RELATIVISTIC EFFECTS IN GEODYNAMICS (*)

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ABSTRACT. Geodesy has now reached such an accuracy in both measuring and modelling that time variations of the size, shape and gravity field of the Earth must be basically considered under the name of Geodynamics. The objective is therefore the description of point positions and gravity field functions in a terrestrial reference frame, together with their time variations.

For this purpose, relativistic effects must be taken into account in models. Currently viable theories of gravitation such as Einstein's General Relativity can be expressed in the solar system into the parametrized post-newtonian (PPN) formalism. Basic problems such as the motion of a test particle give a satisfactory answer to the relativistic modelling in Geodynamics.

The relativistic effects occur in the definition of a terrestrial reference frame and gravity field. They also appear widely into terrestrial (gravimetry, inertial techniques) and space (satellite laser, Lunar laser, VLBI, satellite radioelectric tracking ...) measurements.

1. GEODYNAMICS. AN OVERVIEW

Geodynamics as considered in this report designates all the investigations related to the spacio-temporal determination of the surface of the solid Earth and the gravity field.

The main topics will be :

- realization and maintenance with time of a global terrestrial reference frame comoving and corotating with the Earth under minimal deformations of the surface
- determination of global, regional and local deformation of the surface of the solid Earth with respect to this frame. These deformations with time are the result of various phenomena : plate tectonics, intraplate deformations, deformation of active zones at the boundaries, tidal deformations ...
- determination of the rotation of the terrestrial frame with respect to the local quasi-inertial frame by monitoring the direction and

J. Kovalevsky and V. A. Brumberg (eds.), Relativity in Celestial Mechanics and Astrometry, 241–253.

the amplitude of the spin vector in the terrestrial frame.

In order to reach these goals, numerous types of measurements are now possible, sensitive to position and/or gravity. They can be performed on the ground (gravimetry, inertial surveys, terrestrial geodetic measurements of angles or distances ...), in space (spaceborne gradiometry ...) or by connection between the ground and space (satellite tracking, VLBI, ...).

The present and forthcoming level of precision of these measurements is such that a proper modelling requires to use a relativistic framework.

This report will therefore review current results and problems in the relativistic effects, both for the definition of basic quantities and for the modelling of geodetic measurements.

Considering that other papers will review astrometric and celestial mechanical aspects, these points will not be discussed here, although they are deeply related to the geodetic problems.

2. THEORETICAL FRAMEWORK

This section presents only some useful considerations. More comprehensive investigations can be found elsewhere, especially in literature on experimental gravitation. See for instance Misner, Thorne, Wheeler, 1973; Will, 1981; Teyssandier, 1984..

Almost all existing viable theories of gravitation are metric. This means that :

- the space-time is a 4 dimensional manifold with a metric tensor g
- the world lines of test particles are g-geodesics
- in free falling local systems, the non-gravitational laws have their special relativistic expression

Furthermore, the phenomena occuring in Geodynamics allow us to assume that the gravitational field U is weak and that the velocities v of material particles are small with regard to the fundamental constant c (velocity of light).

Typically in the Solar system

U/c**2 and (v/c)**2 are O(2)

where O(2) remains below 1.E-5 depending on the domain of the Solar system. This upper bound is reached in the vicinity of the Sun while O(2) = 1.E-10 near the Earth.

Under the previous hypothesis, viable metric theories can be expressed in a common formalism, the Parametrized Post-Newtonian (PPN) one, where :

- a class of coordinate systems has been selected, labelled PPN coordinate systems (PCS), which are quasi cartesian and nearly globally Lorentzian
- the metric coefficients in a PCS can be expressed in function of several metric potentials, 10 scalar parameters, named PPN parameters and a 3d vector expressing the velocity of the PCS with respect to the mean rest frame of the Universe.

These PPN parameters are noted :

$$(\beta \quad \gamma \quad \alpha_1 \quad \alpha_2 \quad \alpha_3 \quad \zeta_1 \quad \zeta_2 \quad \zeta_3 \quad \zeta_4 \quad \xi)$$

Two PCS are related by the combination of a space rotation, a post-Galilean transformation, i.e. a Lorentz transformation expanded to the post-Newtonian order, and a standard gauge transformation.

For a given PCS, the various theories are identified by a unique set of PPN parameters. For instance, the Einstein's General Theory of Relativity has for any PCS the following set :

$$(1 , 1 , 0 , 0 , 0 , 0 , 0 , 0 , 0 , 0)$$

It is legitimate to adopt the previous theoretical framework to investigate the phenomena of Geodesy, Geodynamics and Fundamental Astronomy.

Nevertheless, some limitations must be quoted :

a) non metric theories are excluded

b) some phenomena are excluded, e.g. gravitational waves

c) a PCS is a local Lorentz frame for the cosmological background if no anisotropy or heterogeneity occurs (cf. Will, 1981, p. 91). This point must be carefully checked in the case of the motion of a test particle coming from the external universe to the Solar system, such as the propagation of an electromagnetic wave from an extragalactic source to the Earth, as used in VLBI.

In addition to PCS, other quasi-cartesian coordinate systems will be considered. In such a system, the metric will have a signature (-, +, +, +), i.e. we adopt the spacelike convention. The first coordinate x0 defines the coordinate time by

$$x0 = ct$$

and we use a 3d vectorial representation for the three space coordinates xi

$$\bar{x} = (x1,\ x2,\ x3)$$

The quasi-cartesian property means that

$$g = \eta + O(1)$$

where η is the Minkowski metric.

The proper time τ is defined by

$$- c^2\ d\tau^2 = g_{\alpha\beta}\ dx^\alpha\ dx^\beta$$

Other coordinate systems can be deduced by transforming space cartesian coordinates into other ones such as spherical ...

3. BASIC CONCEPTS IN GEODYNAMICS

3.1. Reference frames

As mentioned before, other reviews deal with inertial and terrestrial reference frames and with time scales. Therefore, we give here a summary of current definitions. For further information, see Ashby, 1980; Ashby, Bertotti, 1984; Fujimoto, 1984; Hellings, 1985; Fukushima, Fujimoto, Kinoshita, Aoki, 1986.

Concerning the space frames, three types are of interest in Geodynamics :

- the barycentric frames are quasi inertial and have their origin at the barycenter of the Solar System. Two orientations are considered : ecliptic or equatorial.

For these systems, a PCS is a suitable choice. w will be the velocity of the barycenter B with respect to the universe rest frame. The space orientation will be chosen in order to realize the ecliptic one and the equatorial one. The two PCS will be therefore related by a space rotation.

b will designate the equatorial PCS.

We can express the metric g by :

$$(1)\quad \begin{cases} g_{oo} = -1 + \dfrac{U^b}{c^2} + h^{(4)}_{oo} + O_6 \\ g_{oi} = h^{(3)}_{oi} + O_5 \\ g_{ij} = \left(1 + 2\gamma \dfrac{U^b}{c^2}\right) \delta_{ij} + O_4 \end{cases}$$

with

$$(2)\quad U^b(\bar{X}, T) = G \int \frac{\rho(\bar{X}', T)\, d^3 X'}{|\bar{X} - \bar{X}'|}$$

- the geocentric celestial equatorial frame, e, has to be built. We can adopt the following procedure :

a) we consider the b-frame with the full metric g and we derive a fictious metric, g^*, excluding the Earth's gravitational potential;
b) we solve for the motion of the Earth's center of mass E in the b-frame with the g^*-metric;
c) we build a Fermi normal system around E for the g^*-metric, which implies the following transformation formula :

$$(3)\quad \begin{cases} \bar{X} = \bar{X}_E(\tilde{t}) + \left(1 - \gamma \dfrac{U_{*,E}}{c^2}\right)\bar{\tilde{x}} + \left(\dfrac{\bar{V}_E \cdot \bar{\tilde{x}}}{2c^2}\right)\bar{V}_E \\ \qquad - \dfrac{1}{c^2}\bar{Q}(\bar{\tilde{x}}) + \overline{\delta X} + O_4\, \tilde{x} \end{cases}$$

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$$(3)\quad \begin{cases} T = T_E(\tilde{t}) + \dfrac{\overline{V}_E.\overline{\tilde{x}}}{c^2}\left[1 + (2+\gamma)\dfrac{U_{*,E}}{c^2} + \dfrac{1}{2}\dfrac{V_E^2}{c^2}\right] \\ \qquad + h^{(3)}_{oi}\dfrac{\tilde{x}^i}{c} + \dfrac{1}{c^4}Q_{ij}V_E^j\tilde{x}^i + \delta T + O_5\dfrac{\tilde{x}}{c} \end{cases}$$

where $(cT, \overline{X})$ are b-coordinates, $(c\tilde{t}, \overline{\tilde{x}})$ are e-coordinates, (T_E, X_E) are b-coordinates of E (in the g^*-motion), $\overline{V}_E$ is the b-velocity of E, U_* is the potential which appears in g^* (i.e. without the Earth's contribution), Q is the dragging effect and $(\delta T, \delta\overline{X})$ are curvature corrections of the geodesics into the Fermi coordinates.

d) we finally define the e-frame by the previous formula applied to the b-frame with the complete metric g.

In this frame, the metric will have the following expression :

$$(4)\quad \begin{cases} g_{oo} = -1 + 2\dfrac{U^e_\oplus}{c^2} + \dfrac{\theta_{oo}}{c^3} + h^{e(4)}_{oo} + O_6 \\ g_{oi} = h^{e(3)}_{oi} + O_5 \\ g_{ij} = \left(1 + 2\gamma\dfrac{U^e_\oplus}{c^2}\right)\delta_{ij} + \dfrac{\theta_{ij}}{c^2} + O_4 \end{cases}$$

with

$$(5)\quad U^e_\oplus = G\int_\oplus \frac{\rho' \, d^3\tilde{x}}{|\overline{\tilde{x}} - \overline{\tilde{x}}'|}$$

and where θ is the tidal contribution

- the geocentric terrestrial frame t is defined from e by a space rotation which models the Earth's diurnal rotation

Several slightly different methods can be used to define b-, e- and t-frames, and also to apply the IAU definitions of TDB, TDT and TAI as coordinate times of such frames (CCIR, 1978, and Moyer, 1981); in particular, Fukushima et al., 1986, introduce for e and t the concept of Natural Reference Frame (NRF) by simplifying the formula (3) with

$$Q = 0 \qquad \delta T = 0 \qquad \delta\overline{X} = 0$$

3.2. Positioning on the Earth surface

Two possible relativistic effects have to be mentioned concerning the position of a point at the surface of the Earth :
- relativistic deformations of the solid Earth
- definition of the coordinate system and its unit of length

The first one can be apparently neglected at the present level of accuracy (cm), whereas the second is directly related to the precise definition of the t-frame.

Difference in scale between b and t-frame is 10-8, i.e. a few cm at the surface of the Earth. Such effects occur in models using basically a solar system barycentric frame. For VLBI, see Hellings, 1985. Consequently, one must pay attention to have a consistent model when one compares coordinates derived from different techniques.

3.3. Earth gravity field

A few investigations have been done up to now in order to define the Earth gravity field parameters in the frame of a detailed relativistic model. The gravity potential is defined by

$$U\ (x,\ t) = G \int \frac{\rho(x,\ t)\ d^3\ x'}{|\bar{x} - \bar{x}'|}$$

and therefore depends on the coordinate system. The Earth gravity potential is defined by e- or t-frame coordinates.

The mass of the Earth is defined by its rest mass :

$$(6) \qquad M_{\oplus} = \int \rho^{*}\ d^3\ x = \int \rho \sqrt{-g}\ u^{\circ}\ d^3\ x$$

for e-frame, we obtain :

$$(7) \qquad M_{\oplus} = \int \rho\ \left(1 + \frac{\tilde{v}^2}{2c^2} + 3\gamma \frac{U_{\oplus}}{c^2} + \frac{T_r(\theta_{ij})}{c^2}\right) d^3\ \tilde{x}$$

The gravity vector can be defined as the space part of the 4-acceleration of a test particle on the Earth (see Will, 1981, pp. 153-158).

3.4. Earth rotation

No detailed theoretical investigation on the rotation of the Earth in a relativistic framework is known by us.

Will, 1981, mentions possible annual and semi-annual variations of the rotation rate.

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Amplitude of $\frac{\Delta\Omega}{\Omega}$	Frequency
$2 \times 10^{-8} (\alpha_3 + \frac{2}{3}\alpha_2 - \alpha_1)$	annual
$3 \times 10^{-8}\ \alpha_2$	annual
$3 \times 10^{-10}\ \alpha_2$	semi-annual
$3 \times 10^{-10}\ \xi$	semi-annual

3.5. Motion of an Earth satellite

The rigourous equations of the motion of the mass center of an artificial Earth satellite can be found for a b-frame in Will, 1981 or Dallas, 1979. The conversion in the e-frame, which is the natural choice, could be done in a straightforward way. A transformation formula for acceleration is given in Fukushima et al., 1986. The expression of the lagrangian in the e-frame is also published by Ashby, Bertotti, 1984.

The major effects come from the terrestrial field and have been derived in many publications using the Schwarzschild approximation, especially the secular motion of the perigee which can reach 15" per year. See Singer, 1956, Harkins, 1973, Rubincam, 1975, Rubincam, 1977, Cugusi, Proverbio, 1978.

3.6. Propagation of electromagnetic waves

The propagation of electromagnetic waves can be solved using the geometric optical approximation which provide the equation of a null geodesic in vacuum. The refraction effects of the propagation medium (atmospheres, plasmas) are added then.

In the b-frame, one can express the equations as

$$(8) \qquad \overline{X} = \overline{X}_0 + c\,\overline{N}\,(T - T_0) + \overline{X}_R$$

$$(9) \qquad \frac{d^2\overline{X}_R}{dT^2} = (1 + \gamma) \left[\overline{\nabla} U^b - 2\,(\overline{N} \,.\, \overline{\nabla} U^b)\,\overline{N} - \frac{1}{c}\,\overline{N}\,\frac{\partial U^b}{\partial T} \right] + c\, O_3$$

$$(10) \qquad \left| \overline{N} + \frac{1}{c}\,\frac{d\,\overline{X}_R}{dT} \right| = 1 - (1 + \gamma)\,\frac{U^b}{c^2} + O_3$$

where $\overline{X}_0$, T_0 are initial conditions (see e.g. Boucher, 1978), and $\overline{X}$ is the post-newtonian deviation from the 3d straight line.

https://doi.org/10.1017/S0074180900148260 Published online by Cambridge University Press

In the n-body approximation valid for the solar system in b, one obtains, putting

$$(11) \qquad U^b \simeq \sum_\alpha \frac{\mu_\alpha}{|\bar{X} - \bar{X}_\alpha|}$$

$$(12) \qquad \bar{X}_R = \bar{N}\, X_{R\parallel} + \bar{X}_{R\perp}$$

$$\text{with } \bar{N} \cdot \bar{X}_{R\perp} = 0$$

the following results

$$(13) \qquad X_{R\parallel} = -(1+\gamma) \sum_\alpha \frac{\mu_\alpha}{c^2} \operatorname{Log} K_\alpha$$

$$(14) \qquad K_\alpha = \frac{|\bar{X}_\circ - \bar{X}_\alpha| + |\bar{X} - \bar{X}_\alpha| + |\bar{X} - \bar{X}_\circ|}{|\bar{X}_\circ - \bar{X}_\alpha| + |\bar{X} - \bar{X}_\alpha| - |\bar{X} - \bar{X}_\circ|}$$

where $\bar{X}_\alpha = \bar{X}_\alpha (T_\alpha)$ and T_α is the closest-approach epoch between the test particle and the body α, given e.g. as

$$(15) \qquad \bar{N} \cdot \bar{D}_\alpha = 0$$

$$\bar{D}_\alpha = \bar{X}_\circ + c\, \bar{N}(T_\alpha - T_\circ) - \bar{X}_\alpha(T_\alpha)$$

and

$$(16) \qquad \bar{X}_{R\perp} = (1+\gamma) \sum_\alpha \frac{\mu_\alpha}{c^2} \frac{\bar{D}_\alpha}{|D_\alpha|^2 . |\bar{X}_\circ - \bar{X}_\alpha|} \Big[(\bar{X} - \bar{X}_\alpha).(\bar{X}_\circ - \bar{X}_\alpha) - |\bar{X} - \bar{X}_\alpha| \cdot |\bar{X}_\circ - \bar{X}_\alpha| \Big]$$

See also Moyer, 1971, Misner, Thorne, Wheeler, 1973, Will, 1981, Fanselow, Sovers, 1985.

The expression in a e-frame can be deduced by a straightforward transformation of (14) and (16) by (3).

In the case of two points close to the Earth, (14) becomes in the e-frame :

$$|\tilde{\bar{x}} - \tilde{\bar{x}}_\circ| = c\,(\tilde{t} - \tilde{t}_\circ) + \tilde{x}_{R\parallel}$$

$$(17) \qquad \tilde{x}_{R\parallel} = -(1+\gamma) \frac{\mu_\oplus}{c^2} \operatorname{Log} \frac{|\tilde{\bar{x}}_\circ| + |\tilde{\bar{x}}| + |\tilde{\bar{x}} - \tilde{\bar{x}}_\circ|}{|\tilde{\bar{x}}_\circ| + |\tilde{\bar{x}}| - |\tilde{\bar{x}} - \tilde{\bar{x}}_\circ|}$$

4. MODELLING OF GEODETIC MEASUREMENTS

4.1. Space measurements

4.1.1. Satellite laser ranging. The modelling must be done in the e-frame, taking into account
- the motion of the satellite (see 3.5.)
- the two-way propagation of the laser pulse (see 3.6.)
- the conversion of proper time given by clocks into e-coordinate time
- the choice of station coordinates in t-frame

As all these corrections are small and of the same order of magnitude, it is necessary for precise analysis to consider consistently the complete model. Such corrections can no longer be neglected for cm accuracy as derived with satellites such as LAGEOS.

See Martin, Torrence, 1981, Martin, Torrence, Misner, 1983, Ashby, Bertotti, 1983.

4.1.2. Lunar laser ranging. In the case of Lunar laser ranging, a similar approach has to be adopted, with :
- the relative motion of the mass centers of the Earth and the Moon
- the two-way propagation of the laser pulse (see 3.6.)
- the conversion of proper time given by clocks into e-coordinate time
- the choice of station coordinates in t-frame

The first item is currently treated in the b-frame and has to be converted into e-frame. This type of system is rather sensitive to a breakdown of the Equivalence Principle (so called Nordtdvedt effect), which has been shown to be non-existent using LLR data. See Williams et al., 1976, Will, 1981.

4.1.3. Radioelectric range and range rate. Many possible types of measurements (range, Doppler, ...) can be done using group or phase propagation of radio waves in a simple or double connection between ground and space. Systems such as Transit, GPS are currently used in Geodynamics for decimetric and now centimetric positioning and for the determination of the rotation of the Earth. New systems are also under consideration (DORIS, POPSAT, ...).

Time and frequency transfer is also closely related both on a technical and user point of view.

The relativistic modelling must follow the same steps as satellite laser ranging :
- the motion of the satellite
- the propagation of the radio wave (see 3.6.)
- the conversion of proper time given by clocks into e-coordinate time
- the choice of station coordinates in t-frame

Many references can be mentioned : Gaposchkin, Wright, 1968, Jenkins, 1969, Harkins, 1973, Boucher, 1978, Harkins, 1979, Vessot, 1979, Ashby, Allan, 1979, Malyevac, Tanenbaum, 1981, Gibson, 1983, Laubscher, 1983, Song Chenghua, Li Yulin, 1984.

4.1.4. VLBI. In this case, the modelling will be done more directly in the b-frame, with :

- conversion of proper time at each radiotelescope into b-coordinate time
- conversion of t-frame coordinates into b-frame
- differential propagation of radio signals in b-frame

Up to recently, most of the proposed models were still incomplete, especially for the conversion of space coordinates, which had as a result that coordinates were scaled with regards to t-frame.

See Ma, 1978, Filkenstein, Kreinovitch, Pandey, 1983, Fanselow,1984, Fanselow, Sovers, 1985, Hellings, 1985.

The gravitational effect on differential travel time of signals is large, compared to the high accuracy of measurement (0.1ns), mainly due to the Sun. It was therefore possible to estimate with a precision comparable to the best determinations such as the use of planetary probes (Robertson, Carter, 1985).

4.2. Terrestrial measurements

Most of the terrestrial measurements are not affected by relativity. Nevertheless, one can mention exceptions :
- inertial surveying, for the future (Boucher, 1981)
- gravimetry with the use of very high precise devices such as supraconducting gravimeters (Warburton, Goodkind, 1976, Will, 1981)
- clock comparisons which can provide a determination of the difference of potential (Bjerhammar, 1984)

5. CONCLUSIONS

We can try to draw some conclusions from this short survey, apologizing not to have found enough space to give explicit models the reader will have either to find in the literature or to derive himself from the basic models given in section 3.

a) many measurements presently used in Geodynamics require a relativistic modelling. This has to be done in a complete and consistent way with regard to the adopted level of accuracy. An improvement may oblige to reconsider the formulas in order to take into account higher order terms. This will be shortly true for frequency devices.
b) improvements in precision will surely bring new types of measurement into consideration.
c) a careful definition of space and time reference systems is a very important issue, especially for intercomparisons and study of long term effects.

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* This paper was not formally presented during the symposium because the author was unable to attend due to visa problems.