SOME CONSIDERATIONS IN THE USE OF VERY-LONG-BASELINE-INTERFEROMETRY TO ESTABLISH REFERENCE COORDINATE SYSTEMS FOR GEODYNAMICS

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ABSTRACT

Present knowledge of the number, distribution, proper motion and structures of extragalactic radio sources indicates that there should be no problem in defining a celestial reference frame with stabilities of a few milliseconds of arc over time spans of the order of a decade. One of the limiting factors appears to be the structure of the sources. By measuring and monitoring these structures, the stability could probably be improved by as much as one or two orders of magnitude. Even without this improvement, a network of properly distributed fixed observatories making regular interferometric observations of these radio sources could be used to define a terrestrial coordinate system that could be maintained at the few centimeter level over indefinitely long time periods. Such a stable terrestrial reference system would be useful for a host of modern geodetic and geodynamic applications, including, in particular, studies of the time varying deformations and relative motions of lithospheric plates. The National Geodetic Survey has already begun work on a three station base network of permanent observatories under project POLARIS as a first step toward implementing the new celestial and terrestrial reference frames. It is hoped that others will join in the effort and make the new reference frames a reality by the middle of this decade.

1. Introduction

From the very inception of both astrometry and geodesy, a central problem has been the search for a suitable celestial reference frame from which the motions of the Earth could be measured. Central to this search has been the identification of suitable fiducial points. Galactic stars were used as fiducial points as early as the dawn of history. By the late nineteenth century evidence for both random and systematic motions of these objects had begun to accumulate. Early in the twentieth century the discovery of the extra-galactic nature of spiral nebulae raised the possibility that celestial objects could be located at sufficient distances that their proper motions would be negligible. However, the attempt to use galaxies as fiducial points was hampered by their large

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angular extent and diffuse nature (Sandig, 1974). In 1963 the discovery of the extra-galactic nature of quasars and related radio sources opened the possibility that such compact extra-galactic objects could be used as fiducial points. The development of Very-Long-Baseline Interferometry (VLBI) a few years later not only introduced a technique which enabled observers to measure the positions of such radio sources with unprecedented precision, but also demonstrated that the radio sources were of extraordinarily small angular extent, of the order of a millisecond of arc. At the same time it was quickly demonstrated that the radio sources were not point-like on a scale of milliseconds of arc, but rather contained structure which could be quite complex in form and vary with time. These structures are small, and their effects on the VLBI observations are small (typically a few centimeters). Nevertheless, they must be dealt with if the full precision of the VLBI techniques is to be exploited. These structures are also a function of the observing frequency. Unless otherwise noted, the discussion in this paper will focus on structures at X-band (8 GHz), a commonly employed frequency for geodetic applications.

The study of extra-galactic radio sources is in its infancy. There is at present no consensus among researchers on basic questions such as how many radio sources exist, where they are located, and what physical mechanisms are responsible for their observed structures and features. Preliminary studies of radio source catalogs suggest that there are probably thousands X-band radio sources detectable with present VLBI equipment (Shaffer, 1980), of which only about a hundred have actually been observed. Of that hundred, only about thirty have been studied in enough detail to determine anything about their structure at the millisecond of arc level. Even this amount of information is sufficient to determine that these sources can be used to form a celestial reference frame that is an order of magnitude more stable than the present stellar reference frame, and there are good reasons to hope that improvements of two or more additional orders of magnitude may eventually be achievable. In this paper I discuss some of the observations of radio source structures and their significance for the definition of a celestial reference coordinate system, and also briefly discuss the methods by which such a coordinate system can be related to other useful celestial and terrestrial coordinate systems.

2. Radio Source Characteristics

2.1 Introduction

In interpreting source structure observations it must be kept in mind that in many cases the measurements are extremely limited. A single measurement of the amplitude and phase of the VLBI fringes from one baseline can be used to infer at most a single component of the two-dimensional Fourier transform of the brightness distribution of the source (see, e.g., Cohen, 1973). Therefore, observations over many baselines are required to determine the brightness distribution of the source reliably. Furthermore, the phase information in the VLBI fringes is normally corrupted by systematic errors; as a result many of the determinations of source structure are made using fringe amplitude data alone. The source structure determinations are therefore often based on data which, by themselves, are inadequate to define unambiguously the structures of the radio sources being observed. The interpretations are then based on underlying assumptions or models which, while plausible, may not accurately reflect the real structure of the sources. In other words, many of the structure models contained in the literature are merely consistent with the observed data, rather than required by those data. Recently the use of differenced phase observations (the so-called "closure phase") has enabled experimenters to recover a portion of the phase information of the VLBI fringes, and thereby greatly increase the observational constraints on the structure of the sources (Rogers et al., 1974). This technique, when used with a large number of different baselines, should enable experimenters to determine quite reliable source structure maps in the future. At present, we have sufficient evidence to conclude, first, that structure at the millisecond of arc level does exist, and, second, that the source structure can vary significantly on a time scale of months.

