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THEORETICAL FRAMEWORK FOR PULSAR TIMING

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Abstract

An introduction to the modern theoretical methods of pulsar timing and basic directions of the investigations are given. For simplicity, the consideration is done on the verbal level without the complicated mathematical details. The full text of the paper was presented at the General Assembly of URSI held at Kyoto in August 1993, and will be published elsewhere.

I. *Introduction*

Pulsars were discovered by radio astronomers at Cambridge University in 1967. The unusual properties of these objects were extremely interesting to many astronomers, both observers and theoreticians, which led to the rapid accumulation of observational data and to the appearance of numerous theories attempting to explain the characteristics of pulsars. A number of extensive pulse timing programs were initiated. The first essential efforts were made at Aresibo Observatory, Jodrell Bank, Parkes, the University of Massachusetts, the Jet Propulsion Laboratory and the Puschino Radioastronomical Observatory.

Discovering of millisecond pulsars in 1982 stimulated in the past several years development of a number of new programs all over the world including Japan. The excitement in the new efforts is extended from the deeper investigations of the neutron star structure and testing of General Relativity in the strong field gravity regime to the use of millisecond pulsars as celestial clocks for solving of important problems of fundamental astrometry and time-keeping metrology.

Almost all pulsars are objects of our Galaxy. The observed periods of pulsars lie in the range from 1.56 msec for PSR 1937+21 to 4.31 sec for PSR 1845-19. The extremely high stability of the pulse periods of pulsars and accuracy in determining pulse arrival times from them require an exceptionally high-precision method for processing of pulsar data. This method must include a multitude of factors: the orbital and rotational motion of the Earth, the celestial coordinates, proper motion and phase of rotation of the pulsar, the gravitational potential of the Solar system at the point of observation and along the trajectory of pulse propagation, effects of influence of the Earth's atmosphere as well as interplanetary and interstellar plasma, and, finally, the linear and quadratic Doppler effects.

In the observation of pulsars in binary stellar systems, these factors must be supplemented by classical and relativistic effects associated with the orbital motion of the pulsar around the barycenter of the binary system, propagation of pulses in the gravitational field of the pulsar's companion and motion of binary system with respect to the baricenter of the Solar system.

My goal is to introduce the theoretical framework of these complicated procedure, which includes discussion of the following basic questions:
—coordinate systems in space;
—reference time scales;
—propagation of electromagnetic signals;
—topocentric pulse arrival times;
—barycentric pulse arrival times;
—relativistic celestial mechanics of binary pulsars;
—rotation model of pulsar;
—pulsar parameter estimation formalism.

II. *Coordinate Systems in Space*

We consider the Galaxy as isolated gravitating system consisting of many millions stars including the Solar system and a pulsar under observation. Usually radioastronomers dealing with pulsar timing don't take into account the influence of the Galaxy on the observable pulsar parameters. But the recent work of Damour and Taylor [1] on the orbital period change of the binary pulars PSR 1913+16 forces to reconsider this point of view.

The coordinate systems in space as well as time scales are constructed in modern astronomy within the framework of General Relativity (see [2] and references therein). It is well known that in this theory the properties of a coordinate system and a gravitational field are described by the symmetric metric tensor of the second rank, which is found by solving the Einstein equations with suitably chosen boundary and (or) initial conditions. Moreover, the General Relativity admits the, so-called, gauge invariance under arbitrary coordinate transformations. It follows from that the four restrictions can be imposed on any four of ten components of the metric tensor. We prefer to choose the de-Donder or harmonicity conditions and therefore all of our coordinate systems are called harmonic ones.

For an adequate timing analysis of single pulsars, it is necessary to construct five coordinate systems: the galactic one (GCS), the barycentric one of the Solar system (BCS), the terrestrial one (TCS), the observer one (OCS) and the proper coordinate system of the pulsar (PCS). If the pulsar is a member of a binary system it is necessary to construct additional intermediate coordinate system—the barycentric one of the binary system (BBCS). Besides it is used the coordinate systems which differ from the ones introduced above by a constant or depending on time rotation.

