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Optical positions of seventeen radio stars from circumzenithal observations by the method of equal altitudes

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Abstract. — Positions and proper motions of seventeen radio stars were improved from observations by the method of equal altitudes as performed by circumzenithals in Prague, Pecný and Bratislava during 1980–1994. Average accuracy of right ascensions, declinations and their proper motions is $0\overset{s}{.}004$, $0\overset{\prime\prime}{.}04$, $0\overset{s}{.}001$ y^{-1} and $0\overset{\prime\prime}{.}01$ y^{-1}, respectively.

Key words: radio continuum: stars astrometry — reference systems

1. Introduction

Problem of connecting the optical and radio reference frames, particularly linking the system of the Hipparcos catalog to an inertial frame, represented by the extragalactic radio sources, had caused a necessity of intensive observations of radio stars, the only objects observable by means of the optical and radio astrometry.

In the former Czechoslovakia, three circumzenithals – at the Astronomical Observatory of the Czech Technical University in Prague (successively at two observing sites), Geodetic Observatory Pecný in Ondřejov and the Astronomical Observatory of the Slovak Technical University in Bratislava – participated with observations by the method of equal altitudes in the international cooperation to derive the Earth rotation parameters. From 1980, radio stars were gradually included in their observing programs. The FK4 stars were completed by the non-FK4 stars from the Débarbat's (1986) letter to the final number of seventeen. Radio stars have been regularly observed in Prague and Pecný since 1980 and, in Bratislava, were observed in a period of 1987–1993.

The preliminary results from the first ten years of the Prague observations proved the reliability of the method (Pešek 1993). Now we present the improved positions and proper motions as derived in a global adjustment of the data from observations by the three instruments during 1980–1994.

The adjustment can be modified to derive immediately the parameters of mutual orientation of the optical and radio reference frames provided the coordinates of the radio stars are known in both systems. Due to the lack of positions referred to the extragalactic frame, we are only able to estimate the accuracy, which we can expect for the link based on the discussed data, and cross correlations between the orientation parameters.

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2. Data and the adjustment

The data to be analysed has been obtained from regular observations of three circumzenithals VÚGTK 100/1000 mm (magnification 100×, zenith distance 30°, typical accuracy of one star transit $0.2'' - 0.3''$). The list of the radio stars is shown in Table 1. Coordinates of the observatories, in the case of Prague before and after 1985, are:

	Code	ϕ	$\lambda_{\rm east}$
Prague	PRE	$50^\circ\,04'\,40''$	$0^{\rm h}\,57^{\rm m}\,40.8^{\rm s}$
	PRD	$50^\circ\,06'\,20''$	$0^{\rm h}\,57^{\rm m}\,33.3^{\rm s}$
Pecný	PYD	$49^\circ\,54'\,56''$	$0^{\rm h}\,59^{\rm m}\,09.4^{\rm s}$
Bratislava	BRC	$48^\circ\,09'\,18''$	$1^{\rm h}\,24^{\rm m}\,47.7^{\rm s}$.

A typical observing group consists of 28 reference FK4/FK5 stars and one or more radio stars. The absolute terms of the observation equations, δh (e.g. Vondrák 1991), were originally referred to the FK4, FK4J2000 and FK5 catalogs in different periods of observations, and they all were recalculated, prior to the present analysis, to be referred to the INCA catalog (Turon et al. 1992).

