IMPROVEMENTS TO REFERENCE SYSTEMS AND THEIR RELATIONSHIPS

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Abstract.
Reference Systems include the reference frames and their relationships, time arguments, ephemerides, and the standard constants and algorithms.

The extragalactic, or radio, reference frame will be the basic frame. Achieving milli to microarcsecond accuracies at optical wavelengths will reduce the disparity between optical, radar, and radio reference frame determinations. Thus, the relationships and identifications of common sources should be much more accurate. Another significant change should be the ability to determine distances, and thus space motions on a three-dimensional basis, rather than the current two-dimensional basis of proper motions.

Improvements in ephemerides provide the opportunity to investigate the difference between atomic and dynamical time, the relationship between the dynamical and extragalactic reference frame and the values of precession and nutation.

Also, the relationships between the bright and faint optical catalogs, the infrared, and extragalactic reference frames should be better determined. Reference frames at other wavelengths will become determinable.

1. Introduction

We are on the threshold of the introduction of an extragalactic-based reference frame and a reference system consistent with the general theory of relativity. At the same time, new observational data are becoming available, and new techniques for observation are being considered. Thus, while in the past, arcseconds were the units for astrometry, now the milliarcsecond is

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the standard unit, and the microarcsecond is being used. The technologies of interferometers and charge coupled devices (CCD), combined with space-based observing programs, have, and will, significantly change astrometry in the future. Infrared astrometry is in its infancy. Briefly, this paper will touch on all aspects of reference systems; reference frames, time, ephemerides, and the constants and algorithms that go with them.

2. Radio Reference Frame

The extragalactic reference frame being introduced has approximately 400 sources based on VLBI observations, achieving an accuracy of approximately a milliarcsecond. There are sufficient data available now to recognize that some of these sources may show apparent motions in the range of 25 microarcseconds/year which are mostly structural changes. Improvements in positional accuracy can be anticipated on the basis of space-based antennae combined with ground-based VLBI data and continued VLBI observations. In turn, we can expect that some sources will be resolved, or show motion, such that the defining sources will have to be revised.

3. Optical Reference Frame

The optical reference frame situation is indicated in Table 1. The FK5 is the fundamental catalog, today, with the Astrographic Catalog Reference Stars (ACRS) or the Positions and Proper Motions (PPM) catalogs providing supplementary reference catalogs. The Hubble Space Telescope Guide Star Catalog provides a source of positional information down to 17th magnitude.

A dramatic change in accuracies will be achieved when the Hipparcos and Tycho catalogs become available. The Navy Prototype Optical Interferometer (NPOI) is about to begin observations, and will produce significantly improved ground-based observations, providing a continuation of Hipparcos accuracy with improved proper motions. The Washington Fundamental Catalog, which is in preparation, will provide a final fundamental catalog.

There will be several faint star catalogs in the future. The Precise Measuring Microdensitometer (PMM) of the U.S. Naval Observatory will be measuring Palomar Sky Survey plates from both the first and second epochs, so they will provide a catalog of positions and proper motions for approximately 5 million stars in the 14-20 magnitude range. The Sloan Digital Sky Survey (SDSS) is in the design stage and should begin observing in 1996. This will cover the northern galactic area and survey both stars and galaxies down to 22nd magnitude. The astrometry is expected to provide 50 milliarcsecond accuracies for stars in the range of 8 to 22nd magnitude.

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Table 1. Optical Reference Frame

	Current			Future		
mag	No. stars	Cat	Accuracy mas/mas yr^{-1}	No. stars	Cat	Accuracy mas/mas yr^{-1}
< 9	5000	FK5	20/2	1500	NPOI	3/1
				30,000	W.F.C.	20/1
< 11	300K	ACRS or PPM	80/4	100K	Hipparcos	2/2
				1M	TYCHO	30/5
7-16	15M	Guide Star	500-2000			
14-20				5M	PMM	150/7
8-22				100M	+SDSS	50
10-20					*Roemer+	0.01–0.1
< 15					*Newcomb	0.1
< 16					*GAIA	0.020
< 18					*Points	0.005

+ In development
* Concepts

There are several future space astrometric satellites in the planning stage. These include the Roemer Plus satellite, conceived by Dr. Høg, which would observe stars in the 10 to 20 magnitude range at the 100 microarcsecond accuracy level. There is the Global Astrometric Interferometer for Astrophysics (GAIA) which is designed to provide 20 microarcsecond accuracies for limiting magnitudes of 15 or 16. The proposed Points Optical Interferometer is designed to reach 5 microarcseconds with a limiting magnitude of approximately 18. A scaled-down version of Points to meet the current philosophy of "small, quick, cheap," is called the Newcomb Astrometric Satellite. This would reach 100 microarcsecond accuracy with a magnitude limit of approximately 15.

The added feature that goes with these improved accuracies is the distance scale measurements. So not only are the angular positions of the objects improved, distances are also improved, and a three-dimensional reference frame developed. In addition, the infrared reference frame is needed. For this purpose the USNO Catalog of Positions of Infrared Stellar Sources (CPIRSS), has been prepared by correlating the Infrared Astronomy Satellite Point Source Catalog as observed by (IRAS) with astrometric star catalogs. This catalog has about 34,000 stars with an accuracy of about 200 milliarcseconds and flux information for 12, 25, 60 and 100 microns from IRAS and an estimated value of the flux at 2.2μ. There is a planned ob-

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servational effort called the 2MASS project, which plans to measure at the 2 micron wavelength two million stars with an accuracy of 2 arcseconds. This catalog can be matched with optical catalogs to achieve improved accuracies.

4. The Dynamical Reference Frame

Currently, the dynamical reference frame is defined by DE200/LE200, and the IAU 1976 Astronomical Constants. The uncertainties in this reference frame can be specified by the precession constant, with an uncertainty of 3 milliarcseconds per year, theory of nutation, which is uncertain at the 2 milliarcsecond level, and the equinox, with a 4 milliarcsecond uncertainty. With the adoption of the extragalactic reference frame as the principal reference frame, the question could be raised "Do we need a dynamical reference frame at all?" Observations can be made in terms of the extragalactic reference frame. However, it appears that we will still be observing with respect to the equator of the Earth, and affected by its precession and nutation. The remaining question, then, is whether to use the equinox, or a fiducial point, such as that called the non-rotating origin, or an arbitrary origin.

The solar system presents observational challenges. Lunar laser ranging, radar, and VLBI provide observational techniques at milliarcsecond accuracies. The millisecond pulsars provide significant tests of the ephemerides. The question is "can these observations be used to improve the ephemerides?" The extended objects with phase effects and defective illumination effects present a challenge to obtain milliarcsecond accuracy positional observations. Observing the satellites of the outer planets may be much more accurate than observing the primaries themselves. Alternatively, is there some new technique which can be used to obtain significantly more accurate observations of the bodies?

5. Terrestrial Reference Frame

The terrestrial reference frame is defined by Earth orientation data, determined from VLBI, lunar laser ranging, satellite laser ranging and Global Positioning System (GPS). There are many gravity models for general or specific purposes. The combination of GPS and GLONASS is significantly improving the relative terrestrial reference frame. Improvement of the absolute values of UT1 will be more difficult.

Similarly, the International Atomic Time has an accuracy today of about 10 nanoseconds with a prospective future accuracy of 1 nanosecond. However, this is based on a statistical combination of many independent standards, and, as such, is subject to possible low frequency systematic errors.

Can the millisecond pulsars provide a long-term independent time scale, or is there an alternative source for such a time scale? Does the atomic time scale agree with dynamical time, or is a relationship between these required? In addition, methods of time transfer can be significantly improved by means of GPS and two-way communication satellites.

6. Ephemerides

With new time scales, new constants, accurate planetary masses, new observational data, and the extragalactic reference frame, along with models that include the asteroids, the galaxy, the Kuiper belt, the Oort cloud, and the best possible formulation of the theory of relativity, new ephemerides for the solar system can be determined. Consistency between the radar and optically-based ephemerides can be achieved. Primary improvement should be in the outer solar system, with the exception of Pluto, which is going to require improvement based on a longer period of observational data. The determination of asteroid mass values is the current challenge.

7. Astronomical Constants and Methods

The astronomical constants and the methods used for reduction of observations will continue to be driven by the most accurate observations available. The introduction of an IAU computer database of values and standardized software packages should provide both international standardization plus the mechanism for future improvements by means of standard software replacements.

8. Reference Frame Relationships

With the accuracy of the extragalactic reference system at approximately the milliarcsecond level, the ties for other reference frames depend on how directly the transformations can be determined and on the number of source observations. Thus, where direct observations can be made, the ties can be at the accuracy of the observations. In other cases, a multi-step approach is necessary, due to the magnitude differences between the sources. These relationships will be improved in the future as more accurate catalogs of optical sources covering wider magnitude ranges become available.

9. Summary

In 1976, resolutions were adopted to change from the FK4 to the FK5 star catalogs, from B1950.0 to J2000.0, and to introduce new constants, ephemerides, and time-like arguments. The discrepancies between observations and the old system were one arcsecond and one arcsecond per century. The changes, which were introduced in 1984, have provided significant improvements in accuracy, and new knowledge from the improved astrometry. Also, more accurate observational techniques, such as CCD detectors, VLBI, and space astrometry, have developed.

Now, an extragalactic reference frame and astrometry at the milliarcsecond level are available. The changes must be made to start another cycle of improvement and new knowledge.