THE LASSO EXPERIMENT

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ABSTRACT

The LASSO experiment is an approach towards an internationally coordinated technical assessment of a system which promises to provide a synchronisation of clocks bound to time and frequency standard laboratories, with an accuracy of one nanosecond using existing or near ground-based laser stations via a geostationary satellite (SIRIO-2).

The purpose of this paper is twofold; to present the LASSO mission and the principle of the overall experiment, and to underline the system performance and the technical details concerning :

- on-board equipment,
- ground segment,
- operational configuration.

To conclude, we will show the future prospects of the LASSO experiment together with possible implementations.

1. INTRODUCTION

The permanent long baseline clock synchronisation presents many scientific and practical interests. From a scientific point of view, the standard of frequency or the very accurate synchronisation between clocks allows a correlation of phenomena in the same scale of frequency or time to be performed. The demand for greater accuracy has led to an improvement of the measurement of time and frequency by a factor of at least 10^8 over the past century. While the limiting accuracies are still confined to research laboratories and institutes dealing with time and frequency standards, commercial and scientific users are not far behind in their requirements :

- Digital communication	10 μs
- International telephone communication	1 μs
- Earth-based navigation	1 μs
- Deep-space navigation	20 ns
- Radio-astronomy	1 ns
- Geodesy	as accurate as possible
- Relativity	
- Astronomy	

Applications and research already planned for the next decade will require nanosecond accuracy of better. Present users of time and frequency information have access to a variety of services and techniques for disseminating this information. These include the well-known high and low frequency broadcast services operated by many different Administrations throughout the world, portable clock methods, the use of television transmissions, and satellite techniques (Table 2).

TABLE 1 : METHODS CURRENTLY USED FOR TIME SYNCHRONISATION

Method	Accuracy	Remarks
Very long baseline interferometry (VLB) using pulsars	1 ns	Slow, expensive ground stations
TV-type transmission via satellite	10 ns	Requires a wideband spacecraft transponder
Symphonie B	20 ns	Requires two-way transponder
Portable clocks	30 ns	Slow
Timation-3	100 ns	Military
Loran-C	300 ns	Accuracy limited by propagation phenomena

Although available services can satisfy many of the present user needs in science and application, an increasing need is developing for services which are required to provide improved accuracy, coverage and reliability. For example, the rapid growth of technology as applied to such areas as precise navigation, high-precision geodetic position determination, multiple-access digital communication and metrology results in a need for intercontinental time synchronisation and comparison down to the nanosecond.

While existing services are undoubtedly capable of some improvements, experience with a number of spacecraft - albeit ones that were not specifically designed for dedicated timing missions - indicates that satellite techniques appear to be the best choice for meeting future requirements in the subnanosecond range. Following a proposal presented at the 1972 COSPAR meeting in Madrid, the European Space Agency accepted a proposal from the "Bureau International de l'Heure" (BIH) to implement an experimental space mission and decided to launch a payload package, LASSO (Laser Synchronisation from Stationary Orbit) on the SIRIO-2 spacecraft.

The objective of LASSO is to provide a repeatable, near-realtime method of long distance synchronisation with the nanosecond accuracy for a reasonable price to meet the above requirement.

2. THE LASSO MISSION OBJECTIVES

The mission objectives, backed up by a number of time and frequency standard laboratories, is to provide intercontinental synchronisation of clocks with an accuracy of one nanosecond or better, and is to be considered as an important approach towards an internationally coordinated technical assessment of such a system.

The mission will thus allow the establishment of an improved international network of reference clocks synchronised between themselves and with the Internationally adopted Atomic Time scale (IAT).

It will also impact on other practical applications, such as the tracking of deep space mission spacecraft, the dissemination of standard time and frequency signals to many users, and future generations of space navigation and telecommunication systems.

The LASSO/SIRIO-2 experiment is designed to employ laser techniques and is not only a significant breakthrough in synchronisation techniques but is also a unique opportunity to compare the performance of laser and microwave time synchronisation methods insofar as microwave timing results have become available from the Italian SIRIO-1 time synchronisation experiment started in 1978. Thus, two candidate techniques will be compared on the basis of identical link geometry and satellite type.

3. THE EXPERIMENT

3.1. Principle

The LASSO experiment is based on laser stations emitting, at a predefined time, monochromatic light impulses which are directed towards a geosynchronous spacecraft (figure 1).

On-board the spacecraft :

- an array of retro-reflectors sends back a fraction of the received signal to the originating laser stations;
- an electronic device detects and time tags the arrival of laser pulses.

Each station measures the two-way travel time of the emitted laser pulses and computes the one-way travel time between station and spacecraft, taking into account the station's geographical coordinates, the spacecraft position and the Earth rotation.

The difference between the clocks, which provide the time reference for each of the laser stations, is deducted from the data coming from the spacecraft and the stations (figure 2).

