# PERFORMANCE EVALUATION OF THE SIRIO MANEUVER SYSTEM

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# ABSTRACT

This paper describes the SIRIO maneuver system which consists of the on-board Attitude and Orbit Control system (AOC) and the set of computer programs known as the Flight Dynamics System (FDS). The ground antenna, the telemetry and command subsystems also constitute an important part of the maneuver system, but they are not dealt with here because their functioning does not influence maneuver execution logic.

A brief outline is given of the AOC hardware involved with maneuver execution.

The basic maneuver planning logic, i.e. orbital, attitude and spin rate corrections, is described. The description is limited to problems concerning the geostationary phase of the mission although considerations and data relative to the station acquisition maneuvers are given, wherever they are felt to be useful for a deeper understanding of the maneuver system.

There is also a description and an evaluation of the programming tools used in planning and controlling maneuver execution.

Tables containing data relative to all the maneuvers executed on SIRIO are presented and commented.

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# 1. SIRIO hardware involved in maneuver execution

All the hardware units which play a decisive role in maneuvering the satellite are elements in the Attitude and Orbit Control (AOC) subsystem; a detailed description is given in the SIRIO Spacecraft Operational Manual (see reference 1). Some basic concepts are presented here in order to help the reader, unfamiliar with SIRIO, understand the logic behind maneuver planning and execution.

The units considered are:

1 the tanks
2 the jets
3 the sun and earth sensors
4 the attitude control logic
5 the nutation damper
6 the inertial measurement unit

## 1.1 The tanks

The SIRIO auxiliary propulsion system uses hydrazine ($N_2H_4$) as its propellant. Four spheric tanks constitute two independent subsystems, which are separated by a valve. The fuel in the tanks is pressurized with nitrogen ($N_2$). The following table gives the after fueling nominal values and the observed values concerning tank status.

| | NOMINAL | | AT LAUNCH | |
|---|---|---|---|---|
| Total tank volume | 45485 | $cm^3$ | | |
| Tank pressure system A | 21.09 | $Kg/cm^2$ | 20.44 | $Kg/cm^2$ |
| Tank pressure system B | 21.09 | $Kg./cm^2$ | 21.14 | $Kg/cm^2$ |
| Fuel load system A | 15 | Kg | 15 | Kg |
| Fuel load system B | 15 | Kg | 15 | Kg |
| Temperature system A | 20 | C | 21.2 | C |
| Temperature system B | 20 | C | 24.8 | C |

Tab. 1

It can be seen that the at launch system A tank pressure was lower than the nominal value although the fuel loaded was verified as having the nominal weight; this fact may be explained by a loss of gas pressure during fuel loading. These data are very important as the weight of the fuel contained in the tanks is evaluated, at any time in the mission, on the basis of tank status telemetry data. Applying Boyle's law, the nitrogen and hydrazine volumes are computed from the pressure and temperature data; by multiplying the fuel volume by the density, the fuel weight is obtained. Thus, in order to evaluate correctly fuel consumption, fuel weight, temperature and pressure must be known with precision at least once during mission; this is possible only at launch.

The nominal tank pressure after total fuel consumption is 7 $Kg./cm^2$. This pressure 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. However, as, at the end of fuel reserve, there is a ''fuel sloshing'' effect which means that the fuel is no longer being supplied evenly to the jets, this thrust level may be much lower.

## 1.2 The jets

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. 1 shows the position of the thrusters on the S/C frame relative to the position of the attitude sensors. It can be seen that the axial thrusters are mounted along the spin axis direction with an useful moment-arm for spin axis precession movements of 650 mm. The radial thrusters are mounted in radial direction, in the spin plane.

