# MAINTENANCE OF THE ICRF: OPTICAL

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## 1. Introduction

### 1.1. THE ICRF

The International Celestial Reference Frame (ICRF) is presently realized by the positions of 608 compact, extragalactic radio sources (Ma & Feissel 1997) with milliarcsecond (mas) and sub-mas accuracy, all being on the same system, the International Celestial Reference System (ICRS). The Hipparcos Catalogue (ESA 1997) is the practical realization of the ICRF at optical wavelengths, giving high accuracy positions ($\approx$1 mas) and proper motions ($\approx$1 mas/yr) for 117 955 stars (ESA 1997). The link between the radio and optical frames has been achieved by various methods (Kovalevsky *et al.* 1997). The accuracy of this link is estimated to be 0.6 mas at the mean epoch of Hipparcos (1991.25) for the orientation, and 0.25 mas/year for the system rotation.

### 1.2. WHY DO WE NEED TO MAINTAIN THE OPTICAL SYSTEM ?

The optical frame maintenance, particularly its tie to the defining radio frame, is needed even more than the maintenance of the radio frame itself. Due to the large distances, the frame defining radio sources are basically fixed in the sky, while the optical frame is based on stars displaying significant individual proper motions. Without further observations, the accuracy of the radio frame will remain constant, whereas the accuracy of the optical positions will degrade due to the proper motion error propagation.

### 1.3. THE PLAN

The original plan was to wait $\approx$ 10 years after the Hipparcos mean epoch and then repeat a broad international effort to establish another link of the radio and optical systems at that later epoch. That would improve the system rotation link significantly when combined with the original link effort used for the Hipparcos project. However, some radio–optical link projects have not been completed in time to be fully included in the Hipparcos link program. Results are coming in right now which will help to maintain the alignment of the optical to the radio frame.

## 2. Radio stars

The largest weight in the current link is provided by a few (12) radio stars which were observed optically by Hipparcos and at radio wavelengths by VLBI (Lestrade 1995) on the 1 mas level. Other radio star programs were carried out with MERLIN (Morrison *et al.* 1997) and the VLA (de Vegt & Johnston *et al.* 1998), which involves more stars ($\approx$50), however with lower precision for a single source ($\approx$30 mas). These new observations of the radio stars will improve their radio positions and proper motions with respect to the system defining extragalactic sources. No new independent optical observations are being made. Thus, the existing Hipparcos positions and proper motions for the radio stars will be used for an improved radio–optical reference frame link.

In the more distant future, new high precision, optical observations of radio stars are required for the radio–optical reference frame link, because the accuracy of the Hipparcos positions will



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degrade with time due to proper motion error propagation. The Hipparcos system, realized by the sum of all Hipparcos stars, is much more accurate than the positions and proper motions of individual stars. Optical observations of radio stars referenced to many other Hipparcos stars will be required on the mas level, which currently can best be provided by optical interferometers. The Navy Prototype Optical Interferometer (NPOI) (Armstrong *et al.* 1998) will shortly be able to perform large angle astrometry on the few mas level for stars as faint as 9th magnitude. Besides observing the accessible radio stars, this instrument will also be used to find any possible local frame distortions in the Hipparcos system and to resolve double stars.

## 3. The Extragalactic Link

There are three different methods utilizing extragalactic sources for the radio–optical reference frame link. The Northern (NPM) and Southern (SPM) Proper Motion surveys (Lick, Yale), the Bonn, Potsdam and the KSZ (Kiev) program determine *absolute proper motions* with respect to galaxies without providing much information about the *orientation* link. These data have been used for the current Hipparcos system rotation link. No similar, major, new program is planned. The second method measures separations between selected pairs of Hipparcos stars and extragalactic sources by HST. No major new data is expected soon.

The third method involves direct observations of optical counterparts of the extragalactic radio sources, which represent the reference frame, in order to obtain a position at a particular epoch. Several groups around the world have been and are participating in this effort, with the Hamburg/USNO program making the biggest impact as far as accuracy and number of observed sources are concerned. See (Kovalevsky *et al.* 1997) for a review of all frame link investigations, which were completed in time for the Hipparcos link program.