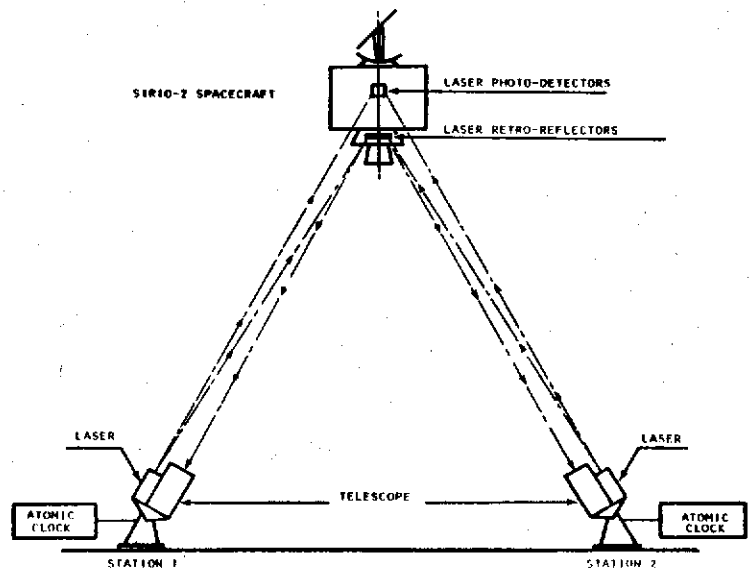


Figure 1. Schematic Diagram of LASSO Experiment

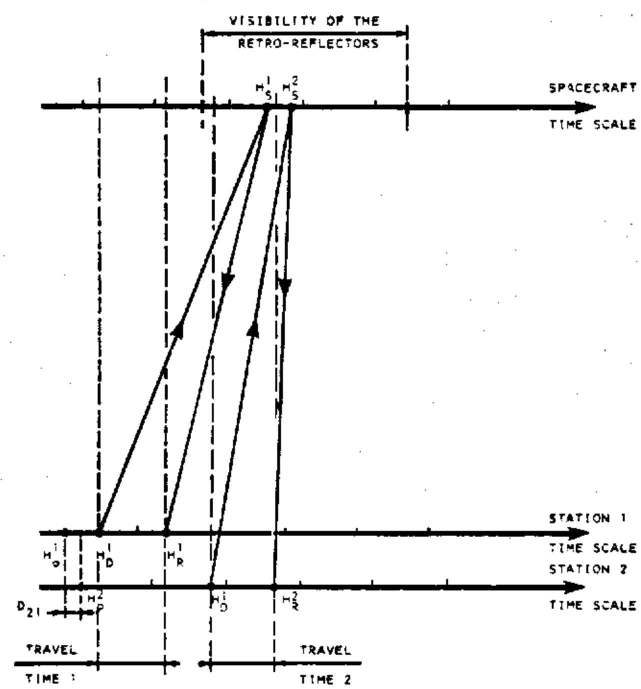


Figure 2. Time Scale Comparison

Consequently, for two stations we have :

$$D_{21} = (H_D^2 - H_D^1) + (T_2 - T_1) - (H_S^2 - H_S^1)$$

where : D_{21} = Time difference between the clocks of stations 2 and 1.

H_D^1 and H_D^2 = Departure time of laser pulses from stations 1 and 2.

T_1 and T_2 = Travel time between stations and spacecraft with $T = \dfrac{H_R - H_D}{2} + \varepsilon$

H_S^1 and H_S^2 = Arrival times on-board the spacecraft of the laser pulses from stations 1 and 2.

H_R^1 and H_R^2 = Return time of laser pulses from stations 1 and 2.

ε = Corrective factor depending on station and satellite positions.

The formula becomes finally :

$$D_{21} = \left(\frac{H_D^2 - H_D^1}{2}\right) + \left(\frac{H_R^2 - H_R^1}{2}\right) + (\varepsilon_2 - \varepsilon_1) - (H_S^2 - H_S^1)$$

3.2. Performance

Error Analysis

Using the above formula, the global error is :

$$\Delta D = \Delta H_D + \Delta H_R + 2\Delta\varepsilon + 2\Delta H_S$$

with : ΔH_D : error on the departure time

ΔH_R : error on the return time

$\Delta\varepsilon$: error on the corrective factor

ΔH_S : error on the arrival time on-board the spacecraft.

The error budget is detailed in table 2 for three different numbers of measurements (1, 15 and 30). In addition, all the laser firing times are in a time window of less than 100 msec.

TABLE 2

ANALYSIS OF ERROR FACTORS			NUMBER OF MEASUREMENTS		
			1	15	30
H_D	.Accuracy of cesium clock	$\leq 10^{-11}$	$\pm$ 1 psec	$\pm$ 1 psec	$\pm$ 1 psec
	.Short term stability	$\leq 2.10^{-11}$	$\pm$ 2 psec	Negligible	
	.Chronometer resolution	0.1 nsec	$\pm$ 50 psec	$\pm$ 50 psec	$\pm$ 50 psec
	.Detection system	0.1 nsec	$\pm$ 100 psec	$\pm$ 26 psec	$\pm$ 18 psec
		$\Delta H_D \leq$	$\pm$ 153 psec	$\pm$ 77 psec	$\pm$ 69 psec
H_R	.Accuracy of cesium clock	$\leq 10^{-11}$	$\pm$ 2 psec	$\pm$ 2 psec	$\pm$ 2 psec
	.Short term stability	$\leq 2.10^{-11}$	$\pm$ 4 psec	$\pm$ 1 psec	$\pm$ 1 psec
	.Chronometer resolution	0.1 nsec	$\pm$ 50 psec	$\pm$ 50 psec	$\pm$ 50 psec
	.Detection system	1 nsec	$\pm$1000 psec	$\pm$ 258 psec	$\pm$ 183 psec
		$\Delta H_R \leq$	$\pm$1056 psec	$\pm$ 311 psec	$\pm$ 236 psec
Σ	.Spacecraft position	$\pm$ 1 km			
	.Station position	$\pm$ 50 km			
		$\Delta\varepsilon \leq$	$\pm$ 40 psec	$\pm$ 40 psec	$\pm$ 40 psec
H_S	.U S O accuracy*	$\leq 10^{-9}$	$\pm$ 100 psec	$\pm$ 100 psec	$\pm$ 100 psec
	.U S O stability	$\leq 10^{-10}$	$\pm$ 10 psec	$\pm$ 3 psec	$\pm$ 2 psec
	.Chronometer resolution	0.1 nsec	$\pm$ 50 psec	$\pm$ 50 psec	$\pm$ 50 psec
	.Detection	1 nsec	$\pm$1000 psec	$\pm$ 258 psec	$\pm$ 183 psec
		$\Delta H_S \leq$	$\pm$1160 psec	$\pm$ 411 psec	$\pm$ 335 psec
D	$\Delta D = \Delta H_D + \Delta H_R + 2\Delta\varepsilon + 2\Delta H_S \leq$		$\pm$ 3.6 nsec	$\pm$ 1.3 nsec	$\pm$ 1 nsec

* U.S.O. : Ultra Stable Oscillator

Liaison Budget

Considering the two planned positions in orbit of the spacecraft (25°W and 20°E), the parameters of the on-board equipment and the assumed characteristics of a certain number of laser stations, we have used different algorithms to compute :

- P_r which is the power density received by the spacecraft,

$$P_r = K \frac{J}{T} \cdot \frac{T_A}{\frac{4}{\pi} \theta^2 D^2}$$

using the following unit :

J (Joule) emitted energy
T (nsec) pulse width
θ (second of arc) beam divergence
D (km) distançe station - spacecraft
$T_A = (0.7)^{1/\cos z}$ atmospheric transmission coefficient (z = zenithal distance)
$K = 0.7$ coefficient of energy distribution

The formula becomes :

$$P_r (\mathrm{mW/cm^2}) = 3.79\ 10^{12} \frac{J}{T} \frac{1}{\theta^2} \frac{1}{D^2} T_A$$