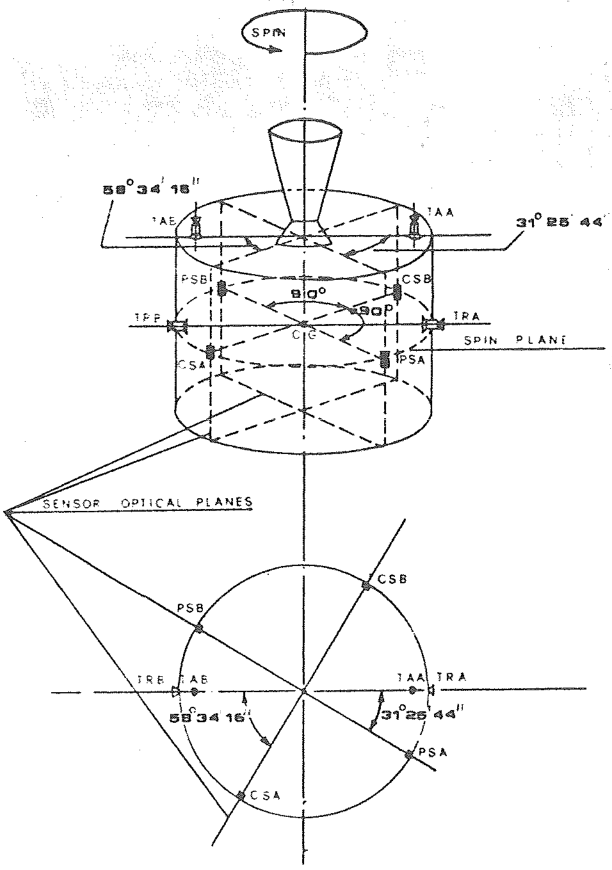

Fig. 1

It can also be seen that all the jets are mounted in a vertical plane, with an inclination of 31° 25' 44'' relative to the optical plane of the PSA-PSB sensor packages or 58° 34' 16'' relative to the CSA-CSB optical plane. This mounting angle is justified by the pulsed firing logic, with particular reference to the attitude precession maneuvers which are performed by firing the axial jets in pulsed mode. The mounting angle has been designed in order to allow the spin axis to precede toward or away from the sun or the earth or in an orthogonal direction, depending on the synchronization type and quadrant selected. (see paragraph 1.4). The ideal thrust centroid value should be exactly 45 degrees, corresponding to one half of revolution firing quarter. The effects due to electronic delays and thrust lags cause the start and stop firing to be delayed by a time interval which moves the centroid from the ideal position by about 13.5 degrees. The mounting angle has been designed in order to compensate for such a delay.

In real flight, the torque centroid points in a different direction because of the effects of a number of factors such as fuel pressure, spin rate and the mounting angle biases of the jets and the sensors. The constructor of the jets provided tables containing the centroid values for different pressure, spin rate and firing duration values as the final result of the pre-flight tests. At mean values of these variables the centroid shift from the ideal is about 20 degrees.

The impulse obtained by firing the jets depends on the following factors:

pressure
firing duration
spin rate
S/C mass

The pressure influences the thrust obtained directly. The firing duration influences the impulse obtained because the thermic transitory of the jets reduces the efficiency of the first pulses or seconds.
Fig. 2 shows the thrust profile for continuous mode firing at maximum and minimum pressure. Fig 3 shows the impulse reduction for pulsed mode firing at maximum and minimum pressure.

The spin rate only affects pulsed firing as the firing duration per revolution is directly proportional to its magnitude.

The S/C mass has one major change which strongly influences the impulse obtained. On firing of the apogee motor, 177.82 Kg. of propellant are consumed, about one half of the S/C weight at launch. The S/C mass decreases during each maneuver by the amount of fuel consumed; this decrease has a relatively slight effect on the impulse obtained.

We will now examine the effects of jet firing. In order to give an idea of these effects, we will refer to two hypothetical examples. Both cases have in common the following:

S/C mass - after apogee motor firing
spin rate - 90 rounds per minute
duration of fire - no warm up effects considered

CASE 1 is characterized by the maximum fuel pressure value (21

Kg./cm$^2$ ); CASE 2 is characterized by the minimum value (7 Kg./cm$^2$).