The GCS is introduced to describe the propagation of light from the pulsar to the observer, to describe the motion of the Solar system and the pulsar with respect to (w.r.t) the barycenter (center of mass) of the Galaxy, and, to establish the scale of the Galaxy time (GT). The GCS is a global and asymptotically Lorentzian coordinate system. It covers the whole 3-dimensional space and has the origin residing at the center of mass of the Galaxy. Its spatial axes do not rotate in either the kinematic or the dynamical sense [3].

The BCS is used to describe the motion of the Earth's center of mass with respect to the barycenter of the Solar system and to introduce the scale of baricentric time (TB). The

BCS has origin at the Solar system's barycenter and is non-rotating w.r.t. GCS in the kinematic sense. It is a local coordinate system. Otherwise, it does not cover the whole space but only space inside and near outside the Solar system.

The TCS is used to describe the motion of an observer located on the Earth's surface w.r.t. the geocenter and to establish the scales of the terrestrial time (TT) and international atomic time (TAI). The TCS has origin at the geocenter, is a local one and has no spatial rotation w.r.t. BCS in the kinematic sense.

The OCS is the coordinate system at the origin of which lies the observer (radio telescope). The OCS is constructed for the description of the observed topocentric times of arrival (TOA) of pulses and to establish the scale of the proper time of observer, which sometimes (in correspondence with jargon of radio astronomers) is called the scale of real time (RT). No necessity to specify the spatial rotation of the OCS.

The BBCS is introduced for description of orbital motion of the pulsar and its companion as well as for construction of barycentric time scale of binary system (BBT). Note that for description of orbital motion of the pulsar it is necessary to use full theoretical apparatus of relativistic celestial mechanics [4–6]. The BBCS has origin at the barycenter of the binary system, is local and nonrotating in the kinematic sense w.r.t. GCS.

The PCS is constructed for description of rotational motion of the pulsar and introducing the scale of pulsar time (PT). This time has the same physical meaning as the Earth's universal time (UT). Knowledge of the rotational motion of the pulsar is required for correct determination of the pulsar's rotational phase.

III. *Reference Time Scales*

The following time scales are to be used for adequate theoretical analysis of timing observations of single pulsars: galactic (GT), barycentric (BT), terrestrial (TT) and pulsar (PT) ones. When pulsar is a member of binary system it is necessary to take into account the barycentric time of the binary system (BBT). All these time scales are introduced as coordinate times of the corresponding coordinate systems. The time scales are different one from another. There is no notion of the absolute time of the Newtonian physics because of effects of the Special and General Relativity (more precisely, the quadratic Doppler shift and gravitational shift of time intervals) are important and can not be ignored in pulsar timing. From these time scale , only the GT is the globally uniform. It means that the GT can be defined in physical terms as time of the inertial (Lorentz) coordinate system coinciding with the GCS at infinity. All other time scales have precise meaning only in restricted spatial domains being covered by the corresponding local coordinate systems and have secular as well as periodic drifts w.r.t. the GT.

From the point of view of relativistic celestial mechanics the description of motion of bodies w.r.t. the GCS is simple if and only if namely the GT is used as independent argument in the equations of motion of the bodies. The analogous statements can be said about the other time scales. For example, the motion of bodies of the Solar (binary) system is simple if and only if the BT (BBT) is used in the corresponding baricentric equations of their motion. As for the TT and PT it has to be noted, that they are quite useful for description of rotational motion of the Earth and pulsar respectively as the use of other time scales will bring to appearance in rotational motion of the bodies the artificial periodic terms which have no physical but mathematical (coordinate) origin.