- $\overline{N}_d$ which is the mean value of photons received by the photo-detector

$$\overline{N}_d \text{ (photons/nsec)} = \frac{N_d}{T} = P_r\, A_{op}\, s\, \frac{\lambda}{hc} \text{, with :}$$

A_{op} = 2.25 gain of optical detection

s = 0.2 mm^2 photodiode sensitive surface

λ_R = 694.3 nm (Ruby)

λ_N = 532.0 nm (Neodyme)

h = $6.6256\ 10^{-34}$ J.sec

c = $2.998\ 10^{8}$ m/sec

consequently :

$$\overline{N}_d = k\, P_r \quad \begin{cases} k_R = 15730 \\ k_N = 12050 \end{cases}$$

- S/N which is the signal to noise ratio,

$$\frac{S}{N} = C.P_r^2$$

with C being a coefficient depending on the optics, the photodiode noise and preamplifier noise.

$$\left(\frac{S}{N}\right)_{dB} = 20 \log_{10} P_r + 10 \log_{10} C,$$

where $10 \log_{10} C = 32$ for Ruby and $= 26$ for Neodyme.

- N_e which is the number of photo-electrons collected at the laser station using the Fournet formula :

$$N_e = E \cdot TR_1 \cdot R \cdot TR_2 \cdot D$$

where $E = KJ \frac{\lambda}{hc}$ — photons emitted by the laser station

$$TR_1 = \frac{T_A}{\frac{\pi}{4}\left(\frac{\pi}{180} \cdot \frac{\theta}{3600} 10^5 D\right)^2}$$ travel effect station - spacecraft

$R = R_{cc} \Sigma f (G_i)$ — retro-reflectors effect

$R_{cc} = 0.75$ (coefficient of reflection)

$\Sigma f (G_i) = 14$ (minimum efficacy)

$$TR_2 = 0.328 \frac{T_A}{D^2}$$ travel effect spacecraft - station

$D = A T_r \rho$ — station detection effect

$A(cm^2)$ is the receiving surface of the telescope,

T_r is the transmission coefficient of the telescope optics ($T_r = 0.8$ without interferential filter, and 0.4 with interferential filter of 3Å),

ρ is the quantum efficacy of the P.M. (20% for Ruby and 25% for Neodyme).

All the computed values are reported in table 3, where the nominal value of the laser beam divergence θ has been considered equal to 15 seconds of arc.

TABLE 3

STATIONS	CHARACTERISTICS				25° W				20° E			
GEOGRAPHICAL LOCATION	Laser Type	Energy Joule	Pulse Duration nsec	Telescope Aperture cm	P_r mW/cm^2	$\overline{N}_d$ Photon/nsec	S/N dB	N_e Photo electron	P_r mW/cm^2	$\overline{N}_d$ Photon/nsec	S/N dB	N_e Photo electron
CAGLIARI (Italia)	R	1	5	50	1.18	18560	33	4	1.42	22340	35	6
DIONYSOS (Greece)	R	4	15	45	1.18	18560	33	7	1.96	30830	38	20
GRASSE (France)	R	15	10	100	8.40	132130	50	211	9.84	154780	52	290
GRASSE (Lune) (France)	R	6	2	154	16.80	264260	57	200	19.70	309880	58	275
KOOTWIJK (Holland)	R	3	4	50	3.40	53480	43	7	4.03	63390	44	10
METSAHOVI (Finland)	R	1	20	63	0.06	944	8	0.2	0.20	3150	18	3
SAN FERNANDO (Spain)	R	3	6	60	3.55	55840	43	24	3.36	52850	43	22
WETTZELL (Germany)	N	0.25	0.2	60	5.0	60250	40	0.4	6.83	82300	43	0.8
ZIMMERWALD (Switzerland)	R	5	17	50	1.52	23910	36	15	1.81	28470	37	21
AREQUIPA (SAO) (Perou)	R	6	15	50	2.38	37440	40	24	OUT OF VISIBILITY			
NATAL (SAO) (Brazil)	R	6	15	50	3.61	56790	43	55	2.0	31460	38	17
WASHINGTON (USA)	N	0.25	2	50	0.48	5780	20	0.4	OUT OF VISIBILITY			
WASHINGTON (USA) Mob.las. 1.3	R	0.75	5	50	0.58	9120	27	1.2	OUT OF VISIBILITY			
WASHINGTON (USA) Mob.las. 4.8	N	0.25	5	75	0.19	2290	12	0.9	OUT OF VISIBILITY			
WASHINGTON (SAO) (USA)	R	6	15	50	1.54	24220	36	10	OUT OF VISIBILITY			

4. THE EQUIPMENT

4.1. General Description of the Spacecraft

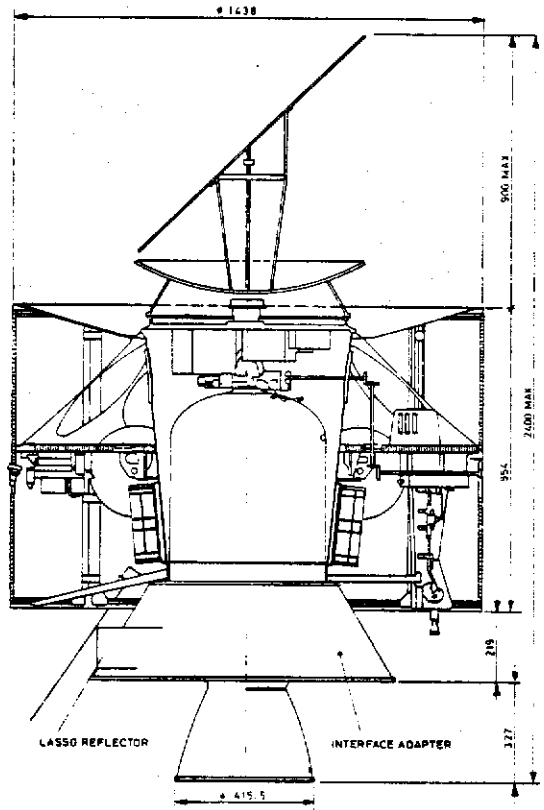


Figure 3. SIRIO-2 Spacecraft

A cross-section of the SIRIO-2 satellite is shown in figure 3. It consists of a drum-shaped central body covered with solar cells, on top of which is mounted a mechanically despun S-Band antenna. The apogee boost motor, which is to be retained after burn, protrudes from the bottom of the spacecraft. While the directional S-Band antenna supports a Meteorological Data Dissemination (MDD) function and transmits the housekeeping telemetry, the omnidirectional turnstile antenna serves telecommand, ranging and back-up telemetry functions in the VHF. As the satellite is to be spin-stabilised at 90 rpm and will act as an inertial gyroscope, attitude re-orientation is achieved by torque-induced precession of the spin axis using axial micro-propulsion thrusters in a pulsed firing mode. North-South stationkeeping is performed by the same thrusters in a continuous firing mode, while a pair of radial thrusters allows the satellite to be displaced in an East-West sense.

