SIRIO IN-ORBIT CONTROL

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1. The SIRIO program and its objectives.

The SIRIO project represents a decision by the Italian National Research Council (CNR) to promote and coordinate experiments on the Super High Frequency narrowband/wideband communications field. The objectives of the project can be summarized as follows:

- to develop advanced technologies in space telecommunications:
- to design and realize a satellite bus for geostationary missions;
- to perform experiments in earth-to-space and space-to-earth links at 12 and 18 GHz to determine the transmission medium characteristics at these frequencies.

1.1 Organization.

In order to accomplish the project objectives, the most qualified Italian space and electronics industries were encharged with the spacecraft design and development under the sponsorship and responsibility of CNR.

CNR has given the prime responsibility for the S/C design and development to CIA SpA in Rome (Compagnia Industriale Aerospaziale), now CNA SpA, and the ground support system design and development to Telespazio SpA in Rome and to CNUCE in Pisa. CNUCE is a computing center and research institute of CNR.

The Space Telecommunications Research Center (CSTS) of the Technology Institute in Milan coordinates the SHF experiments during the mission lifetime.

NASA was requested to provide launch and ground support to launch and position the S/C in its assigned station point. The vehicle provided was a three-stage Delta 2313 augmented by three strap-on solid fuel rocket motors.

The launch site was the Eastern Test Range, Kennedy Space Center, Florida. The launch occurred on August 25, 1977 at 23 hours 50 minutes GMT.

1.2 SIRIO spacecraft and mission.

SIRIO stands for Satellite Italiano Ricerca Industriale Orientata (Industrial Research Oriented Italian Satellite) is a spin stabilized cylindrically-shaped geostationary spacecraft.

The main dimensions of the spacecraft are:

Diameter	1.438 m.
Height	1.999 m.
S/C mass at launch	398 kg. (202 kg. ABM mass)
S/C mass in-orbit	218 kg.

In fig. 1, an exploded view of the S/C, showing its principal components, is given.

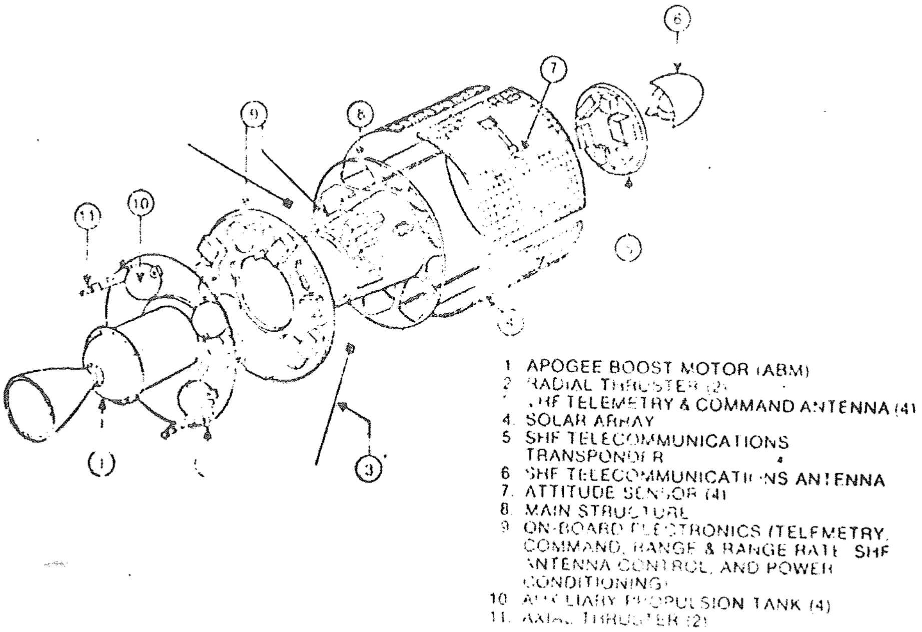


Fig. 1

Other SIRIO characteristics are:

Reliability	73% for two years
Designed life-time	2 years

For the SHF experiment, SIRIO's orbit during the operational phase must be circular, geosynchronous and equatorial. By positioning the S/C in such a orbit at 15 degrees West long., with the spin axis normal to the orbit plane, a continuous line-of-sight trasmission to experimental stations in Europe and on the East coast of North-America, is established (Fig. 2). The on-board SHF antenna is despun in the opposite direction to the rotation speed of satellite, the antenna reflector thus points toward the earth in a fixed direction.