So far it was discussed only coordinate time scales. But how do we can realize them in practice? For this sake it is used TAI—the best time scale which is at mankind's disposal. This time scale is an ensemble average of the individual realizations of atomic time standards at laboratories around the Earth. The each standard has its own weight of measurements varying according to an assessment of their stabilities. The comparison of atomic time scales between standards laboratories and the use of an atomic time at an astronomical observatory (or other remote site) requires a system of time transfer. There are a number of systems for time transfer with different accuracy and specific limitations. The most famous and world wide appropriate from them are using a TV channel, LOng RAnge Navigation C system (LORAN C) and the Global Positioning Satellite system (GPS) consisting of 18 US satellites. This system will be extended for account of several Russian satellites forming GLObal NAvigation System (GLONAS) of the former USSR. GPS allows to transfer time signals with accuracy at the level of 100 ns and in some cases up to 10 ns. It should be stressed that comparison between the time scales requires a correction for relativistic effects [7] and construction of time transfer systems must be based on general relativistic principles [8].

Link of TAI with TT is realized with the help of the simple formula

$$(\mathrm{TT}=\mathrm{TAI}+32.184 \text{ sec.}+(\text{terms of order } c^{-4}),$$

which has been rigorously derived recently by Brumberg and Kopeikin [2].

IV. *Propagation of Electromagnetic Signals*

Pulsar emits radiation in the direction to the observer in the form of narrow pulses. Each pulse represents an electromagnetic radio signal, which moves through the Galaxy along the trajectory with minimal time of propagation. It is a consequence of the Fermat's Principle of geometrical optics which states that the time taken by a light ray when travelling between two points must be minimal.

It is known that there exist two main sources of distortion of straightforward trajectory of electromagnetic signals—a gravitational field and plasma. Moreover, they change also velocity of the signal's propagation that gives an additional time delay.

Gravitational (or the Shapiro) time delay is 135 μs when the signal passes by the limb of the Sun compared to an observation six months later. The delay depends logarithmically on the sum $1+\cos\theta$, where θ is the heliocentric angle between the pulsar and the Earth. In the case of binary pulsar there is the sizeable delay when signal from the pulsar passes by its companion. This delay can be used for testing of General Relativity [9] or for determination of geometrical inclination of the orbit to the line of sight of observer as well as of mass of the companion [10].

There is also the gravitational time delay caused by the gravitational fields of stars of the Galaxy. But this effect are incorporated in the parameters of pulsar and can not be extracted from pulsar timing data in straightforward manner.

Time delay of radio signals in the interstellar plasma is inversely proportional to the square of the frequency of the signal and proportional to the column density of electrons between the pulsar and the Earth, which is called the Dispersion Measure (DM). Since this delay depends on frequency it is possible to measure it directly with the help of observation of the pulsar being done over multiple radio frequencies. The observing frequency is the observatory value and must be corrected by the linear Doppler shift of the moving Earth. In the case of binary pulsar it is necessary to correct the frequency for the account of the linear Doppler shift caused by the orbital motion of the pulsar. In most cases the DM may be assumed to be constant. In long-term observations of pulsars near the Sun, however, one must allow for the dependence of the DM on time and on the angular distance between the pulsar and Sun because of strong influence of the turbulent solar wind. In some cases, especially for observations of millisecond pulsars, may be important effect of time variation of the interstellar medium DM [11]. Dispersion delay in the Earth ionosphere and troposphere are negligibly small in pulsar timing and can be omitted.

Measurement of DM is very important for astrophysicists as it allows to make more precise our knowledge about structure and distribution of the interstellar medium inside the Galaxy. But for the sakes of testing of General Relativity, construction of pulsar time scale and solving other problems of fundamental astronomy the dispersion delay is a "noise" and must be removed from observational data as complete as possible.

Equations describing propagation of electromagnetic signals from pulars to observer make it possible to establish relationship between moments of the signal's emission and the moments of registration (receiving) of these arrival signals.

V. *Topocentric Pulse Arrival Times*

Pulsars are observed with radio telescopes that have a fairly large effective area, using multichannel receivers. The topocentric pulse arrival times (TAT) should be determined relative to the TAI scale, which is the most stable and precise time scale available for practical use. The procedure for determining TATs consists in the following.

