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Precession and nutation from the analysis of positions of extragalactic radio sources

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Abstract.

Corrections to the Earth's precession and nutation have been derived from VLBI observations of extragalactic sources carried out by JPL's Deep Space Network between 1978 and 1994. The analysis is based on the source right ascensions and declinations given in annual position catalogues referring to the J2000.O equator and equinox. These catalogues result from the reduction of the VLBI observables by adopting the 1976 IAU convention on precession and one of the following nutation models: 1980 IAU Theory of Nutation, ZMOA 1990-2 and KSNRE. Differences of the J2000.0 positions of a source obtained at different epochs suggest, the presence of imperfections in the precession and nutation terms.

In contrast to the commonly practiced direct solutions. corrections to the luni-solar precession and the 18.6-yr nutations in longitude and obliquity arc determined by a least squares fit to the differences of positions of individual sources at different epochs. Using the 1980 IAU and KSNRE models gives sizable, largely similar corrections. The ZMOA 1990-2 model, on the other hand, is characterized by small corrections to the nutation terms. Each of the three data sets associated with one of the nutation models provides a solution in right ascension (RA) as well as in declination (Dee). The Dec solution is self-sufficient, whereas the RA solution requires some *a priori* knowledge of the precession and nutation quantities that are to be determined. The self-sufficient declination solutions for the 1980 IAU and the ZMOA 1990-2 models yield the same correction of the luni-solar precession, namely -3. 1±0.2 mas/yr. For the 18.6-yr nutations in longitude and obliquity the IAU model yields −5.4±1.1 mas and 3.8±0.3 mas, while the ZMOA model gives 0.0±0.4 mas and 0.5±0.2 mas, respectively.

group delay, Phase delay, and the time rate of change of phase delay or fringe frequency are in wide use. These observables pass through a rather complex data reduction procedure, called MODEST (Sovers and Jacobs, 1994). Its core is a VLBI model which permits the extraction of the geometric portion of the observed delay from the raw data. In further steps the coordinates of the observed source in the celestial reference frame are derived from the delay data. With the aid of phase delay it is possible to handle fringe frequency observables by means of the same model.

Mark II (1978-89) and Mark III (1988-94) VLBI data have been acquired by DSN over the years 1978 to 1994, with the exception of long periods during 1981 and 1985 when the network was refurbished. The above-mentioned VLBI model was used for processing these data. To account for precession the IAU recommended value (IAU, 1977) was adopted. Part of MODEST is a nutation model. To study the influence of nutations three models have been chosen for data reduction: (1) 1980 IAU Theory of Nutation (Seidelmann, 1982), (2) ZMOA (Zhu, Mathews, Oceans and Inelasticity) 1990-2 nutation model (Herring, 1991), and (3) KSNRE (Kinoshita, Souchay, Non-rigid Earth Theory of Nutation for the Rigid Earth) (see Kinoshita and Souchay, 1990). In the course of the data reduction a grouping of the data in annual catalogues took place, each catalogue comprising only the positions of those extragalactic objects which were made during the corresponding 12-month interval. Exceptions are the early data (1978-80) as well as those around network gaps (1981-2, 1985-6), which have been grouped together, thus yielding three sets of 13 annual catalogues, one set for each of the three nutation models. The positions are given in right ascension (RA, α) and declination (Dec, δ) with reference to the mean equator and equinox of J2000.0 as defined by the 1976 IAU conventions.

The earlier catalogues contain between 100 and 200 objects, while a figure closer to 300 is typical for the more recent ones owing to the increasing efficiency of data acquisition. For confident estimates of precession and nutation corrections, we require a specific object to appear in at least 10 of the annual catalogues, thus ensuring a rather uniform distribution of catalogue positions over the whole time span of 16 years in most cases. This condition is fulfilled by about 75 sources; the study rests entirely on their positions in the respective catalogues.

Attention is drawn to a peculiarity of the source right ascensions. Since radio interferometry determines primarily RA differences, it becomes necessary to define the zero point of RA. In the catalogues referred to above it is adjusted to the RA of the source 0851 + 202 = OJ 287 for which the value $\alpha = 08^h\ 54^m\ 48.8749^s$ was adopted in J2000 coordinates. Its declination derived from observations in 1980 is $\delta = 20^\circ\ 06'\ 30.''63$ in J2000 coordinates. As will be seen later, this RA property introduces complications in further data analysis.