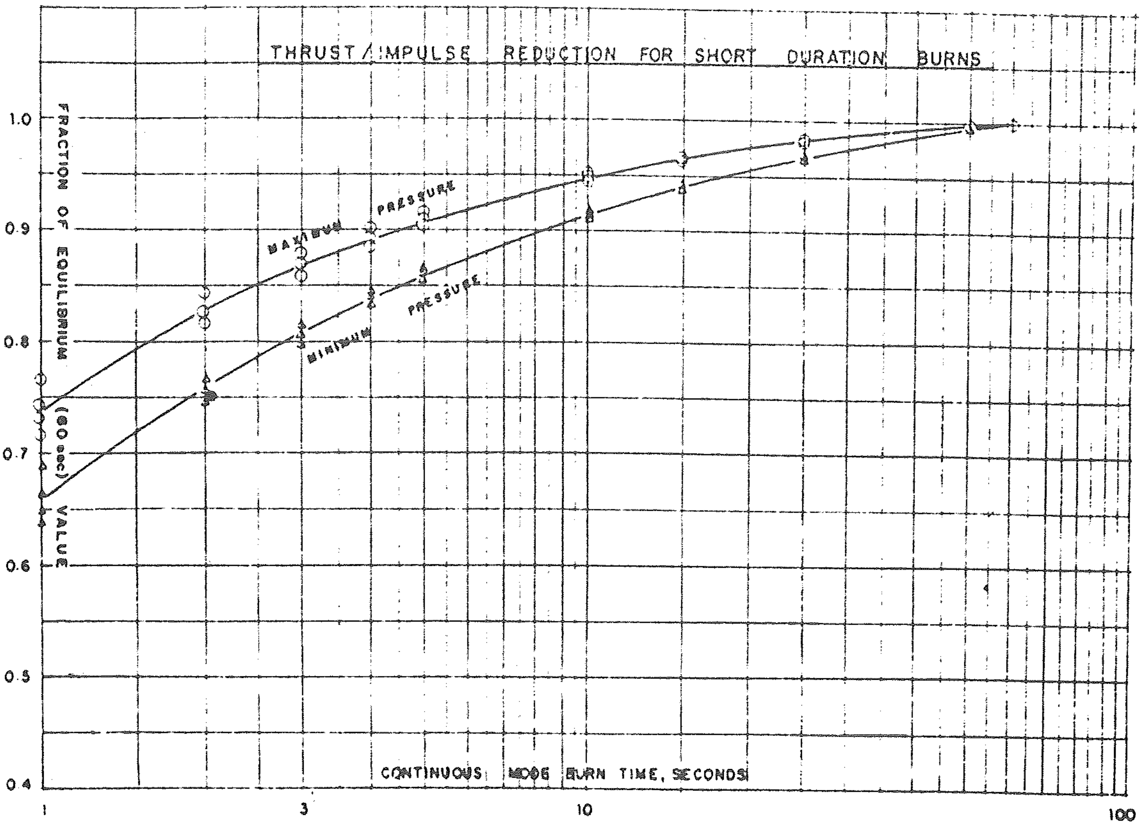

Fig. 2

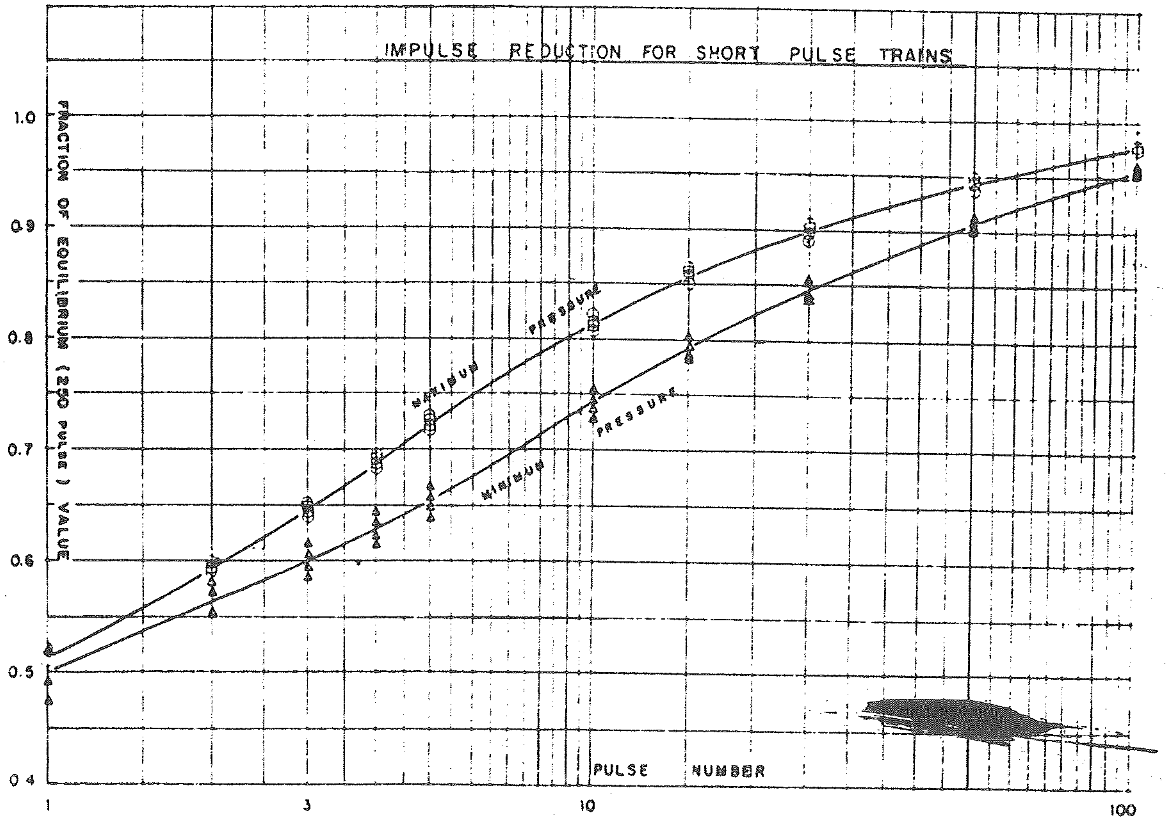

Fig. 3

For large orbit corrections, axial jets are normally fired together in continuous mode; thus the resultant of the forces applied to the S/C lies along the spin axis. The velocity change obtained in both the above mentioned examples (both axial jets active) is:

| | |
|---|---|
| CASE 1 | .205 m/sec. per sec. of firing |
| CASE 2 | .110 m/sec. per sec. of firing |

The axial jets are used in pulsed mode to correct the S/C attitude; the force applied produces an effect on both orbit and attitude. Results obtained in the case of the two examples are:

CASE 1 precession : .225 deg. per pulse
velocity change : 0.013 m/sec. per pulse

CASE 2 precession : .12 deg. per pulse
velocity change : 0.006 m/sec. per pulse

It can be observed that effects on the orbit are relatively small compared with the effects on the attitude.

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. In our two examples we have the following spinning effects:

CASE 1 pulsed : .0055 rounds per pulse
continuous: .03 rounds per second

CASE 2 pulsed : .003 rounds per pulse
continuous: .017 rounds per second

Radial thrusters are mounted on the spin plane which is very close to the S/C center of gravity. The center of gravity moves along the spin axis in relation to the fuel weight contained in the tanks; the radial thrusters thus have a slight effect on the attitude in addition to their main effect on the orbit. The computer programs mentioned in paragraph 3 make allowances for this effect in planning the maneuvers. The effects on the orbit caused by radial jet firing in the two examples given are:

| | |
|---|---|
| CASE 1 | 0.013m/sec. per pulse |
| CASE 2 | 0.006 m/sec. per pulse |

Radial jets have been mounted in the spin plane with an offset of 3.0 degrees relative to the true radial direction in order to obtain a spinning effect. TRB produces a spin up effect while TRA gives a spin down effect. In the case of the two examples, we have the following spinning effects:

| | |
|---|---|
| CASE 1 | .02 rounds per pulse |
| CASE 2 | .012 rounds per pulse |

It can be seen that the spinning effect of the radial jets is considerably larger than the effect of the axial jets, due to the larger offset angle.