The TATs of pulses are initially determined on the scale of the real time (RT), specified by a local time and frequency standard (LS) set up in the immediate vicinity of the ratio telescope antenna. For this sake [12] incoming signals from the telescope are amplified, converted to intermediate frequency, and passed through a "filter bank" spectrometer which analyzes the total accepted bandwidth into channels narrow enough that the observed pulse widths are not dominated by dispersive smearing. Synchronous signal averaging is used to accumulate estimates of a pulsar's average waveform in each of the spectral channels, using electronics under control of a small computer and accurately synchronized with the LS. A programmable synthesizer, whose output frequency is updated once a second in a phase continuous manner, compensates for variable Doppler shifts due to the orbital and rotational motion of the observer and, if necessary, orbital motion of the pulsar. Integrated pulsar waveforms are recorded once every few minutes, together with appropriate time tags.

After the integrated pulse profile has been determined, one finds its center of "mass" and the corresponding TAT, recorded w.r.t. to the RT scale of LS, by cross-correlating the standard profile with the integrated pulse and allowing for the instrumental signal delay and the antenna-LS channel delay. The rms error in determining of the TAT of the integrated pulse for a scan is inversely proportional to the steepness of the edge of the pulse and the signal to-noise ratio in the receiver.

The conversion from the real time scale to the considerably more accurate TAI scale is accomplished using an intermediate scale of universal coordinated time (UTC). To convert from the RT of the LS to the UTC scale one must add to TAT a correction for the travel time of the standard time signal from the radio station transmitting UTC to the location of the LS, and to allow for the correction, which describes the drift of the RT scale from tne UTC scale between the times of comparison of the LS readings with the UTC. This drift is associated mainly with construction features of the LS.

UTC scale is related to the TAI by the simple relation

$$\mathrm{TAI}=\mathrm{UTC}+\mathrm{k},$$

where k is an integer number of seconds introduced to reconcile the lengths of the day determined from atomic time and from mean solar time, given by the Earth's rotation. The specific value of k is given in the *Astronomical Almanac* for a current year.

IV. *Barycentric Pulse Arrival Times*

A model capable of predicting pulse arrival times is most conveniently formulated in an inertial reference coordinate system, for which the BCS of the Solar system is an adequate approximation. Confirmation of this statement, however, requires long and complicated mathematical calculations [13]. A starting point is the equation describing propagation of radio signals w.r.t. the GSC.

This relativistic equation connects moments of emission and receiving of pulse expressed in the GT scale with the spatial coordinates of the points of emission and receiving which are expressed also in the GCS. It is necessary to use the equation namely in the GCS since only it allows to describe dynamics of the Solar system bodies and binary (or single) pulsar in mathematically self-consistent and physically adequate form. But the equation of light propagation w.r.t. the GCS is not convenient for practical applications since contains a lot of parameters which are not measurable directly (for example, distance of the Solar system to the center of the Galaxy) and not incorporated in the modern programs of processing of pulsar timing observational data. So, it is necessary to transform the equation to the BCS. For this purpose it should be used relativistic time and spatial transformations [14] between the GCS and BCS.

Tedious calculations show that it is possible to transform the above mentioned equation of light propagation into the well known form [15] with corresponding redefinition of pulsar parameters, which now include in exact form the slow varying galactic Doppler and gravitational shifts, and the secular aberration of light.

After that the additional transformations are required. These transformations include those from the TB scale to the TT one, and take into account the classical Roemer and Shklovskii delaies, the relativistic Shapiro delay in the gravitational field of the Solar system, proper motion and parallax of the pulsar, as well as redefinition of the pulsar period and its derivatives w.r.t. time [15].

If the pulsar is a member of binary system it is necessary to include transformations from the GT scale to the PT one with using the BBT scale as intermediate step in calculations as well as take into account the Roemer and Shapiro delaies in the binary system, and parallax of the observer w.r.t. the binary system.