3. Conceptual background

On the hypothesis of an isotropic model of the universe as inferred from the 3K background radiation, the rotation of the universe is negligible (Collins and Hawking, 1973). The radial velocities increase systematically with distance up to the level of the speed of light, while the transverse velocities are randomly distributed about zero, independent, of the distance. Thus, objects at large distances of approximately, (1 Gigaparsec) such as quasars and distant galaxies, can only be associated with apparent motions smaller than 6×10^{-2} mas/yr, assuming transverse velocities less than or equal to the speed of light. Motions of such size are normally not detectable by current observation techniques and can therefore be disregarded. Since there is no evidence of any systematic motion that could be identified with a background rotation, it is natural to define a static reference system on the basis that distant extragalactic radio objects are at rest, and to consider the celestial reference frame made up of the positions of these objects as the realization of the static reference system, sometimes also called the "kinematic" reference system (Kovalevsky, 1981).

For practical reasons of a uniform position determination, the above celestial reference frame implies a geocentric, equatorial frame with the equator and equinox of J2000.0 as defined by the 1976 IAU conventions (Kaplan, 1981), including the 1980 nutation series (Seidelmann, 1982). It is assumed that there is no apparent motion of the extragalactic radio sources in the celestial reference frame. Consequently, it is expected that the observations of an extragalactic object made at different epochs and consistently transformed to the frame of J2000.0 lead to identical positions, apart from noise. Any biased departure from the "true" value referred to J2000.0 could be attributed to imperfect values of data reduction parameters which are of secular or long-periodic nature. In general, however, experience shows disagreement among positions at J2000.0 of extragalactic objects observed at different epochs. The position differences can amount to several mas and are significantly larger than the quoted standard deviations. An illustration is shown for the source NRAO 512 (1638+398) in Fig. 1. It may be seen that the coordinates vary smoothly over the 15-year time span. These variations are approximately 1.2 ms in RA and 9 mas in Dec, and are well outside the formal uncertainties. We ascribe such deviations to imperfect values of the luni-solar precession and the 18.6-yr terms of nutation in longitude and obliquity that were used for data reduction. The mathematical approach outlined below is an elaborated and generalized version of the analysis by Walter and Ma (1994) which dealt with precession only. It rests upon the differences of source positions determined at epochs several years apart. On the average, 40 to 50 such epoch differences of 1 to 16 years are available for a regularly observed source. Weighted least-squares adjustment solves for corrections of precession and nutation by fitting them to the set of position differences which result from the individual catalogues for each source, taking account of the different observation epochs.

The following notation is used:

$\alpha_i^{C_k}(t_k, t_l)$ right ascension (RA) of source i in catalogue C_k at observation epoch t_k (first argument), with reference to the mean equator and equinox at epoch t_l (second argument)

$\delta_i^{C_k}(t_k, t_l)$ declination (Dec) of source i in catalogue C_k at observation epoch t_k (first argument), with reference to the mean equator and equinox at epoch t_l (second argument)

t_0 common epoch of mean equator and equinox to which the observations in the catalogues C_k have been precessed

t_k observation epoch of a source in catalogue C_k

t_l epoch of a selected mean equator and equinox. In this context t_l assumes the values of t_0 and t_k

$P_\alpha(\alpha,\delta)$ $= m + n \, sin\,\alpha(t)\; tan\;\delta(t)$ (operator of general precession in right ascension)

$P_\delta(\alpha)$ $= n \cos\,\alpha(t)$ (operator of general precession in declination)

m, n general precession in right ascension and declination, respectively

$\delta m, \delta n$ corrections to general precession, respectively

ψ luni-solar precession

$\delta\psi$ correction of the luni-solar precession

$\Delta\psi$ nutation in longitude

$\delta(\Delta\psi)$ correction of nutation in longitude

$\Delta\varepsilon$ nutation in obliquity

$\delta(\Delta\varepsilon)$ correction of nutation in obliquity

Expressions of nutation in longitude ($\Delta\psi$) and obliquity ($\Delta\varepsilon$), respectively, to the first order in RA and Dee:

$NL_\alpha(t) = \cos \varepsilon(t) + \sin \varepsilon(t) \sin \alpha(t)\; tan\; \delta(t)$

$NO_\alpha(t) = -\cos \alpha(t)\; tan\; \delta(t)$

$NL_\delta(t) = sin\; \varepsilon(t)\; cos\; \alpha(t)$

$NO_\delta(t) = \sin \alpha(t)$

Note that the coordinates α, δ in P_α, P_δ are those valid at the epoch of the equator and equinox of the position catalogues (Lieske et al., 1977), i.e., $t = t_0$, while the coordinates α, δ in the expressions of nutation refer to the mean equator and equinox of date, i.e., $t = t_l = t_k$. ε stands for the obliquity of the ecliptic.

