Systèmes de Référence Temps-Espace

A dynamical reference frame for geophysics and experimental gravitation

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SYRTE -- Observatoire de Paris

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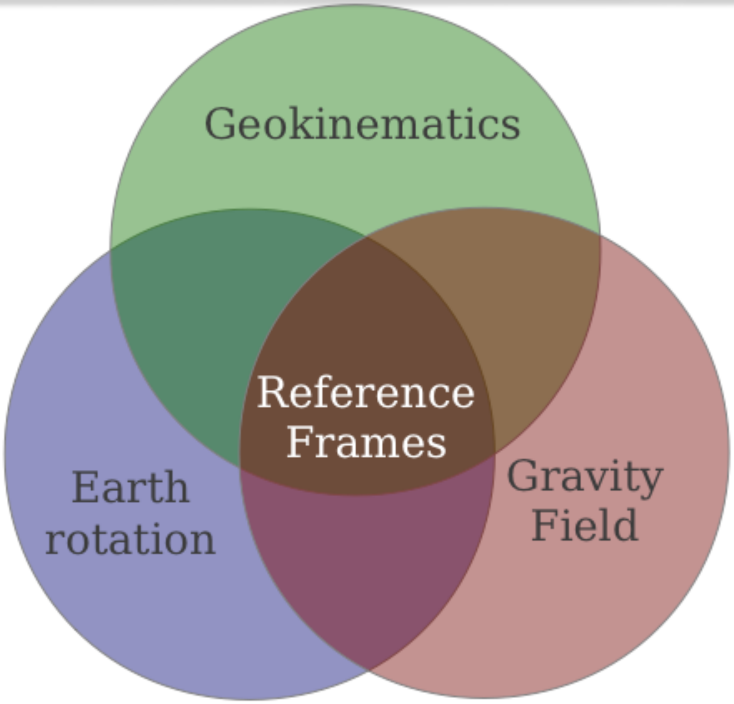
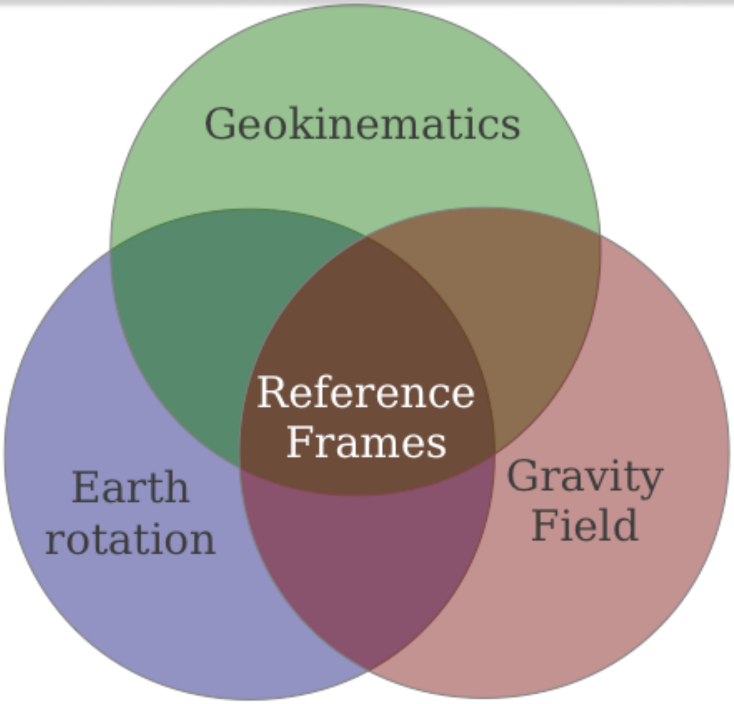
Motivations



The 3 pillars of Global Geodetic Observing System

- Non relativistic framework
- High intricacy of problems
  - Parameters degeneracy
  - Differents kinds of observation make a difficult framework of modelling
  - Coherency of multi-techniques scheme
- Heavy and sometimes dedicated infrastructures (VLBI, tracking stations…)

Motivations



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Question: how can we do better ? ➔ ABC reference system

- Use **Inter-Satellite Links (ISL)** to track the satellites
- Use **satellite orbits as clocks** with long-term stability to correct for satellite clocks

Interest of ABC reference system

- Its realization **does not rely on observations from Earth**
  - No entanglement with Earth internal dynamics
  - No Earth stations for maintaining of the reference frame
- **Stability** and **accuracy**
  - Based on well-known satellite dynamics
  - Satellite orbits are very stable in time, and can be accurately described
- **Positioning system**
  - Observation of the signals sent by 4 satellites allows anyone to know its coordinates
- Full **GR concepts**
  - Up-to-date conception of spacetime
  - Deep understanding of localization in spacetime
- Several **scientific applications**

