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LINK OF THE STELLAR COORDINATE SYSTEM TO THE EXTRAGALACTIC COORDINATE SYSTEM ON SCHMIDT PLATES*

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I. *Introduction*

As were done in Hipparcos observations, the most precise optical star positions are determined "relatively". The "absolute" position of stars, or the "coordinate system" of a catalogue should be determined referring to other non-rotating reference frame, such as the extragalactic radio source catalogue determined by VLBI. The reference frame determined by 610 radio sources is called the International Celestial Reference Frame (ICRF) (IERS 1996).

However, it can neither be simply done by observing radio source positions optically, nor observing optical catalogue star positions by VLBI, because the radio sources determining VLBI coordinate system are optically very faint and the stars constructing precise position catalogues have very faint radio emission (ESA 1997, Vol.3, p388).

Hence come various methods for "linking" coordinate systems constructed by optical star positions (i.e. stellar coordinate system) and by radio source positions (i.e. extragalactic coordinate system). These methods are reviewed in Kovalevsky et al. (1997) and equally in ESA (1997) for the case of constructing the Hipparcos catalogue. The present research is an experiment of one of these methods for linking both systems.

In ESA (1997, Vol.3, Chap.18), these methods are categorized as follows:

1. Precise radio observations of small number of optical catalogue stars.
2. Determining proper motions of catalogue stars referring collective proper motion surveys where the motions of large numbers of stars are measured relative to galaxies.
3. Special photographic link methods where the positions of galaxies and radio sources are optically measured relative to the catalogue stars.
4. Use of Earth orientation parameters.

The present research belongs to 3., using photographic plates taken by a Schmidt telescope in Kiso Observatory of Institute of Astronomy, School of Science, The University of Tokyo. In following sections, we describe a review of the category 3. methods, our observations carried out at Kiso Observatory, estimations of the accuracy of this method which has been revealed insufficient, and a discussion of future view of the methods like this.

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II. *Photographic Link Methods*

Principles and problems of the photographic link method

In this category of methods, optical images of the radio sources are taken on photographic plates or on CCD, and measured their positions relative to the optical star positions which constitute an optical star catalogue.

Instruments used in this method are the Astrograph, the Schmidt telescope, the ordinary long-focus large telescope, or the Hubble Telescope. The Meridian Circle telescope is also used for measuring precise optical star positions, though it uses neither photographic plates nor CCD.

The main problem in this method is a large magnitude difference between optical catalogue stars and ICRF radio sources. For example, typical optical star catalogues "Hipparcos" and "Tycho" list until about 12mag while the average magnitude in the list of optical counterparts of radio sources (e.g. Argue et al. 1984) is about 17.4mag.

Thus the optical images of radio sources are generally taken by large telescopes which have long focus and narrow field. In this case it is difficult to determine a precise optical coordinate system in the field of view, because the field contains only a small number of reference stars.

On the other hand, wide field telescopes such as the Astrograph or the Schmidt telescope (the Meridian Circle as well) can determine the coordinate system, but are very hard to take optical images of radio sources, except the Schmidt telescope. Even on the Schmidt plate, a long exposure time is necessary for taking a radio source image, while the big images of reference stars by the long exposure makes it difficult to determine the reference coordinate system.

To overcome this problem, an intermediate reference star system (or secondary reference star system) in the magnitude range 12 to 14 (ESA 1997, Vol.3, p395) is selected around every radio source. The secondary system can be used to determine the coordinate system on the photographic plate (or CCD) of the large telescope, or on the long exposure Schmidt plate.

In the position observation by the photographic plate, another problem arises: the distortion of the plate emulsion. This appears in its drying process, i.e. the earlier dried part of the emulsion shrinks and thus elongates neighboring wet part of the emulsion. In order to avoid this problem, a réseau was exposed on the plate for correcting the distortion, in the historical "Astrographic Catalogue" project (Eichhorn 1974, p282).

