Rotation of the Earth and Polar Motion, Services

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Abstract. The need of a continuous monitoring of the polar motion appeared at the end of the 19th century, and was at the origin of one of the oldest international projects : the establishment of the International Latitude Service. This service still operates, but other organizations now determine the polar motion, using the astrometric measurements of latitude and time and also Doppler observations of artificial satellites. On the other hand, since the advent of atomic clocks in 1955, the universal time has become a measure of the rotation of the Earth, which is also currently required and which must be evaluated by a Service. The services providing polar motion and universal time data will be described, the precision and accuracy of these data will be estimated.

Introduction

The full description of the rotation of the Earth in space is traditionally given by the motion of the rotation axis with respect to the Earth (polar motion), and in space (luni-solar precession, nutation), and by the angular position around the rotation axis (universal time UT1). Precession and nutation can be fairly well modeled, and require only occasional improvements of their representation ; polar motion and universal time are still unpredictable and require continuous monitoring.

While for several decades, since 1900, the International Latitude Service (ILS) was the only source of the pole coordinates x and y, the development of new astrometric instruments led to the organization of a new service, the International Polar Motion Service (IPMS) in 1962. But the advent of atomic clocks in 1955 made obsolete the division of the work between polar motion and universal time. The Bureau International de l'Heure (BIH), in charge of universal time, began in 1955 to determine its own set of coordinates of the pole needed in the evaluation of UT1. On the other hand, the successful recovery of the pole coordinates using Doppler observations of Transit satellites led national organizations of the USA to determine routinely these coordinates.

Thus the user has the choice among several sets of pole coordinates (but there is only one for UT1), which, of course, differ. This is often considered as a nuisance. But it has, at least, one important advantage : it is a warning against too much faith in the published results. We have too many examples of analyses and interpretations where the limitations of the ILS data where ignored.

Methods

The astrometric methods refer to the directions of the plumb-lines of the observatories. We will assume that the Earth is rigid and that these directions are fixed within the Earth. [This is not true ; some motions due to the luni-solar attraction can be modeled, but others due to various local causes and to the plate motions are not sufficiently known to correct the observations.] Figure 1 shows on an auxiliary sphere of unit radius the directions of the instantaneous North pole P, of a reference fixed pole P_o and of the zenith Z of a station. The origin of the astronomical longitudes is a fixed point O on the equator of P_o. We can see that the astronomical latitude φ and longitude L vary with the coordinates of the pole x and y. The universal time UT1 is simply linked to the angular motion in space of the PO meridian around P ; it is therefore dependent on x and y. The fundamental equations used in classical services are, for each station i, UTC being the worldwide time reference,

$$x(t)\cos L_{o,i} + y(t)\sin L_{o,i} = \varphi_{t,i} - \varphi_{o,i} \ , \quad (1)$$

$$[-x(t)\sin L_{o,i} + y(t)\cos L_{o,i}]\tan\varphi_{o,i} + [UT1-UTC]_t = [UT0_i - UTC]_t \ , \quad (2)$$

where $\varphi_{o,i}$ is the initial fixed latitude. $L_{o,i}$, the initial longitude, does not explicitly appear, but it is used in deriving $UT0_i$, which is therefore computed assuming x = y = 0.

Except for the ILS, the computations of $\varphi_{t,i}$, $[UT0_i - UTC]_t$ are made by the contributing observatories themselves, using the values of astronomical constants recommended by the International Astronomical Union. The role of the central services is thus to combine the equations (1) and (2). There is no standard procedure to accomplish that ; the main choices are related to

- the weighting factors, according to the quality of the observations,
- the choice of initial latitudes and longitudes,