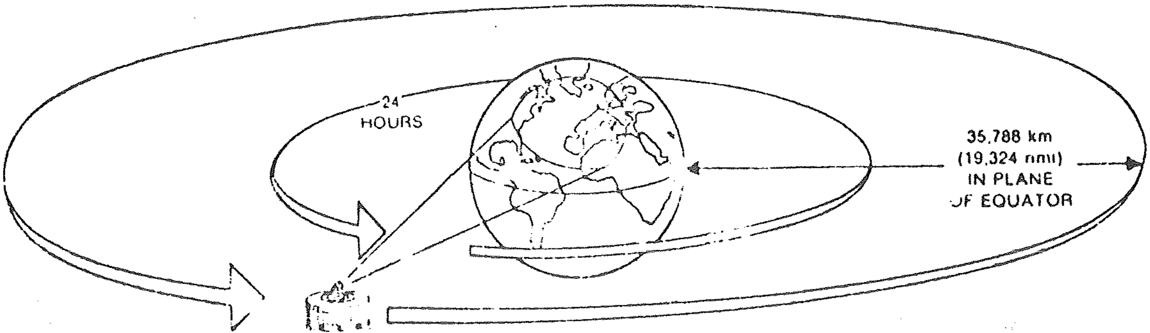


Fig. 2

Because of the SIRIO S/C and SHF payload design, in order to cover the above mentioned areas, the following constraints must be imposed on the S/C in orbit position:

S/C longitude	± 1 deg. from the nominal value (15 degrees West)
orbital plane inclination	± 0.3 degrees
S/C spin axis alignment	± 0.5 deg. from the orbit normal

1.3 - The NASA-CNR phase.

The first part of the SIRIO mission, up until the spacecraft on-station positioning, was supported by NASA personnel and facilities under complete CNR responsibility.

The nominal mission time-line was:

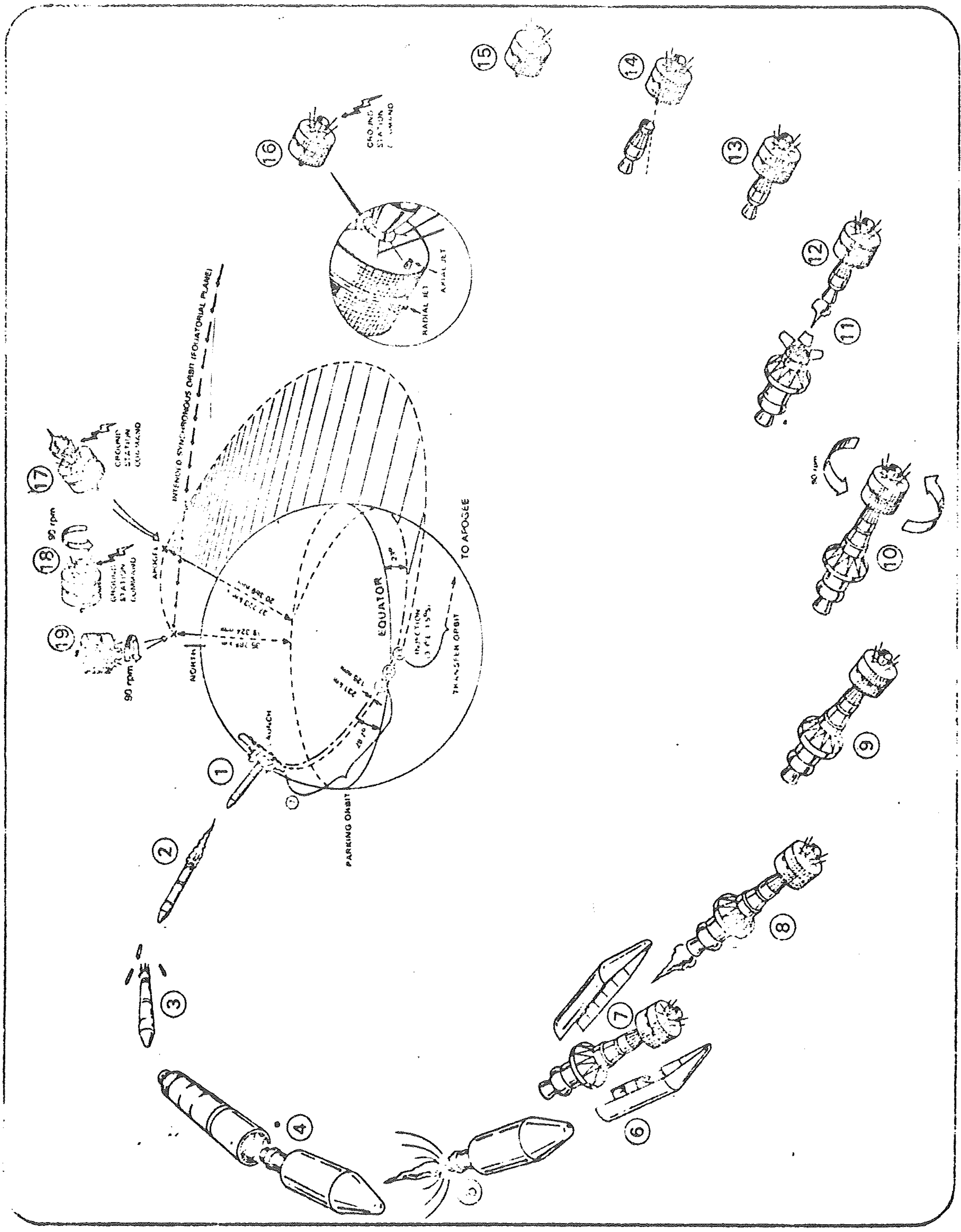
- launch from ETR on August 25, 1977 with a launch window of 70 minutes, starting at 23 50 GMT,
- injection into the parking orbit, 28.7 degrees inclined on the equatorial plane, after 8' 54'',
- injection into a high-elliptical transfer orbit, 23 degrees inclined, after 24' 35'',
- ABM firing at the fourth apogee of the transfer orbit, 39 hours after launch,
- S/C on-station positining about fourteen days after liftoff.