The monopropellant hydrazine fuel is contained in four symmetrically located spherical tanks. The telemetered readings from on-board infrared earth and V-slit sun sensors are used to determine the satellite's attitude in space. The satellite is powered by the solar cells and by a battery sustaining a minimum load configuration during eclipse transits.

The LASSO payload is comprised of retro-reflectors, photodetectors for sensing ruby and neodyme laser pulses, and an ultra stable oscillator/counter to time-tag the arrival of the pulses. These time-tags will be encoded in time-division multiplex with spacecraft housekeeping information before transmission to the ground.

The overall block diagram is given in figure 4.

The industrial effort for the SIRIO-2 project is led by the Compagnia Nazionale Aerospaziale (CNA) in Rome.

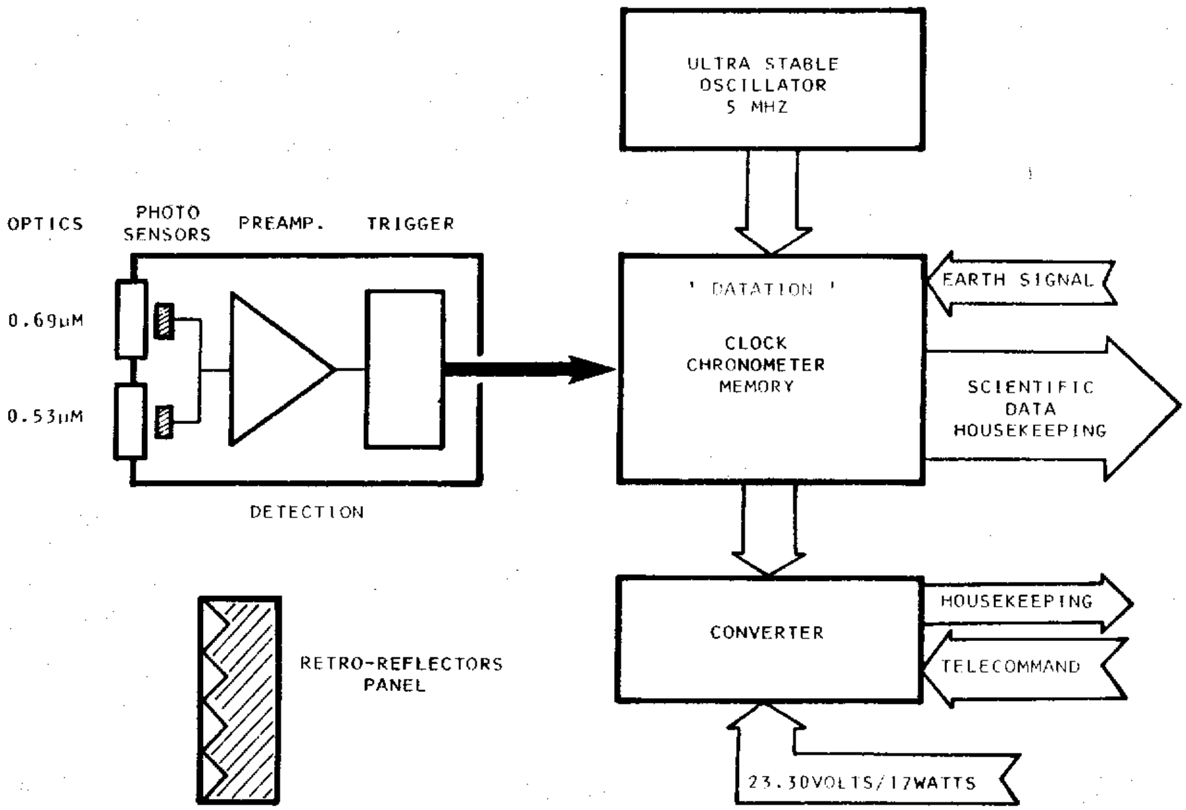


Figure 4: LASSO Equipment Block Diagram

The figure 5 gives the simplified industrial organisation of the SIRIO-2 programme.