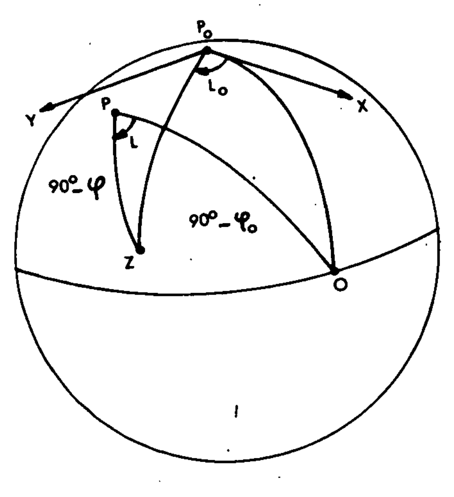

Fig. 1. Variation of astronomical latitude and longitude with the coordinates of the pole.

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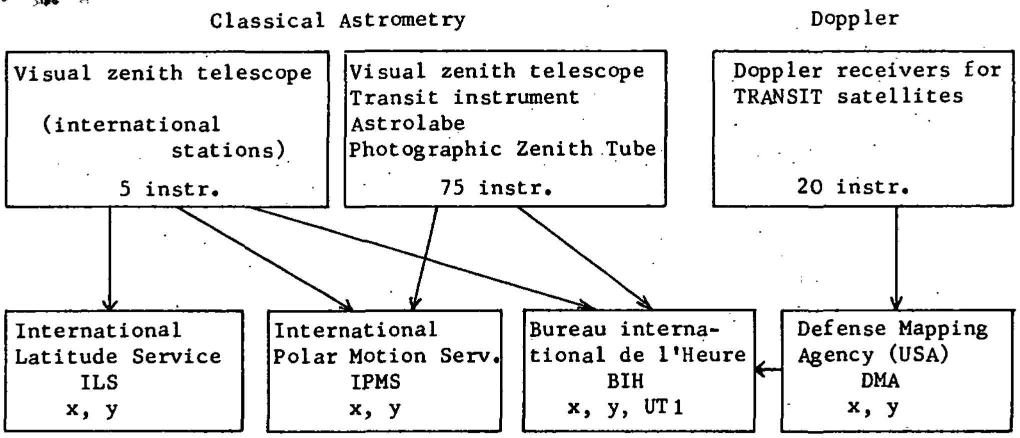

Fig. 2. Data flow to the services.

- the way of removing some systematic errors,
- the averaging time,
- the smoothing techniques on observational data and evaluated results.

The Doppler determinations of polar motion is an example of the satellite techniques for the study of Earth rotation, which are discussed by Aardoom [1978] at this Conference. Therefore we will only point out that in these techniques, instead of referring the observations directly to the quasi-non-rotating directions of stars, one uses intermediary objects, the directions of which are computed in the non-rotating reference frame. Providing that the motion of the object can be correctly modeled, UT1, x and y can be derived from the observations. In practice, a spurious drift of UT1 cannot be avoided, but the coordinates of the pole can be obtained to a large extent free from systematic errors and drifts.

Although astrometry only measures angles, we will use the meter as the unit for polar motion, assuming that the radius of the auxiliary sphere is the polar radius of the Earth.

Figure 2 shows the general organization of the services in 1978.

Precision and accuracy of the results

A matter of importance is the degree of confidence the user may have in the results published by the Services. This problem is not easily solved. In most cases, the data are given without any information on their precision. In some cases a standard deviation is given, computed from the internal consistency of the data contributing to the determination of a raw value over a given averaging time τ. But even when this information is given, it is far from being sufficient : it is well known that the errors are not a white noise and that the standard deviation does not vary proportionally to $1/\sqrt{\tau}$.

Let us suppose that A_o, $A_1, \dots, A_n$ are measured quantities obtained at instants t_o, $t_o + \tau, \dots$, $t_o + n\tau$, by averaging over intervals τ. If a_o, $a_1, \dots, a_n$ are the random errors of these quantities, it is possible to characterize the random noise by the pair variance (or Allan variance)

$$\sigma_a^2\,(\tau) = \text{mean of } \frac{(a_{i+1} - a_i)^2}{2} .$$

This function is represented by stability curves (Fig. 3), as it is customary for the characterization of the stability of oscillators [Barnes et al., 1971] . Thus instead of speaking loosely of the precision of the results, we can speak of their stability.