A pictorial view of the most significant events from liftoff to on-station spin-axis erection is given in Fig. 3.

Flight dynamics support for the SIRIO mission from launch to on-station was provided by the Goddard Space Flight Center. The active support period spanned 21 days and encompassed 13 auxiliary propulsion system maneuvers in addition to the apogee motor firing.

Flight dynamics support for SIRIO was nominal in all respects. Both the ground and spacecraft systems performed satisfactorily; no difficulties were experienced with either of the systems which impacted flight dynamics operations. The preflight nominal maneuver plan was followed throughout with in-flight adjustments only as the results of normal, expected dispersions.

The total hydrazine propellant loaded was 30 Kg., a maximum consumption of 18 Kg. was foreseen for the station acquisition phase however, as a result of the on-board and ground systems nominal functioning, only 7.6 kg. of hydrazine had been consumed up to hand-over thus leaving 22.4 kg. of Hydrazine on-board, sufficient for over five years of active station-keeping.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LAUNCH
NORTH
EQUATOR
PARKING ORBIT
TRANSFER ORBIT
TO APOGEE
INJECTION
APOGEE
INTENDED SYNCHRONOUS ORBIT (EQUATORIAL PLANE)
GROUND STATION COMMAND
90 rpm
RADIAL JET
AXIAL JET

Fig. 3

2. SIRIO spacecraft and ground support systems.

As reported above, SIRIO is a spin-stabilized geosynchronous satellite; its structure and hardware, therefore have the common characteristics of this kind of satellite. These are mainly a cylindrical body, an Auxiliary Propulsion System based on the use of radial and axial liquid propelled jets for active attitude and orbit control, and a Sun-Earth detector system to provide spacecraft spin rate, position data and jet firing control.

Some basic concepts are presented here in order to help the reader, unfamiliar with SIRIO, to understand the logic behind maneuver planning and execution.

2.1 The Auxiliary Propulsion System (APS).

The SIRIO Auxiliary Propulsion System uses hydrazine (N2H4) as its propellant. Four spheric tanks constitute two independent subsystems, which are separated by a valve.

The tank pressure after total fuel consumption ensures that, at the end of fuel reserve, maneuvers can be performed with the jet thrust level only slightly below half maximum pressure thrust level.

The two tank subsystems are each connected to one axial and one radial thruster. Thruster Radial A (TRA) and Thruster Axial A (TAA) are connected to system A; TRB and TAB are connected to system B. All the thrusters deliver the same nominal thrust of 22 Newtons with a nominal dispersion of ± 10 percent and a repeatability of ± 5 percent after initial warm up.

Axial thrusters may be fired in continuous and in pulsed mode; radial thrusters may be fired only in pulsed mode. Firing in continuous mode means firing from a given start time to a given stop time for the entire revolutions. Firing in pulsed mode means firing during a quarter of revolution only, for a given number of revolutions.

Fig. 4 shows the position of the thrusters on the S/C frame relative to the position of the attitude sensors.