## 1.3 The attitude sensors

The attitude sensors are mounted in four packages around the S/C spin plane as shown in fig.1. 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 :

- one 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.

For SIRIO attitude determination see refs. 3 and 9.

## 1.4 The attitude control logic

Two electronic circuits, ACL1 (Attitude Contol Logic 1) and ACL2 (Attitude Control Logic 2), may be choosen to preset firing for:

- firing modes (continuous or pulsed)
- quadrant selection (1,2,3 or 4)
- pulse synchronization selection (earth or sun)
- jet selection (TAA,TAB,TRA,TRB or TAA+TAB)

ACL1 activates TAA and TRA jets while ACL2 activates TAB and TRB jets.

When firing in continuous mode, a start and a stop firing time are specified. When firing in pulsed mode the number of pulses is specified, and the firing quadrant is selected, i.e. the revolution quarter during which the jet has to be fired. To fire in a quadrant means that firing is initiated by a pulse generated by a sensor and terminated by a pulse generated by the next sensor in sequence. Either the sun sensors from both packages or earth sensors from both packages will be used. By definition, the quadrants are identified by the sequence of the sensor packages on the frame following the spin motion. This sequence is :

PSA,CSA,PSB,CSB

Firing in the first quadrant means that the PSA sends the start impulse when the sensor field of view is crossing either the sun or the earth, depending on the type of synchronization; CSA sends the stop impulse. Firing in the second quadrant means firing 90 degrees ahead in spin direction ; therefore, CSA starts the firing and PSB stops it. The four quadrant definitions are:

ACL1

| Quadrant | Start | Stop |
|---|---|---|
| 1 | PSA | CSA |
| 2 | CSA | PSB |
| 3 | PSB | CSB |
| 4 | CSB | PSA |

There are two possibilities for generating the quadrants: sun synchronization and earth synchronization. With sun synchronization, when firing in the first quadrant, the resultant torque produced by axial jets firing is directed away from or towards the sun depending upon the chosen jet; the resultant force produced by radial jets is normal to the sun direction. Each next quadrant selected causes the force applied to be rotated 90 degrees ahead in the direction of the spin.

With earth synchronization start and stop firing is generated by the earth sensors mounted on the four sensor packages. The quadrants are defined in the same way as for sun synchronization while the firing direction is shifted by an angle equal to the earth right ascension (angle between earth and sun in an equatorial plane) relative to the firing direction obtained with sun synchronization.

Firing duration with earth synchronization is not exactly 90 degrees because of the differences between the earth horizon detector of the sensor which initiates the pulse and of the sensor which terminates it. Each pulse is initiated (or terminated) by the earth-in crossing of a PS package which takes place when the ILF field of view is tangent to the earth equator and is terminated (or initiated) by the earth in crossing of a CS package which takes place when the field of view of the INF sensor crosses a parallel of the earth surface. Therefore, when a PS package starts the pulse and a CS package stops it, the pulse will be larger than 90 degrees while, when a CS package starts the pulse and a PS package stops it, the duration will be shorter.

The magnitude of the variation depends on the S/C spin axis direction which determines the parallel circle intersected on the earth surface by the INF sensors and consequently determines the time delay relative to the CS sensors equator crossing. In the geostationary position, with the applied constraints on spin axis direction, the variation of the quadrant duration is about 2-3 degrees. The computer program for maneuver planning takes into account the quadrant duration variation and the implied variations of the torque centroid.

The ACL is also used to preset the jets for firing. As we have already said, radial jets may be fired only in pulsed mode; moreover only the two axial jets may be fired together. It must be noted that, when the two axial jets are fired together, they are commanded by separate logic circuits (ACL1 and ACL2) and the start and the stop firing are given at different times for each jet so that, at the beginning and at the end of firing, a single jet is operating. The time delay normally used in real operations is two seconds. The criteria used in selecting the jets to perform a specific maneuver are explained in paragraph 2.

## 1.5 The nutation damper

Impulsive jet thrusts originate S/C vibrations which, because of the spinning motion, generate a nutational motion.

The on-board nutation damper reduces the magnitude of the nutational motion by converting the kinetic energy into heat generated by the viscosity of the damping fluid (mercury).

A small portion of the nutational energy is transformed into spin motion. See paragraph 4.

## 1.6 The inertial measurement unit

The on-board inertial measurement unit measures the acceleration component in the direction of the spin axis. The magnitude and period of the nutational motion are computed, using this measurement.

## 2. Maneuvers

This section briefly describes the different types of maneuvers which are performed to control S/C orbit, attitude and spin rate; the description is limited to the geostationary phase maneuvers, but, in paragraph 4, tables showing all the maneuvers executed are presented.

### 2.1 Orbit control

During its operational life, SIRIO orbit must be circular, equatorial and geosynchronous, and the subsatellite point must be located at a longitude of 15 degrees West. The following tollerances have been imposed on these constraints, and the satellite is thus constrained within a 0.6x2 degrees wide 'box':

- inclination of orbital plane ± 0.3 degrees,
- S/C longitude ± 1 degree from nominal value.

