EUROPEAN PLANS FOR NEW CLOCKS IN SPACE

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Abstract

An outline of the future European space research program where precise clocks are necessary is presented, pointing out how space applications are posing impressive requirements as regards clock mass, power, ruggedness, long life, accuracy and, in some cases, spectral purity.

The material presented was gathered in some laboratories; useful information were obtained from the Space Agencies of France (CNES), Germany (DARA) and Italy (ASI), but the bulk is coming from a recent exercise promoted inside ESA (the European Space Agency) and aimed to prefigure space research activities at the beginning of the next millennium. This exercise was called Horizon 2000 plus; *the outcomings were summarised in two reports, presented by ESA in may 1994.*

Precise clocks and time measurements are needed not only for deep-space or out-ward space missions, but are essential tools also for Earth oriented activities. In this latter field, the European views and needs were discussed in October 1994, in a meeting organized by ESA and devoted to Earth Observation problems.

By a scrutiny of these reports, an analysis was performed on the missions requiring a precise clock on board and the driving requirements were pointed out, leading to a survey of the necessary PTTI developments that to same extent are in the realm of possibility but that pose serious challenges. In this report the use of frequency standards in the satellite navigation systems is not considered.

1. INTRODUCTION

A large number of frequency standards are used in every spacecraft, mostly for telecommunication purposes or as time reference for the on-board computers. In some cases clocks are required for the time-tagging of data, but in other instances the mission of the spacecraft itself requires the availability of precise frequency standards or clocks. Well known examples are the navigation satellites in which the frequency stability or accuracy play a fundamental role in all the methods, conical as ARGOS, hyperbolic, as one way TRANSIT and TSIKADA and DORIS [1], and circular, as one way GPS and GLONASS or two-way PRARE [2].

[1]DORIS - is a satellite based radio positioning system, designed and operated by CNES, France. It is an "inverted" TRANSIT, operating at higher carrier frequencies and with transmitters on ground and reception and data collection on board.

[2]PRARE - Precision Range And Range-rate Experiment, is a satellite based tracking system, following, at the same time, the conical, hyperbolic and two way circular navigation system. The system was designed at the University

Being satellite navigation requirements, as regards frequency standards, covered adequately in the literature, the aim of this paper is to deal with less known topics, such as the use of precise frequency standards in space research. Also the "precise" navigation of these satellites, if required, is not here considered, because methods and devices are similar to those of navigation or geophysical satellites or are using instruments, such as the star tracker, not based on frequency standards.

The occasion of this study was offered by the results of a request of proposals called by the European Space Agency in 1993. That call for ideas was devoted to Space research beyond 2000; the resultant activity was called **Horizon 2000 plus**, since it should be the continuation in time of the program **Horozon 2000**, now in implementation, with a number of missions launched between 1995 and 2005.

The second section of this paper is devoted to an outline of the program **Horizon 2000 plus**, limited to the satellites having special requirements as regards time and frequency Metrology in order to fulfil their mission while the third section deals with the **Earth Observation** topics. This latter section relies on the conclusions of an ESA–sponsored meeting, held in October 1994.

The fourth section covers the principal methods used, the fifth lists the "precision" requirements, while the last one presents some actions, researches and goals to be performed and reached in the next years, in order to make feasible the bold program of Space research.

To complete the panorama, not only the on board clocks and standards are considered, but also the related devices used on ground, moreover also laser sources, when used as frequency reference or timing devices, are considered in this survey.

It appears that PTTI and in particular precise clocks will play a fundamental role in space mission, particularly when verifications of fundamental physics are involved. Such needs of precise clocks and PTTI technology challenge our current technology and practice and, by turn, will give insight to the PTTI community of possible improvements

2. THE ESA HORIZON 2000 PLUS SURVEY

In 1993, ESA launched a call for proposals for the realm of "Space Sciences", and for the next Century. In ESA jargon Space Sciences are formed by :