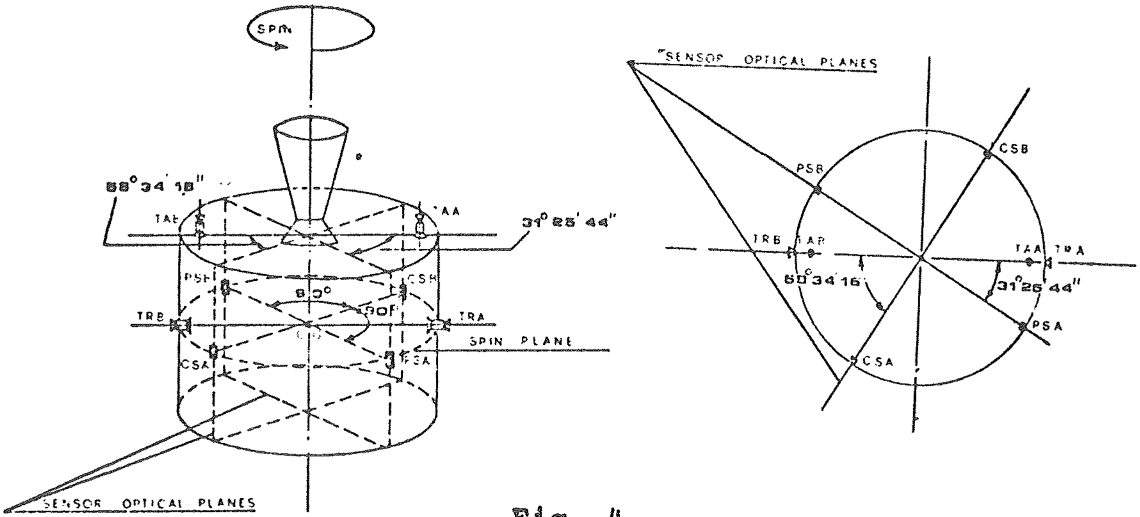


Fig. 4

In order to obtain a spinning effect, each of the two axial thrusters has an offset angle of .75 degrees in the plane tangential to the S/C body: TAA spins up the S/C while TAB spins it down. The spinning effect is thus obtained as a side effect of other maneuvers. The spinning effect of the radial jets is considerably larger than the effect of the axial jets, due to the larger offset angle.

2.2 The Attitude Control System

The attitude sensors are mounted in four packages around the S/C spin plane, as shown in Fig.4. Two different packages, CSA (Colatitude Sensor A) and PSA (Plane Sensor A), furnish data to determine the spin axis orientation, the spin rate and provide the maneuver synchronization pulses.

The redundant packages CSB and PSB have the same characteristics as CSA and PSA.

Each Plane Sensor package consists of:

- one Solar Plane Field sensor (SPF) which provides a synchronization pulse to the Auxiliary Propulsion System (APS) for maneuver control and measures the spin rate;
- one Infrared Large Field earth sensor (ILF), which is used to provide maneuver control synchronization pulses and to measure the sun-to-earth-in and sun-to-earth-out dihedral angles in conjunction with the SPF sensor. Each colatitude Sensor package consists of:
- a solar V-Beam sensor (SVB), which is used to measure the sun angle (angle between the direction of the spin axis and the S/C-sun direction) :
- two Infrared Narrow Field earth sensors (INF) which provide two separate earth width measurements.

2.3 - The SIRIO Italian Operations Control Center.

The ground support built up to control the SIRIO mission and the SHF experiments, is mainly constituted by two SHF stations located in different areas of Italy and a VHF station for telemetry and command data handling. Local computing facilities at the stations permit the real-time data communication and processing, while a large computing Center, connected to the VHF station, performs attitude-orbit determinations and maneuver computations.

In Fig. 5, the SIRIO ground equipment is presented. One SHF station is located at Lario, Northern Italy, the other SHF station and the VHF station are located at Fucino, 80 miles east of Rome, together with the SIRIO Italian Operations Control Center (SIOCC). The computing center CNUCE is located in Pisa, 50 miles west of Florence.

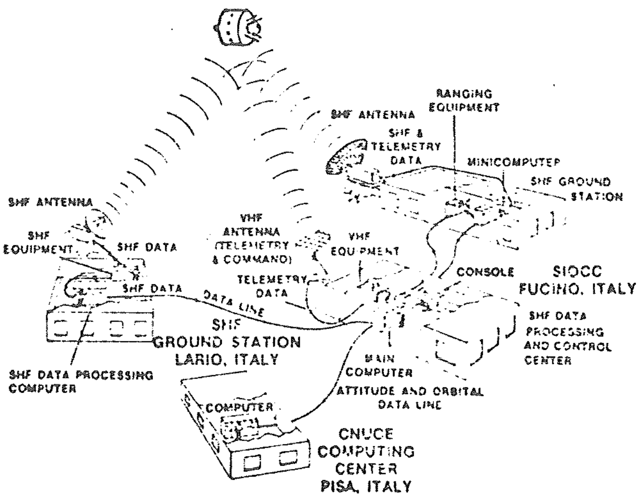


Fig. 5

From the telemetry data, SIOCC evaluates the spacecraft status and collects the SHF experiment data.

SIOCC receives the telemetry data from both the VHF and SHF antennas. The VHF link is used mainly during periods of eclipse or during attitude and orbit maneuvers. The VHF link is also used to up-link commands to the satellite in the GSFC tone digital standard command system. The attitude and ranging data are transmitted by dedicated data lines to the CNUCE computing center. Some telemetry data are also transmitted to the SHF ground station at Lario to monitor the operational status of the satellite while performing the SHF experiments.

2.4 - Software tools for S/C flight control.

The SIRIO flight control system has been designed to cover all the needs of the mission.

The philosophy adopted has been the development of several stand-alone working modules for the specific needs of the S/C control. These modules are grouped in a system which allows the management of common data files and data flow from one module to another, making it easier the user to perform the S/C control functions, speeding up such operations and increasing the reliability of the results obtained. This system is the SIRIO Flight Dynamics System (FDS).