Finally one has the formula connecting intervals of the PT scale with ones of the BT scale, which is used in the following analysis of observational data.

VII. *Relativistic Celestial Mechanics of Binary Pulsars*

Relativistic celestial mechanics of binary pulsars has long and interesting history [4, 5, 16]. At present it based mainly upon the solution of the Einstein equations of the General Relativity. Solution of the equations for the problem under consideration can not be found directly. So, many approximation schemes were constructed for this sake. It is widely used two of them—the post-Newtonian (PNA) [16, 17] and the post-Minkowskian (PMA) [16] ones. The former has two small parameters ε and η which characterize correspondingly slowness of motion (ε) and weakness of gravitational field (η). The later has only one small parameter η and can be used for calculation of equations of motion of fast moving bodies.

PNA and PMA admit an iterative external solution of the Einstein equations far outside pulsar and companion. But in the immediate vicinity from pulsar and its companion it is necessary to use another approximation scheme which allows to find small perturbations of the exact Kerr solutions describing the gravitational field of the pulsar and companion. This iterative internal solutions must be matched with external one to give a precise mathematical and physical meaning for parameters of the external solution. In a such way it was proven that the parameters are the Schwarzschild (relativistic) masses of the pulsar and companion [18]. Moreover, it was derived by the asymptotic matching method the post-Newtonian equations of translational motion of the centers of mass of the pulsar and its companion [18].

The discovery in 1974 of the first binary pulsar PSR 1913+16 by Hulse and Taylor and essential improvement of accuracy of pulsar timing observations brought about new interest to the problem. Three independent investigations [4–6, 19] of the orbital motion of the pulsar gave exhaustive answers on the questions: how the pulsar moves in conservative approximations, how emission of gravitational waves of the binary system changes its orbital period and osculating elements of the orbit, what form has relativistic lagrangian of two body problem in high order approximations [20].

At the last several years interests of theoreticians aim to the investigation of influence of the post-radiative corrections to the orbital motion of binary pulsars (see, for example, [21, 22]). It is important for precise calculation of the form of spectrum of gravitational waves emitting by binary pulsars. Probably, at the nearest future gravitational wave antennas of new type allow to observe a fine structure of the spectrum [23]. Comparison of theoretical predictions on this structure with observational data will give a new qualitative possibility to test General Relativity.

VIII. *Rotation Model of Pulsar*

The simplest model for a rotating neutron star is based on the suggestions that pulsar's body has a spherically symmetric shape and its angular velocity is decreased monotonically owing to external electromagnetic braking torque. It consists of an initial phase, a rotation frequency and a frequency derivatives. The model for the phase residuals is a simple polynomial:

$$\varphi(t)=\varphi_0+\Omega t+\dot{\Omega}t^2/2+\ddot{\Omega}t^3/6,$$

where t is the PT scale, Ω is the rotation frequency of the pulsar at the initial moment of time and dot means derivative w.r.t. time. For a long time this rotation model was adequate and gave very good results. However, it can not be applicable for investigation more subtle effects connected with pulsar variable rotation and relativistic effects of aberration and gravitational deflection of light by the pulsar's companion.

Indeed, a pulsar is a self-gravitating body having oblateness and a complex interior structure, which include thin crust, mantle, liquid and rigid cores. Moreover, the major part of the pulsar's matter is a superfluid containing a set of quantum vortices frozen in the crust [24]. Rotation of such system is very complicated. It may admit a free nutation similar with the pole motion of the Earth as well as forced nutation and precession owing to external gravitational torque from companion. Presence of liquid core may be responsible for appearance of resonance rotational modes which are known in the theory of the Earth rotation as ones of free core nutation [25]. In addition, some pulsars occasionally show sudden increases in the rotation rate ("glitches") followed by gradual recoveries that may last days or years. These events are thought [26] to be consequences of angular momentum transfer between a solid crust, which rotates at the measured pulsar periodicity, and a more rapidly rotating "loose" component of the superfluid part of the mantle.
Improvement of the initial rotation model of pulsar brings to appearance on the right hand side of the formula for phase residuals additional terms analysis of which can give information on the interior structure of pulsar, its rotational motion and value of angles of aberration and gravitational deflection of light in the gravitational field of the pulsar's companion.