2.1.1 Structure Characteristics

A wide variety of structures has already been identified, including simple points, points with halos, double and multiple points, jets, etc. (See, e.g., Wittels et al., 1975, Shaffer et al., 1975, Schilizzi et al., 1975, and Kellerman et al., 1977.) The effect of a typical millisecond-level structure on the VLBI observables was considered by Cotton (1980). According to his calculations, this effect should have a maximum amplitude of about 5 cm. Further, his results indicate that this maximum amplitude is reached only at points close to nulls in the fringe visibility function. By avoiding such nulls it should be possible to keep the effects of millisecond-level structures well below the level of 5 cm. Although this has not been rigorously established for all possible structures, it seems unlikely that the case considered by Cotton is atypical. Therefore, it seems likely that with only the most rudimentary allowances for structure effects (e.g., avoiding data close to nulls in the fringe visibility function) it should be possible to limit the systematic errors in baseline estimation caused by source structures to a level substantially less than a decimeter.

It is only when we wish to improve dramatically on this level of accuracy that the necessity for dealing with source structures arises. Two strategies for dealing with source structures suggest themselves. The simplest course would be to make an exhaustive search for a set of radio sources, well distributed in the sky, which have no detectable structure at the level of accuracy desired. If such a set of sources could be found, then presumably errors resulting from unmodeled structure effects would cease to exist. A more general course of action would be to determine the structure of a set of sources to the desired precision by means of VLBI observations. Once the structure is known, then corrections to the VLBI observations can be made to the desired degree of accuracy.

2.1.2 Time Variations of Radio Source Structure

The source structure problems introduced in section 2.1 are further complicated by the fact that the structure may vary with time. In fact, variability appears to be the rule among radio sources rather than the exception. Large numbers of radio sources exhibit considerable variation not only in total brightness (Dent and Kapitzky, 1976), but also in detailed structure. The observed changes could be caused by either physical motions of compact components of the sources, or changes in brightness of relatively stationary components, or both. It is not always easy or even possible to distinguish between these possibilities. In one sense it doesn't matter which possibility proves to be correct, because both phenomena would require corrections to the VLBI observations of about the same magnitude. However, as we shall see, it should be easier to deal with the case of stationary components of varying brightness than the case of sources whose components are physically moving.

The magnitude of the problems caused by source structure variations is indicated in Table 1. Here I have listed the apparent relative velocities of compact components of radio sources as inferred from various VLBI observations, tabulated in order of increasing red-shift (Z) of the radio source. In most cases the interpretation of the observed changes in the source structures as motions of discrete components is somewhat controversial (see, e.g., Cohen et al., 1977). The differences between the tabulated velocities for a given source could be a result of different observing techniques, different model assumptions, actual variations in the radio sources themselves, or all of the above. In spite of the possible unreliability of specific inferred velocities, these velocities can be used to estimate the scale of the corrections required. The magnitudes of the velocities in table 1 range from several milliseconds of arc per year, in the case of 3C120, down to a small fraction of a millisecond per year. In other words, in the absence of explicit corrections for these effects the source structure variations could lead to systematic errors in VLBI position determinations at the decimeter level on a time scale of years to decades.

The best method for dealing with effects of variations in source structure will depend on reliable determinations of the exact nature of the variations. The obvious and simplest strategy would be to select sources whose structure is observed to not vary. One serious problem with this idea is the possibility that the sources so selected might be simply in a temporarily quiescent phase, and on a time scale of years might begin to exhibit serious structural changes. Unfortunately there is at present no adequate way to guarantee that this will not occur. None of these structure variations have been monitored for more than a decade. A longer observing span will be required before we can discuss their long-term behavior with confidence. An idea which bears investigation is the possibility that stable sources could be found among radio sources with high red-shifts, on the assumption that their (presumed) greater distance will mitigate the effects of actual variations within the source. (Note that the red-shift of each of the objects listed in Table 1 is fairly low.