The main areas of operations covered by the FDS software are:

- orbit determination
- attitude determination
- orbit control
- attitude control

For each of these main tasks, a computer program has been developed in accordance with the FDS prime requirements i.e. flexibility in hardware support and simplicity in its use (Faconti, Trumpy, 1977).

2.5 Operational planning criteria.

The SIRIO in-orbit operational planning is divided into:

- long term operations (six months)
- medium term operations (one month)
- short term operations (one week)

Long term operations.

When planning the long term operations the criteria for the difference telecommunications experiments (i.e. propagation or communications) are established.

This criteria are based on the agreements reached with national and international experimenters during the meetings held every six months.

Other activities such as : orbital and attitude maneuvers, on-board commutations of redundant subsystems and eclipses are also taken into account even if the details are established when the medium term operations are planned.

Medium term operations.

In the medium term planning all the activities to be carried out during each day of the next month are scheduled. These activities include orbital and attitude maneuvers, eclipsis, on-board commutations, in-orbit check-outs and other activities such as the ground system maintenance. All the medium term operations are described in a monthly program.

Short term operations.

In the short term operational plan, the activities mentioned in the monthly program are set forth in detail. The weekly plan will therefore include the details of each operation to be carried out by the ground stations.

The information necessary to prepare the detailed daily procedure for the control center and the list of all the commands to be up-linked are derived also from this weekly plan.

3. SIRIO Attitude/Orbit determination and control

The SIRIO satellite, positioned in its orbit, is subject to several forces which tend to move it from the initial position. These forces are mainly:

- the tesseral acceleration which attracts the spacecraft westwards;
- the soli-lunar attraction which produces a 'wobbling' of the orbital plane;
- the solar radiation pressure which causes a precession movement of the S/C spin axis.

The spacecraft position must therefore be continuously checked and corrected if necessary, maneuvering the satellite by means of the on-board Auxiliary Propulsion System.

3.1 Orbit determination.

SIRIO orbit is determined every 30 days, on the basis of the angular pointing data measured at the Fucino and Lario stations. To achieve the required accuracy in orbit estimation, the tracking data at a sampling rate of two angles per hour (azimuth and elevation), are collected for a time period of ten days.

A comparison between NASA and Telespazio orbit determination for the early phase of the SIRIO operational mission is presented (Tab. 1). It should be emphasized that the NASA determinations were performed with data acquired from two stations (Santiago and Ascension); therefore even though the data and the ground geometry were considerably different from those handled by Telespazio, the results are in good agreement.

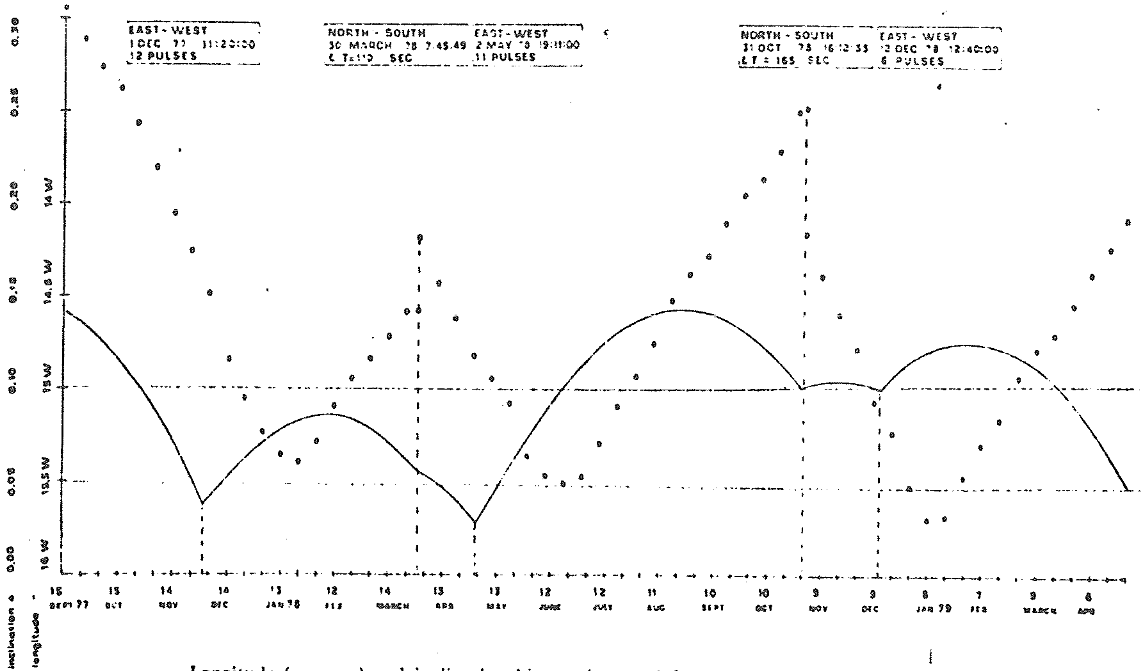
3.2 Attitude determination.

