COMMISSION 52	**RELATIVITY IN FUNDAMENTAL ASTRONOMY**
	RELATIVITÉ DANS ASTRONOMIE FONDAMENTALE

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TRIENNIAL REPORT 2006 - 2009

1. The new Commission

The tremendous progress in technology which we have witnessed during the last 30 years has led to enormous improvements of observational accuracy in all disciplines of fundamental astronomy. Relativity has been becoming increasingly important for modeling and interpretation of high accuracy astronomical observations during at least these 30 years. It is clear that for current accuracy requirements astronomical problems have to be formulated within the framework of General Relativity Theory. Many high-precision astronomical techniques have already required the application of relativistic effects, which are several orders of magnitude larger than the technical accuracy of observations. In order to interpret the results of such observations, one has to construct involved relativistic models. Many current and planned observational projects can not achieve their goals if relativity is not taken into account properly. The future projects will require the introduction of higher-order relativistic effects. To make the relativistic models consistent with each other for different observational techniques, to formulate them in the simplest possible way for a given accuracy, and to formulate them in a language understandable for astronomers and engineers who have little knowledge of relativity are the challenges of a multidisciplinary research field called Applied Relativity.

The new IAU Commission 52 on *Relativity in Fundamental Astronomy* (RIFA) has been established during the IAU XXVI General Assembly (Prague, 2006) to centralize the efforts in the field of Applied Relativity and to provide an official forum for corresponding discussions. The general scientific goals of the Commission are:

- clarify geometrical and dynamical concepts of Fundamental Astronomy within a relativistic framework;
- provide adequate mathematical and physical formulations to be used in Fundamental Astronomy;

- deepen the understanding of the above results among astronomers and students in astronomy;
- promote research needed to accomplish these tasks.

2. The work of the Commission over the period September 2006 - June 2008

During this period the work of the Commission has been initiated. A web page containing all the information concerning the work of the Commission has been created and activated: `<astro.geo.tu-dresden.de/RIFA>`. The invitation to join the Commission has been widely distributed in the astronomical community.

Several scientific and educational projects have been initiated in 2007. The educational projects include compilation of a list of open problems in the field of applied relativity as well as a list of frequently asked questions. The Relativistic Glossary for astronomers has been also created and is available on the web page of the Commission. These three tools are intended to serve the broad astronomical community. The corresponding documents are expected to be updated and enriched in the future by the Commission itself and by future Working Groups of the Commission.

The following three scientific topics were identified by the Commission as important to discuss in the years to come:

1. 'Units of measurements' for astronomical quantities in the relativistic context

   In the literature (including very recent papers) one can find different units used in precise work: 'TDB units', 'TCB units', 'TT units' along with 'SI units'. The co-existence of these units is related to the relativistic scaling of time and space coordinates. On the other hand, the IAU 1991 resolutions clearly state that only SI units without any additional relativistic scaling should be used for all astronomical quantities (astronomical units like AU are not meant here). A balanced approach to this issue should be suggested and discussed. This would help to unify the notations and numerical values of astronomical constants throughout the literature. As a material for discussions Klioner (2008) has published a concise review of the problem of relativistic scaling of astronomical quantities.

2. 'Astronomical units' in the relativistic framework

   It is known that a significant freedom exists in the definition of the system of astronomical units in the framework of relativity. This freedom has been discussed in a number of recent publications, but up to now no standard choice has been agreed upon. Moreover, the complexity of relativistic modification of the current system of astronomical units together with the fact that the original reasons for astronomical units are no longer important for current practice naturally invokes a discussion on a possible simplification of the system of astronomical units. This question is clearly a delicate one since it concerns many parts of astronomy. Nevertheless, it seems to be right time to discuss these issues at the level of IAU Commissions and Working Groups.

3. Time-dependent ecliptic in the GCRS

   An improved definition of ecliptic adopted by the IAU XXVI General Assembly is given in the Barycentric Celestial Reference System. On the other hand, theories of Earth rotation for which ecliptic plays an important role should be defined in

the GCRS. Therefore, a GCRS ecliptic has to be discussed. It has to be clarified if relativistic effects can affect the definition of the ecliptic at some perceptible level of accuracy.

Besides this activity, the Commission has decided to propose an IAU Symposium on *Relativity in Fundamental Astronomy: Dynamics, Reference Frames, and Data Analysis* in 2009. This proposal has been accepted as IAU Symposium No. 261. It has the goal to overview and summarize the progress that Applied Relativity has made during the past quarter of a century (the first and only IAU Symposium devoted to that field, namely IAU Symposium No. 114 on *Relativity in celestial mechanics and astrometry* has been held in StPetersburg, Russia, in 1985) and to develop the basis for the future of this discipline. Principal topics of the IAU Symposium No. 261 include

- astronomical reference frames in the relativistic framework;
- relativistic modelling of observational data;
- astronomical tests of relativity;
- relativistic dynamical modelling;
- relativity in astrodynamics and space navigation;
- modern observational techniques in fundamental astronomy;
- time measurement and time scales; and
- astronomical constants and units of measurements.

3. Plans for the period July 2008 - July 2009

The first attempt to discuss the issue of 'TDB units' (the first item in the list above) has been undertaken. To this end an ad hoc discussion forum, a so-called task team, has been initiated. The work of the task team 'TDB units' is planned to be finished within one year from now. Conclusions concerning the choice of wording and semantics when speaking about units of measurements will be made available afterwards.