4. **Adjustment of right ascensions**

Over the 16 years of data acquisition the source 0851-:202 has been observed regularly within each annual interval. Throughout the annual catalogues the RA of this source was chosen as reference for the relative right ascensions, with the consequence that 0851 -t 202 has identical RA's in all the catalogues. On the assumption of imperfect values of precession and nutation, however, different RA's would be expected.

To take account of possible parameter imperfections, a correcting term $\Delta\alpha_k$ is introduced. In the case of precession, the contribution to $\Delta\alpha_k$ depends on the difference At between the observation epoch of 0851 -+ 202 in one of the individual catalogues (k) and in the arbitrarily chosen reference catalogue (R) among the set of catalogues. For convenience we selected the catalogue containing the positions of 1980 as reference catalogue to keep At positive. The nutation part of the correcting; term is a function of the same epochs. As the observations are generally fairly uniformly distributed over the year, we approximated these epochs by the middle of the year without loss of accuracy, denoting them t_k^m and t_R^m.

Bearing in mind that the catalogue right ascensions are the result of the original RA differences with respect to the reference source, effects of the general precession in right ascension (δm) are not preserved in the relative RA's, while the effects of general precession in declination (δn) will show up owing to the different source positions in a catalogue. After these remarks the correcting term to be added to the catalogue RA's reads

$$\Delta\alpha_k = \Delta\alpha_k(prec) + \Delta\alpha_k(nut). \quad (1)$$

To first order one gets

$$\Delta\alpha_k(prec) = (\delta m + sin\,\alpha\, tan\,\delta\, \delta n)\,(t_k^m - t_R^m) \quad (2)$$

with δm = O (see above) and

$$\begin{aligned} \Delta\alpha_k(nut) &= NL_\alpha(t_k^m)\delta(\Delta\psi(t_k^m)) \\ &+ NO_\alpha(t_k^m)\delta(\Delta\varepsilon(t_k^m)) \\ &- [NL_\alpha(t_R^m)\delta(\Delta\psi(t_R^m)) \\ &+ NO_\alpha(t_R^m)\delta(\Delta\varepsilon(t_R^m))]. \end{aligned} \quad (3)$$

The coordinates α and δ are taken from the reference catalogue. To start with, numerical values for the corrections of precession and 18.6 yr nutations have to be introduced. Either one adopts present best estimates obtained elsewhere by independent methods, e.g., Williams et al. (1991))01 one introduces the estimates resulting from the declination observations as carried out in the next section. Resorting to the solution from declinations is possible, since they are absolute observations and, unlike right ascensions, do not require such adjustments.

5. Observational equations

10 first order, the variations of RA and Dec due to precession and nutation are given by

$$\begin{aligned} \alpha^{C_k}(t_k, t_k) &= \alpha^{C_k}(t_k, t_0) + P_\alpha(t_k - t_0) \\ &+ NL_\alpha(t_k)\Delta\psi + NO_\alpha(t_k)\Delta\varepsilon \end{aligned} \quad (4)$$

$$\begin{aligned} \delta^{C_k}(t_k, t_k) &= \delta^{C_k}(t_k, t_0) + P_\delta(t_k - t_0) \\ &+ NL_\delta(t_k)\Delta\psi + NO_\delta(t_k)\Delta\varepsilon \end{aligned} \quad (5)$$

For sources of homonymous designations having different epochs, the coordinates $\alpha^{C_k}(t_k, t_0)$ and $\delta^{C_k}(t_k, t_0)$ should be identical, according to the basic assumptions of Sect. 3. The entries of the individual catalogues, however, show differences of a few mas, which is significantly larger than the position uncertainties. By analogy with the study by Walter and Ma (1994), we introduce corrections $\delta P_\alpha, \delta P_\delta, \delta(\Delta\psi)$ and $\delta(\Delta\varepsilon)$ in order to constrain the positions to one single but unknown true position α_{iv}, δ_{iv} identical for all observation epochs t_k of a source. One gets

$$\alpha_i^{C_k}(t_k, t_0) - (t_k - t_0)\delta P_\alpha - NL_\alpha(t_k)\delta(\Delta\psi) - NO_\alpha(t_k)\delta(\Delta\varepsilon) = \alpha_{iv} \quad (6)$$

and

$$\delta_i^{C_k}(t_k, t_0) - (t_k - t_0)\delta P_\delta - NL_\delta(t_k)\delta(\Delta\psi) - NO_\delta(t_k)\delta(\Delta\varepsilon) = \delta_{iv}, \quad (7)$$

