New possibilities for solution of problems in astrometry, geodynamics, and geodesy by ultralong-base radiointerferometric methods*

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The striking results that have been obtained in astrophysics by the use of radio interferometers with ultralong bases on the order of the diameter of the earth are well known. Ultralong-base radiointerferometers (ULBR) have been used to measure the sizes of a number of radio sources with angular resolution down to 0.2–0.5 msec. ULBR methods have brought out the complex structure of quasars. Many of them have been found to consist of a whole series of compact components and details with angular dimensions amounting to fractions of milliseconds of arc. Determination of the sizes of quasars has made it possible to estimate their brightness temperatures, which are unusually high—on the order of 10^{12} °K. Systematic measurements of quasar structure have led to the detection of relative motion of these components at apparent velocities several times the velocity of light.

Measurement of the curvature of radio-wave paths in the solar gravitational field was a brilliant demonstration of the possibilities inherent in the ULBR.

There is hardly a need to enumerate the many other astrophysical ULBR results. The possibilities of the ULBR in the field of astrometry are much less familiar. This is because the range of these applications is only now beginning to develop and major technical difficulties stand in the way of building the corresponding ULBR systems. The difficulties arise from the need to use broad-band apparatus.

Astrometry is an ancient science that forms the foundation of modern astronomy; the solutions of many practical problems are based on it, so that progress in astrometry means progress in these fields. This accounts for the implausibly broad spectrum of applications of the method that is indicated by the title. It has now become clear the ULBR method offers ways to solve classical problems of astronomy with accuracy one and sometimes two orders higher than is possible with optics. The present paper is devoted to analysis of these possibilities.

It must be said that contemporary classical astrometry is, in a certain sense, up a blind alley, since no method of improving substantially on the accuracy of optical measurements appears to be within the grasp of modern technology.

Thus, the principal problem of astrometry is to establish an inertial celestial coordinate frame in which the positions of the stars and other objects can be determined. A spherical system of celestial coordinates, the so-called equatorial system, has emerged from many centuries of practice. This system is fully analogous to the system of geographic coordinates—latitude and longitude—where the reference direction used is the axis on which the earth rotates. The coordinates of a source are defined in the equatorial system by its declination δ (the analog of latitude) and right ascension α (the analog of longitude), the latter reckoned from the point of the Vernal Equinox, i.e., the intersection of the celestial equator with the ecliptic. This coordinate frame is now fixed on the sky by the so-called fundamental catalog of coordinates of the stars of our Galaxy.

Use of Galactic stars means that noninertial effects will appear in the chosen system both due to the chaotic proper motion of the stars and their rotation together with the Galaxy.

In addition, the Vernal Equinox moves as a result of lunisolar precession and nutation of the earth's axis of rotation.

All of these things make it necessary to relate the equatorial coordinate system to a specified epoch and to measure not only the positions of the stars, but also the velocities and directions of their proper motions. These data are also included in modern catalogs for calculation of corrections.

The use of faint stars and other galaxies, which are so remote that the proper motions will not distort the coordinate frame for a long time, is promising for optical astrometry. Hence the problem, now being solved, of preparing a fundamental catalog of faint stars (CFS). At this time, the fundamental coordinate system is defined by the catalog FK-4, which contains about 1500 stars. Its absolute accuracy is unknown. It is estimated from the difference from the preceding catalog. The errors of declination and right ascension are about ± 0.2 second of arc.

Optical astrometry is based on the measurement of angles. These angle measurements are made with mechanical goniometric devices whose principles were laid down many centuries ago, while their designs have been more or less finalized during the past two centuries.

The basis of the angle-measuring system is an optical telescope fitted with crosshairs and capable of rotation around horizontal and vertical axes. The rotation angle of the telescope is determined from scales engraved on sufficiently large circles. All coordinate measurements are made with the instrument set up in such a way that the sighting line of the telescope will move in the plane of the local meridian during rotation on the horizontal axis. The telescope's vertical axis is aimed in the direction of the plumbline at the particular locality. The measuring principle consists in determining the direc-

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tion of the earth's axis on the instrument's circular scale from observations of stars at their upper and lower culminations. Then the angle $90^\circ - \delta$ between the axis and the star is determined.