For operational reasons (see ref.8), these tollerances have been reduced to ± 0.20 degrees for the inclination and ±0.5 degrees for the S/C longitude.

Whenever the satellite reaches one of these imposed limits, a maneuver is necessary for position correction.

The S/C, positioned in orbit, is subject to several forces. The most important of these are: soli-lunar attraction, which causes a 'wobbling' of the orbital plane and considerably perturbs the inclination and node, and tesseral acceleration caused by earth oblateness, which modifies the S/C drift rate and attracts the satellite westward.

Studies on the behaviour of the inclination of near-equatorial circular orbits (see ref. 10), have realized analytical methods which can be used to determine the initial node position necessary in order to maximize the time during which an orbit can be kept within a given inclination value. For SIRIO, assuming inclination to be constrained below 0.3 degrees, the optimal initial node value is 270 degrees, and this maintains the satellite orbit within the imposed limits for approximately 300 days. It should be emphasized that the study is time dependent, within a cycle of about 18 years, and the above node value has been computed assuming August 1977 as epoch time.

The inclination and node correction is performed by firing the axial jets in continuous mode while the satellite is crossing the relative node line (intersection between the current and the target orbital plane). This is the most expensive maneuver in terms of fuel; consuming about 1.5 kg of hydrazine for a firing time of 100-150 seconds, under normal conditions.

In planning an orbit inclination correction the spin axis alignment is critical; if this is not properly normal to the medium value between the initial and the target inclination, a component in the plane is produced which considerably perturbs the S/C drift rate. The direction of the in-plane component will affect the east-west drift rate. For maneuver planning optimization, this direction should be opposite to the S/C velocity vector in order to delay the S/C exit from the box.

Because of the accuracy of the attitude determination system, when the S/C spin axis declination is within 0.2 degrees from the 90 degrees declination, the right ascension (the direction of the spin axis projection on the orbital plane) is known to about ± 35 degrees; therefore, the computation of the drift rate variation has 15-20% uncertainty. In addition, for operational reasons, the axial jets are not fired simultaneously, but with a 2 seconds time-gap. At the beginning and at the end of the maneuver, an unpredictable spin-axis precession is produced (see paragraph 4) and the effects of this perturbation increase this 15-20% uncertainty.

The tesseral acceleration causes the S/C to move westward with a constant acceleration of about 0.0002 degree/day, at nominal longitude. When the S/C is approaching its west boundary, a maneuver must be executed in order to reverse the drift rate and to give the S/C an eastward acceleration that maximizes the time spent within the tolerance limits, or causes the S/C position and drift rate have specified values at a certain date for maneuver strategy optimization. This time is generally about 4-5 months.

East-west maneuvers are performed by firing a radial jet at the moment that the thrust resultant is tangent to the orbit and in the opposite direction to the S/C velocity vector.

An element which must be taken into consideration when executing an East-West correction is the spin axis precession direction during maneuver (see the next paragraph).

## 2.2 Attitude control

The mission constraint for spin axis orientation is to have a maximum deviation from orbit normal of .5 degrees. Since the S/C orbit inclination is maintained at very low values (below .2 degrees), the controlled parameter in real flight is the spin axis declination. The value of this parameter has been constantly maintained above 89.5 degrees; generally it has been around 89.8 degrees. Deviation from the S/C orbit normal depends on the spin axis right ascension which may compensate or increase the effects of the orbit inclination.

The actual spin axis position is perturbed by:

-the solar pressure.

The resultant of solar pressure varies with the sun angle in intensity and direction. Generally it does not pass through the gravity center of the S/C. A moment is thus generated causing a spin axis precession.
Several months generally pass before the spin axis drifts outside the tolerance limit for this effect.

- radial jet firing.

These perturbations are caused by the fact that the S/C center of gravity does not lie on the jet mounting plane but is situated at a distance which varies as the fuel reserve decreases. The direction and the amount of these perturbations are computed in order to make it possible, when firing the radial jets in east-west maneuvers, to move the spin axis in a desired direction. In addition, since east-west maneuvers are generally made up of a small number of pulses, the perturbations on the attitude are very small.

- axial jet firing in continuous mode.

This perturbation is caused by impulsive thrusts at the beginning and at the end of firing. The two effects may or may not be in phase, therefore the final effect is practically unpredictable. The amount of the perturbation may be relatively large if compared with the tolerance limit. Data concerning these perturbations are given in paragraph 4.

If one of the above mentioned effects should bring the spin axis close to the tolerance limit or if the spin axis has to be directed in a direction which allows the optimization of the in-plane effects when performing an orbital plane correction (see paragraph 2.1), an ideal target position is identified in order to plan the maneuver. Paragraph 3.2 describes how it is possible to achieve this target in practice and how to control it after maneuver execution.

Two basic logics are available for moving the S/C spin axis: sun synchronization and earth synchronization. With sun synchronization, as described in paragraph 1.4, it is possible to realize a spin axis movement toward or away from the sun or in an orthogonal direction, depending on the quadrant selected. The four directions change by one degree per day following the sun motion; in order to realize a precession in the ideal target direction, unless this direction coincides with one of the four quadrant directions at maneuver time, it will be necessary to perform the maneuver in two legs , in different quadrants so that the resultant motion will be in the desired direction. Another way is to accept an effective target which can be reached with a single leg maneuver which is not the ideal one but is still satisfactory.