Table 1. Observed velocities of radio source components, in milliseconds of arc per year.

SOURCE	Z	VELOCITY	REFERENCE
3C84	0.018	0.8 ± 0.3 ms/yr	Kellerman et al., 1971
		0.12	Preuss et al., 1979
3C120	0.032	1.5	Shaffer et al., 1972
		1.1	Shaffer et al., 1972
		4.2	Shapiro et al., 1973
		5.0	Kellerman et al., 1973
		1.0	Kellerman et al., 1973
		1.2	Kellerman et al., 1973
		0.6	Wittels et al., 1975
		1.8	Cohen et al., 1977
		2.9	Cohen et al., 1977
		1.51 ± 0.13	Seielstad et al., 1979
		3.12 ± 0.34	Seielstad et al., 1979
3C273B	0.158	0.99	Cohen et al., 1971
		0.47	Cohen et al., 1971
		0.9	Schilizzi et al., 1975
		0.32	Cohen et al., 1977
		0.41	Seielstad et al., 1979
3C279	0.538	0.43 ± 0.1	Whitney et al., 1971
		0.72	Cohen et al., 1971
		0.66	Cohen et al., 1971
		0.26	Cohen et al., 1971
		1. (?)	Kellerman et al., 1974
		0.27	Cohen et al., 1977
		0.5 ± 0.1	Cotton et al., 1979
3C345	0.595	0.2	Cohen et al., 1976
		0.09	Wittels et al., 1976A
		0.09 ± 0.03	Wittels et al., 1976B
		0.17	Cohen et al., 1977
		0.16 ± 0.01	Seielstad et al., 1979

It may in fact not be possible to find a set of sources that are reliably free of structure variations. In that case the observing strategy to be followed would depend heavily on the nature of the structure variations. The simplest case would be one in which the structure variations were caused by changes in the radio brightness of relatively stationary components of the source. In this case it would be necessary first to map the relative locations of the components (with VLBI observations), and then monitor the intensity variations and make the corrections discussed in section 2.1. The accuracy achievable in this case would be comparable to that discussed in section 2.1. Indeed, the only difference between this case and the case of nonvarying structure is the time-varying nature of the corrections and the concomitant necessity of monitoring the changes in the radio source. The case in which structure variations are caused by actual physical motions of components of the radio source is considerably more complicated. It may be possible in this situation to identify a portion of the structure (e.g., the center of expansion of an expanding source) whose motion is, if not zero, at least demonstrably less than the motion of the faster components. If this can be done, then the slower moving point can be used as a reference point to which the changing source maps can be referred, thereby reducing or eliminating the problem.

The worst case that we need to consider is the case that all radio sources will be found to have moving components, and stationary components cannot be identified. It would then be necessary to rely on averaging techniques, based on the assumption that the average motion of all of the radio sources has no bias, to determine the coordinate system. This technique would then resemble the technique used in classical astrometry for dealing with the proper motions of stars, but with two important differences: the motions are orders of magnitude smaller, and biases are unlikely to occur in the radio source motions of the sort that are introduced in stellar motions by the rotation of the Milky Way galaxy.

2.2 Relative Proper Motion Measurements

Up to now we have been dealing only with observations of single sources. Another important set of constraints on the behavior of radio sources comes from differential measurements of closely spaced pairs of radio sources. The significance of the close spacing of the sources in the sky is that many of the systematic errors affecting VLBI observations (e.g., atmospheric effects) can be very nearly cancelled out, allowing the exploitation of the full precision of the VLBI fringe phase observables. In a case recently reported in the literature (Shapiro et al., 1979), the relative coordinates of 3C345 and NRA0512 were measured with an uncertainty of about 0.3 millisecond of arc, and an upper bound of 0.5 millisecond of arc per year was placed on the relative proper motion of the centers of brightness of the two sources. Notice that this upper bound is larger than the apparent motion of components within 3C345 itself. The importance of this result is two fold: first, it demonstrates a technique for determining the relative coordinates of radio sources with sub-millisecond of arc precision; second, it suggests that proper motions of radio sources should not introduce systematic errors in the determinations of terrestrial coordinates at the few centimeter level for at least several years. Furthermore, since this particular determination of relative proper motion is merely an upper bound, we can hope that the actual motion (if any) and its effects are considerably smaller.

2.3 Conclusions

The effects of radio source structures and time variations appear to pose no difficulty for the definition of coordinate systems with precisions at about the level of a few milliseconds and time scales of less than a decade. In order to progress much beyond these limits, it will become necessary to deal with source structure effects. The level of difficulty involved in this task will depend on whether or not a sufficient number of well-behaved radio sources can be found. If ten to twenty point-like, time invariant sources can be found, then the task will be easy. It should be noted that there are selection effects operating in many of the source structure determinations completed to date. Many studies of radio source structure have been done by scientists whose main interest has been the study of the behavior of the radio sources themselves. Therefore, the work has quite naturally been biased toward the most complex and highly time variable (and therefore the most intrinsically interesting) radio sources. Another important selection effect results from the limited sensitivity of many early VLBI systems. This limited sensitivity forced the observers to concentrate on the brightest radio sources in the sky (e.g., 3C84); in many cases these bright sources have had highly complex structure. As a result the literature on the subject of source structure may very well not present a representative sample of radio source behavior. In order to define a celestial coordinate system which can be used to make terrestrial measurements whose accuracy is much greater than 5 cm, a detailed search is needed to discover and monitor the sources most suitable for defining a reference coordinate system.

3. Relating a Coordinate System Based on Radio Sources to Other Useful Coordinate Systems

In order to utilize a coordinate system based on radio source locations, we will have to relate that coordinate system to other useful celestial and terrestrial coordinate systems. The following is a brief sketch of some of the methods that could be employed for some of the more commonly used coordinate systems.

3.1 Terrestrial Coordinate Systems

3.1.1 Geographic Coordinate Systems

If we define a geographic coordinate system in terms of the locations of fixed radio observatories, then VLBI observations can be employed to relate such a coordinate system directly to a coordinate system based on radio source locations. If the Earth were perfectly rigid this would suffice to form a basic reference network to which other types of geodetic measurements could be referred. For the real Earth the radio observatories are attached to crustal plates, which not only move relative to each other, but may not be perfectly rigid themselves. The motions of the plates relative to each other are believed to range from a few centimeters per year up to around 15 centimeters per year. Just as in the case of radio source structure problems, the simplest method for dealing with such tectonic motions may prove to be a policy of simple avoidance. It should be possible to find stable areas in the interior of continental plates where the relative motions of points on the plates are substantially smaller than the relative motion between plates. (If it were not possible to find such areas, that is, if points within plates move relative to each other with velocities comparable to the velocities of the relative plate motions, then the entire concept of crustal plates would cease to have much meaning.) We should therefore be able to situate radio telescopes in areas where their relative motions are expected to be of the order of centimeters per decade or less, and we could then use such a network for local geodetic control. More importantly, we could use the network as a reference grid from which measurements into less stable areas could be made. In the same fashion, measurements made between similar grids located on different plates could be used to define the magnitude and time scale of interplate motions.

3.1.2 Spin axis and Equator

By monitoring the orientation of an array of fixed radio telescopes as the Earth completes a diurnal rotation, it is possible to estimate the orientation of the Earth's spin axis with respect to the geographic coordinate system defined by the location of the telescopes ("polar motion" or "wobble") as well as its orientation with respect to the celestial coordinate system ("nutation"). At the same time, it is possible to monitor the Earth's rotation about its spin axis ("UT1"). The capability of VLBI observations to link a celestial coordinate system directly to the two most important terrestrial coordinate systems forms the basis of the National Geodetic Survey's project POLARIS, which will be discussed in section 4.

3.2 Celestial Coordinate Systems

Curiously, it is more difficult to connect a celestial coordinate system based on radio sources to other celestial coordinate systems than it is to connect it to terrestrial coordinate systems. Nevertheless there are several promising methods for making such connections, which should be pursued.