Examples of the photographic link method

The examples are referred in the Hipparcos Catalogue explanations (ESA 1997, Vol.3).

de Vegt & Gehlich (1982) have determined optical positions of 28 radio sources. An intermediate star system of 12-14mag was linked to FK4 system, using an Astrograph of the Hamburg Observatory, and the radio sources were observed optically by 1.5m L.Figl reflector and 3.6m ESO reflector.

This project is succeeded by the USNO group (the final report is in Zacharias et al. 1995). They used the Twin Astrograph of USNO, Black Birch, New Zealand, for secondary reference system. For radio sources, they used AAT 4m, KPNO 4m, or ESO Schmidt telescopes. They also developed a new method using 2K CCDs at 0.9m KPNO and CTIO telescope for this purpose, and attain the accuracy better than 30 mas.

There is an example of observing secondary reference system using the Meridian Circle telescopes of Bordeaux and Carlsberg Observatories (Morrison et al. 1990).

A special catalogue is compiled for secondary reference system (de Vegt et al. 2001).

III. *The Direct Photographic Link Method Made by a Schmidt Telescope*

As described above, only the Schmidt telescope with a large aperture can take optical images of both wide field catalogue stars and faint radio sources.

Though there is a difficulty of "large magnitude difference" described above, it seems worth trying a simultaneous observation of catalogue stars and radio sources by the Schmidt telescope. If there is any ingenious method for measuring precise positions of large images of bright stars, or if there is any method for extincting bright star images, the Schmidt plate can directly link both radio and optical systems without using any secondary reference system.

The following are our trials of testing various methods to overcome the difficulties:

1. Use a multi-exposure observation, a long exposure for radio sources, and several short ones for reference stars.
2. Use the spider patterns of bright star images, in order to measure their precise positions.
3. Use a neutral filter with a small hole in its center.
4. Special cares are taken in the drying process of plates, i.e., an axi-symmetrically uniform drying method in a dust-free room.
5. Use a fine grain plate (e.g., IIIaJ) with enhanced sensitivity.

Actually, 3. was not tried as discussed in the following sections.

IV. *Observations and Plate Processing*

The observations have been carried out as follows:

Period: from Oct. 1986 to Mar. 1989

Telescope: the 0.9m Schmidt telescope at Kiso Observatory, Institute of Astronomy, School of Science, The University of Tokyo

Number of nights observed: 31

Number of plates used: 135

Number of plates examined: 96

Number of plates with good seeing (image size $\leq$ 3") in above 96 plates: 38

Number of multi-exposure plates in examined ones: 29

Number of plates with radio source images: 84

Number of plates with measurable radio source images: 54

Number of 3C273B observations in above 54 plates: 6

Number of radio sources with measurable image: 37

The list of 96 good plates is shown in Table 1. In the table, each column name means:

Kiso#	the plate identification number used in Kiso Schmidt observations
r.src	the IAU name of radio sources
date	date of the beginning of observations
emul.	emulsions (3aJ=IIIaJ, 03aO=103aO, 2aO=IIaO, etc)
filter	name of filters used at Kiso Schmidt
exposure	exposure time in seconds ("+" and "*" means multi exposures, "'" reversed telescope)
seeing	estimated seeing by image size in arcseconds (A = good image, B = fairly good, C = big or asymmetric image)
r.s.q.	quality of radio source images (A = good, B = measurable, C = worth trying, a = show structure, b = doubtful, c = not measurable)