$$i = 1,..., s; \; 1 \leq k \leq N,$$

where s is the number of different sources taken from the catalogues, and k refers to those catalogues out of the total of N to which source i belongs. Let $k(i)$ be the number of catalogues in which source i appears; then, for any given source i there arc $k(i)$ equations (6) and (7) with identical right-hand sides. On forming combinations of cq. (6) two at a time, say p and q, and subtracting equation p from equation q, one gets $k(i)[(k(i) - 1]/2$ observational equations for RA, and in like manner for Dec. They become, after substitution of δP_α and δP_δ,

$$\begin{aligned}(t_p - t_q)\delta m + \{sin\, \alpha_i \, tan\, \delta_i(t_p - t_q)\}\delta n \\ +\{NL_\alpha(t_p) - NL_\alpha(t_q)\}\delta(\Delta\psi) \\ +\{NO_\alpha(t_p) - NO_\alpha(t_q)\}\delta(\Delta\varepsilon) = \alpha_i^{C_p}(t_p, t_0) + \Delta\alpha_p \\ - [\alpha_i^{C_q}(t_q, t_0) + \Delta\alpha_q] \quad (8)\end{aligned}$$

and

$$\begin{aligned}cos\, \alpha_i(t_p - t_q)\delta n \\ +\{NL_\delta(t_p) - NL_\delta(t_q)\}\delta(\Delta\psi) \\ +\{NO_\delta(t_p) - NO_\delta(t_q)\}\delta(\Delta\varepsilon) = \delta_i^{C_p}(t_p, t_0) - \delta_i^{C_q}(t_q, t_0). \quad (9)\end{aligned}$$

The RA adjust, ments of eq. (1) have been added to t hc cat alogue right ascensions on the right-hand side of cq. (8). Note in this equation that the term with δ m is included for formal reasons. Actually, the original RA differences measured by VLBI arc not sensitive to m, since they refer to the adopted RA of the reference source 0851 + 202. As a consequence, the right-hand sides do not contain effects of δm. Therefore, δ *m* is indeterminable and the term with δ *m* is dropped from eq. (8).

Ultimately, wc strive for corrections to the general precession in declination *(n)* and to the 18.6-yr nutation coefficients from annual position catalogues using eqs. (8) and (9). To this end the nutation series in longitude and obliquity, $\Delta\psi$ and $\Delta\varepsilon$, are truncated, leaving only the first term of each with the 18.6-yr coefficient of nutation in longitude and obliquity. Then, eqs. (8) and (9) arc suitable for estimating the three desired corrections by a weighted least-squares fit. Weighting is in inverse proportion to the sum of squares of the formal errors of the respective pair of sources. To distinguish the two solutions from RA observations on the onc hand and Dec observations on the other, the unknowns arc designated $\delta n_\alpha, \delta(\Delta\psi)_\alpha, \delta(\Delta\varepsilon)_\alpha$ and $\delta n_\delta, \delta(\Delta\psi)_\delta, \delta(\Delta\varepsilon)_\delta$, respectively. For lack of true positions? the numerical treatment uses the catalogue positions in calculating the precession and nutation terms. As they are good appr oxidations of the true values, the loss of accuracy is undoubtedly of second order.

6. Case studies

6.1. Numerical results

Three sets of annual catalogues arc treated. Their posit ions differ from one another, since different nutation models have been employed for data reduction, while in all cases the data reduction is based on the 1976 IAU precession. Set 1 or the 1 AU set follows from the 1980 IAU Theory of Nutation (Seidelmann, 1982), set 2 or the ZMOA set from the ZMOA 1990-2 nutation model (Herring, 1991), and set 3 or the KSNRE set from the Kinoshita-Souchay nutation model (Kinoshita and Souchay, 1990).

The strength of the RA and Dec solutions of eqs. (8) and (9) profits from large epoch differences and from the frequency with which a source appears in the catalogues. Thus, only those sources are considered which appear in at least 10 of the 13 annual catalogues. Omitting spurious coordinates, approximately 75 sources have been singled out which fulfill the above condition. They gave rise to nearly 3800 pairs of observational equations in RA and Dec.

The observational equations associated with the three data sets arc subjected to a weighted least-squares process yielding the numbers of Table 1. They are preceded by the parameters for right ascension adj ustments. A proper value of generally accepted magnitude was chosen for precession. Values compatible with the respective nutation models have been adopted for the correction of nutation, i.e., for the IAU and KSNRE models wc used the corrections given by Williams et al. (1991), while no correction was applied to the ZMOA model. The *a priori* error of the observation of unit weight is set equal to 1 mas. To facilitate the comparison of results, we give $\delta\psi = \delta n / sin\, \varepsilon$ instead of the immediate solution δn; ε is the obliquity of the ecliptic.