With earth synchronization, for each orbit, it is possible to fire in any direction by choosing a firing time in which one of the four quadrant directions coincides with the desired direction of precession.

## 2.3 Spin rate control

The SIRIO spacecraft is stabilized by means of a spin rate which has a nominal value of 90 revolutions per minute.

The satellite has been designed to operate correctly if this spin rate is controlled within ±10% of nominal value.

The control of the S/C spin rate depends on the following factors:

- the S/C angular momentum variation as fuel is expended firing the on-board jets;
- the spin up or spin down effect caused by the jet thrusts.
- the spin rate change caused by the nutation damper system.

The first of these effects is always present during maneuver execution and, if the thrust effect is ignored, causes the spin rate to decrease (due to SIRIO tank and jet geometry).

The spin rate change caused by the jet firing effect is a direct consequence of the torque vector produced by the thrust component in the spin plane when this component does not cross the spin axis (see paragraph 1.2).

When the SIRIO propulsion system is activated for maneuver execution, a nutation movement of the S/C spin axis is generally induced as a side effect of the jet firing. The nutation damper progressively reduces this movement by transforming a part of the kinetic energy into heat, the remaining part increases the spin rate. As the nutation is a very unpredictable phenomena, the value of the spin rate produced by the nutation damper is not computed in advance. In paragraph 4 some observed data for the nutation damper effect on the S/C dynamic behaviour are reported.

At the moment, the S/C spin rate is controlled by using radial jet B , which spins the satellite up, during East-West maneuvers, and by allowing for the spin rate increase due to the nutation damper effects; the spin up correction is necessary to nullify the spin down effect produced by the North-South maneuvers, which decrease the S/C spin rate by about 0.5 r.p.m. each time.

## 3. Programming tools for maneuver planning and verification

The software used to support the SIRIO S/C flight is the SIRIO Flight Dynamics System (FDS) (see ref. 2) and has been designed mainly to perform:

- orbit determination
- attitude determination
- attitude and orbit maneuver computation.

### 3.1 The Orbit Maneuver Program

The FDS program used to support the maneuver computation is the Orbit Maneuver Program (OMP).

The basic program inputs are the orbital elements and the S/C attitude and spin rate; these data are previously computed by other FDS programs and then passed to the OMP. Other S/C dependent data used in the program are the physical and functional characteristics of the subsystems involved in the S/C control.

The thrust models, the attitude and spin rate perturbation models and the functioning of the ACL are included in the OMP.

There are two alternative ways of using the OMP; the first is to define the maneuver objectives in terms of the desired variation of the orbital elements. The jets firing sequence to modify the S/C orbit is computed by the program and a command sheet containing complete information on the maneuver execution is produced. In addition, the program gives information on the computed perturbations following the maneuver with reference to the orbit and S/C status (spin rate, attitude, tank pressure and fuel weight).

The second choice is to compute the effects, in terms of S/C orbit and status perturbations, during and following a user determined firing sequence. In this case, the user enters, as input data, the jet(s) selected, the firing time, mode, synchronization and duration and the dynamic elements (orbital elements, S/C attitude and spin rate). The output will be a set of tables containing the maneuver parameters as they change during maneuver. The user can obtain a detailed printed 'scenario' of the given maneuver with a resolution of a single pulse for pulsed firing and of a second for continuous firing. The program thus functions as a maneuver simulator.

To compare the differences between the S/C performances as computed using the S/C models contained in the program, and those really observed during operations, some parameters have been defined as additional program inputs. The user is, thus, able to introduce corrective factors deduced from previous experiences.

The most important of these parameters are the thrust and the centroid calibration factors. The first makes it possible to adjust the theoretical thrust magnitude computed at a particular instant, to obtain a value closer to the effective one. The centroid calibration factor is introduced to specify possible misalignments of the thrust or torque directions when compared with the theoretical directions.

### 3.2 Target and maneuver planning

It should be noted that, although the OMP optimizes maneuvers, it has not been designed to allow for many other essential parameters, e.g. operational requirements for ground station management or SHF experimentation. Since maneuver side effects can be used as an aid in general station keeping strategy (see ref. 8), a maneuver is normally planned by using the OMP scenarios.

Only three typical station-keeping corrections are needed to control the spacecraft within the mission constraints:

-East-West maneuvers (S/C drift-rate change) -North-South maneuvers (orbit inclination and node change)
-Attitude maneuvers.

East-west corrections.

For this maneuver, the thrust must be tangent to the orbit and in the opposite direction to the current S/C velocity vector. To realize this situation, four elements must be defined : synchronization (earth or sun), radial jet (A or B), quadrant for jet firing and maneuver time.

The radial jet B is generally used owing to its spin up effect. The sun synchronization is normally preferred. Under this conditions , it is possible to have the thrust direction exactly tangent to the orbit only once, for each of the four quadrants, during a complete orbit. In performing this maneuver, the spin axis precession should be generally directed toward the best position with respect of the mission requirements. This fact further limits the quadrant choice to that one which best approaches the desired attitude. The last parameter to be defined is the pulse number which is estimated on the basis of the desired drift rate change and that produced in firing a single pulse. The pulse number so determined is increased by few units in order to take into account the lower efficiency of the first pulses.