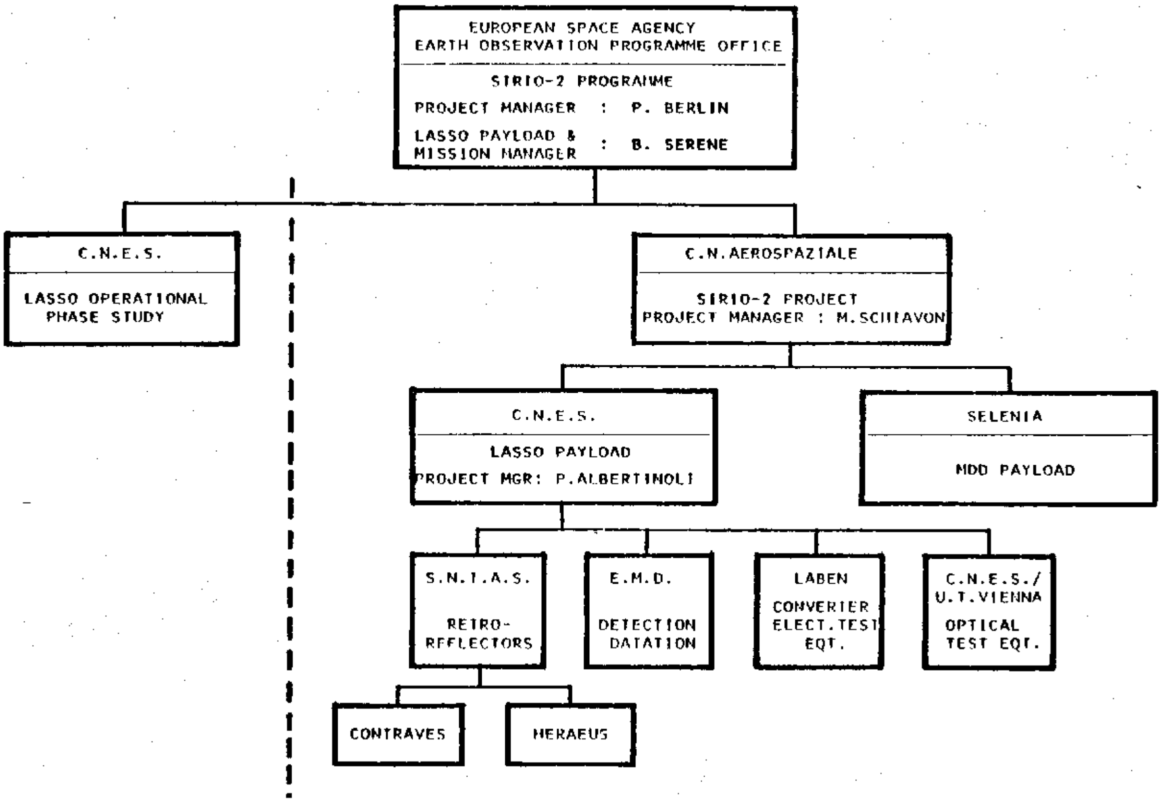


Figure 5 : Industrial Organisation

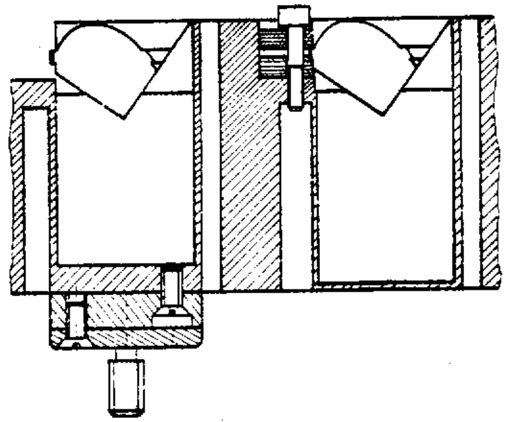
4.2. Details of the On-board LASSO Equipment

Retro-reflectors

The retro-reflector panel is an assembly of 98 aluminised corner cubes which are held by a mechanical structure thermally coated and decoupled from the spacecraft (figure 6). The panel, which is mounted on the launch interface adaptor and aligned with the field of view of the photo-detectors, has the following characteristics :

- weight : 2,5 kg
- dimensions : 155 mm x 340 mm x 35 mm
- minimum global efficacy : 14.

Each corner cube presents a diameter of 20 mm, with a reflection factor of more than 75%.



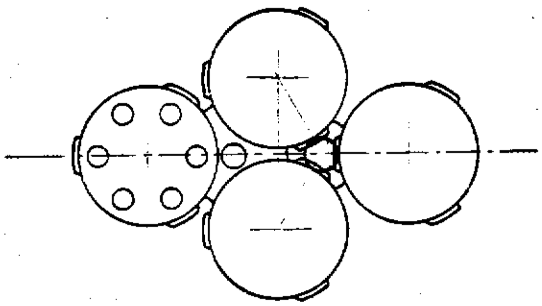


Figure 6. Mechanical Detail of the
Retro-Reflectors

Photo-detection

The detection box is located on the main platform near the skin of the spacecraft and views through an aperture in the solar panels. This unit detects laser pulses and converts them into electrical signals which are transferred to the time-tagging unit.

The block diagram given on figure 7 shows :

- the optics (one for each laser type) including interferential filter, focusing lens and the avalanche photodiode,
- the broadband pre-amplifier (1 GHz),
- the threshold amplifier with the AGC system.

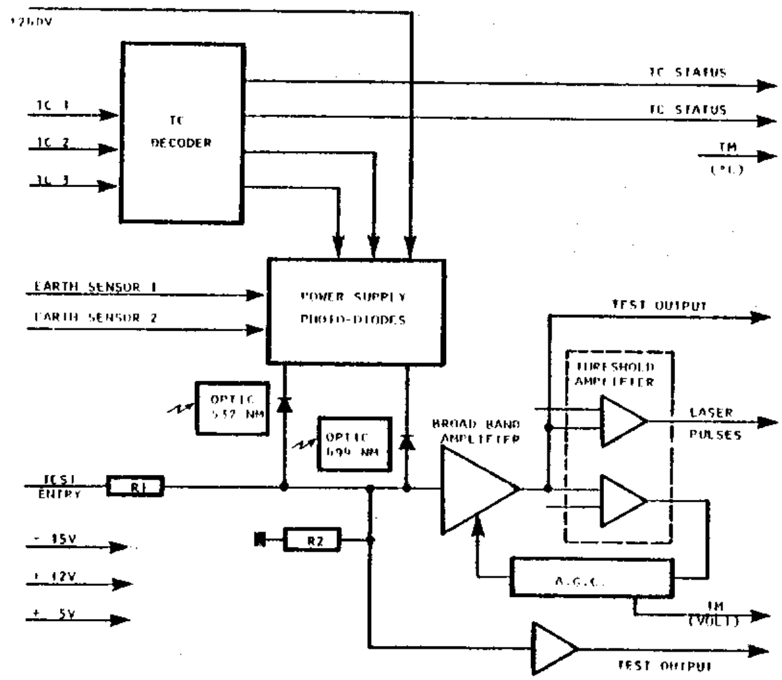


Figure 7 : Photo-detection Block Diagram

The main characteristics of the unit are :

- interferential filter bandwidth : 100 Å
- optical incident angle : ± 10 deg
- minimum detectable power density
  - . ruby : 0.25 mW/cm^2
  - . neodyme : 0.50 mW/cm^2
- false detection : ≤ one per minute
- non detection probability of a laser pulse : ≤ 1/100

Time Tagging

The time tagging unit, which is time-synchronised by an ultra-stable oscillator, clocks in the pulses coming from the detection unit.

The time events are buffered in a memory before being sampled and transferred to the ground via the spacecraft telemetry. The block diagram given on figure 8 shows :

- the ultra stable oscillator (USO)
- the clock counter (clock of minutes)
- the chronometer (0.1 nsec)
- the memory (1 kbits)

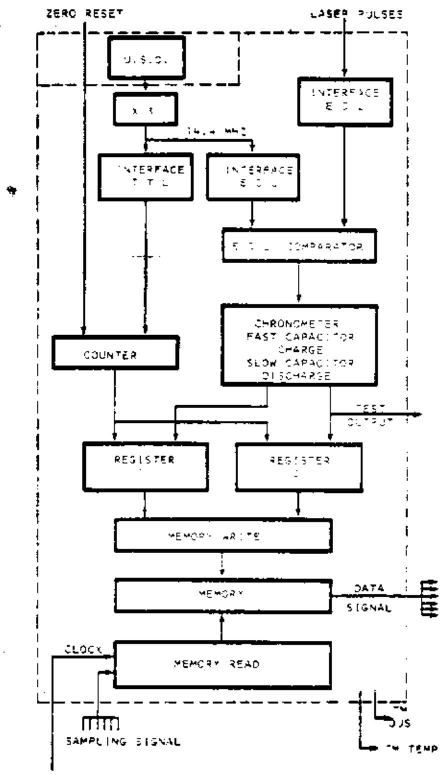


Figure 8. "Datation"
Block Diagram

The main characteristics of this subsystem are :

USO

nominal frequency	4.804434 MHz
short term stability (100 msec)	$\sigma(\frac{\Delta F}{F}) \leq 1.10^{-10}$
medium term stability (3 days)	$\lvert \frac{\Delta F}{F} \rvert \leq 5.10^{-10}$

Clock and Chronometer

chronometer resolution	# 100 psec
dead time	$\leq$ 200 μsec
time tag encoding	42 binary digits

The overall statistical accuracy (over 100 couples of events) on the elapsed time between two events in the same time window of 70 msec will be better than 0.5 msec.

5. THE GROUND SEGMENT

The LASSO experiment consists of a space and a ground segment with the aim of obtaining a very high-precision synchronisation between remote clocks at intercontinental distances and will be used in a pre-operational mission in order to demonstrate the validity of the LASSO concept and overall performance.

In addition, the laser stations should fulfil a certain number of requirements to participate in the LASSO experiment.

The modes of operation described here are only tentative and should be frozen at the beginning of 1980.

5.1. Mission Duration and Duty Control

A total duration of two years for the LASSO mission is planned, with two positions in orbit : 25°W and 20°E.

During its useful life in orbit, the LASSO experiment will perform "working sessions" with an average duration of one hour per day. There will be no technological constraints on the time of the day when one or more sessions will be performed.

5.2. Mode of Operation

Each daily working session comprises 2 periods :

1st period : synchronisation of laser pulses
Synchronisation of pulse transmission of each station participating in the session with respect to the rotation of the spacecraft, and to other stations.

2nd period : time measurements
Due to LASSO on-board equipment, laser pulses of the various operating laser stations must arrive at the spacecraft with the time distribution shown on figure 9.

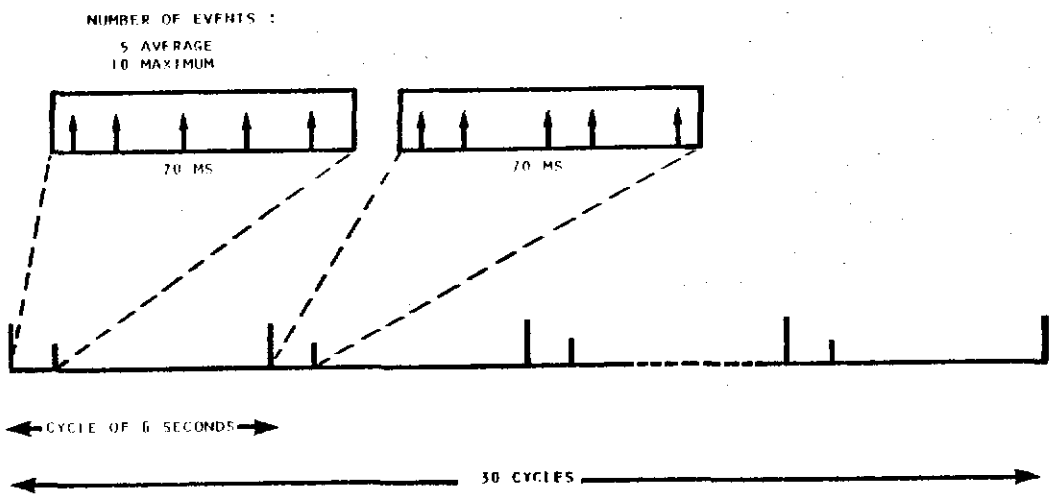


Figure 9 : LASSO Operation Mode

Each sequence of measurements lasts approximately 6 seconds (bound to the minimum pulse rate of laser stations).

In each sequence a certain time slot of 5.10^{-3} sec. is reserved for the arrival of the laser pulse from a given laser station to the spacecraft (this figure is bound by the accuracy of the time of departure of the pulse from the station and by the accuracy of the computation of the time of transit of light from the station to the spacecraft).

Successive sequences differ one from the others since not all of the laser stations send pulses at each sequence. This permits ground processing by pattern recognition techniques to eventually discard false pulses detected by the on-board equipment.

Presently another mode of operation is investigated : the asynchrone mode.

Following each daily working session, measurements made by spacecraft equipment and laser stations are used for data processing. Currently, several data processing modes are under study, and before final implementation, the different principal investigators will be consulted.

5.3. Laser Stations Requirements

Localisation

Because of the necessity to correct the transit time of light from the laser station to the spacecraft, the laser station should be located in a common earth reference frame with an accuracy of :

- latitude : $\pm$ 10" (or $\pm$ 300 m)
- longitude : $\pm$ 10" (or $\pm$ 300 m)
- altitude : $\pm$ 50 m

Performance

Two conditions are imposed on laser station characteristics :

- one by the satellite detector and retro-reflector characteristics,
- one by the laser station detector system.

Conditions for detection on-board the spacecraft :

In order to have sufficient energy flux to be detected on-board the spacecraft, the laser station must deliver a sufficient energy in a sufficiently narrow beam during a maximum time.

- If (J) is the total energy of the light in the beam during one pulse of the laser station in Joules,
  (T) is the equivalent pulse duration in nanoseconds,
  (θ) is the laser station beam divergence in second of arc,
- and considering the link budget from the laser station to the spacecraft, and the sensitivity of the detectors on-board the satellite,

the laser station should satisfy the performance relationship shown in table 4 below :

TABLE 4

ELEVATION	DISTANCE STATION S/C	BEAM DIVERGENCE IN SECOND OF ARC	
		RUBY LASER	NEODYME LASER
90°	35786 km	$\Theta \leq 128 \left(\frac{J}{T}\right)^{1/2}$	$\Theta \leq 86 \left(\frac{J}{T}\right)^{1/2}$
55°	36780 km	$\Theta \leq 120 \left(\frac{J}{T}\right)^{1/2}$	$\Theta \leq 80 \left(\frac{J}{T}\right)^{1/2}$
25°	39070 km	$\Theta \leq 92 \left(\frac{J}{T}\right)^{1/2}$	$\Theta \leq 62 \left(\frac{J}{T}\right)^{1/2}$
15°	40061 km	$\Theta \leq 69 \left(\frac{J}{T}\right)^{1/2}$	$\Theta \leq 46 \left(\frac{J}{T}\right)^{1/2}$

Conditions for detection of return-pulse by the laser station :

In order to detect the return pulse with the retro-reflectors on-board of SIRIO-2 spacecraft (544 cm^2 of surface, reflexion coefficient=0.75, efficacy = 14), the laser station should :

(a) transmit with sufficient energy J in a sufficiently narrow beam Θ,

(b) collect the light reflected by the spacecraft in order to get a sufficient number of photons on the laser station detectors.

If A (in square centimeters) is the effective area of the telescope used to collect the light,

T_R is the transmission factor of the telescope,

J (in Joule) is the energy of the laser flash,

Θ (in second of arc) is the beam divergence,

N is the number of photons collected by the telescope equipment, and considering the link budgets from the laser station and back to the laser station of reflection on the spacecraft,

the laser station should satisfy the relationship shown in table 5 below :

TABLE 5

ELEVATION	DISTANCE STATION S/C	NUMBER OF PHOTONS RECEIVED	
		RUBY LASER	NEODYME LASER
90°	35876 km	$N = 13 \frac{J}{\Theta^2} (T_R A)$	$N = 10 \frac{J}{\Theta^2} (T_R A)$
55°	36780 km	$N = 10 \frac{J}{\Theta^2} (T_R A)$	$N = 8 \frac{J}{\Theta^2} (T_R A)$
25°	39070 km	$N = 3 \frac{J}{\Theta^2} (T_R A)$	$N = 3 \frac{J}{\Theta^2} (T_R A)$
15°	40061 km	$N = 1 \frac{J}{\Theta^2} (T_R A)$	$N = 0.8 \frac{J}{\Theta^2} (T_R A)$

The number of photo-electrons detected is :

$Ne = N.\rho$

ρ = (quantum efficacy of photo-multiplier).

Minimum beam divergence

A sufficient beam divergence is necessary for the laser station in order to ensure that the pulse arrives at the satellite, taking into account small errors in the satellite position (known within $\pm$ 1 km). Then the laser stations must have a beam divergence of :

$\Theta \geq 10'' + 2 \times$ (angular error of tracking)

Performance of time-measurement devices in the laser stations

- Laser stations participating in the LASSO experiment should permit synchronisation with a standardised time of their zone (ex. IAT ...) by the terrestrial means on a daily basis with a precision of about a few microseconds.
  Maximum error on the synchronisation between two laser stations participating in the LASSO experiment should be less than 1 millisecond before measurements by LASSO.

- Each pulse transmitted by the laser station should be able to be preprogrammed at TO. If T1 is the real time at which the laser pulse was transmitted, one should have :

  (TO - T1) < 1 millisecond.

  T1 should be measured with an accuracy of $\pm$ 0.1 nanosecond, "a posteriori".

- If T2 is the time of arrival of the pulse back from the satellite, it should be measured with an accuracy of $\pm$ 1 nanosecond. Maximum time elapsed from start to return of a given pulse :

  270 msec > T2 - T1.

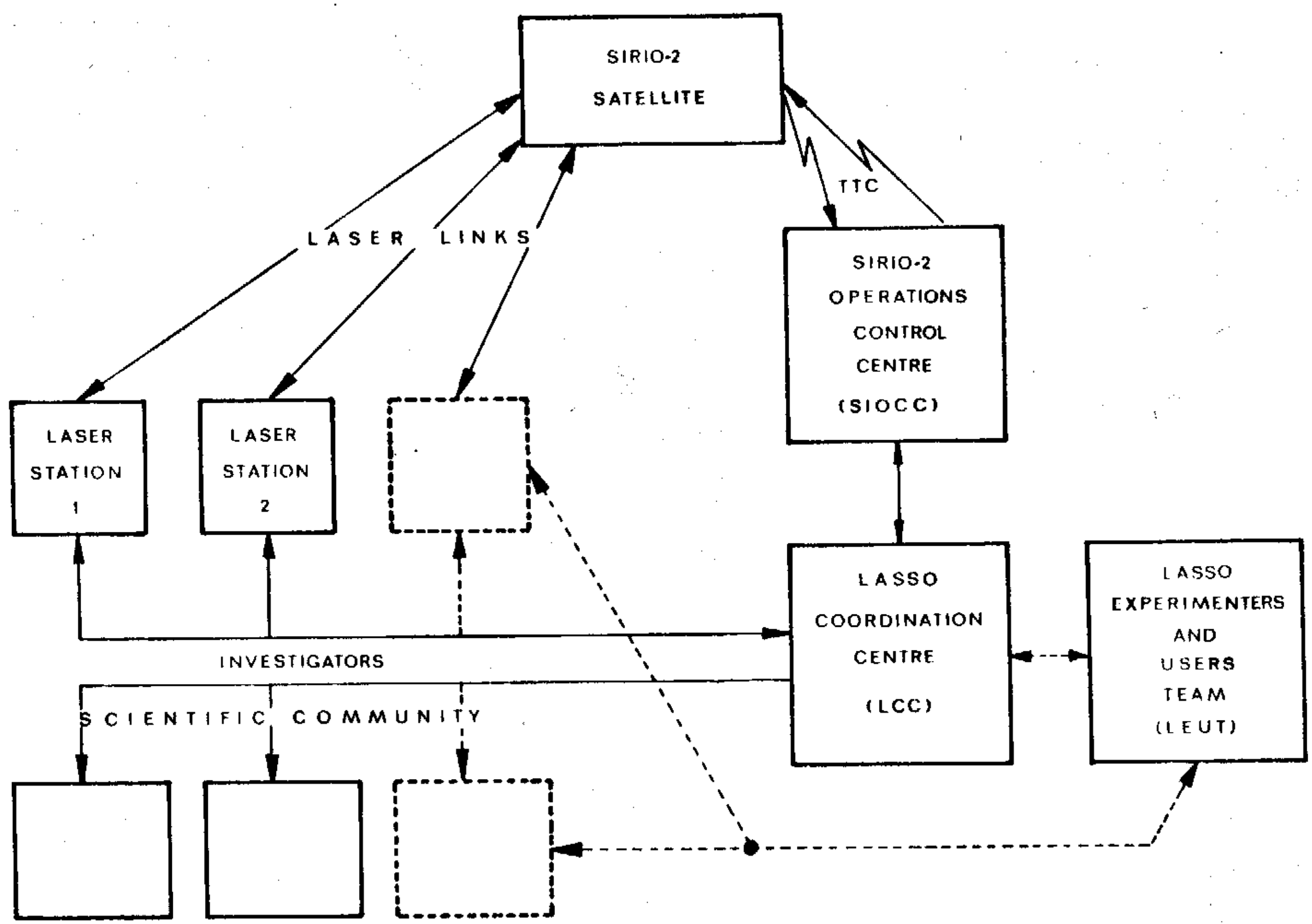
6. THE OPERATIONAL ORGANISATION

The overall possible organisation for the two-year period of LASSO operationas is given on figure 10.