The zero reference, the α point of the Vernal Equinox, is established with the aid of a clock from coordinated observations of the sun, the planets, and Fundamental Catalog stars.

The various instrumental errors of astrometric instruments stem from more than ten sources. Books devoted to investigation of these errors have now been written, and, as we have noted, practically all possibilities for their reduction have been exhausted.

In the inverse astrometric problem—that of determining the geographic coordinates of the observing point—the principal error source is the use of the gravity vector to set the instrument in the plane of the meridian. It is known that various deviations of the direction of gravity from the exact directions to the earth's center and axis of rotation are observed. The variations of the gravity vector with time amount to several seconds of arc. Elimination of these errors requires worldwide gravimetric measurements. This relation to the gravitational field is a fundamental property of absolute optical measurements of geographic coordinates.

The ULBR embodies a totally different measurement principle. The basis of the absolute source-coordinate measurements in this method is measurement of the projection of a certain length onto the direction to the radio-emission source, i.e., the quantity

$$r = \mathbf{s}\mathbf{d},$$

where $\mathbf{s}$ is the vector to the source and $\mathbf{d}$ is the vector of the baseline, which passes between the centers of radio telescopes. Let us first consider the question as to the accuracy of angular measurements made with an ULBR. The interferometer makes it possible to measure the time-of-arrival difference of a single wave front from a point source at the two antennas. For this purpose, both stations make records of the source noise signal oscillations in a certain frequency band Δf. Time markers from an atomic clock are included in the record. The records are reduced together and an attempt is made to align them in such a way that interference arises between the oscillations. This means that the same wave front arrived at the times t_1 and t_2 marked on the records. However, the interference range occupies a certain interval $1/\Delta f$—the signal-correlation interval or interference-visibility interval.

The clock-reading difference $t_1 - t_2$ gives the delay time $\tau(t)$ distorted by the error of determining the interference-visibility maximum and by the disagreement between the clock readings. For an equatorial base we have

$$r(t) = c\tau(t) = c\Delta\tau_0 + cBt + d\cos\theta(t),\ \theta(t) = \Omega t + \alpha - \Lambda;$$

where t is the Greenwich Time read from an atomic clock or Universal Time, $\theta(t)$ is the angle between $\mathbf{s}$ and $\mathbf{d}$, $\alpha - \Lambda$ is the initial angle, Λ is the longitude of the baseline direction, c is the velocity of light in a vacuum, $\Delta\tau_0$ is the clock-zero difference, B is the rate of the clock, and Ω is the velocity of rotation of the base (of the earth). It is evident from this relation that by measuring $\tau(t)$ several times a day (at least four times) for the same source, we can find d, the clock correction $\Delta\tau_0$, B, and Ω. Then, knowing d, $\Delta\tau_0$, B, and Ω, we can find the value of the angle $\theta(t)$ and $\alpha - \Lambda$ at any time. But what are the errors of measurement of the angles, the base length, and the clock comparison?

Three chief sources of error can be named. They are the clock difference between the stations, the error of fixing the correlation maximum in time, and the error of the correction for the increase in path length in the atmosphere and ionosphere. The method has no other errors that are in any way comparable with these. As for the clock-disagreement errors, we see that the measurement method itself results in comparison of the clocks for any given time, thus practically eliminating this error source, especially when clocks with stability $\sim 10^{-14}$ are used.

With consideration of other factors, the optimum range is $2 \le \lambda \le 15$ cm. The entire additional path in the atmosphere amounts to about 220 cm and depends on pressure, temperature, and humidity. It is now believed that this path can be taken into account accurate to 5—10 cm, i.e., that the error in r(t) is of the order of 5—10 cm. The influence of the ionosphere can be practically neglected for $\lambda \le 5$ cm.