In general, for small values of τ, $\sigma_a(\tau)$ follows a law in $1/\sqrt{\tau}$, as in the case of white noise, but for larger values of τ, $\sigma_a\,(\tau)$ reaches a minimum which is called the flicker floor. For still larger values of τ, $\sigma_a\,(\tau)$ generally increases. In this latter domain it is sometimes difficult to make the distinction

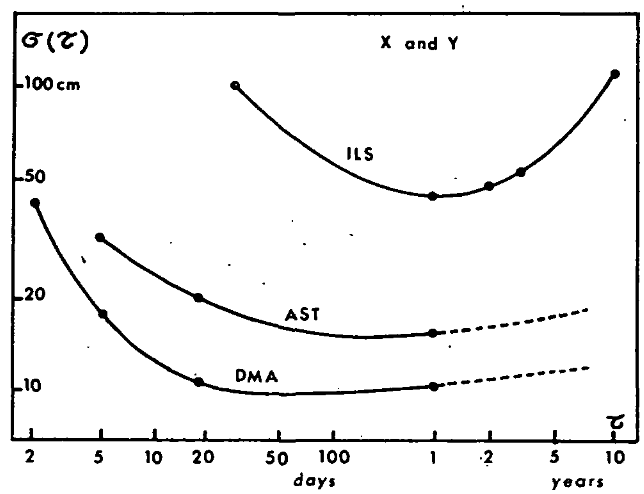

Fig. 3. Precision of the pole coordinates as a function of the averaging time τ. $\sigma^2(\tau)$ is the pair variance. AST stands for global astrometric services : IPMS and BIH special solution for astrometry alone. The current BIH results including DMA have about the same precision as DMA.

between random and systematic errors. For instance, for the Earth rotation parameters, the increase of $\sigma_a(\tau)$ with τ can be the consequence of changes in the network of observing stations, changes of programs and methods in the stations, and/or plate motions.

In the following, the stability curves will be given. One must be aware that they represent an estimation. For values of τ smaller than a month, we can assume that the observational noise is larger than the true noise of the observed quantities themselves, and the use of a high-pass filter gives fairly reliable values of the random errors a. But for larger values of τ , one has to make less reasonable assumptions. The "three-corner-hat method" is not available because there are only two truly independent series of data, the astrometric and the Doppler.

The accuracy of a series of results expresses the degree of conformity with an adopted standard. In our case, the standard is not well defined. Let us take the motion of the pole. In the case of astrometry, we only define the direction of the pole relative to the direction of the zeniths. On account of plate motions, the reference to the zeniths is vague. The satellite method refers the position of the pole to the Earth. Similarly, the plate motions displace the stations and also the plate on which the pole moves. Nevertheless, some types of errors can be recognized, such as annual terms due to wrong positions of stars, or drifts due to erroneous proper motions of stars. An attempt to identify these sources of errors will be made.

Services, Series of Results

International Latitude Service (ILS)

The ILS was born from the recognition of the existence of polar motion in 1880-1890. This recognition is not a sudden discovery. Its complicated history [see Sevarlic, 1957] began with Euler's theoretical work, but in spite of many attempts to measure polar motion, this motion was not undoubtedly found in the observations until Künstner's work in 1884-86. Further campaigns of observations, the analysis by Chandler, Nyren, Marcuse and others, the famous interpretation of the Chandler period by Newcomb (in 1892), showed the necessity of continuous monitoring of the pole. The original proposal of Fergola, presented to the International Association of Geodesy (IAG) in 1883 by Schiaparelli, to organize systematic determinations of latitude was reintroduced in 1889 by Förster, then followed by the creation of the ILS (IAG meetings of 1895, 1896 and 1899).