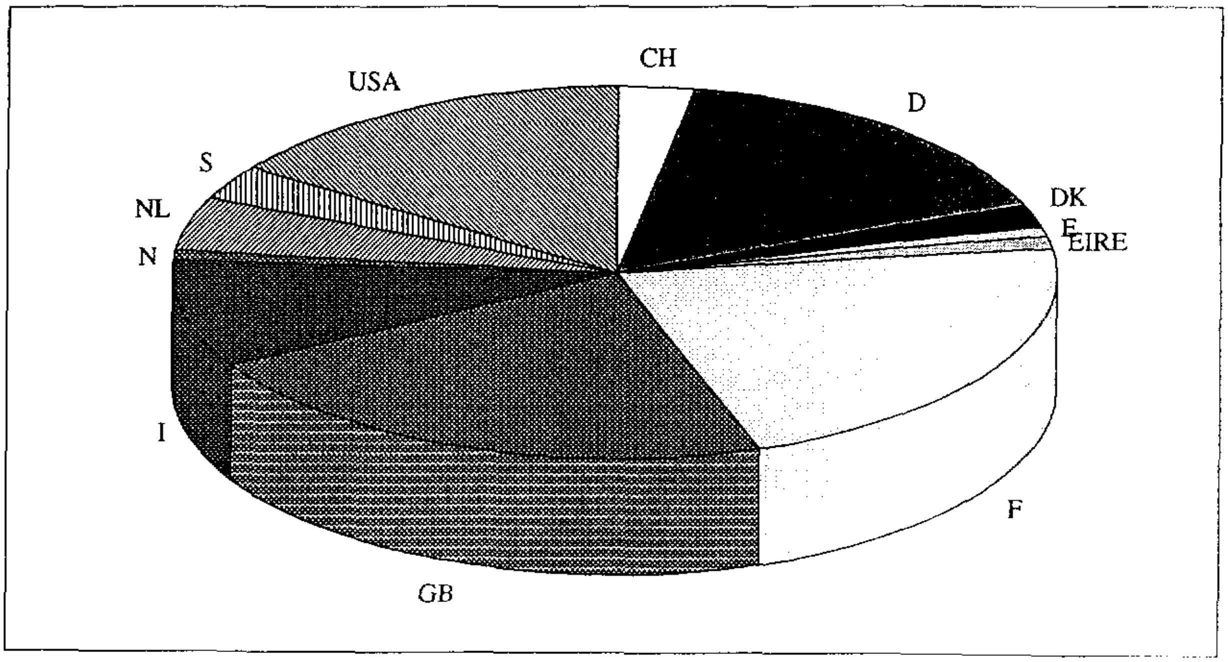
- - astronomy
- - solar system
- - fundamental physics.

By the end of 1993 about one hundred Laboratories, from both sides of the Ocean, answered to the call for ideas [1]; as a matter of record for the three above mentioned areas, the proposals

of Stuttgart, Germany, it is presently under test on Meteor III and it will be flown also on ERS-2 with launch planned in 1995. The use of PRARE is proposed also for other missions.

were respectively 35, 41, and 30. It's interesting to note that of the 106 proposed ideas, almost 90 came from European institutions while the remaining part came from USA (considering the project leader). The inputs arrived from different countries as visualized in the table and drawing below.

CH	D	DK	E	EIRE	F	GB	I	N	NL	S	USA
3	17	2	1	1	23	23	10	1	5	3	16



To asses the value of the proposals, ESA formed five "topical teams" or groups of experts, whose conclusions and recommendations were presented to the scientific community during a meeting held in Italy in May 1994 [2,3].

Out of the 30 odd proposals presented in the Fundamental Physics sector, 12 are considering the use of frequency standards, clocks of frequency–stabilized lasers as the key component of the mission. In the other sectors, some proposals were considering the use of "precise" frequency standards inside the positioning, navigation or telecommunication systems. As pointed out in Section 1, these mission are disregarded in this survey.

2.1 MISSIONS IN THE FUNDAMENTAL PHYSICS SECTOR

After receiving the proposals, the topical team specifically devoted to fundamental physics mission analysis stated that:

- - a cornerstone mission should be the detection of gravitational waves in space;

- - three scientific topics are of foremost importance: gravitational waves, universality of free fall, and the relation between space–time curvature and matter. The following projects were selected as the best proposals in these areas respectively:
  - LISA Laser Interferometry Space Antenna,
  - STEP Short Range Equivalence Principle experiment,
  - SORT Solar Orbit Relativity Test;
- - some existing technologies need developments, among them: lasers, frequency standards and time transmission.

During a recent meeting (Oct. 1994), three additional missions have been recommended among which one concerns an interferometric observatory and an other a gravitational wave observatory. The missions requiring PTTI devices on board, are listed in Table I, with their acronyms, a brief synthetic description, the originating Laboratory and Nation, and the characteristics of the needed frequency standards.

Some other proposals involving the use of "precise" clocks are circulating now in Europe, and are listed with the same criteria in Table II.