Currently, the S/C attitude is computed weekly by collecting 250 telemetry frames spread over an entire orbit, avoiding the data transmitted when the angle, as seen from the satellite, between the Sun and Earth line-of-sight is close to 0 or 180 degrees. During such an occurrence, the geometry is not suitable for the models used in the Attitude Determination Program (ADP).

An analysis of the on-board sensor performances and the accuracy of the assumptions made in defining the relative mathematical models used in ADP has been made by studyng the most significant phases of the mission. This analysis was necessary because some observed Earth width values were slightly different from the simulated ones, and the difference could not be eliminated by modifing the S/C state vector (the attitude vector and the sensor biases). The analysis proved that some simplified assumptions in defining the model of the SIRIO Attitude Control System were not completely correct; this analysis gave a better evaluation of the attitude determination uncertainty, calculated at approximately 0.03 degrees (1σ value).

3.3 Station-keeping strategy.

In Tab. 2 the maneuvers performed to control the SIRIO flight during its first year of operations are presented. The S/C longitude and the orbit inclination history for the same period is shown in Fig. 6.



Longitude (———) and inclination history (o o o) from September 16, 1977 to April 1979.

Fig. 6

It can be seen that maneuvers were performed to correct the S/C orbit when certain orbital elements moved close to the imposed limits, and no attempt was made to optimize the station-keeping maneuvers, to couple the North-South and West-East corrections, or to maximize the time spent by the satellite in its box, owing to the following reasons :

- at handover, the orbit inclination and node were such as to remain at least eight months within the imposed limits;

- the drift rate at that moment was such as to move the S/C out of the box in three months;
- improved acquaintance with APS performances was necessary.

In addition, longer experimentation of the attitude and orbit determination systems was desirable in order to be able to refine the methods used and to set up standard operative procedures to guarantee the full reliability and repeatability of the obtained results.

The analysis of the S/C performances during these maneuvers enabled the computation of the calibration factors (input variables to the maneuver computation program) which permit the fine tuning of the entire attitude and orbit control system performances, making allowance for any hardware and software model misalignments.

At the end of 1978, it was decided to perform, for the first time, the North/South-East/West combined maneuver; the mechanism of this maneuver is based on the following considerations.

To change the orbital plane inclination, when the S/C crosses the line of the relative nodes (the intersection of the initial and final orbit planes), a ΔV must be applied to the S/C velocity vector to obtain the desired inclination variation, see Fig. 7.

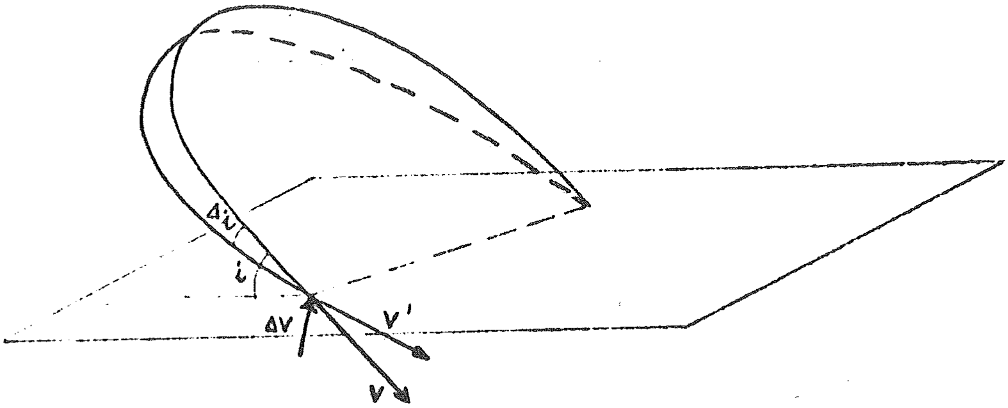


Fig. 7

V = S/C velocity vector before maneuver execution
ΔV= thrust delivered velocity vector
V'= S/C velocity vector after maneuver execution
Δi= orbit inclination variation
i = initial orbit inclination.

If the ΔV magnitude is such as to reverse the inclination of the orbital plane with respect to the reference plane, a 180 deg. node rotation will be obtained.

The $V' - V$ magnitude determines a variation in the S/C drift rate after maneuver. The relationship between the drift rate variation and the $|V'| - |V|$ (for near circular and geosynchronous orbits, such as the SIRIO orbit), can be assumed

$$dD = -351.3\ (|V'| - |V|)$$

where dD represents the drift rate variation in deg/day and V and V' are measured in Km/sec.

Furthermore, as δ (the S/C spin-axis codeclination), i and Δi are very small angles, the ΔV alignment can be computed by(A.Cardillo, N.Celandroni, A.Foni, S.Trumpy, 1980) :

$$\delta = -i + \frac{\Delta i}{2} - \frac{|V'| - |V|}{V \Delta i}$$

To maximize the time during which the SIRIO orbit inclination can be kept below the imposed values, the North/South maneuver is performed rotating the nodes line by approximately a 180 degrees angle, to the optimum value which is around the 270 degrees (A.Kamel,R.Tibbits, 1977). The results obtained by maneuvering the satellite during 1979 (Tab. 3.), have confirmed that the confidence reached in the S/C performances, together with the high reliability of the SIRIO FDS and the ground stations, enable the satellite to be controlled well within the mission imposed tollerances.

The S/C longitude and the orbit inclination history for the 1979, is presented in fig. 8.

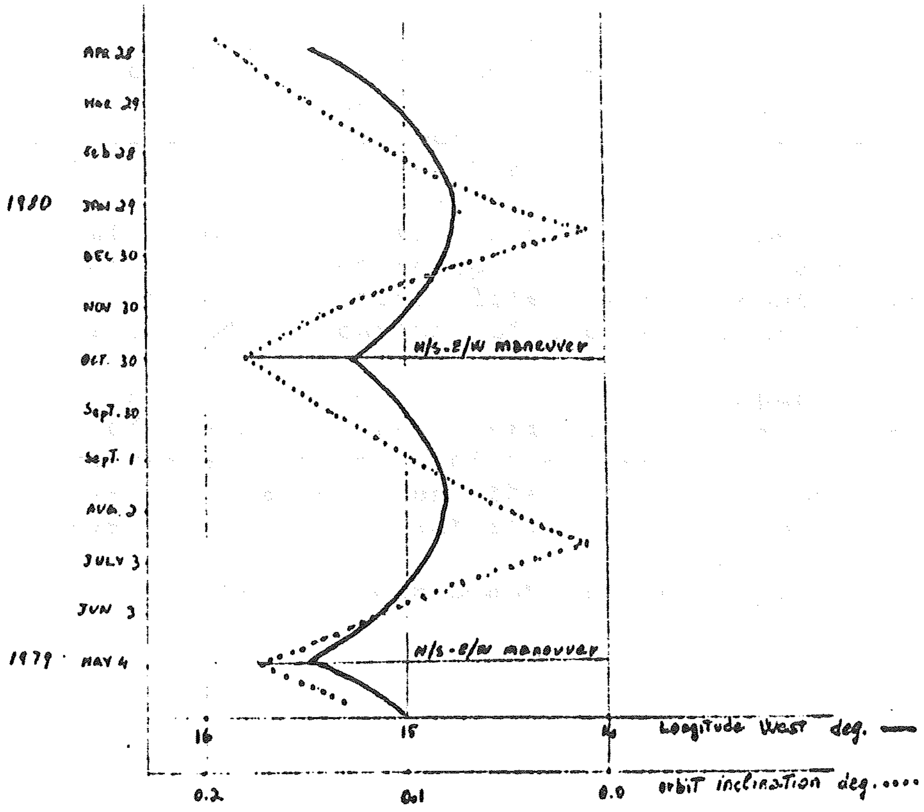


Fig. 8

5. Conclusions.

After more than two and an half years of SIRIO operational life, the following conclusions can be drawn.

Even though the mission constraints are not very restrictive, the granularity of the control and the repeatability of the maneuvers are well within satisfactory limits.

The acquaintance with the Attitude and Orbit Control System acquired during the first year of operations has allowed the optimization of the station-keeping maneuvers as described in this paper. In particular, the jet calibration factors (N.Celandroni, A.Foni, S.Trumpy, 1979) used in maneuver computation have been found to give a very exact modelling of the on-board Auxiliary Propulsion System, enabling the achievement of the maneuver goals with a dispersion below 1%.

The role played by the S/C on-board hardware, VHF link and ground station equipment in achieving these results must be remembered. In fact, the nominal functioning of all these systems has been the basis on which we have been able to succesfully achieve the results herein described.

At present, the extension of the operational phase up until September 1980 is foreseen.

References.

(1) Compagnia Industriale Aerospaziale : SIRIO Spacecraft Operation Manual. Cia publication. S-om-004, March 1977.

(2) N. Celandroni, A. Foni, S. Trumpy: Performance Evaluation of SIRIO Attitude/Orbit Control System. Alta Frequenza, June 1979.

(3) W. Bryant : SIRIO Flight Dynamics Postflight Summary. NASA internal Report, November 1977.

(4) A. Kamel, R. Tibbits : Some useful results on initial node location for near-circular satellite orbits. Celestial Mechanics, August 1977.

