 6-9 show the velocities in this reference frame, which is conceptually attached to the stable, eastern part of the North American plate. The error ellipses are three formal sigmas. Figure 10 shows the velocities in Europe relative to Wettzell, Germany with the vector direction between Wettzell and Onsala, Sweden held fixed. The solid triangles on each figure indicate sites for which the VLBI data are insufficient to determine a velocity, usually because the time interval is too short. Data acquired from O'Higgins, Antarctica and Ussurijsk, Russia have not been of useful geodetic quality and these stations are omitted. (Also omitted to save space are two sites in Chile, without measured velocities, and one site in South Africa.)

It should be noted that there are 104 sites summarized above. The site at Fort Davis, Texas is absent because its anomalous behavior at the few cm level cannot be modeled as a uniform linear motion. Its position

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Figure 6 Eastern North American velocities, Westford reference site, Westford–Richmond azimuth fixed.

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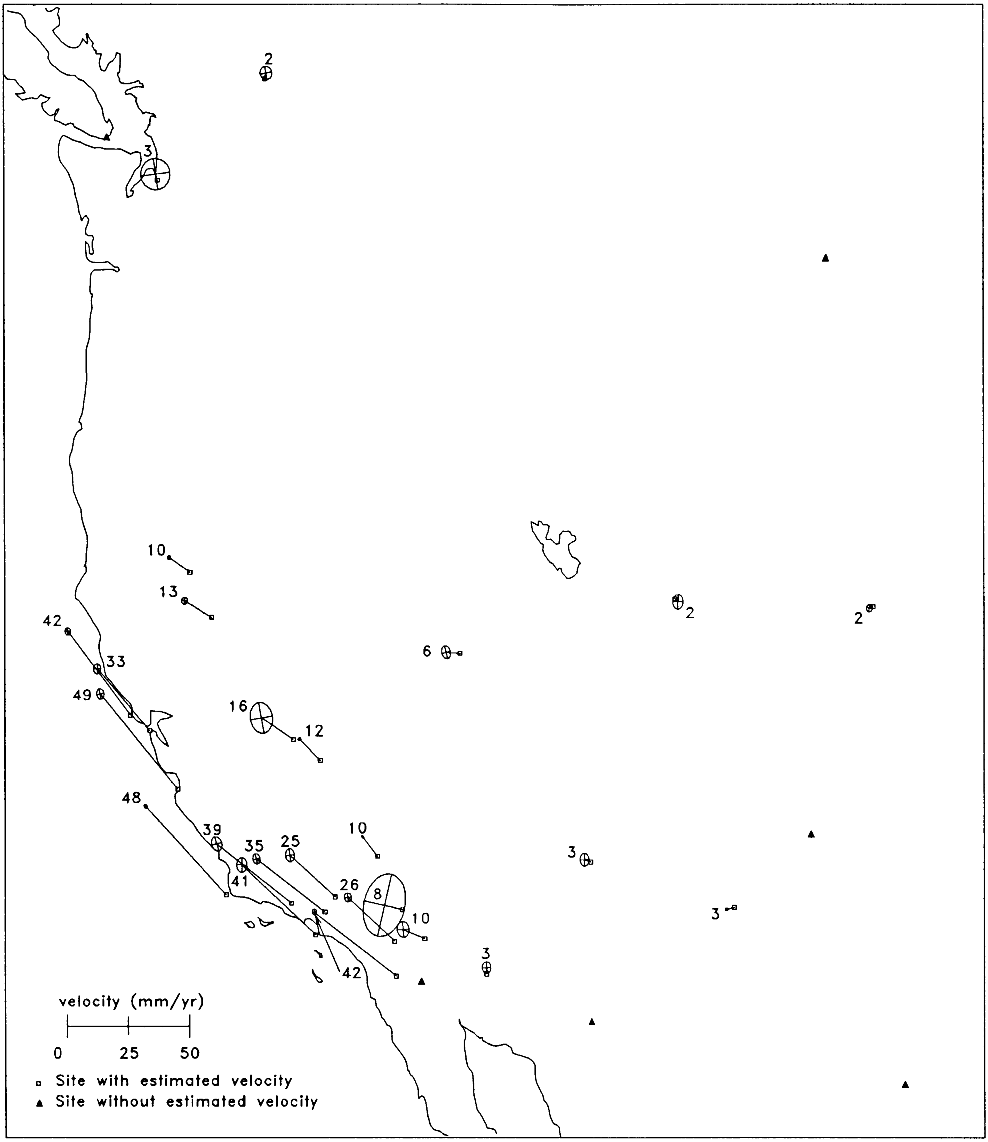

Figure 7 Western North American velocities relative to stable North America.

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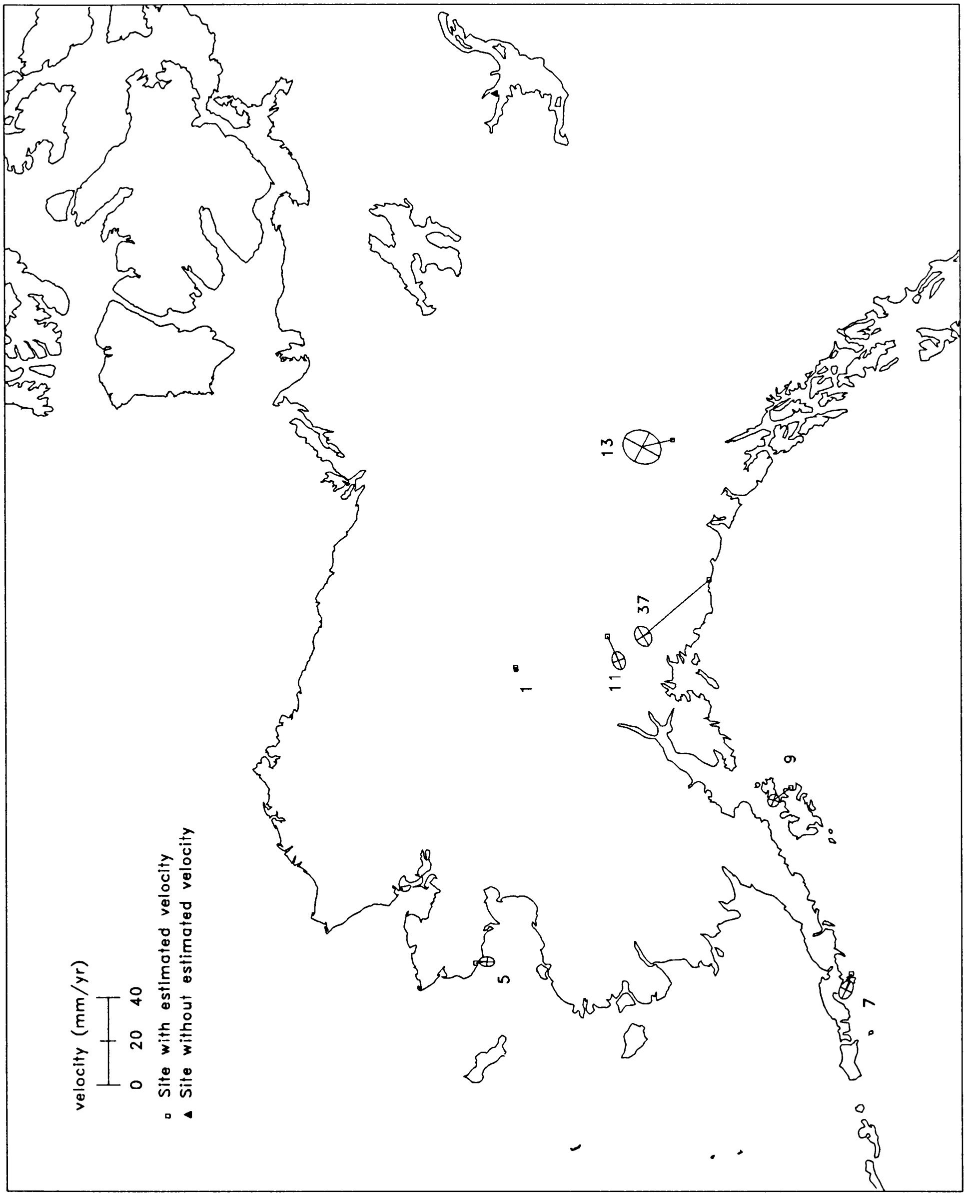

Figure 8 Alaskan and northwestern Canadian velocities relative to stable North America.