Table 1. List of the radio stars with number of observations

Star identification					Number of observed west/east transits				
INCA	Name	FK	BD	HD	PRE	PRD	PYD	BRC	Total
3693	ζ And	27	+23 106	4502	6/20	24/29	52/50	16/16	98/115
6669		2096	+22 226	8634		13/17	24/16	8/1	45/34
14576	β Per	111	+40 673	19356	14/15	25/37	32/37	26/15	97/104
20070	b Per		+49 1150	26961		21/29	12/10	27/12	60/51
27913	54 Ori		+20 1162	39587				11/11	11/11
37629	σ Gem		+29 1590	62044		33/5	7/17	21/26	61/48
51814	37 UMa	398	+57 1277	91480	23/3	31/1	0/7	19/22	73/33
61281	κ Dra	472	+70 703	109387	3/9	33/51	70/49	20/10	126/119
62512			+61 1320	111456				7/12	7/12
66257	HR 5110	502	+37 2426	118216	18/22	53/43	64/56	23/23	158/144
71115	26 Boo	3151	+22 2715	127739				12/6	12/6
79607	σ CrB A		+34 2750	146361		34/21	53/18	31/10	118/49
92420	β Lyr	705	+33 3223	174638	9/14	54/41	89/83	22/27	174/165
94013			+52 2350	179094				6/13	6/13
108317	VV Cep	3756	+62 2007	208816		27/34	9/55	2/35	38/124
113561	V509 Cas	3839	+56 2923	217476		19/53	39/92	3/11	61/156
116584	λ And	890	+45 4283	222107	10/47	22/89	35/126	17/26	84/288

The method of equal altitudes is based on a principal assumption that the zenith distance is exactly the same for all stars observed in one group. The real observations, however, suffer from systematic errors which appear as deformations of the apparent almucantar of the instrument. These deformations reach to $0.1'' - 0.2''$ and change slowly with azimuth a and time τ. They can be approximated by the formula (Pešek 1995)

$$D(a,\tau) = \sum_{k=2}^{K} \{[c_k + \sum_{n=1}^{N} (c'_{skn} \sin 2\pi n\tau + c'_{ckn} \cos 2\pi n\tau)] \cos ka \; + + [s_k + \sum_{n=1}^{N} (s'_{skn} \sin 2\pi n\tau + s'_{ckn} \cos 2\pi n\tau)] \sin ka\} \,,$$

where time $\tau = \frac{1}{N}(\mathrm{JD} - \mathrm{JD}_0)/365.2422$ is expressed in terms of the analysed period of N years from an initial epoch JD_0. Parameters c_k, $\ldots$ s'_{ckn} are to be estimated from the adjustment. Due to a non uniform distribution and insufficient density of observations, only the main features of the deformations could be modelled in the present analysis. The azimuthal expansions were restricted to the degree of $K = 3$ for the Prague and Pecný circumzeniths, and to $K = 2$ in the case of Bratislava.

The linearized observation equation is generally a function of four 'group' unknowns z, $\dot{z}$, UT0 − UTC and ϕ (zenith distance, its time derivative, clock correction and latitude) of each group, of the deformation parameters c_k, $\ldots$ s'_{ckn} of all instruments/sites, of the coordinates, α, δ, and proper motions, μ_α, μ_δ, of the stars being improved. Let us denote the parts corresponding to the group unknowns, deformation parameters and corrections to the star positions as g, d and s, respectively, and the residual as v. The observation equation for the j-th transit will then read

$$\sum g_{uj} + \sum d_{mj} + \sum s_{wj} = \delta h_j + v_j \,. \qquad (1)$$

For a particular transit, the only nonzero terms in the above sums are the following: g_u – for all transits observed in the u-th group, d_m – for all transits observed by the m-th instrument and, s_w – for all transits of the w-th radio star.

The part s of the observation equation (Eq. 1) is

$$s = (\mathrm{d}\alpha + \mu_\alpha \Delta T) \cos\phi \sin a + (\mathrm{d}\delta + \mu_\delta \Delta T) \cos q \,, \qquad (2)$$

where q is parallactic angle and ΔT time elapsed from the mean epoch of observation of the respective star. As it can be seen, the coefficients of the unknowns (and also the accuracy of derived star coordinates) depend on azimuth of the transit. As a consequence, we did not estimate declinations of five stars, whose coefficients $|\cos q|$ are less than 0.22. Different number of east and west transits implies a correlation between α and δ,

$$r_{\alpha\delta} = (n_\mathrm{E} - n_\mathrm{W})/(n_\mathrm{E} + n_\mathrm{W}) \,.$$

3. Results and discussions

The observation equations (Eq. 1) yield an extensive system of normal equations. The group unknowns can however be easily separated, so that a much smaller system for the star coordinates, proper motions and almucantar deformations is to be solved in the adjustment.