Autonomous Basis of Coordinates (ABC) Reference System

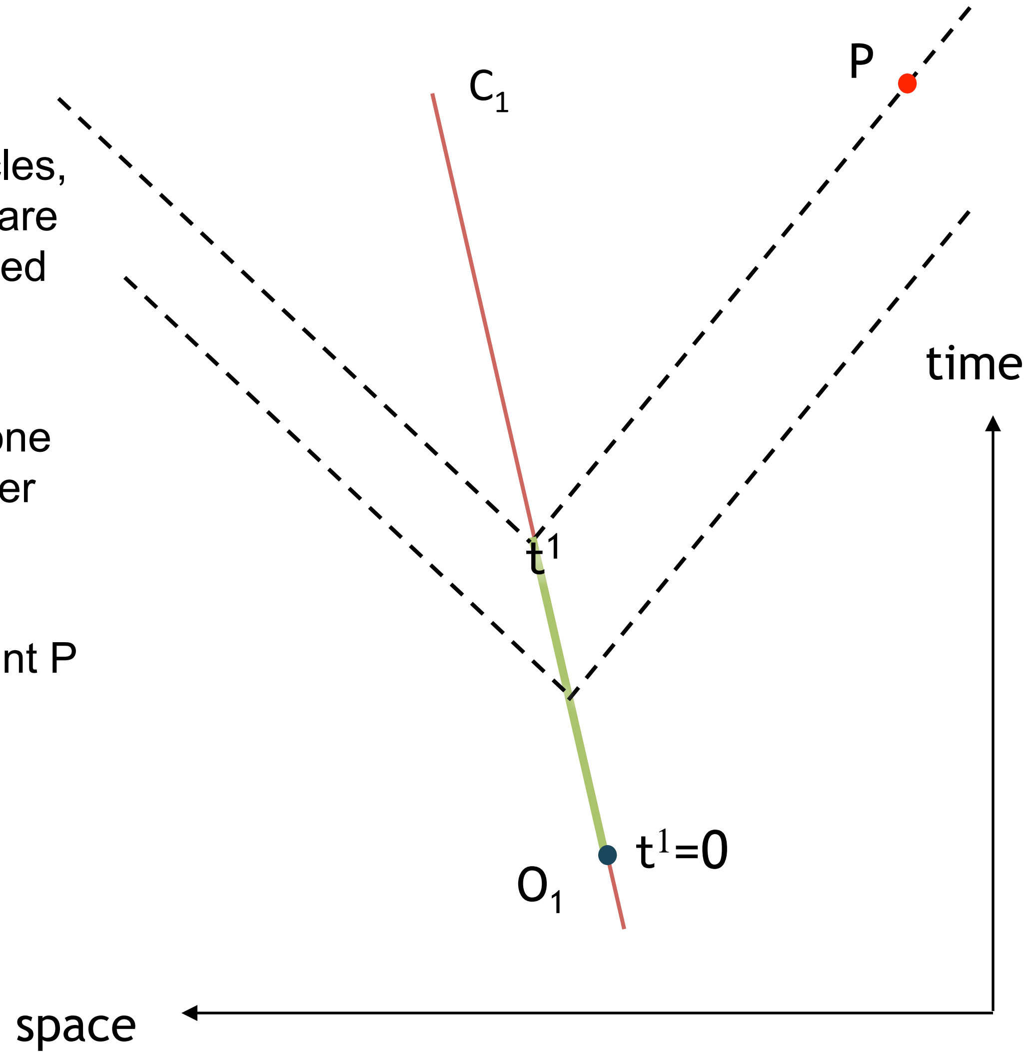
- **Concept**: coordinate system based on dynamics given by a hamiltonian (describes the spacetime geometry & non gravitational forces)
- **Physical structure**: satellites in Earth orbit & electromagnetic signals between the satellites (create a physical spacetime web)
- **Modeling**: choice of the hamiltonian (Minkowski, Kepler, Schwarzschild, …)
- **Realization**: numerical simulation of the satellite constellation and signals