IX. *Pulsar Parameter Estimation Formalism*

Knowledge of all preceding steps is necessary for construction of pulsar parameter estimation formalism which consists of three main parts:
—phenomenological analysis of pulse structure;
—phenomenological analysis of ephemeris data;
—phenomenological analysis of orbital data.
The structure of pulsar signals (intensity, pulse shape, linear polarization, . . .) and its variation with time provides a wealth of information about physical conditions in pulsar magnetospheres and the nature of the radio emission mechanism. Theoretical and practical

investigation of structure of pulses of 23 pulsars based on relativistic model of pulsar polarization has been done recently in the work [27]. It should be noted as well that for binary pulsars, pulse-structure data can also contain information about gravitational physics. For example, there exist possibility of detecting, through a secular change of pulse shape, the relativistic precession of the spin axis of PSR 1913+16 because of spin-orbit coupling [28, 29]. Another source of potentially measurable effects on pulse structure is the aberration caused by orbital motion of the pulsar, which offers the possibility to measure several otherwise inaccessible parameters [30]. General description of the approach applicable to binary pulsars has been done recently by Damour and Taylor [31].

Ephemeris data (initial phase and epoch, rotation frequency and its derivatives, astrometric coordinates in the sky, proper motion, parallax, dispersion measure) are passport of a pulsar. These data for all pulsars form a pulsar astrometric catalog which can be used for solving different problems of modern astrometry. For example, it is possible to make refinement of the position of the barycenter of the Solar system in space [32], a more accurate determination of the inclination of the ecliptic to the equator [33], the comparison of dynamical reference frames that are constructed in independent ways [34]. Moreover, creation of new pulsar time scale crucially depends on accuracy of determination of the ephemeris parameters of the pulsars used as time and frequency standards [35]. Modern algorithms for extracting of the pulsar ephemeris parameters based on the least square method and are exposed, for instance, in [9, 15].

The first timing model for phenomenological analysis of orbital data of binary pulsars was suggested by Blandford and Teukolsky [36] soon after the discovery of PSR 1913+16. This model assumed that the pulsar and its companion move according to the Keplerian laws and included the five "keplerian parameters"—the orbital period P_b, the epoch of periastron passage T_0, the eccentricity e, the angular distance of periastron from the node ω, and the projected semimajor axis of the pulsar orbit, $x=a_1 \sin i/c$ (where a_1 is the semimajor axis of the pulsar orbit, and i the inclination between the orbital plane and the plane of the sky). They incorporated in their model the largest short-period relativistic effect—an algebraic sum of the first-order gravitational redshift and special relativistic quadratic Doppler shift, quantified by one extra parameter called γ, and allowed for secular drifts of the main orbital parameters: P_b, ω, e and x.

The model of Blandford and Teukolsky was improved by Epstein [37], and later by Haugan [38], which derived, in the framework of the General Relativity, the relativistic contributions arising both from the gravitational Shapiro time delay in the gravitational field of the companion, and from relativistic post-Keplerian effects in the orbital motion.

Then Damour and Deruelle [39, 40] noted that it is possible in the first post-Keplerian approximation to describe all relativistic orbital effects in a simple mathematical way common to a wide class of alternative theories of gravity. They reparametrized post-Keplerian orbit of the Haugan and bring it to Keplerian one, but with three different eccentricities, which contain a main information about gravitational theory having been used. The Damour-Deruelle model includes additional 8 post-Keplerian separately measurable parameters and 4 not separately measurable ones. The model is used at present at Aresibo by Joe Taylor with collaborators for data processing of observational data of binary pulsars and experimental test of General Relativity (see, for example [41]).

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