Table 1. Corrections of precession and 18.6-yr nutations for three models of nutation using external best estimates for right ascension adjustment.

	IAU	ZMOA	KSNRE
RA adjustment:			
Precession [mas/yr]			
$\delta\psi$	-3.08	-3.08	-3.08
Nutation: 18.6-yr terms [mas]			
$\delta(\Delta\psi)$	-7.80	0	-7.80
$\delta(\Delta\varepsilon)$	3.00	0	3.00
Results:			
Precession [mas/yr]			
$\delta\psi_\alpha$	-3.14±0.07	3.21±0.04	3.24±0.07
$\delta\psi_\delta$	-3.11±0.08	3.05±0.05	3.35±0.08
Nutation: 18.6-yr terms [mas]			
$\delta(\Delta\psi)_\alpha$	-9.05±0.05	0.35±0.03	9.04±0.05
$\delta(\Delta\psi)_\delta$	-5.40±0.45	0±0.28	6.49±0.45
$\delta(\Delta\varepsilon)_\alpha$	4.68±0.17	0.85±0.10	4.06±0.16
$\delta(\Delta\varepsilon)_\delta$	3.81±0.09	0.56±0.06	3.28±0.09
Error of unit weight [mas]			
me(α)	1.89	1.13	1.83
me(δ)	2.04	1.26	2.03

The correlation coefficients of the unknowns are less than 0.25 with one exception: it reaches 0.88 for $\delta\psi_\delta$ and $\delta(\Delta\psi)_\delta$, which is not surprising because of the insufficient separability of precession and nutation in obliquity as expressed by the observational equations.

Judging only from the error of unit weight after the fit, the ZMOA nutation model is superior to the IAU and KSNRE models. Ideally, the error of unit weight should be 1 mas, which is closely approximated by the ZMOA solution. The IAU and KSNRE solutions yield approximately 2 mas, indicating the possibility of model inadequacies and systematic errors in the data.

At first glance the corrections of precession and 18.6-yr nutations appear reasonable, falling in line with results derived by quite different methods from lunar Laser Ranging data (LLR) and VLBI data, e.g., Williams et al. (1991), Chariot et al. (1995), Williams et al. (1995). What is disturbing in our solutions is the discrepancy between the RA and Dec solutions, which in some cases is larger than inferred from the formal standard errors. In fact, more or less identical results should be expected because of the independence of the RA and Dec observations, apart from correlations of the coordinates. Below, attempts are made to reconcile the discrepancy of the two solutions and the inconsistency of RA adjustment parameters and RA solutions,

one reason for the discrepancies could bc related to the RA adjust ments based on preliminary estimates. The Dec solutions, being free of such assumptions, suggest to substitute thcm as estimates for iterated RA solutions. Results using the self-sufficient Dec solution arc shown in Table 2 for the three nutation models. Wc have left out the Dec solutions, since they arc identical with those in Table 1.

The small differences of the RA and Dec solutions persist even after the substitution of RA adjustments consistent with the self-sufficient Dec solut ions. obviously, these differences arc to some extent related to the RA adjustment parameters, which arc chosen so that the differences are minimized. This minimum is achieved, however, at the expense of incompatibility of adjustment parameters with the RA solution. in other words, the RA solution dots not reproduce the starting parameters used for RA adj ustment. Moreover, if the adjustments arc calculated from the RA solution of the previous cycle, the iterations do not converge. Although the RA solutions arc marked by this inconsistency, they produce numerical results of acceptable order of magnitude. The disturbing effect seems to bc inherent, in the RA positions being more pronounced in case of the IAU than the ZMOA models of nutation, which supports the assumption that the effect depends on the nutation model used for data reduction. It cannot bc excluded that correlations of precession and nutation cause this inconsistency) which is also found when only the single-parameter solution of precession is performed taking the 18.6-yr nutation parameters from an improved nutation model (e.g., Williams ct al., 1991).

'1'able 2. Corrections for precession and 18.6-yr nutations using the Dec solutions of Table 1 as estimates for right ascension adjustments.