Relativistic concept suited to GNSS

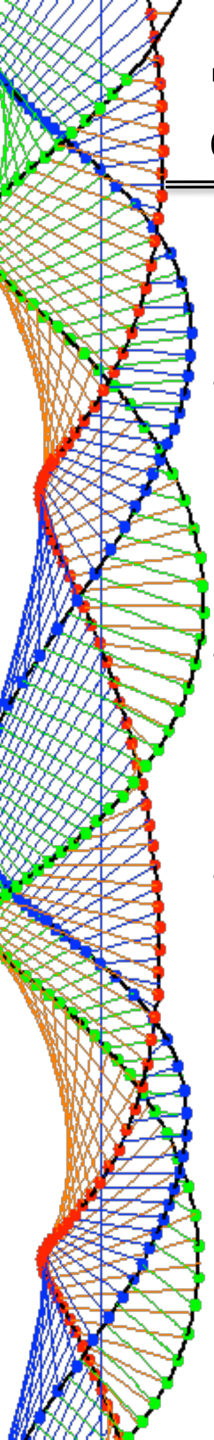
→ Use of **Emission Coordinates**

The emission coordinates …

- General relativity + 4 test particles, whose time-like trajectories C_a are exactly known and parameterized with proper times t^a.
- Given a point P, its past light cone intersects the trajectory at proper time t^1.
- Then t^1 is one coordinate of point P → **emission coordinates**

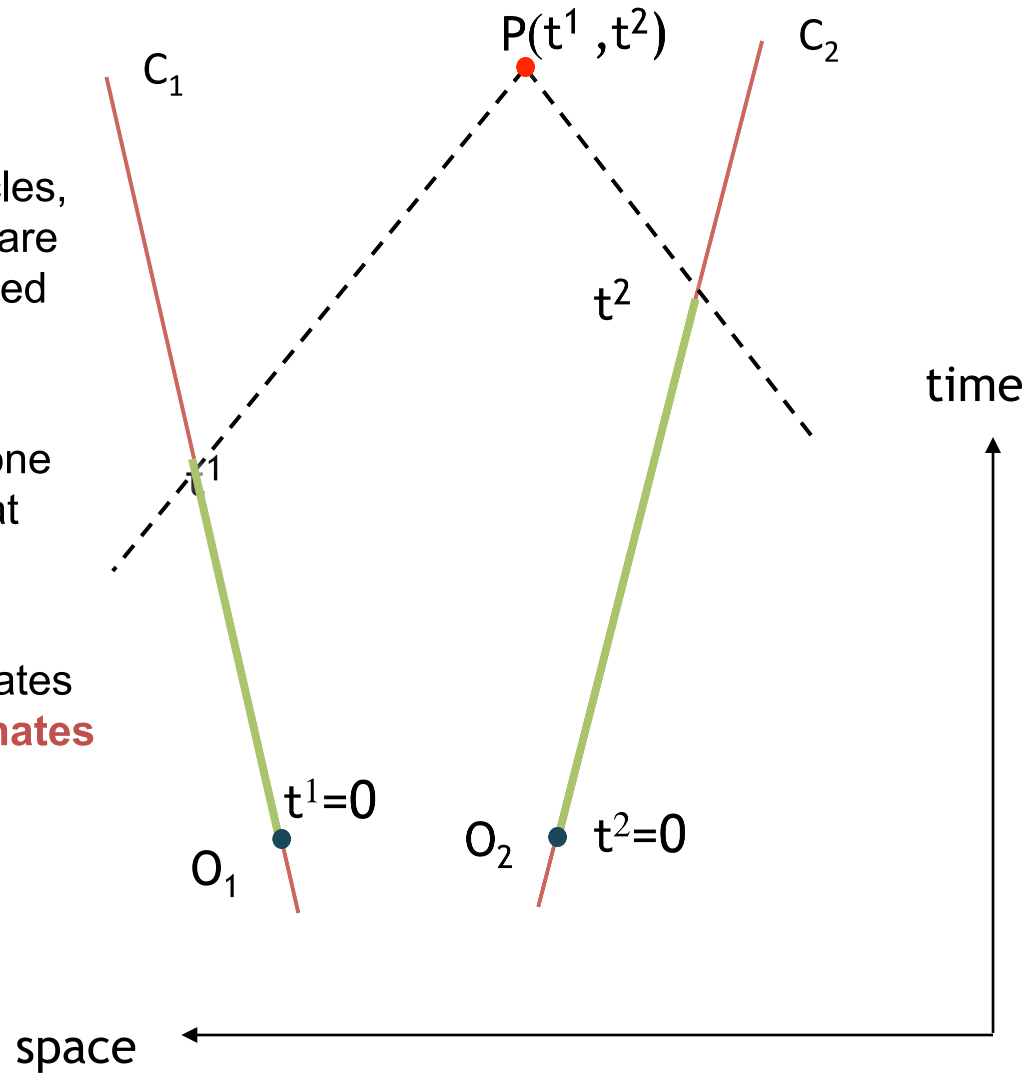


Rovelli, PRD **65** (2002)
Coll & Pozo, CQG **23** (2006)