These data are given as input to the OMP which then computes orbit and S/C status perturbations simulating these firing conditions. Thus a set of data is available to determine the stopping time of the firing sequence and, therefore, to allow a more precise maneuver goal achievement.

Generally, several OMP runs are made with slightly different input data, in order to verify, analyzing the obtained printed scenarios, the initial condition which must be chosen to achieve the best results in the maneuver execution.

North-south corrections.

In geostationary conditions, if the initial node is positioned around 270 degrees and the inclination is 0.2 degrees, this node decreases to 90 degrees in about 5 months; at the same time, the inclination initially decreases to almost 0 and than arises again up to 0.20 degrees; at this point, a correction is required to set the situation at the initial conditions. Since the initial value which maximizes the time spent below 0.2 degrees is time dependent, when a correction must be performed, different maneuvers are computed by the OMP assuming the target nodes slightly different to the theoretical ones. The post-maneuver orbits obtained are successively propagated for more than 5 months and the target node relative to the orbit which has a maximum time with inclination below .2 degrees, is assumed as the definitive target node.

Considering the in-plane effects of the north-south maneuver, if the S/C spin axis position is such that the thrust in plane component is approximately in the drift rate direction, an attitude trim correction must be planned to reverse the spin-axis right ascension.

Attitude corrections.

Relatively small attitude changes are normally required in the spin axis control. When the desired corrections are not obtained as a side effect of orbital maneuvers, appropriate actions are taken to modify the S/C attitude.

In firing the SIRIO auxiliary propulsion system, the minimum thrust is obtained with a single pulse and for short inpulsive firing sequences (less than 5 pulses),and under normal conditions, this causes a S/C spin axis precession of about 0.1 degrees per pulse. Sun synchronization is generally selected (see paragraph 1.4) which enables the S/C spin axis precession from or toward the sun or in the orthogonal directions, depending on the quadrant selected; under these conditions, it is extremly difficult to reach exactly the ideal target. Therefore, the pulse number and the direction which permit the best approach to the desired attitude are chosen; the so-determined firing sequence is given as input to the OMP which computes the maneuver results. Then the post maneuver computed attitude is assumed to be the effective target of the attitude correction.

## 3.3 Evaluation of maneuver results

After a maneuver has been executed, the most important data to be analyzed are the new S/C orbital elements and the attitude and spin rate because these elements confirm whether the correction has been executed as predicted. To achieve an accurate attitude determination, telemetry data must be collected for a complete orbit (see ref. 9). Thus, the post-maneuver attitude is generally available on the day following the maneuver. A different procedure must be followed to obtain the new orbital data; with the method adopted, a complete week of azimuth and elevation data must be collected to reach the desired precision. Because of the SIRIO mission constraints and the strategy adopted for controlling the S/C, these time delays are not critical, but represent a technical delay in the S/C performance evaluation. It should be remembered that a rough idea of the maneuver effects can be obtained by verifying the S/C attitude immediately after maneuver completion, using a program which provides a first attitude estimation after 30 minutes of telemetry data acquisition and gives successive improvements as more data are acquired.

The possibility of estimating the S/C performance by analyzing its attitude is dependent on the fact that each maneuver produces a perturbation in the S/C spin axis position; a post-firing attitude close to that predicted usually indicates a maneuver completed as predicted.

As soon as the final orbit and attitude determinations are available, a more detailed analysis of the correction effects can be made. If the measured data are sufficiently close to those predicted, an adjustment of the initial data used to compute the executed maneuver is made to obtain, in successive OMP runs, predicted results which more nearly coincide with those measured. This adjustment is made in order to achieve more precise calibration factors and a better evaluation of the orbital and attitude determination accuracy.

If the post-maneuver results should be quite different from those expected, a deeper analysis must be made. The printed scenario produced by the orbit control program can be very helpful. The analysis results, examined together with the S/C status data, can enable more precise hypotheses on the causes of different-from-predicted S/C behaviour.

## 4. Maneuver tables

In tables 2, 3 and 4 the complete maneuver scenario up to the present is shown. In the tables, pressure and temperature values are not given since we have found no correlation between these values and calibration factors.

In the following part some considerations about maneuvers most significant parameters are given.

### 4.1 Calibration factors

The calibration factors are the input variables of the OMP that consent fine tuning of the entire attitude and orbit control system with respect to the auxiliary propulsion system performances; they make allowance for all hardware and software model misalignments. Two variables (A and B ) are used by the OMP to define calibration factors ( C ) as follows:

$$C = An + B$$

where n is the duration of the maneuver (number of pulses or seconds). These calibration factors are relative to thrust efficiency for jets fired in continuous and in pulsed mode and to the centroid for jets fired in pulsed mode only. These factors are evaluated by introducing the two variables (A and B) into the OMP; by choosing the most sensitive convergence parameter with respect to the thruster to be calibrated; by performing a number of maneuver simulations. For each maneuver simulation, the calibration variables must be modified by the ratio between the determined and the new obtained convergence parameter until this falls within a reasonable tollerance. In order to determine A and B the results of at least two maneuvers of different duration must be considered.