	IAU	ZMOA	KSNRE
Precession [mas/yr]			
$\delta\psi_\alpha$	--2.7830.07	3.22±0.04	3.03±0.07
Nutation: 18.6 yr terms [mas]			
$\delta(\Delta\psi)_\alpha$	--6.4030.05	- 0.37±0.03	7.47±0.05
$\delta(\Delta\varepsilon)_\alpha$	4.74±0.15	0.89ZE0.10	4.09±0.15
Error of unit weight [mas]			
$m_0(\alpha)$	1.70	1.14	1.71

The KSNRE results behave similarly to those obtained from the IAU model, inasmuch as the orders of magnitude of the corrections arc equal. The slightly larger absolute values in precession and nutation may be explainable by the strong correl ation between the two quantities. In the framework of this analysis it is realized that the overall effects of the KSNRE and IAU models arc equivalent, although the nutation coefficients differ from each other in general. The similarity is probably due to the fact that both models share the annual and semiannual nutation coefficients, while ZMOA revises thcm substantially. For the above reasons wc omit K SNRE in further discussions.

6.2. Accuracy assessment ancl discussion

In order to quote errors that are more realistic than formal statistical standard deviations, which normally represent the lower bound of the true error, wc process a variety of observational data which arc subsets of the total number of catalogue positions of the roughly 75 suitable sources mentioned before. Two paths have been taken in the choice of the subsets: (1) selection by catalogues providing two subsets consisting of the even and odd annual catalogues, respectively; (2) selection by positions from the total sequence of positions. In the second case, the subsets were formed by retaining only the even and odd positions in the total sequence, and by retaining two (three) out of three (four) consecutive positions, giving rise to 12 subsets. In the absence of systematic errors, each of the subsets should yield the same values for the unknowns. The precession corrections resulting from the individual subsets, however, differ by as nmch as 10% and 5% in case of the IAU and ZMOA nutation models, respectively. Differences of up to **25%** are found among the corrections of the IAU nutation terms, while the absolute values of the corrections of the ZMOA nutation terms arc small. Nevertheless, they cause relative differences of more than 60%. These figures indicate some dependence, although weak, on the selection of source positions and their temporal distribution.

Moreover, the RA solutions are subject to an additional error which originates in the uncertainties of the precession and nutation parameters employed for the RA adjustment. The point of departure of this error type is the self-sufficient Dcc solution and its errors given in Table 1. Allowing variations of the parameters for RA adjustment within the error ranges of the Dcc solutions, one obtains RA solutions between the following lower and upper limits:

IAU: $2.85 \text{ mas/yr} < \delta\psi_\alpha < -2.70 \text{ mas/yr}$
$-6.94 \text{ mas} < \delta(\Delta\psi)_\alpha < -5.85 \text{ mas}$
$4.73 \text{ mas} < \delta(\Delta\varepsilon)_\alpha < 4.75 \text{ mas}$

ZMOA: $-3.27 \text{ mas/yr} < \delta\psi_\alpha < -3.18 \text{ mas/yr}$
$-0.72 \text{ mas} < \delta(\Delta\psi)_\alpha < -0.03 \text{ mas}$
$0.88 \text{ mas} < \delta(\Delta\varepsilon)_\alpha < 0.89 \text{ mas}.$

The rms error of these solutions is taken as a measure of the additional error caused by the uncertainty of the RA adjustment. One finds:

IAU: $\sigma(\delta\psi_\alpha) = 0.06$ mas/yr
$\sigma(\delta(\Delta\psi)_\alpha) = 0.40$ mas
$\sigma(\delta(\Delta\varepsilon)_\alpha) = 0.01$ mas

ZMOA: $\sigma(\delta\psi_\alpha) = 0.05$ mas/yr
$\sigma(\delta(\Delta\psi)_\alpha) = 0.32$ mas
$\sigma(\delta(\Delta\varepsilon)_\alpha) = 0.00$ mas.

We define the realistic error of the precession and 18.6-yr nutation corrections as the rms error of the mean of the RA and Dec solutions for different subsets of RA and Dec positions. For RA solutions this error is augmented in the quadratic sense by the above-listed rms errors due to RA adjustment. The mean values of the corrections to luni-solar precession and the 18.6-yr nutations, together with realistic errors derived from a sample of 15 position selections, are given in Table 3. This sample consists of the standard set comprising the total number of eligible positions, 2 subsets corresponding to the even and odd catalogues, and 12 subsets formed by systematic position selection as outlined above.

Table 3. Mean values of the corrections to precession and 18.6-yr nutations derived from 15 different sets of catalogue positions.