… are physically realized by a constellation of four satellites

- General relativity + 4 test particles, whose time-like trajectories C_a are exactly known and parameterized with proper times t^a.
- Given a point P, its past light cone intersects the four trajectories at proper times t^1,t^2,t^3 and t^4.
- Then (t^1,t^2,t^3,t^4) are the coordinates of point P → **emission coordinates**



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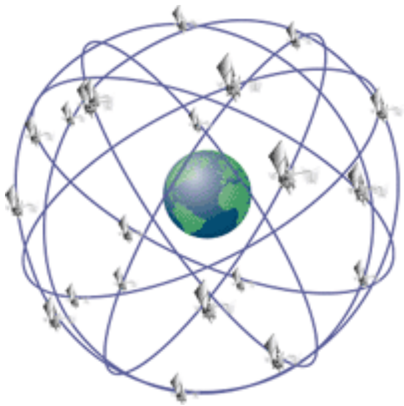
From emission to local coordinates



Satellite tracking from Earth

Emission coordinates

Satellites constants of motion

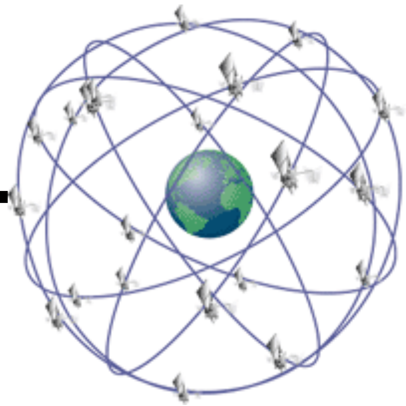
User

Coordinate transformation

Inter-Satellite Links (ISL)…

Inter-Satellite Links (ISL)

Emission coordinates



Emission coordinates

User

- **Autonomous constellation** → defines a dynamical (ABC) Reference Frame
- Orbital periods are used to **correct the satellites clocks**

~~Satellite tracking from Earth~~

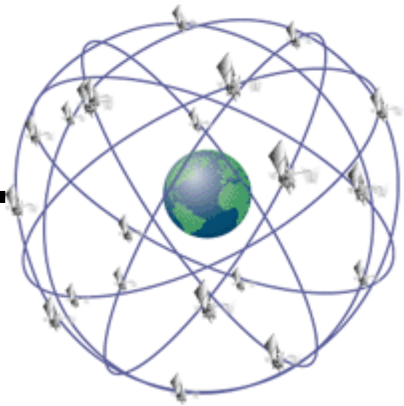
Satellites constants of motion

Coordinate transformation to the ABC Reference Frame

...to realize the dynamical ABC reference frame

Inter-Satellite Links (ISL)

Emission coordinates



Clock correction and data reduction

Realization of the ABC reference frame

Satellites constants of motion

Emission coordinates

User

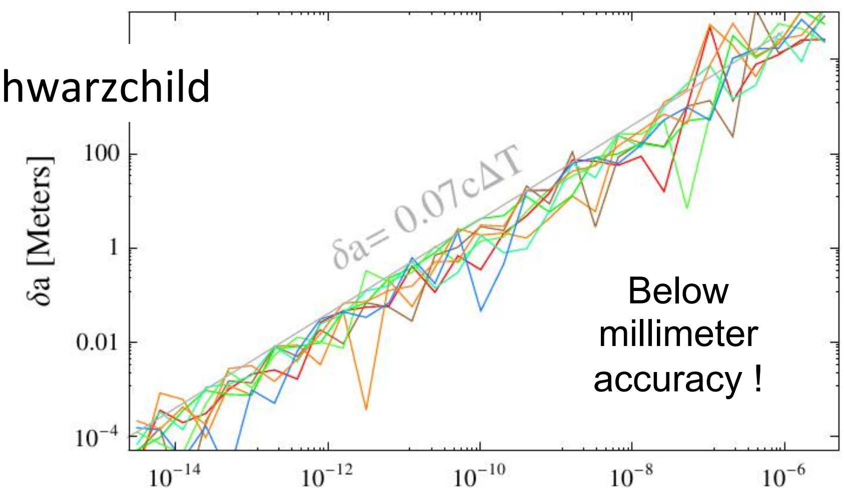
Coordinate transformation to the ABC Reference Frame