### 3.1. THE HAMBURG/USNO EXTRAGALACTIC PROGRAM

The Hamburg/USNO program aims at radio and optical observations of about 400 compact, extragalactic sources globally to establish a radio–optical reference frame link (Johnston *et al.* 1988). Only a relatively small fraction (20%) of the data could be reduced in time (Zacharias *et al.* 1995) to be included in the current Hipparcos link. A multi–step procedure is used to relate the faint ($\approx 17$ to 20 mag) optical counterparts of the compact optical radio sources to the bright ($\approx 7$ to 9 mag) Hipparcos stars.

The first step is the wide–field astrograph program, which also determines the epoch of the reference frame orientation link. Mostly between 1980 and 1993 observations have been performed with the Hamburg astrograph for the Northern, and the USNO astrograph at Black Birch, New Zealand, for the Southern Hemisphere. Over 400 fields globally have been mapped on photographic plates, which were then measured at Hamburg Observatory. From these plates secondary reference stars with 50 mas accuracy have been obtained in a one square degree field centered on each source. In addition the Lick astrograph was used for over 100 fields.

The second step is the determination of each reference frame source position in the secondary reference star systems. Most of that data were obtained by CCD imaging with the 0.9–meter telescopes on Kitt Peak and Cerro Tololo (over 600 fields). Some faint sources required additional CCD observations made with 4–meter telescopes. Subframes of those images in FITS and GIF format have been made available on the Web at `ftp://rorf.usno.navy.mil/OID/oid.html`. For general information and the radio data see also `http://maia.usno.navy.mil/rorf/rorf.html`.

On the average a total standard error of 35 mas per source position has been obtained for the 78 sources used for the Hipparcos link. Two error contributions dominate the overall accuracy of this program. Firstly, the field distortion pattern (FDP) of the 0.9–meter telescopes is insufficiently known, with poorest image quality at the CTIO instrument. Unfortunately, each observing run had its own FDP. The other major error contribution is the relatively poor limiting magnitude (13 to 14) of the wide field photographic work, providing relatively few secondary reference stars at high galactic latitude fields. Recent observations with wide–field CCD cameras at the Hamburg and USNO astrographs significantly improved the FDP determination. The Hamburg/USNO observing program is now complete and the final publication is in preparation.

### 3.2. THE UCAC–S PROJECT

The USNO CCD Astrograph Catalog South (UCAC–S) project (Gauss *et al.* 1996) will map the entire Southern Hemisphere to about 16th magnitude. A catalog positional accuracy of 20 mas is expected for stars in the magnitude range of 7 to 14. A direct tie to the Hipparcos and Tycho stars is part of the program, and additional long exposures at the astrograph and other telesocpes will provide a strong link to the counterparts of extragalactic radio sources ($\approx$ 10 mas per source). This will provide another radio–optical *orientation* link at a much later epoch than for the original Hipparcos Catalogue link effort. The resulting improvement over the current Hipparcos *system rotation* link from the UCAC–S project alone is estimated to be significant (factor 1.5 to 2).

## 4. Structure of optical counterparts

Structure analysis on the sub–mas level of the reference frame sources is now being performed regularly at radio wavelengths (Fey & Charlot 1997). At optical wavelengths no comparable resolutions can be achieved in the foreseeable future. A few, relatively nearby, compact galaxies and BL Lac reference frame objects show optical structure on the arcsecond level. Observations by HST can reveal structure on the 0.1 mas level. However, relevant for the reference frame tie are the internal structures of the dominating, compact cores of these sources. Even currently planned space interferometer missions with mas resolution will not be able to observe most of these sources because of their faintness at optical wavelengths. Imaging of the ICRF sources in the infra–red has just started (USNO project). Currently, the best option to reveal structure problems of a source is by comparing radio interferometric observations made at different frequencies. Also, the radio–optical *position residuals* for each individual source will reveal problematic candidates, which should then be excluded from the frame link process. These problematic candidates, however, are of astrophysical interest and justify high resolution follow–up observations.

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