The fundamental idea, in organizing the ILS, was to remove the systematic errors due to the poorly known star positions by using stations on a common parallel, with identical instruments and programs. The adopted latitude measurements, according to the Horrebow-Talcott method,consists of meridian measurements of zenith distances, the divided circles and refraction uncertainties being avoided by the use of pairs of stars at nearly equal distances, North and South : only differential zenith distances are measured, which requires well calibrated micrometer screws. The stations, located on the 39°8'N parallel are now :

Mizusawa, Japan,	longitude	141° E
Kitab, URSS,	"	67° E
Carloforte, Italy,	"	8° E
Gaithersburg, USA,	"	77° W
Ukiah USA,	"	125° W

Initially, the declination errors were removed by the so-called chain method. Two or more groups of stars are observed every night. Assuming that the latitude does not vary during the night, the difference between group results represents the contribution of declination errors. As only night observations are possible, a full year is required for a complete evaluation of the declinations, which permits to refer all the observed latitude to the same standard before solving equations (1). Next year, the cycle is resumed and the star positions can be improved. That explains that no definitive results can be published, as long as the same stars are observed (normally during 6 to 12 years, because after some time precession makes the list of stars obsolete).

This procedure was improved in 1922 by Kimura, who gave the ILS its present form. The Kimura z term of equation (3)

$$x(t)\cos L_{o,i}+y(t)\sin L_{o,i}+z(t) = \varphi_{t,i}-\varphi_{o,i} \qquad (3)$$

contains all the non-polar effects common in the observed latitudes of the stations.

A further improvement was the "latitude control method" [Markowitz, 1961] , which eliminates the influence of wrong micrometer screw calibrations, and which is now currently used as a check.

With the Kimura method, the results of the ILS could be made available within short delays. But only Yumi, in 1962, took advantage of this possibility when he started to publish the Monthly Notes of the IPMS, giving the ILS results with a delay of about 3 months. In addition detailed results are given in the IPMS Annual Reports with a delay of the order of two years. In the past, it happened that the volumes of definitive results were published more than 20 years after the observations.

The ILS obtains the raw values of x and y monthly. It is customary to give smoothed values at 0.05 year intervals.

According to its organization, the ILS should give accurate results if there were no local errors : the fixed network of stations and the z-term ensure in that case a perfect geometrical solution to the polar motion determination. That is why, in 1967, the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (UGGI) defined the "Conventional International Origin" (CIO) for the pole by giving conventional values of the five initial latitudes $\varphi_{o,i}$ of the present stations. However, after solving equations (3), it can be seen that the local residuals are not random. In particular, they exhibit annual components, showing that there are local seasonal effects (on instruments, refraction...), and that therefore the annual path of the ILS pole is not accurate. Another source of systematic uncertainties lies in the tectonics. The stations are poorly established in active areas, so that we cannot be sure that the observed drift of the pole toward Canada, at a rate of 10 cm/year, is real.

The precision of the ILS coordinates is schematically shown by figure 3. The long-term noise is due to changes of observers, of reference latitudes, of methods, of instruments. The figure gives a very rough estimate, since the noise in the results is not stationary. Not only the number, but also the quality of the stations changed. After the enthusiasm of the beginning, there has been a period of lack of interest, until the development of the Earth sciences in 1950-60. Presently the Service suffers from the lack of observers and from the discouragement in view of the better results obtained by IPMS and BIH and of the expectations from new techniques.

Nevertheless, the 80-year series of the ILS is invaluable. It can be improved by using modern techniques of computation, better initial star coordinates and astronomical constants, a more homogeneous set of initial latitudes. The enormous work of revision was undertaken by Yumi and his staff, and is nearly achieved. In the mean-time Vicente and Yumi [1969] published an homogeneous set of coordinates of the pole since 1900, based on ILS results.