Table 1. List of Plates

Kiso#	r.src	date	emul.	filter	exposure	seeing	r.s.q
5154	2200+420	861023	2aD-	GG495	5	10C	A
5160	0229+131	861028	2aD-	GG495	15	5D	c
5161	0229+131	861024	2aD-	GG495	15	7C	c
5162	2200+420	861022	2aD-	GG495	5	5A	A
5163	2200+420	861027	2aD-	GG495	5	5B	A
5164	2200+420	861025	2aD-	GG495	5	7B	A
5166	0229+131	861027	2aO-	GG385	30+1*4	7C	C
5167	0229+131	861024	2aO-	GG385	30+1*4	3B	B
5168	0229+131	861029	2aO-	GG385	30+1*4	3B	B
5171	2200+420	861022	2aO-	GG385	5+1*4	3C	A
5253	1226+023	861210	2aD-	GG495	3+6	5B	A
5254	0234+285	861217	2aD-	GG385	20	3B	A
5255	0229+131	861224	2aO-	GG385	20+1*4	5B	B
5256	0234+285	861220	2aO-	GG385	20+1*4	2B	A
5257	0316+413	861224	2aD-	GG495	5+1*4	2B	a
5258	0316+413	861229	2aD-	GG495	10+1*4	3C	a
5263	0716+714	861222	2aD-	GG495	5	8C	C
5264	0851+202	861222	2aD-	GG495	10	8B	c
5266	0851+202	861229	2aD-	GG495	10+1*4	5B	B
5267	1226+023	861228	2aD-	GG495	3*4	5B	A
5268	1226+023	861223	2aD-	GG495	3*2	5A	A
5302	0552+398	870110	2aO-	GG385	30+1*4	5B	C
5303	0716+714	870117	2aO-	GG385	5+1*4	8A	B
5304	0851+202	870117	2aO-	GG385	10+1*4	5A	c
5305	0716+714	870111	3aJ+	GG385	5+1*4	8B	c
5306	0851+202	870117	3aJ+	GG385	10+1*4	8B	c
5307	1226+023	870117	3aJ+	GG385	5	8B	A
5311	0235+164	870123	3aJ+	GG385	30	5B	b
5314	0316+413	870125	3aJ+	GG385	10	3B	a
5315	0851+202	870125	3aJ+	GG385	10+1*4	5B	B
5316	0716+714	870127	2aO-	GG385	10+1*4	5B	B
5399	1219+285	870322	2aO-	GG385	10	3A	B
5400	1418+546	870321	2aO-	GG385	10	3A	B
5402	1611+343	870320	03aO-	GG385	30	7A	A
5404	1219+285	870320	03aF+	RG610	15	4A	C
5407	1226+023	870322	3aJ+	GG455	5*4	8B	A
5408	1404+286	870327	3aF+	RG610	15	6B	c
5409	1404+286	870321	3aJ+	GG385	10	6A	B
5411	0552+398	870328	03aO-	GG385	30+1*4	4A	C
5412	0923+392	870327	03aO-	GG385	30+1*4	4A	B
5414	1219+285	870324	3aJ+	GG385	15+1*4	4A	A
5415	1226+023	870323	3aJ+	GG385	5*4	4A	A
5418	1641+399	870327	3aJ+	GG385	30+1*2	4B	B
5592	0229+131	871121	03aO-	GG385	30	7B	C
5593	0229+131	871125	03aO-	GG385	30	6B	c
5597	0642+449	871125	03aO-	GG385	30	6B	c
5600	0954+658	871125	03aO-	GG385	30	6B	B
5610	0827+243	871123	3aJ+	GG455	30	3A	B

TABLE 1. LIST OF PLATES (continued)