The principal instrumental error is that of determining the time of the signal-correlation maximum. It equals

$$c\Delta\tau_u = \frac{c}{\Delta f}\frac{1}{N} = \lambda\frac{f_c}{\Delta f}\frac{1}{N} \approx \lambda;$$

where N is the signal/noise ratio.

The quantity $f_c/(\Delta f \times N)$ is determined by the technology. It is smaller the broader the receiver bandwidth, the larger the antenna, and the lower the receiver noise level. It can now be made of the order of unity. Thus, the total rms error does not exceed 10—15 cm. For a 5000-km base length, this gives an error of only $\Delta\theta = 5 \times 10^{-3}$ second of arc in the absolute measurement of the angle θ, and the error in determination of the period of the earth's rotation will accordingly be $\Delta T = \Delta\theta/\Omega \approx 0.3$ msec, the error in the base length $\Delta d \approx 10—15$ cm, and the error $\Delta\tau_0 \le 1$ nsec.

Let us now consider the general case of the measurement, in which the source has the coordinates α and δ and the base direction is arbitrary. The position of the base in the body of the earth will now be determined by the two coordinates ψ and Λ and $r(t) = c\Delta\tau_0 + cBt + d\sin\psi\sin\delta + d\cos\psi\cos\delta \times \cos(\Omega t + \alpha + \Lambda)$, where $d\sin\psi$ is the projection of the base onto the earth's axis and $d\cos\psi$ is its projection onto the plane of the equator. There are seven unknowns in the equation: $\Delta\tau_0$, B, d, ψ, $\alpha - \Lambda$, δ, Ω. Five independent equations determining the underscored quantities can be obtained for one source. To obtain the necessary number of equations, it is necessary to make measurements for two more sources. This adds four more unknowns—$\alpha_2 - \Lambda$, $\alpha_3 - \Lambda$, δ_2 and δ_3—and six new equations, i.e., the system is solved.

Thus, the ULBR can be used to measure the absolute values of δ, ψ, d, Ω, the source right-ascension difference $\alpha_i - \alpha_k$, and the difference $\alpha_1 - \Lambda$, as well as the values of the initial and present time-scale desynchronizations $\Delta\tau_0$ and B at the receiving stations. It is also possible to make differential measurements, in which the delay difference

$$r_1(t) - r_2(t) = \mathbf{s}_1\mathbf{d} - \mathbf{s}_2\mathbf{d},$$

which is related only to the mutual positions of the sources and the interferometer base vector, is formed from two sources that are observed simultaneously or with a sufficiently small time difference.

These measurements are accordingly most adequate to determinations of differential quantities: the change in the mutual positions of two sources, the change in the parameters of the interferometer base vector, for determination of the velocity of the earth's rotation and its variations. The potential resolution of differential measurements on a 5000-km base is 10^{-3}—10^{-4} second of arc for angle increments (depending on the angular distance between the sources) or 3—5 cm for linear variations of the base vector.

Differential measurements can also be used with observations of a minimal group of five sources to formulate a solvable system of equations for their declinations and right-ascension differences and the parameters of the interferometer base. It is essential that the time-scale desynchronization parameters do not enter into the measured quantity in the differential methods, and that the influence of tropospheric inhomogeneities is greatly reduced.

Table I assembles the calculated data on the errors of determination of absolute and relative radio-source coordinates, and Table II lists the errors for the parameters of the interferometer-base vector and the elements of its rotation as obtained over the diurnal cycle of observations made on the group of sources. Also given for comparison are the errors of measurements by other methods. We should note that some of the errors stated have already been confirmed in various experiments.