TABLE I

Mission	Aims	Source	Needed Clocks	
			why	which
CASP Close Approach Solar Probe	relatitvity test	Smithsonian Astrophysical Observatory USA	1st and 2nd order red–shift measurement	H maser
CRONOS on MILLIMETRON Clock Relativity Observations of Nature of Space–time	relativity and gravitational test (based on RADIOASTRON II)	Observatory of Neuchatel CH	red–shift and gravitational background radiation measurement	2 H masers on board + 1 on Earth in future: cold H maser or cold microgravity clocks
ORT Orbiting Radio Telescope	radioastronomy VLBI in space	Onsala Space Observatory Sweden	high resolution angular measurements	H maser on board? GPS receiver on board?
SMRPM Small Mercury Relativity and Planetology Mission	around Mercury relativity test Limit on $\dot{G}$	Interplanetary Space Physics Institute Italy	delay measurement	H maser
SORT Solar Orbit Relativity Test	relativity test	Observatory of "Cô d'Azur" France	red–shift measurement	H maser (ESA and and Russia) or cooled atomic clocks (CNES)

TABLE I continued

STUFF Strong Test on the Universality of Free Fall	similar to SMRPM	Montana State University USA	delay measurements ?	H maser?
VULCAN solar probe	similar to CASP	University of London UK	red–shift measurement	H maser (or cooled atom/ trapped ions
				Needed stable Lasers
ISLAND Inverse square LAw using iNertial Drift	verification of the inverse square law of gravitation	University of Strathclyde Scotland UK	displacement measurement linewidth 1 Hz @ 532 nm	1 Nd YAG laser @ 1.064 μm frequency doubled
LARGO Long Armlength *Relativistic* Gravitational Observatory	detection of gravitational	Jet Propulsion Laboratory, *California* USA	spacecraft baseline variation detection	10 Watt Nd YAG laser
LISA Laser Interferometer Space Antenna	Gravitational wave detection	Max–Planck Institut für Quantumoptik, Garching D JPL USA	interferometer length variation	3 Watt stabilized Nd YAG laser @ 1.064 μm, stability $=10^{-13}/\sqrt{Hz}$@ f=1 mHz
				Needed System Timeing
LATOR Laser Astrometric Test of Relativity	Sun gravitational deflection of light	Rutherford Appleton Laboratory Didcot UK	sending “laser flashlight” in solar orbit	suitable time measurement system
VLO Very low frequency *Lunar Observatory*	Exploring the 100 kHz – 30 MHz *window*	Observatoire Paris, France	pulsar studies	suitable time reference system

TABLE II				
Mission	Aims	Source	Needed Clocks	
			why	which
CASSINI	gravitational wave detection and	Jet Propulsion Laboratory, CA USA	Doppler shift measurement	Rb clock $\sigma_y \approx 10^{-12}$ @ 100s; acceleration sensitivity $\approx 10^{-12}/g$
QUASAT	VLBI interferometry	ESA		H masers on ground
LAGEOS III LAser GEOdetic Satellite	relativity tests on gravitomagnetic field	Italian Space Agency ASI, NASA	orbit determination	Cs clocks on Earth (laser ranging)
ExTRAS Experiment on Timing Ranging and Atmospheric Sounding	geodesy atmosphere physics and relativity tests on METEOR M	Russian Space Agency ESA Obs. Neuchatel	position measurement; low phase noise reference	2 H maser; time time transfer with precision of 10 ps
CRONOS on RADIOASTRON I (similar to the Japanese VSOP)	Space Very Long Baseline Interferometry	Russian Space Agency ESA Obs. Neuchatel	high resolution angular meas.; 10^{-6} accuracy red-shift measurement	one H maser on board + several on Earth

3. EARTH OBSERVATION NEEDS

Also in the case or Earth–oriented satellites, the Navigation requirements, in some cases very stringent, are disregarded in this survey. From the meeting held at ESTEC, Noorwijk, Holland, in October 1994, quite unexpectedly the major request for better "navigation and positioning" and consequently "better frequency standards", went from the community of Oceanographers.

It seems that the models of oceanic currents circulation require near one order of magnitude improvement in the High harmonics of the Geopotential, i.e. the very accurate tracking of satellites in circular orbit, flying at about 160 km, for a period of half or one year. This craft, named ARISTOTELES, will pose difficult problems of navigation, since every fortnight the satellite should be re–boosted. The use of GPS system is planned, with differential corrections coming from ground.

Other Frequency and Time requirements come from the short term frequency stability of the radar–altimeters and of the reference sources for space borne Synthetic Aperture Radars.

4. WHY "PRECISE" CLOCKS ARE NEEDED

The topics to be investigated and consequently the measurements to be performed are listed in Table III.

TABLE III		
topic		**measurement**
relativity effects	equivalence principle	frequency variation time advance
	photon trajectories (bending of light)	propagation time variation
	gravitomagnetic field (Lens–Thirring effect)	spacecraft position
	gravitational wave detection	spacecraft position (with reference to the Earth) interferometry
reference frames		spacecraft relative positions
pulsar timing		time of arrival versus TAI (models of time scales)
ranging to interplanetary spacecrafts		time of propagation (relativity corrections)
radioastronomy geodesy		phase measurements (extra long baseline interferometry)

Most of these activities are moreover requiring the introduction of relativistic effects [4]. For instance, in 1983 it has been shown [5], that the bending of light by the sun can amount to as much as 36 ns of additional time delay.

Out of General Physics, quite a deal of investigations are possible with "precise" clocks on board, such as Earth limb sounding (the ionospheric gradients around the Earth), or measurements on the interplanetary or the interstellar medium.

A new brand of Space Activities requiring "precise" clocks are planned on the very special satellite formed by the Moon. In the far side of the Moon currently ESA–sponsored studies are in progress in Europe, investigating, between the others, the concept and the feasibility of a Very Low Frequency Array (VLFA project), in the band 100 kHz – 30 MHz (for radioastronomers 100 kHz is a very low frequency ...) for interferometric operations.

Consequently, coming back to Table III, the kinds of measurements to be performed are well known activities of the Frequency and Time Metrology; the problems to be solved are the utmost accuracies or stabilities to be offered and the need to fulfil formidable requirements, as regards mass, unattended operation, life, power and general reliability, and in some cases harsh environment.

5. FREQUENCY AND TIME REQUIREMENTS

With reference to Tables I and III, the general "precision" i.e. accuracy and stability requirements were calculated or gathered from the existing literature; in some cases, assumptions were made. As regards the environment and life requirements, information was usually not available in the literature and consequently the estimates are responsibility of the authors.

Results and estimations are gathered in the last two columns of Table I, in which, when possible, an indication of the proposed device is provided.

6. RECOMMENDED ACTIONS

As regards the science and technology developments to be planned for the next years, as a logical prerequisite to the implementations of the proposed post 2000 scientific space missions, information can be gathered from two ESA documents [1, 3], from which the following list is extracted:

- drag free systems
- position sensors
- acceleraometers
- **lasers for interferometry**
- lasers for transmission of time signals
- active optics technology
- **frquency standards + clocks**
- **time transmission and comparison methods**
- lightweight materials
- **cryogenics also applies to clocks (cold H maser)**
- high speed data transmission
- **cooled atomic frequency standards**

From discussions with experts in the field, it seem that the most desirable strives should be toward the following devices:

- **a frequency standard with mass less than 25 Kg, stability 10^{-15}/d, life 5 years, power 15—20 W, accuracy not critical (for interferometric operations)**

- **a frequency standard with mass less than 50 Kg, stability 10^{-17}/d, life 5 years, power 15—20 W**
- **frequency stabilized solid state lasers, with stability of 10^{-15}/1000s, mass a few Kg, power 5 W (for long range interferometric operations)**
- **time transfer and comparison methods with a resolution of about 10 ps**

The use of accurate (and stable) clocks on deep space probes or orbiting satellites could allow a one-way measurement of the velocity of light. This measurement would be an important test of the isotropy of c, but it would require the development of

a frequency standard with mass less than 25 Kg, stability 10^{-14}/d, accuracy 10^{-14}, life 5 years, power 10 W.

The revised interest for the Space Station and its attached Columbus module, would offer the very promising possibility to test in space atomic clocks, without stringent mass requirements and with the possibility of servicing directly on the craft.

Along these technical developments, parallel improvements must be reached in propagation time models, relativistic corrections, interplanetary (in the far future interstellar) plasma effects, and, for Earth based measurements, ionospheric and tropospheric effects.

ACKNOWLEDGEMENTS

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QUESTIONS AND ANSWERS

PETER WOLF (BIPM): To test the isotropy of speed of light, you don't necessarily need accuracy in your frequency standard. If it is sufficiently stable and you watch it during a certain period, you can syntonize it and determine its frequency offset – and correct for it. I will say more about this in my paper tomorrow.

SIGFRIDO LESCHIUTTA: Thank you. You are comp;etely right. You and your colleagues will cover that tomorrow.