International Polar Motion Service (IPMS)

The ILS organization has the drawback of not allowing the use of data from outside stations. Excellent series of latitude measurements obtained by the observatories of Greenwich, Pulkovo, Washington, from 1912 to 1952 have been very little used in the investigation of polar motion. This situation could no longer be accepted when in 1950-60 many new instruments, photographic zenith tubes, astrolabes, improved visual zenith telescopes for the Horrebow-Talcott method, photoelectric transit instruments, came into use. Although many astronomers were reluctant to combine the data from these various sources, in 1962, the ILS was reorganized into the IPMS with the task of deriving polar motion from latitude and universal time data of all astronomical instruments (UGGI and UAI decisions in 1960 and 1961). The IPMS was located at the International Latitude Observatory in Mizusawa, Japan. S. Yumi became director in 1962 after the death of T. Hattori.

Although the ILS formally disappeared, it is advantageous to keep the ILS designation, as we did, for the particular pole coordinates set based on the international stations-a continuation of the former ILS.

The IPMS began to publish the coordinates of the pole based on all latitude measurements, on a current basis, with the issue for January 1975 of the Monthly Notes of the IPMS. In this issue the coordinates for 1974 were also given. Solutions starting from 1962, based on latitude alone, and on latitude and time were given in the IPMS Annual Reports for 1972 and 1974.

The number of stations contributing to the IPMS work is fairly stable and of the order of 80. For instance, in the IPMS Annual Report for 1975 we see that 21 stations participate with latitude only, 26 with UTO only, 29 with both UTO and latitude.

The method of computation is based on the monthly averages of latitude and UTO data [S. Yumi, 1976]. It requires a coherent set of initial latitudes and longitudes. As the quality of the contributing observations is much different for the various stations, the weighting procedure is important. The weights are computed from the scattering of individual measurements. Several solutions were attempted, using equations (1) and (2), and also similar equations with auxiliary unknowns to take into account the errors in the development of the celestial nutation. The raw results are monthly values of x, y (and also UT1-UTC, although the IPMS does not currently publish these results). The smoothed results are given at 0.05 year intervals.

In the IPMS, the work is based on latitude and UTO data forwarded by the observatories. In these observatories, the only way of taking into account the star position errors is to use the chain method, or similar methods. It is well known that these methods do not eliminate spurious annual terms on account to apparent variations of latitude and UTO during the night, due to temperature effects and refraction. Therefore the IPMS annual term of the pole motion cannot be accurate (a remark which also applies to the BIH work). Similarly the local drifts due to erroneous proper motions contribute to a spurious drift of the IPMS (and BIH) pole. Nevertheless, these effects are reduced by the averaging procedure. The peak-to-peak spurious annual variation is probably less than 1 m (of the same order as for ILS) and the spurious drift of the pole less than 3 cm/year (smaller than for ILS).

The estimated stability curve is given by figure 3. The long term unstability is mainly due to changes in the station list and in the programs.

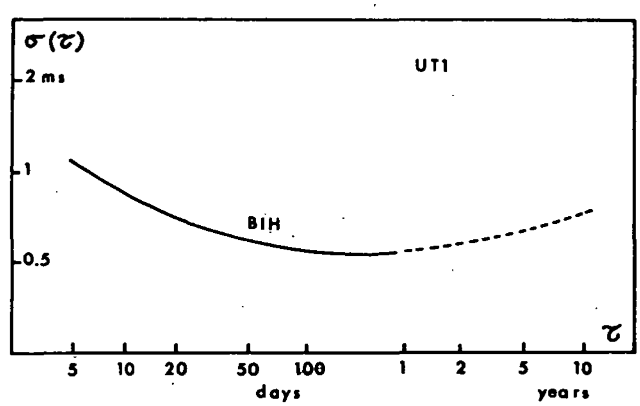

Fig. 4. Precision of UT1 obtained by BIH. $\sigma^2(\tau)$ is the pair variance, as a function of the averaging time τ.