This diagram shows the inter-relations between four important bodies :

- The Scientific Community and the laser stations,
- The LASSO experimenters and users team (LEUT),
- The LASSO Coordination Centre (LCC),
- The SIRIO-2 Operations Control Centre (SIOCC).

Figure 10: Possible Organization of LASSO Operations



The Scientific Community, supported by laser stations, will submit to the LEUT their reply to the announcement of opportunity. After evaluation, principal investigators will be appointed and will become members of the LEUT for the duration of the proposed experiment.

The LEUT, attached to the ESA project group, is in charge of the international coordination of the LASSO experiment and the establishment of the utilisation schedule for the two-year life time of SIRIO-2. During the experiment phase selection, the LEUT is a nucleus of experts and will be enlarged afterwards by all the principal investigators.

The LCC, which is the key point between laser stations, SIOCC and LEUT, has the primary tasks to :

- exchange information with SIOCC (orbit parameters, spin phase and speed, telemetry data),
- compute laser firing times,
- exchange information with laser stations (pointing angles, firing times, time events, data),
- select the operational mode (synchrone, asynchrone, one way, ...),
- pre-process scientific data and ensure the dissemination,
- create and run the data bank,
- perform special data processing (on request).

The SIOCC is in charge of the spacecraft control and monitoring during two years under ESA's responsibility. In the frame of LASSO, SIOCC will be intrusted with :

- performing VHF ranging,
- providing attitude and orbit data for spin phase and speed computation,
- decoding of TM format to extract LASSO data,
- sending necessary LASSO telecommands,
- monitoring housekeeping information.

7. FUTURE PROSPECTS

In collaboration with CNES, the ESA project group will perform some preliminary investigations to evaluate the possibility of embarking equipment on board European spacecraft with the goal of achieving a 0.1 nsec synchronisation accuracy.

This evolution of LASSO might include :

- a three-axis stabilised spacecraft on geosynchronous or low polar orbits,
- a centroid detection system, self-adjustable, for laser pulse width from 50 psec to 25 nsec, with faster photodiodes,
- a digital chronometer with 10 psec resolution,
- possibly a space-qualified rubidium or cesium standard on board.

8. CONCLUSION

The LASSO experiment on-board the SIRIO-2 spacecraft aims at proving possibility to synchronise clocks over intercontinental distances by means of laser stations.

The pioneering aspect of this first experiment, the small amount of space and power available on-board, and the very tight schedule (18 months), have led us to maintain, for the design of the on-board equipment, relatively simple technical solutions.

In addition, the fact that SIRIO-2 is spin stabilised requires the laser stations firing times to be synchronised with the rotation of the spacecraft. This aspect makes the operational use of the system more complicated; however we are examining the possibility of using an asynchrone mode, and even a one way mode.

Taking into account the studies performed by CNES on the LASSO experiment and the results we have had during the testing of the breadboards, a certain number of improvements has led us to consider a second generation of LASSO.

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QUESTIONS AND ANSWERS

DR. CARROLL ALLEY, University of Maryland

There are several things that those of us who are planning to participate in this experiment need to know a little more detail about. One would be an explicate value for the differential scattering cross section for the corner reflector array. Are you able to provide that at the present time?

DR. SERENE:

Not really. Actually, tests of the reflector are ongoing at CNES and each corner cube will be tested and all we can say is it is a bad one, which has a very bad, well, equivalent defraction pupil will be rejected, but I can give you actually only value. The only thing I can say, we ought to get a higher efficacy and to overpass the figure of 14 we gave in this presentation.

DR. ALLEY:

Yes. It is not 14. What is the actual cross section of individual corner reflectors? Circular reflectors?

DR. SERENE:

(Nods affirmatively.)

DR. ALLEY:

What diameter?

DR. SERENE:

Twenty millimeter. I think it is 20 millimeter diameter, the corner cube with a circular section, yes?

DR. ALLEY:

The second question. I have some concern about achieving even a nanosecond precision without some form of constant tracking discrimination for the received electrical signals. We have discussed this question before. Is there any possibility of including that kind of equipment on this first go?

DR. SERENE:

No. As I mentioned to you previously also, we are actually on a certain time schedule which is quite tight. We have to load the spacecraft. We are not the only passenger on-board and it will be the subject of LASSO number two on board of another spacecraft.

DR. ALLEY:

And one more. What will be the actual, with respect to receiver, area, including these additional objects that you have mentioned and what is the actual threshold of detection in terms of energy or photons for the detector?

DR. SERENE:

The threshold has been evaluated in terms of photon by something like 3,900 for Ruby and 2,050 for Neodyme I think. We have fixed the threshold because the threshold actually has been fixed to 20 dB as you have seen on the table for the different laser stations. Yes that is right. The number of photons per nanosecond riding up the detection element at the threshold is 3,900 photons per nanosecond arriving for Ruby lasers and 2,500 for Neodyme lasers.

DR. ALLEY:

What is the actual resolution of the on-board event timer?

DR. SERENE:

The actual-- The official one or the measured one?

DR. ALLEY:

The resolution. Can you resolve down to a tenth of a nanosecond or is it one nanosecond?

DR. SERENE:

Actually, I was two weeks ago in Paris where is Marcel Darseau and the breadboard was giving on the chronometer 50 picosecond for an average of 300 measurements. It is a statistical value.

DR. ALLEY:

What is the standard deviation of that? Do you know?

DR. SERENE:

Not really, because actually we are waiting for the last Hewlett-Packard counter to be able to perform a more accurate one because we are at the limit of the test equipment. The breadboard is looking better than all test equipment actually available, except this latest Hewlett-Packard counter.