In order to obtain the calibration factor variables A and B necessary as input for the OMP, we examine the behaviour of the thrusters shown in the tables reported above. The calibration factors data reported in these tables are relative to C coefficients.

From table 2 we see that thrust efficiency values of 0.95 and 0 respectively for B and A can be assumed (for TAA and TAB jets used together and in continuous mode). It can be seen that the only exception is the value 0.939 for the first station acquisition maneuver. This can be explained by the fact that this was the first time that fuel system B was used.

We used the semi major axis (SMA) as the convergence parameter for in-plane maneuvers and the inclination and node parameters for out of plane maneuvers. It was not possible to evaluate calibration factors for the 3 March 1978 N/S maneuver because, for the node position corresponding to the maneuver ignition time, $\Delta V$ magnitude is greatly influenced by the initial and final values of the R.A. of the ascending node. This cannot be determined without considerable error owing to the low inclination of the orbit plane.

TABLE 2. - *Orbital maneuvers performed with TAA + TAB jets in continuous mode.*

<table>
<tr><th rowspan="2">Maneuver description</th><th rowspan="2">Date (year, month, day)</th><th rowspan="2">Igtime (h, min, s)</th><th rowspan="2">Duration (s)</th><th colspan="2">Δ spin rate</th><th rowspan="2">Spin axis precession (deg)</th><th colspan="6">Convergence parameters semimajor axis</th><th rowspan="2">Thrust efficiency calibration factor</th><th rowspan="2">Fuel expended (kg)</th></tr>
<tr><th>Predicted</th><th>Observed</th><th colspan="2">Initial</th><th colspan="2">Final predicted</th><th colspan="2">Final determined</th></tr>
<tr><td>Station acquisition 1</td><td>77. 8.29</td><td>13.49.25</td><td>59</td><td>— 0.18</td><td>— 0.07</td><td>0.08</td><td colspan="2">41 809.33</td><td colspan="2">42 090.47</td><td colspan="2">42 089.22</td><td>0.939</td><td>1.047</td></tr>
<tr><td>Station acquisition 2</td><td>77. 8.31</td><td>1.38.10</td><td>90</td><td>— 0.25</td><td>— 0.0</td><td>0.64</td><td colspan="2">42 088.81</td><td colspan="2">41 644.79</td><td colspan="2">41 646.92</td><td>0.956</td><td>1.536</td></tr>
<tr><td>Station acquisition 3 (second phase TAA only)</td><td>77. 9. 1</td><td>12.52.27</td><td>100</td><td>2.67</td><td>2.83</td><td>N.C.</td><td colspan="2">41 646.35</td><td colspan="2">41 862.26</td><td colspan="2">N.C.</td><td>0.948</td><td>0.789</td></tr>
<tr><td>Station acquisition 3 (second phase TAA + TAB)</td><td>77. 9. 1</td><td>12.54.07</td><td>53</td><td>— 0.16</td><td>— 0.07</td><td>0.45</td><td colspan="2">41 862.26</td><td colspan="2">42 094.99</td><td colspan="2">42 093.28</td><td>0.948</td><td>0.834</td></tr>
<tr><td>Station acquisition 4</td><td>77. 9. 3</td><td>0.42.56</td><td>56</td><td>— 0.09</td><td>— 0.13</td><td>N.C.</td><td colspan="2">42 092.88</td><td colspan="2">41 846.38</td><td colspan="2">41 846.11</td><td>0.953</td><td>0.864</td></tr>
<tr><td>Station acquisition 5</td><td>77. 9. 4</td><td>12.13.14</td><td>59.5</td><td>— 0.08</td><td>— 0.08</td><td>N.C.</td><td colspan="2">41 846.00</td><td colspan="2">42 096.70</td><td colspan="2">42 096.39</td><td>0.953</td><td>0.888</td></tr>
<tr><td>Station acquisition 6</td><td>77. 9. 6</td><td>12.06.04</td><td>17</td><td>— 0.02</td><td>— 0.04</td><td>N.C.</td><td colspan="2">42 096.61</td><td colspan="2">42 165.15</td><td colspan="2">42 165.02</td><td>0.952</td><td>0.250</td></tr>
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<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><th>Inc.</th><th>Node</th><th>Inc.</th><th>Node</th><th>Inc.</th><th>Node</th><td></td><td></td></tr>
<tr><td>N/S station keeping</td><td>78. 3.30</td><td>7.45.49</td><td>109.5</td><td>— 0.37</td><td>— 0.25</td><td>0.23</td><td>0.144</td><td>132.17</td><td>0.180</td><td>269.94</td><td>0.169</td><td>272.23</td><td>N.C.</td><td>1.534</td></tr>
<tr><td>N/S station keeping</td><td>78.10.31</td><td>16.12.33</td><td>165</td><td>— 0.39</td><td>— 0.35</td><td>0.06</td><td>0.254</td><td>86.24</td><td>0.187</td><td>270.70</td><td>0.185</td><td>273.09</td><td>0.946</td><td>2.208</td></tr>
</table>

TABLE 3. - *Spin axis reorientation maneuvers performed by TAA jet in pulsed mode.*

| Maneuver description | Date (year, month, day) | Igtime (h, min, s) | Sync | Duration (pulses) | Attitude |  |  |  |  |  | