REFERENCE FRAMES IN ASTROMETRY

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Abstract. Present and near future advances in astrometry at radio and optical wavelengths will allow at least an order of magnitude increase in the precision with which fundamental reference frames are defined compared with those available ten years ago. A brief review is given of the present status of fundamental celestial reference frames with a view towards defining the problems encountered in establishing a fundamental reference frame and methods of linking these reference frames. An estimate is made of the progress to be made in reference frames over the next ten years.

1. INTRODUCTION

The establishment of reference frames in astrometry is now approaching unheard of accuracies. The measurement of positions at radio frequencies is at the milliarcsecond level for large angles (> 45 degrees). With the advent of HIPPARCOS, the accuracy of optical positions of 100,000 selected brighter stars will reach a few milliarcseconds. At the present time there appears to be discrepancies in the optical FK4 reference frame of order tenths of an arc second in the northern hemisphere. In the southern hemisphere this situation appears to be more severe, especially at the south polar cap. The advent of the FK5 reference frame and the availability of the SRS catalog on the southern sky will hopefully decrease systematic errors of the reference frame to levels below 0.1 arcseconds over the entire sky. Therefore the optical reference frame will be inferior to the present radio reference frame in the northern hemisphere. This situation is reversed south of declination -40 degrees as precise radio measurements have not yet been made. Before space based astrometric measurements become available, detailed knowledge of the relationship of the optical and radio reference frames can lead to an improvement in the optical reference frame in the northern hemisphere. In the southern hemisphere both improved radio and optical measurements are needed. Here we will attempt to evaluate the present status of radio and optical reference frames, describe methods

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of linking these reference frames and estimate what the next ten years will bring in improved reference frames.

2. THE RADIO REFERENCE FRAME

Radio astrometry is evolving rapidly. In the last ten years radio astrometry has shown that accuracies of order milliarcseconds can be achieved over large arcs. This technique is now used to monitor earth rotation parameters on a routine basis. The precise radio catalogs appear now to be limited only by our knowledge of astronomical constants dealing with the motions of the earth, the earth-moon barycenter, the sun, etc. Other motions such as polar motions need to be monitored constantly. The best available radio catalogs at this time are based upon long term VLBI monitoring programs. These are described in Fanselow et al. (1984) (JPL 832), other JPL catalogs (JPL 86), Ma et al.(1986) (CMA), and Robertson et al. (1986) (POL). The quoted errors in these catalogs are as low as 0.1 milliarcseconds.

From the results of earlier catalog comparisons (de Vegt and Gehlich 1982) and the problem of not adopting a definitive precession constant in these catalogs, it is expected that a rotation between any two catalogs will occur. Comparison of these catalogs indicates that this is true. A small rotation of the form:

$$\Delta\alpha'' = -a_{12} - a_{13}*\sin(\alpha)*\tan(\delta) + a_{23}*\cos(\alpha)*\tan(\delta)$$
$$\Delta\delta'' = -a_{13}*\cos(\alpha) - a_{23}*\sin(\delta)$$

is found between these catalogs. The magnitude of the rotation terms are of order milliarcseconds and are listed in Table 1 together with their mean errors which are listed below the rotation terms. The quoted parameters are from a weighted solution; weights have been adopted from the squared sum of individual m.e. of both catalogs. The number of sources in common is denoted by N. In the last column, the mean error of unit weight is given, computed from a unweighted solution, it is in good agreement with the adopted m.e. as quoted in the individual catalogs.

Table 1. ROTATION BETWEEN RADIO CATALOGS (Unit = 1 mas)

Catalog Diff.	a_{12}	a_{13}	a_{23}	N	Sigma
JPL86-C.MA	-1.9	-0.1	-1.6	47	25
	0.2	0.3	0.3		
JPL86-POL	-1.2	0.3	-0.7	19	25
	0.3	0.4	0.4		
C.MA-POL	1.0	-0.4	0.7	26	11
	0.1	0.1	0.1		
JPL832-C.MA	-1.5	-3.3	-1.0	47	41
	0.4	0.5	0.5		
JPL832-POL	-0.8	-3.5	-0.5	18	37
	0.6	0.7	0.7		
JPL86-JPL832	-0.5	2.7	-0.5	101	41
	0.3	0.3	0.3		

The parameters from the unweighted solution do not deviate substantially from the weighted solution, furthermore the solutions were stable against weight changes for single sources. Although the parameters are small, they are significant. The differences of these catalogs after removal of these rotations still appear to display systematic differences that are larger than the quoted errors in the individual catalogs. The scatter in right ascension versus residuals does not appear systematic. In declination versus residuals we see the definite signature of an error in the Bz term of the baseline or atmospheric effects. The most significant result is the systematic pattern in the declination residuals ($\Delta\delta$) versus declination plots, for example Figure 1 displays JPL832-CMA.

A common feature is that all differences become larger with decreasing declination, especially south of -20 degrees. This is due to the fact it is difficult to separate the position in declination from the polar baseline length and atmospheric effects. The present VLBI data were obtained almost entirely with predominately east west baselines in the northern hemisphere.

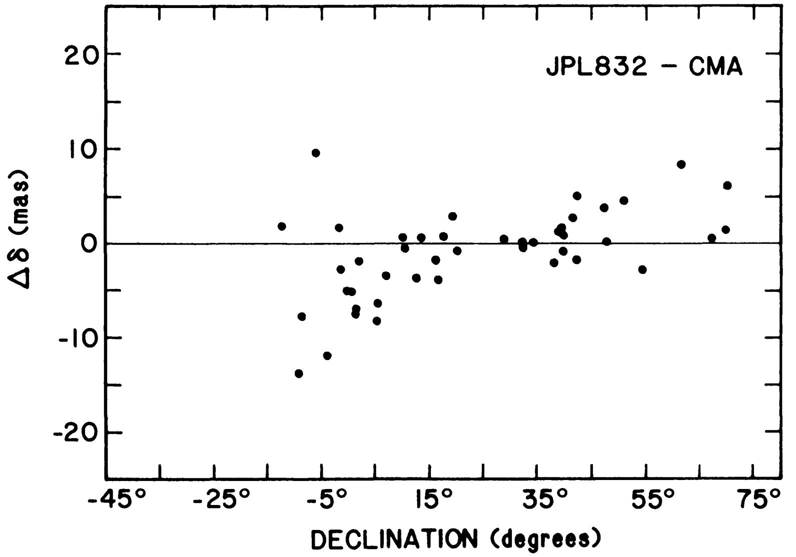

Figure 1. The differences in declination between the catalog of Fanselow et al. (1984) and that of Ma et al. (1986) versus declination.

The best overall agreement is found between the JPL86 and CMA catalogs, having the greatest number of sources in common and covering the largest declination range.

One of the shortcomings of radio astrometry is that it is not global in

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nature. Most VLBI nets are concentrated in the northern hemisphere. Thus the most accurate catalogs contain only sources in the northern hemisphere. Below -40 degrees declination, there are no positions accurate to better than 0.1 arc seconds. There is a great need for a global VLBI net which can achieve comparable accuracies over the entire hemisphere.

3. THE OPTICAL REFERENCE FRAME

The VLBI global extragalactic reference frame has already reached mas accuracy in the measurement of large arcs between radio sources, whereas in the optical domain no comparable level of accuracy is available. The present stellar fundamental reference frame is still based on the FK4 which contains only 1535 mostly bright stars. Besides the problem of random accuracy, systematic regional errors in the FK4 are severe, especially in the southern hemisphere. Both independent reference frames differ by at least a factor of fifty in systematic accuracy. The expected availability of the FK5 at the end of 1986 will change this situation only partly. Three major changes characterize this transition: a) the inclusion of many recent epoch absolute and relative transit circle catalogs will improve the individual positions and proper motions significantly, b) systematic position and magnitude dependent regional errors in the positions and proper motions especially in the southern hemisphere will be removed and c) the transition to J2000 will be accomplished. In a second step eventually several thousand additional fainter stars with good observational history will be added to the 1535 primary stars.

One of the fundamental differences of the radio and stellar reference frame is the proper motion of the objects that define the frames, i.e., most stars have proper motions of order arc seconds to milliarcseconds while no significant proper motions have been detected for extragalactic objects. Therefore, due to the law of error propagation, the accuracy of any stellar position is time dependent, decreasing with increasing time from the mean epoch of observation. The expected accuracy of the FK5 positions and proper motions will be about 0.03 arcseconds and 0.0005 arcseconds/year at epoch 1986 (Astronomisches Rechen-Institute Heidelburg 1986). Even if the final FK5 should contain about 5000 stars globally, the density and magnitude range is not adequate for the general purpose of determining positions of objects anywhere on the sky. Based on the fundamental stars as the principal primary reference frame, several large catalogs have been constructed in the past from internationally coordinated transit circle campaigns to provide a more dense net of reference stars for the determination of the photographic positions of faint objects. Those catalogs, for instance the AGK3R and the SRS, provide a density of about one star/square degree and are strictly on the FK4 system. However the original epochs are 1960 and 1968 respectively, thus the accumulation of proper motion errors now gives positional errors of 0.20 and 0.15 arcseconds, in addition no definite proper motion system is available for the SRS (Smith 1980 and Smith and Jackson 1985). Combining these two main catalogs to the international reference system (IRS), a global pole-to-pole reobservation campaign has been started at USNO with the 6-inch transit circle (Washington) and the 7 inch transit circle (New Zealand) to observe the about 40,000 stars in a fundamental manner (Hughes 1982), results cannot be expected before the early nineties.

Going to fainter magnitudes the situation is still worse, the northern hemisphere is covered by the AGK3 whereas in the southern hemisphere the CPC2 awaits its final reduction (Nicholson et al. 1984). These catalogs provide a density of about 10 stars/square degree down to about magnitude 10. Present accuracies are about 0.5 and 0.17 arcseconds respectively. No homogeneous position catalog exists for fainter magnitudes. In summary, with the exception of the FK4/5 itself, there are no stellar positions better than 0.1 arcseconds at present although special astrometry programs in particular areas can easily reach 0.01 arcseconds (de Vegt 1982). Great efforts are urgently required to alter this unsatisfactory situation.

With special emphasis on a global reference frame substantial improvement in this situation will be achieved by applying space-based astrometric techniques. The HIPPARCOS satellite promises to achieve a global stellar net of 100,000 stars with an accuracy of 0.002 arcseconds and proper motions of 0.002 arcseconds/year at mean epoch 1990. This is to be accomplished by scanning the sky with constant speed and changing orientation at a fixed angle. This technique uses the superposition of two fields of view in the telescope image plane, separated by a fixed angle of 58 degrees. The two fields are superimposed by using a complex mirror. The technique is very similar to interferometric techniques which uses a fixed angle such as POINTS which is 90 degrees. In contrast to the HIPPARCOS mission where the integration time is limited by the scanning speed, the interferometric techniques allow long dwell times on sources which allows fainter magnitudes to be reached and in particular direct observations of extragalactic objects may be made. The expected accuracy of such techniques will be limited only by source structure. It can be envisioned to achieve accuracies of order 0.0001 arcseconds. If the density of such a net is sufficient, these accuracies can be reached for any faint magnitude object by interpolation using an astrometric telescope in space. With a suitable field which must contain two primary net sources together with the object, such relative measurements may reach microarcsecond accuracy.

In principle, ground-based astrometric techniques have the potentialities to reach 0.01 arcsec accuracies in moderate fields < 10 degrees diameter, for very small fields even mas accuracies are possible. The fundamental problem of ground-based work is the determination of large, global arcs, this task, today exclusively executed by transit circles, is severely limited by the refractive properties of the earth's atmosphere. Here a fundamental gain can be achieved in the future by space-based techniques.

The following table summarizes the situation for the optical reference frame for a foreseeable future. It is obvious that ground-based catalog work has to be speeded up substantially and extended to fainter magnitudes to meet the requirements of the coming space age.

TABLE 2

PROPERTIES OF OPTICAL REFERENCE STAR CATALOGS

	Primary Catalogs				
	ground based			space based	
	1986	1990	1995	1993	> 1995
Global	FK4	FK5	FK5	HIPPARCOS 100,000 stars	Space Interferometer stars, quasars
Northern H.	AGK3RN	AGK3RN	USNO pole-to-pole TC catalog (IRS)		
Southern H.	SRS	SRS			
	Secondary Catalogs (mag < 12)				
Global	....	....	....	Tycho, 10^6 stars	????
Northern H.	AGK3	AGK3	AGK3		
Southern H.	CPC2	CPC2	USNO		
	Catalogs of Faint Stars (mag > 14)*				
Global	HST Guide Star Cat 20,000,000 stars			??????	??????
Northern H.			POSS CIT/USNO		

* only survey accuracy (~ 0.3 arc seconds)

4. LINKING THE REFERENCE FRAMES

The radio reference frame is defined by extragalactic compact radio sources which do not necessarily have optical counterparts. The direct transformation between both systems is therefore restricted to such sources which display optical counterparts which are faint optical sources. Optical positions of such link objects in the FK4 system can be obtained from direct photography using large reflectors in the prime focus mode. Reference stars of intermediate brightness are then needed to determine the source position on the prime focus plates relative to the secondary net of the AGK3RN and the SRS. The intermediate frame is usually obtained from wide angle astrograph plates. Special techniques have to be used to bridge the considerable magnitude interval between the primary FK4 and the faint object. However the number of suitable link candidates on the whole sphere is only about 200 at present. This technique assumes that the regional errors in the optical frame are smooth enough to allow interpolation between control points. Work is underway to achieve this (Johnston et al. 1985).

Stars which display radio emission provide a direct link if their radio positions can be determined precisely with respect to the radio reference frame. The problems of proper motion, parallax, double star nature and location and structure of the radio emission with respect to the optical photocenter hinder a direct comparison. Only a few radio stars are themselves FK4 stars. From extended VLA programs it appears obvious that the number of suitable radio stars may be as small as 75.

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Because the ground based net of fundamental stars contains regional errors, the required number of radio stars is prohibitively large if the errors are to be reduced to a level 10 mas. The proposed HIPPARCOS satellite will for the first time generate a rigorous internal stellar net. Therefore it is expected that only a small number of radio stars will be necessary to define the orientation of this net to the radio reference frame. As a complication, the HIPPARCOS stellar net rotates. To determine the rotation, either absolute radio proper motions of the link stars are required or the rotation must be determined independently from other means such as the HST fine guidance system measurements of the relative motion of HIPPARCOS program star-quasar pairs.

5. FUTURE

The radio reference frame is well defined by extragalactic radio sources. The accuracy of radio interferometric techniques has been demonstrated at near milliarcsecond levels. It remains however to be seen whether the radio reference frame will truly become a global reference frame at these levels of accuracy.

The optical reference frame at present is defined by stars moving in the galactic system. Until the optical reference frame is defined by objects which display no proper motion such as quasars, it will deteriorate with time from its mean epoch. Future space-based instruments which are capable of directly observing an extragalactic optical net will solve this problem. Thus the radio reference frame will remain the most accurate reference frame in the near future.

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DISCUSSION

R. King: How independent are the JPL and GSFC or NGS radio catalogs?

Reply by Johnston: The JPL and GSFC/NGS catalogs are independent in that they were made using different telescopes and data reduction packages. The GSFC and NGS catalogs were made using the same hardware and software. However, different subsets of extragalactic radio sources make up these catalogs.

Reply by ?: The "POLARIS/IRIS" Source Catalogue published in *Astronomical Journal* paper by Robertson et al. was the direct output of adjustment of POLARIS–IRIS observations only, without reference to JPL–GSFC results. The POLARIS–IRIS observations are certainly included in the data set used by GSFC, but to the best of my knowledge, not in the JPL data set. POLARIS–IRIS and GSFC solutions should be completely "independent" from the JPL solutions.

R. Treuhaft: So many systematic errors in VLBI are correlated. The $\Delta\delta$ vs. δ problem could be connected with the atmosphere. We have been able to simulate some of the $\Delta\delta$ vs. δ systematic errors in the catalog comparison (JPL86E–JPL832) by assuming reasonable atmospheric errors, so we may get to the bottom of this problem soon. We have not yet been able to eliminate the problem with improved atmospheric modelling.

Reply by Johnston: Yes, this could be an error source that could contribute to this effect.

G. Kaplan: When will the FK5 be available?

Reply by Hughes: The 1535 star FK4 stars should be available on **FK5** in the winter of 1986-1987. The additional stars of which there are approximately 5,000 will be available later.