Kiso#	r.src	date	emul.	filter	exposure	seeing	r.s.q
5697	1404+286	880216	2aO-	GG385	30	8C	A
5698	1435+638	880213	2aO-	GG385	20'+20	8C	C
5699	1435+638	880210	2aO-	GG385	20	8C	B
5700	0716+714	880215	3aJ+		20	2A	A
5703	1253-055	880217	3aJ+		30	2A	A
5704	1253-055	880216	3aJ+	GG455	30	5B	c
5707	0552+398	880215	3aJ+	GG385	30	2A	C
5708	0607-157	880218	3aJ+	GG385	30	2B	C
5713	0836+710	880213	3aJ+	GG385	19'+19	6B	c
5716	0859-140	880217	3aJ+	GG385	30	6B	B
5789	0952+179	880508	3aJ+		30	3A	B
5790	1127-145	880502	3aJ+		30	3A	b
5793	1150+812	880503	3aJ+		30+30'	4A	c
5794	1749+096	880506	3aJ+		20	5B	C
5795	1807+698	880502	3aJ+		20	4B	A
5796	1928+738	880507	2aO-		20	4A	A
5827	1821+107	880614	03aO-		30	4B	b
5828	1821+107	880616	3aJ+		30	5B	b
5829	2030+547	880617	3aJ+		30	2A	A
5838	2128-123	880914	3aJ+		30	3A	A
5841	2251+158	880913	3aJ+		30	2A	A
5843	2201+315	880916	2aO-		30	3A	A
5845	0116+319	880919	3aJ+		30	2A	C
5846	2254+074	880914	3aJ+		30	2A	C
5848	2320-035	880913	3aJ+		30	1A	C
5849	2145+067	880916	3aJ+		45	3C	b
6115	0735+178	890219	3aJ+		30	4A	A
6116	0738+313	890212	3aJ+		30	3A	A
6117	0828+493	890211	3aJ+		30	4B	C
6120	0736+017	890218	03aO-		30	5B	A
6121	0839+187	890215	3aJ+		30	4B	A
6123	1039+811	890217	3aJ+		30	3A	C
6124	0906+015	890218	3aJ+		30	4B	a
6125	1038+064	890218	3aJ+		30	3C	A
6126	1034-293	890215	3aJ+		30	3C	C
6127	1144-379	890211	03aO-		30	3C	a
6128	1302-102	890217	03aO-		30	2B	A
6129	1148-001	890216	3aJ+		30	3A	A
6130	1228+126	890216	3aJ+		3*4	3A	a
6131	1510-089	890210	3aJ+		30	2A	A
6173	1345+125	890316	3aJ+		30	6B	a
6178	1656+053	890312	3aJ+		30	4A	B
6179	1652+398	890319	3aJ+		15	3B	A
6183	1252+119	890319	3aJ+		30	5A	A
6184	1354+195	890313	03aO-		30	3A	B
6185	1637+574	890316	03aO-		30	4B	C
6188	1244-255	890313	03aO-		30	3B	b
6189	1546+027	890319	03aO-		30	2B	B

V. *Analyses of Observations*

In this section, we discuss the possibility of using Schmidt plates for linking radio and optical coordinate systems. First we inspect images of radio sources and reference stars, both short (about 5sec) and long (about 30sec) exposures. Then we estimate the accuracy of position measurement of these images.

Images

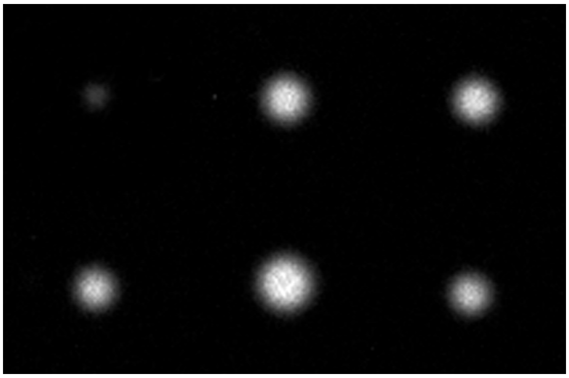
Examples of star images of a short exposure (3sec) are shown in Fig.1.

The top-left image is that of the optically brightest radio source 3C273B (12.86mag). Others are those of reference stars, 5 samples from 27 stars (9.1 - 10.4mag). The scales are: abscissa = 1.136mm × 3, ordinate = 1.136mm × 2. The scale factor of Kiso Schmidt telescope is 62.5"/mm. The scanning pixel size is 1.0" × 1.0" (i.e. 16μm × 16μm).

Long exposure images of these reference stars show a large "spider" patters caused by light diffractions in the telescope, while those of radio sources are very faint in the cases of typical objects (16 - 17mag). Most objects in the list of Argue et al. (1984), with 18 - 20mag, do not show any measurable image even in the long exposure plates. This is an unexpected result judging from the limiting magnitude (~ 20mag) of Kiso Schmidt telescope. The reason is presumed due to the unfavorable seeing conditions in our case.

Several bright radio sources show some structured images (e.g. 3C84), and are not suitable for our purpose.

FIG. 1. SAMPLES OF STAR IMAGES OF SHORT EXPOSURE



Accuracy of position determination

The accuracy of position measurement with these images are estimated as follows:

image of the brightest radio source (3C273B) in short exposure:

The accuracy of bisection measurement (i.e. the accuracy of position determination) can be estimated theoretically by taking into account the randomness of measured pixel values. The result is about 0.14”. However, actual bisection errors measured by the plate-to-plate differences are about 0.4”. The difference seems to be caused by that the randomness is limited by the effect grain structures of photographic emulsions.

images of reference stars (8 - 11mag) in short exposure:

Theoretical estimation of the bisection accuracy is almost the same with the above case. However, actual measurement by plate-to-plate difference is about 0.5”, much larger than the above case. Since we selected about 25 reference stars in a plate, the estimated accuracy of determining coordinate system is 0.1” (i.e. $0.5/\sqrt{25}$).

images of reference stars in long exposure:

These images are, as described above, with distinct spider patterns, and cannot be measured the positions by the usual bisection method. It was expected to use the sharp spider patterns to determine the unique positions of these images. However, the spider images are neither symmetric nor the same shape with every stars. This is because the spider images are caused by the light diffractions in the telescope, and the structures of apparatuses in the telescope are not symmetric. Also the effect of apparatus structure is different to the off-axis light paths, and the marginal star images show different diffraction patterns. So these images cannot be used for position determination.

faint images of radio sources (16 - 17mag):

The measured accuracy of these faint images by the method of plate-to-plate difference is about 0.4” (an overall estimate, though it depends on the image size). As we have only one radio source on a Schmidt plate region, this estimated accuracy directly determines the system accuracy of one Schmidt observation. This becomes the main cause of accuracy limitation of our project, as discussed below.

Possibility of Schmidt observations for linking radio and optical coordinate systems

As discussed above, the estimated accuracy of our method is actually limited by the accuracy of measuring radio source images. The system accuracy of one Schmidt observation is 0.4”, and expected to be 0.04” of coordinate system accuracy, if we accumulate 100 observations.

The comparison of accuracies of various methods for linking coordinate systems is discussed in ESA (1997). In the discussion, the comparison is shown in Figure 18.5 in which the regions of right ascention and declination axes are 10mas (0.01”).

In the figure, the accuracy of photographic methods is estimated as about 5mas (0.005”). Taking into account of these accomplishments, our Schmidt results are for the present insufficient in these modern coordinate linking methods.

However, it is estimated that the reference star positions with short exposure time can be measured with sufficient accuracy, that is, the system accuracy of one observation is 0.1” and expected to be 10mas accumulating 100 observations.

VI. *Conclusions and Discussions*

We have examined various techniques of coordinate liking methods by the Schmidt observations on the photographic plates. However, all of these methods are concluded to be insufficient for the purpose of coordinate linking, compared with those of recent technologies.

There remained some other possibilities to use the Schmidt plate observations for this purpose, i.e., selecting better seeing conditions, searching for environmental amelioration of the telescope for better seeing, or much longer exposure time observations using a special neutral filter discussed before.

However, the era of photographic plate observations has now come to an end because of the appearance of CCD. The Kiso observatory also decides that the Schmidt telescope should be operated only by CCD apparatus.

Thus for further investigations we must develop a new methods for linking coordinate systems by using CCD. This will be discussed in another paper.

The large number of Schmidt plates taken in our project can be used for selecting new reference stars around the radio sources, as was done by de Vegt et al. (2001). This work is now under continuation by the present author.

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