Table 2. Radio star optical positions and centennial proper motions as derived from circumzenithal observations (mean epoch of observations, equator and equinox J2000.0, reference catalog INCA)

	Positions and proper motions					Mean errors			
INCA	α	μ_α	δ	μ_δ	Epoch	$\sigma(\alpha)$	$\sigma(\mu_\alpha)$	$\sigma(\delta)$	$\sigma(\mu_\delta)$
3693	$0^{h}47^{m}20^{s}.429$	$-0^{s}.672$	$24^\circ16'02''.80$	$-9''.56$	1987.15	$0^{s}.003$	$0^{s}.086$	$0''.02$	$0''.57$
6669	1 25 35.652	−0.073	23 30 41.75	−1.07	1989.30	0.006	0.181	0.04	1.07
14576	3 08 10.128	0.103	40 57 20.34	−0.68	1987.84	0.002	0.054	0.04	1.00
20070	4 18 14.564	0.481	50 17 44.56	–	1990.03	0.003	0.161	0.09	–
27913	5 54 23.096	–	20 16 35.16	–	1990.81	0.014	–	0.07	–
37629	7 43 18.681	0.462	28 53 02.63	−23.89	1990.51	0.003	0.167	0.03	1.73
51814	10 35 09.596	0.779	—	–	1987.80	0.003	0.088	–	–
61281	12 33 29.072	−1.305	69 47 17.58	5.23	1988.08	0.004	0.095	0.07	1.67
62512	12 48 39.323	–	—	–	1990.97	0.009	–	–	–
66257	13 34 47.720	0.735	37 10 56.86	0.92	1987.35	0.002	0.043	0.03	0.68
71115	14 32 32.597	–	22 15 35.55	–	1991.43	0.013	–	0.04	–
79607	16 14 41.052	−2.237	33 51 31.93	−7.71	1990.63	0.003	0.111	0.04	1.49
92420	18 50 04.795	−0.012	33 21 45.69	−0.23	1987.67	0.002	0.043	0.02	0.57
94013	19 08 25.881	–	—	–	1991.09	0.008	–	–	–
108317	21 56 39.152	0.005	—	–	1990.27	0.003	0.144	–	–
113561	23 00 05.103	0.191	—	–	1989.01	0.002	0.069	–	–
116584	23 37 33.657	1.553	46 27 34.41	−41.04	1987.72	0.002	0.050	0.04	1.19

Contribution of individual instruments to the final solution depends on number of observations and their internal accuracy. Dispersions of the results, derived for each instrument separately, from the results of the common solution, $\sigma^2 = \sum[(\Delta\alpha\,\cos\delta)^2 + \Delta\delta^2]/n$ (n is the number of radio stars observed by the respective instrument), yield the weights 0.77, 1.00 and 0.59 for Prague, Pecný and Bratislava, respectively.

Adjusted coordinates and centennial proper motions of all seventeen radio stars and corresponding mean errors are listed in Table 2. The positions are referred to the mean epochs of observations, equator and equinox J2000, and to the INCA catalog.

Table 3. Comparison with Bordeaux automatic meridian circle (in the sense 'circumzenithals minus meridian circle'). INCA values were used for proper motions not listed in Table 2. [$\Delta\alpha$ in $0^{s}.001$, $\Delta\delta$ in $0''.01$]

INCA	$\Delta\alpha$	$\Delta\delta$	INCA	$\Delta\alpha$	$\Delta\delta$
3693	+4	−16	66257	+3	−4
6669	+2	−1	71115	−23	−32
14576	+3	+2	79607	+3	+5
20070	+5	+20	92420	+1	+1
27913	+10	+17	94013	−8	–
37629	+2	−13	108317	0	–
51814	+5	–	113561	−4	–
61281	+1	+9	116584	−2	0
62512	−4	–			

Mean errors of four stars, namely 27 913, 51 814, 71 115 and 94 013, exceed substantially the average error level of $0^{s}.004$ and $0''.04$ in right ascension and declination, obviously due to a small number of observations during a short period of only six years. We cannot explain the insufficient accuracy of proper motion of 20 070 which was very often observed during a whole period of observations. Consequently, we have omitted proper motions of those stars in the Table.