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· *Comparison between NASA and Telespazio orbit determinations during the first months of the mission.*

Epoch	Sept. 15, 1977 · 18.00 GMT		Oct. 27, 1977 · 00.00 GMT		Dec. 2, 1977 · 00.00 GMT	
	NASA	Telespazio	NASA	Telespazio	NASA	Telespazio
Semimajor axis (km)	42 165.530	42 165.458	42 168.584	42 168.216	42 164.359	42 164.117
Eccentricity	0.348×10^{-3}	0.321×10^{-3}	0.261×10^{-3}	0.259×10^{-3}	0.215×10^{-3}	0.202×10^{-3}
Inclination (deg)	0.306	0.309	0.235	0.244	0.161	0.154
Ascending node Ω (deg)	250.728	251.140	250.752	249.371	249.363	247.986
Argum. of perigee ω (deg)	239.119	239.957	237.562	239.334	234.912	239.754
Mean anomaly M (deg)	120.112	118.883	251.875	251.496	290.806	287.356
Sum of Ω, ω, M (deg)	249.959	249.980	20.189	20.201	55.081	55.096

Tab. 1

· *Orbital and attitude maneuvers performed on SIRIO from September* 1977 *to December* 1978.

Epoch	Purpose	Jet	Firing mode	No of pulses or burntime	Fuel consumption (kg)	Syncronism	Quadrant
Dec. 1, 1977 11:20:00	East-West station keeping	Radial B	pulsed	12 pulses	0.015	sun	1
Dec. 1, 1977 11:50:00	Attitude trim to orbit normal	Axial B	pulsed	4 pulses	0.005	sun	2
Mar. 30, 1978 7:45:49	North-South station keeping	Axial A + Axial B	continuous	110 s	1.535	sun	not applicable
May 2, 1978 19:11:00	East-West station keeping	Radial B	pulsed	11 pulses	0.013	sun	4
May 2, 1978 19:41:00	Attitude trim to orbit normal	Axial B	pulsed	2 pulses	0.002	sun	3
Oct. 31, 1978 9:00:00	Attitude trim to orbit normal	Axial B	pulsed	3 pulses	0.004	sun	3
Oct. 31, 1978 16:12:33	North-South station keeping	Axial A + Axial B	continuous	165 s	2.107	sun	not applicable
Dec. 12, 1978 12:40:00	East-West station keeping	Radial B	pulsed	6 pulses	0.005	sun	1

Tab. 2

MANEUVER	DATE	IGNIT. TIME	DURAT.	ORBIT INCLINATION AND NODE (DEGREES)						SPIN RATE VARIATION		FUEL EXPEND. (KG.)
				INITIAL		FINAL PREDICTED		FINAL OBSERVED		(r.p.m)	(r.p.m)	
	D.M.Y.	H.M.S.		INCL.	NODE	INCL.	NODE	INCL.	NODE	PREDIC.	OBSERV.	
N/S-E/W STATION-KEEPING	4. 5.1979	4.17.17	(sec.) 152	0.201	91.32	0.184	259.89	0.185	272.08	-0.27	-0.27	2.312
N/S-E/W STATION-KEEPING	31.10.1979	16.38.11	150	0.186	98.39	0.179	259.39	0.179	259.97	-0.19	-0.07	2.044
				S/C ATTITUDE (DEGREES)						SYNC	QUADR. USED	JET USED
				INITIAL		FINAL PREDICTED		FINAL OBSERVED				
				R.A.	DEC.	R.A.	DEC.	R.A.	DEC.			
ATTITUDE TRIM	3. 5.1979	9.30.00	(Pulses) 2	48.0	-89.73	16.7	-89.73	N.C.	N.C.	SUN	IV	TAA
ATTITUDE TRIM	30.10.1979	9.30.00	3	285.0	-89.92	6.0	-89.78	0.0	-89.78	SUN	I	TAA

Tab. 3

MAIN PARAMETERS VALUE AT BEGINNING OF LIFE AND AT PRESENT TIME				
			BEGINNING OF LIFE	PRESENT TIME
POWER	SOLAR ARRAY	AVALAIBLE POWER (WATTS)	143 W	140 W
	BATTERIES	END OF DISCHARGE MINIMUM VOLTAGE (VOLT)	28.2 V	26.5 V
VHF TELECOMMUNICATION	REGULATED VOLTAGE (VOLTS)	TLM TRANSMITT. A	20.8	20.8
		TLM TRANSMITT. B	20.8	20.8
		CMD RECEIVER A	17.5	17.4
		CMD RECEIVER B	17.3	17.2
		CMD DECODER A	19.8	19.7
		CMD DECODER B	19.8	19.8
	R.F. POWER (WATTS)	TLM TRANSMITT. A	6.2	5.9
		TLM TRANSMITT. B	5.9	5.9
	TLM ENCODER'S CURRENT (mA)	PROCESSOR 1	160	160
		PROCESSOR 2	16	16

Tab. 4

STAMPATO PRESSO IL
SERVIZIO TECNOGRAFICO
DEL CNUCE