IAU Symposium No. 261 on *Relativity in Fundamental Astronomy: Dynamics, Reference Frames, and Data Analysis* will be held from 25 April till 1 May 2009 in Virginia Beach, USA. The Proceedings of this Symposium are expected to be ready by the next IAU General Assembly and are intended to serve as a reference for the field of Applied Relativity for the years to come.

4. Recent developments in Applied Relativity

Not pretending to completeness, let us give a list of recent interesting developments in the field of Applied Relativity.

Like many other research fields, General Relativity in general and Applied Relativity in particular has many old ideas which have been abandoned or insufficiently developed in the past. It is certainly useful to recall and critically re-consider some of these ideas which seem to be forgotten undeservedly. One such idea was recently reiterated by Brumberg (2007) who demonstrated that in accordance to the old idea of Infeld the variational principle of the Einstein field equations may be used to derive the commonly employed Einstein-Infeld-Hoffman equations of motion from the linearized metric. Although this approach does not seem to lead to new practical results in the first post-Newtonian approximation, it might be interesting to apply this idea to simplify the derivation of the equations of motion of a system of N arbitrary shaped bodies in higher post-Newtonian approximations.

Recent re-definition of TDB adopted by the IAU XXVI General Assembly has created the possibility to define the time scales of new solar system ephemerides in full consistency with General Relativity. The ephemeris groups at JPL and in Paris Observatory have positively reacted on this possibility (Fienga, Manche & Laskar 2007; Folkner 2007). This fosters the hope that in the nearest future the solar system ephemerides will become consistently 4-dimensional as required by the nature of General Relativity.

Earth rotation is the only astronomical phenomenon which is observed with very high accuracy, but modelled in a Newtonian way. Although a number of attempts to estimate and calculate the relativistic effects in Earth rotation have been undertaken, no consistent theory has appeared until now. At least two projects have been recently started to improve the situation. Brumberg & Simon (2007) consider the formally Newtonian equations of rotational motion with all quantities relativistically transformed into dynamically non-rotating version of the GCRS. Klioner, Soffel & Le Poncin-Lafitte (2008) have started to develop the fully post-Newtonian theory of Earth rotation using numerical integration of the post-Newtonian equations of rotational motion.

A series of recent papers (Kouba 2004; Larson *et al.* 2007) consider additional relativistic effects in the GPS model. Although the relativistic model for GPS is relatively simple, the technical complexity of the GPS observations makes it difficult for experts in relativity to go beyond the simplest model. For this reason every step towards understanding of higher-order effects is important and potentially has a significant impact on the future high-accuracy applications of GPS, GLONASS and Galileo. A detailed review on Relativity in Geodesy has been published by Müller, Soffel & Klioner (2007).

The investigation of relativistic light propagation in the gravitational field of non-spherical, rotating and moving bodies has been continued. Kopeikin & Makarov (2007) have constructed a compact model for light deflection of sources observed close to giant planets of the solar system. This model will be used in the interpretation of the future high-accuracy experiments. Le Poncin-Lafitte & Teyssandier (2008) have developed an algorithmic procedure enabling one to determine explicitly the light ray connecting any two points located at a finite distance in the gravitational field of an isolated axisymmetric body.

Considering the possibility to have very accurate clock (stable and accurate at the level of $10^{-16} - 10^{-17}$) in space in the near future, special care must be taken in practical relativistic modelling of such clocks. Duchayne, Mercier & Wolf (2007) have investigated the relativistic modelling of high-accuracy clock on board of an Earth satellite, and time and frequency comparison with such a clock. The requirements for the accuracy of orbital data have been also investigated.

Another important research area is planning and verifying astronomical tests of General Relativity and alternative theories of gravity. Bertotti, Ashby & Iess (2008) have discussed the effect of the motion of the Sun on the light travel time in experiments such as Cassini relativity experiment. After an analysis of NASA's Orbit Determination Program (ODP) the authors confirm the claimed accuracy of the Cassini experiment (Bertotti, Iess & Tortora, 2003). Considering the anticipated accuracy of the future relativistic experiments it is important to go beyond the standard least-square fits and to provide realistic errors of the achieved estimates of relativistic parameters. A sophisticated statistical analysis of the relativistic experiments with ESA's mission BepiColombo (Milani *et al.* 2002) has been performed by Ashby, Bender & Wahr (2007).

ESA's second space astrometry mission, *Gaia* is progressing towards its launch in 2011. The unprecedented accuracy of *Gaia* (up to a few microarcsecond) makes it especially

difficult to keep the whole data processing chain fully compatible with General Relativity. Significant efforts are being made in this area by the *Gaia* scientific community. A detailed description of the relativistic models will be made available to the public in due time.

Finally, the work on the improvement of the relativistic formulations and semantics of the IERS Conventions has been continued. One can hope that the wording in the next version of the IERS Conventions will be more consistent from the point of view of General Relativity.

5. Closing remarks

Applied Relativity is a multidisciplinary research field. Progress here requires dedicated efforts both from the side of theoretical work and from the side of practical implementation of relativistic concepts and ideas into every-day astronomical practice. It is clearly a challenge to combine knowledge in theoretical general relativity and in practical observational techniques and modelling of complex astronomical phenomena. IAU Commission 52 allows us to organize a dynamic and fruitful exchange between the experts in these areas, and thus give a direction to future developments in the area.

Sergei A. Klioner
president of the Commission

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