The high accuracy of solution of the basic astrometric problem—that of determining the coordinates of cosmic sources—combined with highly accurate determination of long geographic distances (chords) in all-weather measurements, justifies the statement that a new trend in positional astronomy—radio astrometry, which will enable us to solve traditional problems on a qualitatively different level and to broaden the class of solvable astrometric problems substantially, can be created on the basis of ULBR methods. The basic problems in whose solution radio-astrometric methods using ULBR equipment will be substantially helpful can be represented as follows.

TABLE I. Inertial Coordinate System

Quantity	Errors of measurement, arc-sec			
	Interferometry		Optical	Remote
	At present	Past		
Declination δ	10^{-2}—10^{3}	10^{-1}	$2\cdot10^{-1}$	Over a day
Right ascension α*)	10^{-2}	10^{-1}	$2\cdot10^{-1}$	"
Right-ascension difference $\alpha_i - \alpha_k$	10^{-3}—10^{-4}	10^{-1}	$(2-5)\cdot10^{-2}$	"
Precession Pr	10^{-3}	—	10^{-2}	3-5 yr
Nutation, N	$6\cdot10^{-3}$	—	10^{-2}	"
Derivative of angle ϵ between equator and ecliptic	10^{-3}	—	$3\cdot10^{-2}$	"

*With allowance for the error of the right ascension "zero point"

TABLE II

Quantity	Errors of measurement, arc-sec		
	Interferometry		Other methods
	At present	Past	
Distance d	15 cm/day	100.5 cm/day	200-500 cm; laser-satellite
Latitude ψ	5×10^{-3} cm/day		0.2–0.1 sec; laser-satellite
Difference between longitudes of base vectors, $\Delta_i - \Delta_k$	5×10^{-3} arc-sec		0.3; laser-satellite
Position of pole P	15 cm/day		300 cm/day; optical, latitude service
Length T of day	0.5–0.1 msec/day	2 msec/day	10 msec/day; optical, time service
Clock comparison, $t_i - t_k$	0.3×10^{-9} sec	10^{-9}	10^{-4}; coordinated time service

1. Fundamental astrometry. The objects of study by ULBR methods are radio sources with extremely small angular dimensions, including quasistellar radio sources and the nuclei of radio galaxies, whose great distances makes them almost ideal for creation of a network of fixed reference objects. Therefore the determination of their coordinates by radio-astronomical methods opens new possibilities for the construction of an inertial coordinate frame. This system can be made 1—2 orders of magnitude more accurate than the existing fundamental system. In turn, use of optical observations of quasars will make possible control against the inertial coordinate system with reference quasars of the existing fundamental star catalog and eventually of the catalog of faint stars. The right ascension zero point of the inertial coordinate system can be established from the combined results of radio-astrometric and optical measurements and equalization of the errors, or within the radio-astrometric method, by placing a radio beacon on a planet and controlling it against quasars. Thus, a universal inertial coordinate system that creates conditions for study of the motion of Galactic stars and certain extragalactic objects with accuracy on the order of 10^{-2}—10^{-3} second of arc can be created. Within a few years, it should be possible to observe the rotation of the Galaxy and to measure distances within the Galaxy on the basis of the parallaxes, which can be determined accurate to 10^{-4} second of arc. Analysis indicates that the precession and nutation parameters of the geocentric coordinate system may be improved by an order of magnitude after a few years.

2. Studies in celestial mechanics and solar system dynamics; space navigation. The planting of radio beacons on the surfaces of planets will make it possible to use the ULBR method to study the elements of the motion of these beacons, including the orbital motion of the planet and its axial rotation.

The placement of several beacons on the surface of a planet will make it possible to separate these elements, with determination of the directions of the rotation axis and their precession. It is essential that the parameters will be calculated in the inertial coordinate system if the interferometer base vector is determined from quasar observations. Thus, the orbital parameters of solar system planets can be improved, primarily in the cases of Venus and Mars, to within 10^{-3} second of arc, and, in particular, it will be possible to investigate the motion of the planet's perihelion to determine its non-Newtonian part.