Bureau International de l'Heure (BIH)

The BIH was created in 1912 and has been located at the Paris Observatory since that date. Its present director is B. Guinot (since 1965).

The initial task of the BIH was to unify time by publishing the time of emission (in universal time or at that time mean solar time) of radio time signals. With the improvement of time comparison methods and the advent of operational atomic time standards in 1955, the universal time measurements could be referred to a common very uniform time scale, presently designated by International Atomic Time TAI, or to its sister time scale UTC. Thus, besides establishing TAI and UTC, the traditional task of the BIH evolved in giving the difference between universal time and TAI or UTC - a measure of the irregularity of the Earth rotation. On the other hand the increase of the observational precision necessitated taking into account the polar motion (IAU recommendation, 1955), leading to the definition of UT1. As the coordinates of the pole were not available from the ILS in due time, N. Stoyko, formerly in charge of the BIH, began to establish his own set of coordinates from the latitude data of an increasing number of participating observatories. In 1965, in order to reduce the delays of availability of the results, Guinot began to solve equations (1) and (2) simultaneously. Thus, the overlap of functions with IPMS appears to be complete ; but this was unavoidable, because the scientific unions did not make a comprehensive evaluation of the situation in 1962 when creating the IPMS.

There have been many changes in the BIH work since its creation, due to the evolution of techniques. The following information refers to the present situation. The BIH uses all data on Earth rotation from any source, as soon as their systematic errors can be sufficiently well modeled. Until 1972.0, only astrometric data (the same as for IPMS) were used. Since 1972, it was possible to use the pole determinations by satellite observations from the DMA (see below). The computational methods were described by Guinot and Feissel [1968] and with more details by Feissel [1972] . They consist first in establishing a "system" by determination of the initial latitudes and longitudes, and the annual systematic corrections to data. Then, equations (1) and (2), with appropriate weights, are solved for individual measurements of $\varphi_{t,i}$ and $[UTO_i - UTC]_t$. It is thus possible to adopt a short averaging time.

Raw five-day values of x, y, UT1-UTC have been available since 1967. In 1972.0, the satellite data began to contribute to these raw values ; they presently receive about half the total weight for polar motion. Nevertheless, for comparison purposes a solution from astrometry only is continued ; it is based on the same data as IPMS work. Smoothed five-day values are published filtered with a cut-off at about 30 days ; they extend in an homogeneous series since 1962.

The current results for month m are published in BIH Circular D at the beginning of month m + 2, with provisional raw values. Improved results for the year a are published towards June of year a + 1, in an Annual Report. In addition, the BIH operates a rapid service, giving with lower precision the results of week w on Thursday of week w + 1, under a contract with the Jet Propulsion Laboratory (USA).

The BIH computations are devised in order to keep the spurious annual term as constant as possible. The satellite data are introduced after annual corrections, which express them in the initial BIH system. Thus the annual systematic error is due to the annual errors of astrometric measurements at initial epoch, in 1968 ; for polar motion, it is of the same order as for IPMS (1m peak-to-peak) ; for UT1 it can be of the order of 3 ms, peak-to-peak. The spurious drift of the BIH pole should be less than 3 cm/year. The spurious drift of UT1 is mainly due to the drifts of the star catalog equinoxes ; a drift of 1 ms/year appears possible.

The precision of the BIH results is given by the stability curve of figure 3 and 4.

The BIH is involved in the EROLD project (Earth rotation by Lunar Distances) and in the MEDOC experiment (Polar motion by Doppler observations of satellites). A revision of past data was recently undertaken by Feissel.

The BIH, as the IPMS, sends its current results free of charge to about 800 addresses. These data are reproduced in several national publications.