Technical how-to

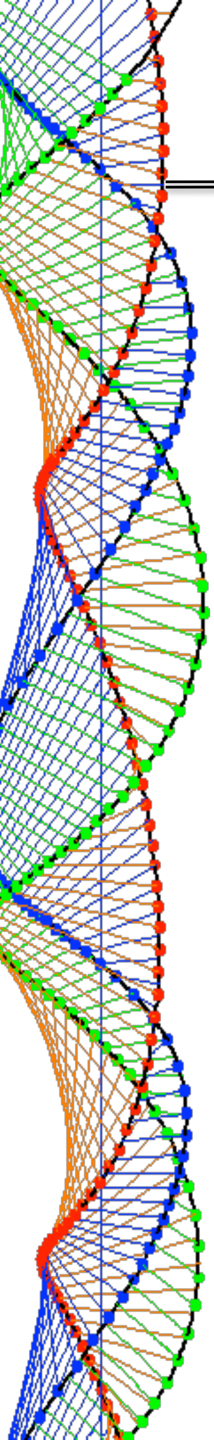
- **Solve** the set of non-linear differential equations describing the satellites and the light (ISL) geodesics
- **Numerical code**
  - coordinate transformations from emission to local coordinates (and the inverse problem)
  - constellation of N satellites, known constants of motions
  - Effects of **non-gravitational perturbations** on the positioning system, clocks errors, drag…

- **Simulation** of data pairs (t*,t)_{ij} with additional random noise dT
- **Robustness** of recovering constants of motion with respect to noise in the data
- **Consistency** of description with redundant number of satellites
- Possibility to use the constellation as a clock with **long term stability**

Schwarzchild



GALILEO ~1 ns/day



Scientific applications

- **Experimental Gravitation**
  - **Relativistic geodesy, time and frequency transfer**
  - **"Riemannian gravimeter":** satellites and inter-satellite links create a spacetime web that "probe" its geometry
  - Test of the **equivalence principle** by modelling or measuring non-gravitational perturbations accurately
- **Reference frames**
  - Comparison between the ABC reference frame and the International Celestial Reference Frame → how the local geometry is integrated into the global arena of space-time
- **Geophysics**
  - Absolute positions of markers on the ground with **sub-millimeter accuracy**
  - Interior structure of the Earth, continental drift, earthquake prediction…
  - Gravitational potential difference, ocean currents

A scientific example

relativistic geodesy:

Imagine a set of ground clocks linked to a constellation of satellites

- Realization of a relativistic equipotential, *i.e.* where clocks beat at the same rate in the ABC frame ➔10cm accuracy with optical clocks
- Measurement of static and time-varying gravity field by comparing clocks at different locations
- First demonstration of relativistic geodesy : ACES/PHARAO experiment (see the talk of P. Delva tomorrow)

Conclusions

- Data sets and dynamics treated in a coherent frame, independent of Earth internal dynamics → **high stability and accuracy**
- Operation of the experiment for many decades, with continuous data flow, constantly refining the dynamical model (Hamiltonian)
- Very few studies on **inter-satellites links** (GNSSPLUS, ADVISE), that do not take advantage of the autonomy and the dynamics of the constellation
- Going further:
  - how inter-satellite links ameliorate existing systems through the study of spatio-temporal positioning for different type of users
  - Study different technologies and system configuration (secondary constellation, …)
  - Organization of a workshop in 2012 in Ljubljana (Slovenia) around scientific uses of Inter-Satellite Links

Future workshop

RELATIVISTIC POSITIONING SYSTEMS AND THEIR SCIENTIFIC APPLICATIONS

Brdo near Kranj, Slovenia,19-21 September 2012

We are pleased to announce that a three-days workshop on relativistic positioning systems and their scientific applications will be held at Brdo near Kranj, Slovenia, on 19-21 September 2012.

The workshop is organized by the Faculty of Mathematics and Physics of the University of Ljubljana (UL) and ESA (Advanced Concepts Team). The goal of the workshop is to bring together those interested in the development of Relativistic Positioning Systems (RPS) and, in particular, to share ideas and establish future lines of research and collaborations.

The deadline for abstract submission is 1st July 2012.

More information can be found on http://rgnss.fmf.uni-lj.si/workshop

Topics of the workshop include:

- Formulation of relativistic positioning systems and properties of emission coordinates
- Application to GNSS, relativistic reference frames, pulsar-based navigation and localization
- Inter-satellite links and autonomous GNSS
- Relativistic celestial mechanics (coordinate systems, Hamiltonian techniques...)
- Application to Earth sciences, astronomy and metrology.

Also other contributions in line with the aims of the workshop will be considered.

Scientific Organizing Committee:

Bertram Arbesser-Rastburg (ESA)
Sante Carloni (ESA)
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Clovis Jacinto de Matos (ESA)
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