	IAU	ZMOA
Precession [mas/yr]		
$\delta\psi_\alpha$	−2.79±0.23	−3.25±0.09
$\delta\psi_\delta$	−3.08±0.16	−3.06±0.10
Nutation: 18.6-yr terms [mas]		
$\delta(\Delta\psi)_\alpha$	−6.44±0.42	−0.39±0.35
$\delta(\Delta\psi)_\delta$	−5.35±1.08	0.01±0.39
$\delta(\Delta\varepsilon)_\alpha$	4.89±0.55	0.95±0.33
$\delta(\Delta\varepsilon)_\delta$	3.79±0.30	0.54±0.16

On comparing the RA and Dec solutions in Table 3, both for IAU and ZMOA, the differences between the RA and Dec solutions generally fall within the error bars of the differences. In the case of nutation in obliquity, the differences exceed the error bar slightly. Despite this satisfactory result, we favour the Dec solution, bearing in mind the possibility of adulteration of the RA solutions by the adjustment parameters. Thus, in the case of the 1980 IAU Nutation Theory, the corrections obtained for luni-solar precession and 18.6-yr nutations are in turn −3.1 ±0.2 mas/yr, −5.4±1.1 mas, and 3.8±0.3 mas. In the case of the ZMOA 1990-2 nutation model, the respective corrections are −3.1 ±0.1 mas/yr, 0.0±0.4 mas, and 0.5±0.2 mas. For comparison with the IAU adopted values, we have added the corrections of the Dec solution to the respective starting values in order to display total values of luni-solar precession and 18.6-yr nutations in longitude and obliquity:

IAU adopted values:

$$\psi = 50.3878''/\text{yr}, \quad \Delta\psi = -17.''1996, \quad \Delta\varepsilon = 9.''2025$$

IAU nutation model:

$$\psi = 50.3847''/\text{yr}, \quad \Delta\psi = -17.''2050, \quad \Delta\varepsilon = 9.''2063$$

ZMOA nutation model:

$$\psi = 50.3847''/\text{yr}, \quad \Delta\psi = 17.''2067, \quad \Delta\varepsilon = 9.''2058.$$

The method of position analysis applied to the IAU as well as ZMOA reduced data sets provides the same value of the luni-solar precession, and values of the 18.6-yr nutation coefficients differing by approximately 1 mas.

7. Conclusions

The method presented in this paper is an alternative to estimating precession and nutation corrections from direct fits to the original VLBI observables, and has the virtue of potentially exposing systematic problems in one or both methods. We have demonstrated the possibility of determining corrections to the luni-solar precession and the 18.6-yr nutation in longitude and obliquity from catalogue positions obtained at annually spaced epochs between 1978 and 1994. The method of analysis was applied to three models of nutation, the 1980 IAU Theory of Nutation, the ZMOA 1990-2 nutation mode) and the Kinoshita-Souchay nutation model. All three cases produce correction values approximating closely those of independent methods. The first and third model yielded almost identical results.

In principle the method pursued here supplies two solutions, one derived from the positions in RA and the other from positions in Dec. While the Dec solution is self-suf%cient, the RA solution requires *a priori* information on precession and nutation, allowing the adjustment of the differential RA's, which are referred to a uniform zero point in the annual position catalogues. Both solutions show the same trend, and their differences remain nearly within the statistical error of the differences.

In, case of the IAU nutation model, the arithmetic mean of the RA and Dec corrections to 'precession and 18.6-yr nutations following from Table 3 is in turn - 2.9±0.3 mas/yr, - 5.9± 1.2 mas, 4.3±0.6 mas. These results are in reasonable agreement with independent determinations from Lunar Laser Ranging data (Williams et al., 1994) and from VLBI/LLR data (Chariot et al., 1995). The first paper arrived at 3.2±0.3 mas/yr, -5.0±3.3 mas, 1.8+ 1.2 mas for the unconstrained in-phase solution, and the second one at -3.0± 0.2 mas/yr, - 7.0±1.0 mas, 2.7±0.2 mas, respectively. On the other hand, when using the ZMOA nutation model, Table 3 yields for the mean correction of precession -3.2±0. 1 mas/yr, while the mean corrections to the 18.6-yr nutations are as small as 0.2±0.5 mas and 0.7±0.4 mas, emphasizing that no significant correction to the ZMOA nutation model is indicated by our method.

The above-mentioned results confirm that secular and quasi-secular effects such as precession and 18.6-yr nutations are accurately preserved during the complex VLBI data reduction process, and propagate intact into the final source positions. Therefore, if only luni-solar precession and 18.6-yr nutations are under investigation, it is possible to determine corrections from position catalogues referring to reasonably spaced epochs of observation. The technique serves also as a check of the cohesiveness and believability of the VLBI measurements. There is an additional ad vant age that position catalogues belonging to a variety of VLBI networks are eligible for a combined treatment, provided there is adequately detailed documentation of the fundamental quantities adopted for the reduction to celestial coordinates.