To check the external accuracy, we compared our results with positions obtained from observations on the Bordeaux automatic meridian circle (Réquième & Mazurier 1991). The differences listed in Table 3 show a very good agreement of both results; only the differences in declination of 3 693 and 71 115 exceed slightly the correponding mean errors of $0''.14$ and $0''.22$, respectively.

The 79 607 (σ CrB A) is the brighter component of a close binary with the components separated by only $5''$. Thus we could expect a greater uncertainty in its position, since observers tend to coincide images of the photocenter rather than those of the primary. This suspicion was, however, disproved not only by small internal errors but also by a good agreement with the Bordeaux position.

4. Expected accuracy of link to the extragalactic frame

The procedure described above gives positions of individual stars. Provided the radio star coordinates are known in both optical and extragalactic system, the adjustment can be easily modified to derive immediately six parameters of mutual orientation of the two reference frames.

According to Lindegren & Kovalevsky (1995) notation, the parameters are three rotations ε_i around axes of optical rectangular equatorial system and their time derivatives $\omega_i = \dot{\varepsilon_i}$. When

$$\begin{aligned} \mathrm{d}\alpha + \mu_\alpha \Delta T &= (\varepsilon_x + \omega_x \Delta T)\cos\alpha\tan\delta + \\ &+ (\varepsilon_y + \omega_y \Delta T)\sin\alpha\tan\delta - (\varepsilon_z + \omega_z \Delta T)\,, \\ \mathrm{d}\delta + \mu_\delta \Delta T &= -(\varepsilon_x + \omega_x \Delta T)\sin\alpha + (\varepsilon_y + \omega_y \Delta T)\cos\alpha \end{aligned}$$

are assigned to Eq. (2), observation equations can be solved for the orientation parameters.

For the moment we do not have reliable star coordinates and proper motions referred to the extragalactic frame. Thus we could only estimate the expected internal accuracy of ε_i, ω_i and cross correlations between the unknowns as shown in Table 4.

Table 4. Expected accuracy of the orientation parameters from circumzenithal observations

	mean error	correlation ε_x	ε_y	ε_y	ω_x	ω_y	ω_z
ε_x	$0''.010$	1.0					
ε_y	0.012	0.2	1.0				
ε_z	0.012	0.2	-0.1	1.0			
ω_x	$0''.002$ y^{-1}	0.4	0.1	0.1	1.0		
ω_y	0.003	0.1	0.4	0.0	0.2	1.0	
ω_z	0.003	0.1	0.0	0.4	0.1	-0.2	1.0

5. Conclusions

Up to seventeen radio stars were regularly observed by the method of equal altitudes by circumzenithals VÚGTK 100/1000 mm at observatories in Prague, Pecný and Bratislava during a period 1980–1994. The data was homogenized by transforming to the INCA catalog. Systematic errors of various origin appear as deformations of the apparent almucantar of the instrument. Parameters of the deformation models were derived along with coordinates and proper motions of the radio stars in a global adjustment. The star positions are referred to the mean epochs of observations and to the equator and equinox J2000. Average mean errors in right ascensions, declinations and their proper motions are $0^{s}.004$, $0''.04$, $0^{s}.001$ y^{-1} and $0''.01$ y^{-1}, respectively.

The data can also be used to derive directly the mutual orientation of two reference frames, e.g. optical and extragalactic, provided the radio star positions are known in both systems. For the moment we could only estimate the expected accuracy of orientation angles ε_i and their rates ω_i to be $0''.01$ and $0''.003$ y^{-1}.

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