Measurement of the orbits of satellites of planets will make it possible to investigate the dynamics of the planet-satellite system and the gravitational field of the planet. Accurate (to 10^{-3} second of arc) determination of the relative positions of a fixed beacon and a self-propelled lander on the planet's surface will make it possible to use ULBR methods for space navigation and in the specification of scales for cartography of the planets. For the moon, the highly important problem of determining the physical libration and the dynamics of the moon-earth system is also being solved. Prospects are opening for solution of the problems of earth-tide energy dissipation, momentum exchange, etc.

3. Geophysics, geodynamics, universal time and latitude service. Determination of the interferometer base vector accurate to 15–30 cm and of its variations accurate to 3–10 cm will make it possible, when many bases are used, to state the physical shape of the earth in terms of chords and to study the "breathing" of the earth and the motion of blocks of the earth's crust on global and regional scales. This specification of the earth's surface will be unrelated to gravitational measurements and will not be affected by features of the earth's gravitational field. Hence the possibility of investigating tidal and tectonic motions and establishing the relation between a change in the shape of the earth or of regions of the earth on the one hand and motion of masses within the earth and earthquakes on the other. Determination of the earth's rotation vector and the variations of the directional moments of rotation with resolution to 10^{-3} second of arc will make it possible to investigate their short-period variations and their relation to the circulation of the atmosphere and the motion of earth masses, to improve the secular retardation of the earth's moment of rotation, the elements of the free and forced nutation, etc.

The use of ULBR methods will make it possible to organize a radio-astronomical universal time and latitude service. A relative error of $(1-5) \times 10^{-9}$ in determination of the diurnal average velocity of rotation of the earth and a corresponding error of $\sim 0.1 \div 0.5$ msec in determining the variation of universal time UT_0 over the daily cycle of measurements are attainable; then the position of the earth's rotation axis (latitude) will be determined accurate to ~ 0.01 second of arc. The correction of UT_0 for the motion of the pole accurate to ≤ 30 cm/day and for the seasonal variations of the earth's rotational velocity will produce significantly improved values of the universal times UT_1 and UT_2. We note that it will be desirable to have a two-base ULBR system with meridional and equatorial base orientations in order to separate the time components related to the axis of rotation of the earth and the motion of the poles.

4. Geodesy. Coordinated time. Determination of ULBR base lengths accurate to ≤ 30 cm on distances of up to 10 000 km will make it possible to create a network of highly accurate geodetic bases, which are needed, for example, for topographic control of continents and the triangulation networks of various regions. Within a region, specification of reference points on the earth's surface by this method will make it possible to improve the parameters of the reference ellipsoid. Use of ULBR facilities in combination with satellite-geodesy methods (radio beacon on satellite) will be especially effective. In this case, the position of the satellite in the inertial coordinate system is determined with high accuracy by the ULBR method, and a reference geodetic base is formed; synchronous photography of the satellite from the ends of the interferometer baseline will make it possible to determine the direction of the base vector in the system of the fundamental star catalog. Then, having the coordinates of the satellite, we can solve the problem with either conventional satellite-geodesy or ULBR facilities; it will be possible to simplify the ULBR systems substantially if the radio emission from the satellite is powerful enough.

Together with this, radio astrometry using ULBR systems will make it possible to synchronize time scales accurate to 1 nsec, something that cannot yet be done by any other method. This will make possible highly accurate comparison of the scales of the standards used by the coordinated time services.

Thus, the far from complete list given above shows the ULBR to be a multifunctional instrument capable of solving a broad class of scientific and practical problems. It is significant that all of the problems are solved in coordinated fashion, using a common method and in a common reference system, and that this favorably distinguishes the ULBR method from others.

The minimal outfit needed for solution of the basic problems should consist of one base telescope with a dish diameter of 70 m and two or three 30-meter-diameter antennas spaced at distances of 3000 to 5000 km. In the future, ULBR systems might be used to combine all of the largest radio telescopes into a single complex and to synthesize a radio telescope with a span on the order of the earth's diameter.

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