3.2.1 Stellar Coordinate Systems

There are two general methods for relating radio source coordinates to stellar coordinates. Both methods require the existence of sources of radiation that are sufficiently bright to be detected in both the optical range and the radio range of the spectrum. A large number of radio sources have optical counterparts whose coordinates could be measured with optical techniques. Unfortunately the optical counterparts tend to be exceedingly faint (magnitude 14 or smaller), too faint to be observed with classical astrometric instruments. Another problem is that the uncertainty of the classical observations is several orders of magnitude larger than that of the VLBI observations. Both of these problems could be alleviated by using the U.S. National Aeronautics and Space Administration's (NASA's) forthcoming space telescope for optical astrometric work, a possibility which is currently under study (Shelus, 1980). A second method for relating the two coordinate systems entails finding ordinary stars which radiate significant amounts of energy in the radio portion of the spectrum. Unfortunately nearly all stars are exceedingly faint in this portion of the spectrum. To date, only a single star in the FK4 catalog, Algol, has been observed with radio interferometry, and that one only during infrequent radio "flare" periods (Clark et al., 1976). Both of these methods for relating the coordinate systems depend heavily on the assumption that the location of the origin of the radio radiation is coincident with the origin of the optical radiation. Much time and further study will be required to shed light on the validity of this assumption.

3.2.2 Ecliptic Coordinate Systems

Identifying the location of the ecliptic plane and other Solar System coordinates relative to the location of radio sources is made difficult by the paucity of sources of radio energy in the Solar System. One method which could be of use involves monitoring the occultation of extra-galactic radio sources by the Moon. At present the accuracy of this method is limited mainly by our knowledge of the details of the lunar limb. Another useful method involves the observation of artificial radio sources (spacecraft) with VLBI techniques. Some promising results have been obtained from observations of the VIKING spacecraft in orbit around the planet Mars (Ratner, 1980). This method is limited mainly by the difficulty and expense of acquiring suitable spacecraft.

4. Operational Plans for Defining Radio Source Based Coordinate Systems

The following is a brief outline of some of the present operational plans for defining and making use of a celestial coordinate system based on radio sources.

4.1 Project POLARIS

The U.S. National Oceanic and Atmospheric Administration's National Geodetic Survey has begun to develop a network of three VLBI stations within the continental United States under project POLARIS. The project is described more fully in Carter (1980). The primary objective of this project will be the determination of polar motion and universal time with a precision of ten centimeters or better on a time scale of several observations per week. A secondary objective of this network will be the determination of fundamental reference coordinate systems for geodetic and astrometric work. The basic network was selected to provide as large a triangle as possible within the United States without involving tectonically unstable areas such as the far western portions of the United States. The network will involve stations in Massachusetts, western Texas and southern Florida. Testing of portions of the network will begin in September, 1980, in conjunction with the IAU/IUGG project MERIT. Full operational status of the three U.S. stations should be achieved by 1983. Since the usefulness of such a network would be greatly enhanced by cooperative observations from additional stations, particularly stations located outside the North American plate, the National Geodetic Survey will invite and would like to encourage such cooperation. In addition, the possibilities for employing the transportable VLBI receivers currently under development by NASA in conjunction with the POLARIS network are being actively considered. Such receivers would be useful in helping to resolve a host of modern geodetic and geodynamic problems, including such things as time varying deformations and relative motions of lithospheric plates. The detailed operational plans for the POLARIS network are in a rudimentary state of development; many important questions including the amount of observing time that can be dedicated to research into the nature and behavior of radio sources, or the amount of time dedicated to crustal deformation studies remain to be resolved on the basis of the maximum available scientific return, consistent, of course, with the basic objectives of the project.

4.2 NASA/DSN Plans

NASA's Deep Space Network intends to operate its three 210 ft antennas as a VLBI network in order to provide polar motion and UT1 determinations in support of spacecraft tracking operations. The plans for this operation are outlined in a paper by Fanselow et al., (1980) presented at this conference.

4.2 Other

There are several other groups of scientists doing research in VLBI, including groups at NASA, JPL, M.I.T., Haystack Observatory, Cal Tech, NRAO, also groups in Canada, Europe, Japan, and China. Their activities are too numerous and varied to be cataloged here, and while most of these groups do not plan to make regularly scheduled observations for the purpose of determining reference coordinate systems, their work will nevertheless make an important contribution to this effort, particularly in the areas of source structure determinations, source catalog observations, and studies of tectonic activity.

5. Conclusions

The goal of using VLBI observations to establish a reference coordinate system for geodynamics with a precision at the sub-decimeter level seems to be within our grasp. Serious possibilities exist for improving this precision level by an order of magnitude or more. A great deal of work is currently underway to achieve these goals, and a large number of researchers around the world are working on aspects of this problem. The full realization of the goals of determining and making use of such coordinate systems will be achieved only with a high degree of international cooperation of the sort which this conference can help to foster. Given such cooperation, the future is likely to see a pattern of important and interesting new developments and discoveries.

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