Defense Mapping Agency (DMA)

The computation of the pole position based on Doppler observations of Transit satellites originated at the Naval Weapons Laboratory, USA, (now the Naval Surface Weapons Center), as a consequence of the research of Anderle and Beuglass [1970]. A service was organized under the name of Dahlgren Polar Monitoring Service, giving the coordinates of the pole since 1969. In April 1970, the responsibility for the computation of the orbits of the Transit satellite, and therefore of the pole motion, was transferred to the Topographic Center of Defense Mapping Agency, without changes of the computation programs.

Many improvements took place, which are reported, together with a comprehensive bibliography by Oesterwinter [1978]. The most important one appeared in the 1972 results, where the polar motion, instead of being derived from station residuals, was computed directly in the least square solution together with the orbit parameters. Other improvements resulted from better gravity field models, from better station coordinates, from the increase of observing stations (about 20 presently).

The reduction techniques were described by Anderle [1973]. It is reminded that 48-hour time spans are used, leading to two-day raw values of the pole coordinates for each satellite. These values, with their standard deviations, are made available within a few days in DMA reports. Five-day averages are also given weekly in the USNO Series 7 Circulars.

The possibility of systematic errors due to the model of forces was investigated by Taton [1972] and by Bowman and Leroy [1976]. Errors with periods 5 to 6 days and 11 days were found, but they can be easily filtered. Longer term errors may exist, but are probably small when compared to the errors due to changes in the station network and plate motions. The size of seasonal effects, if any, cannot be estimated, but appears to be much smaller than for astrometry.

The precision curve is given by figure 3. A source of long term, noise could be the successive refinements of the model of forces : these effects are now very small.

Thus, the DMA maintains a polar motion service which is not officially recognized by scientific unions, but is essential, as being more accurate, more precise and more rapid than the official ones. The possibility of managing a Doppler network by scientific organizations is being tested in the MEDOC project [Guinot and Nouel, 1976 ; Nouel and Gambis, 1978].

Other series of results

As prior to 1962 no latitude series other than those of northern ILS stations contributed to the official work on polar motion, Fedorov and his collaborators at the Kiev observatory computed the polar motion from all known measurements. They were able to get some coordinates starting from 1846, and high precision coordinates from 1890.0 to 1969.0 Fedorov et al., [1972].

The Gosstandard of USSR computes a solution for UT1 based on the 21 instruments for universal time measurements operating in USSR and neighbouring countries. This solution is based on an original optimum estimation ; it is published in the bulletins "Vcemirnoe Vremja" (Series E) of the USSR Gosstandard.

Conclusion

Although their organization is not optimum, the services have produced uninterrupted series of pole coordinates and UT1 values, with good homogeneity. They have proved their ability to issue routinely the data with the short delays needed in modern research. The causes of this success are worth considering when preparing new services.

The work of the visual observers was (and is still) essential. One must be reminded that the same person has often to work more than six hours in the middle of the night, at outside temperatures, ignoring holidays and week-ends. Even with new automatized instruments the importance of the attendance should not be under-estimated, in service operation.

The astronomical instruments are very reliable. The Doppler receivers can be easily replaced in case of failure. Are we sure that other techniques, with sophisticated devices, will not suffer from interruptions, especially when based on a small number of stations ?

The operation of a service is quite different from an experiment. It has to run continuously, at the highest level of quality, in spite of many difficulties : vacations, illnesses, pregnancies, strikes, computer failures... Although requiring good scientists and technicians, this metrological work is not considered as attractive ; it is not easily supported by national and international organizations, which prefer to grant new projects.

Acknowledgments

The IPMS and BIH are services of the Federation of Astronomical and Geophysical Services (FAGS), a member of the International Council of Scientific Unions (ICSU). The allocation of FAGS to the services, based on ICSU and UNESCO funds, although essential, only represents 5 to 10% of the real cost of the central bureaus. The remaining is supported mainly by the host countries, and also by many establishments of outside countries, private fundations, and other international organizations.

The observation stations, the Doppler service are entirely supported by national sources.

It would be much too long to give a list of all contributors, they will recognize themselves, and accept our thanks in the name of the scientific community.

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