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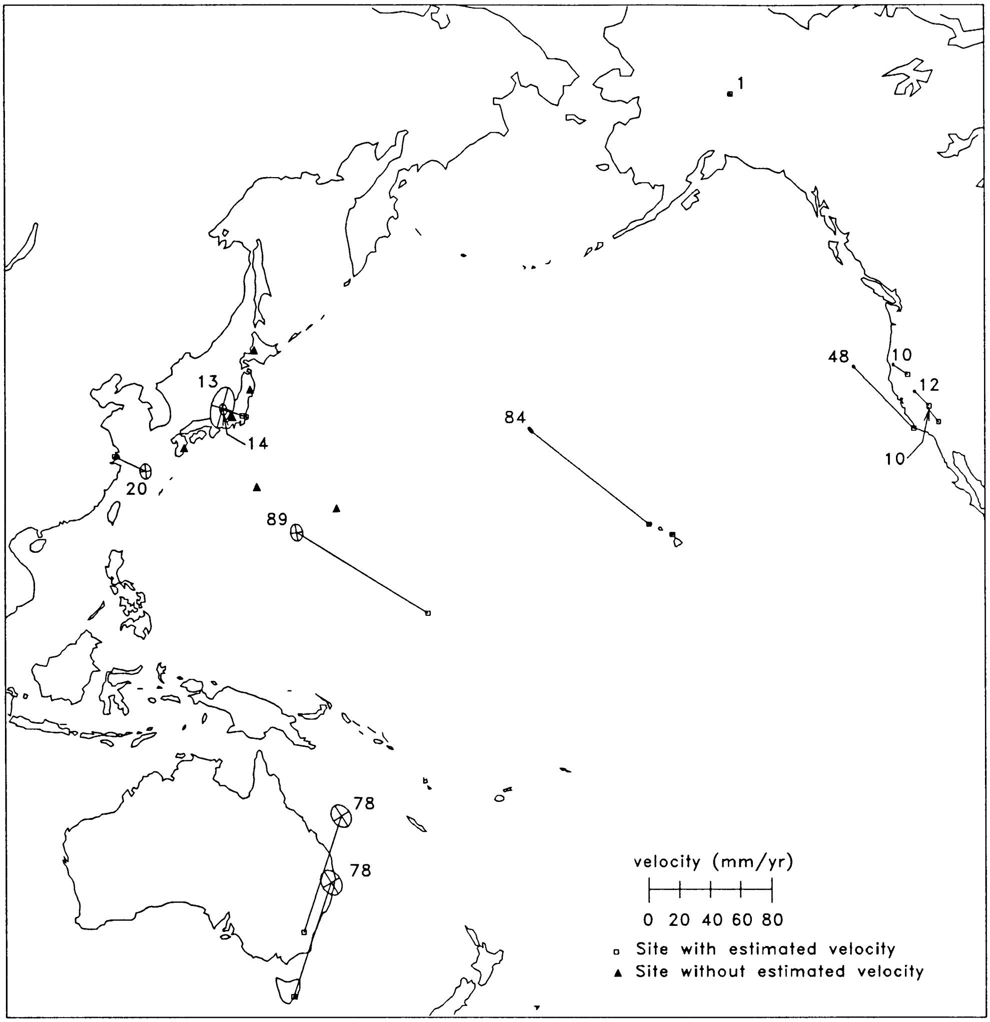

Figure 9 Pacific velocities relative to stable North America.