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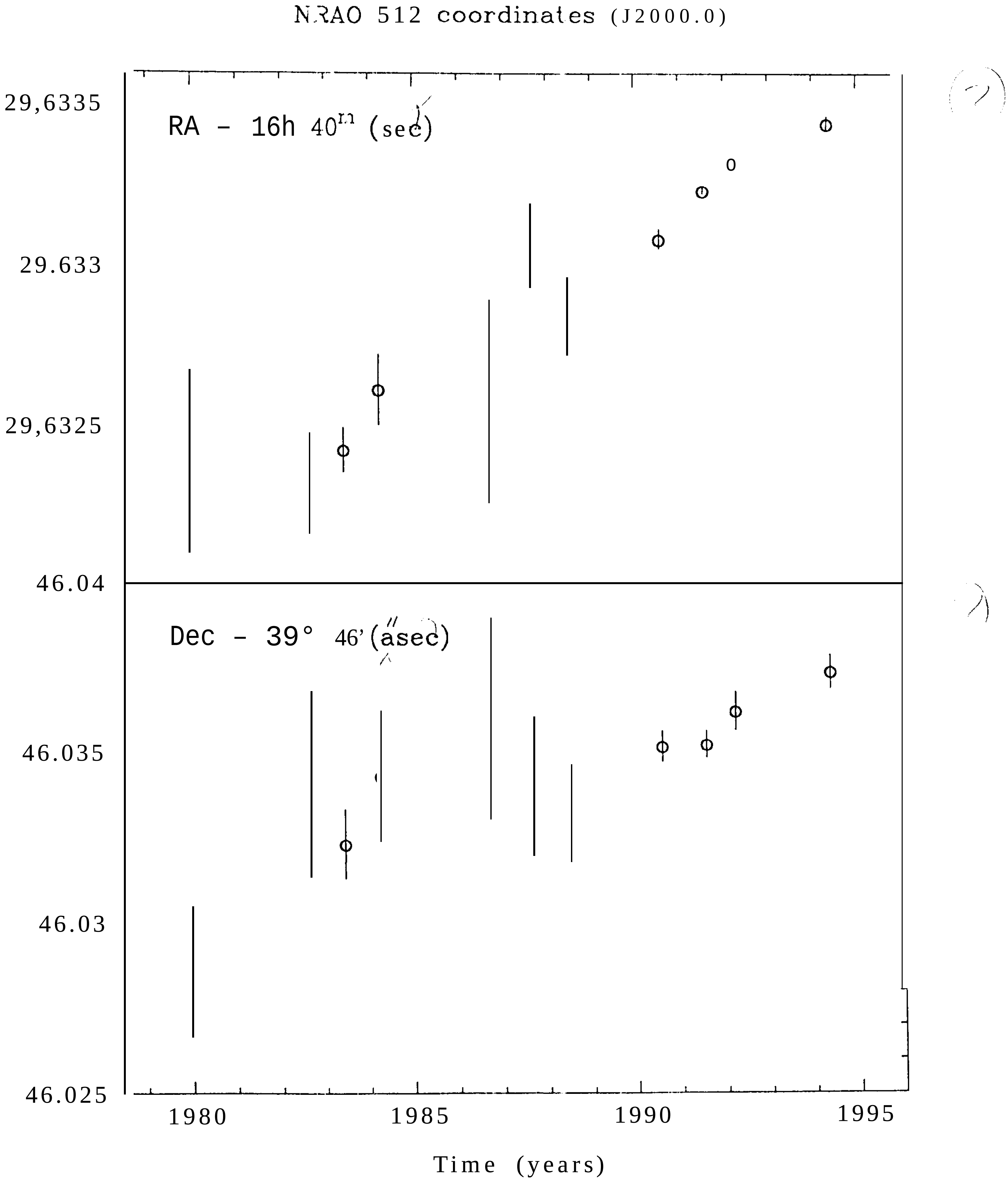
Figure Caption

Fig. 1. Right ascension (a) and declination (b) of NRAO 512 from yearly catalogues, determined with the 1976 IAU precession and ZMOA 1990-2 nutation models.


NRAO 512 coordinates (J2000.0)
RA - 16h 40m (sec)
Dec - 39° 46' (asec)
29,6335
29.633
29,6325
46.04
46.035
46.03
46.025
1980
1985
1990
1995
Time (years)