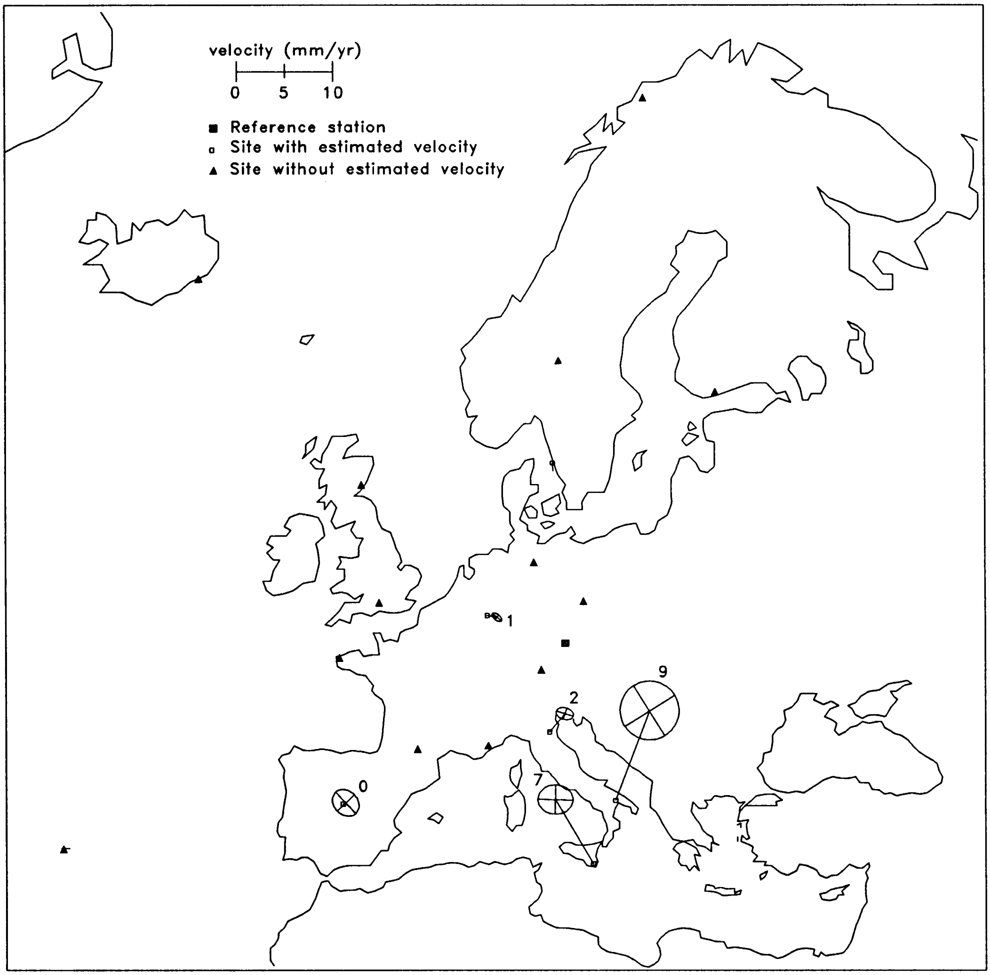

Figure 10 European velocities, Wettzell reference site, Wettzell–Onsala azimuth fixed.

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is parametrized in the solution by a piecewise linear, continuous function with two-month linear segments. Sites in Alaska and California that have discontinuous motions because of earthquakes are parametrized with a velocity that is the same before and after the coseismic motion while the positions before and after are estimated separately.

Because of changing program priorities, mobile VLBI observations in North America have been stopped. The existing mobile systems are being used to densify the fiducial network in Europe, and programs are planned in Africa, an area where space geodetic measurements have been lacking.

6. CONCLUSIONS

The past and continuing astrometric and geodetic VLBI observing programs have produced precise realizations of the celestial and terrestrial reference systems useful for many areas of research. The two efforts are strongly coupled and mutually supportive. The future astrometric activities should result in a definitive radio/optical catalog as the fundamental definition for celestial positions. Expansion and maintenance of the VLBI terrestrial reference frame will be subject to budgetary limitations and program priorities.

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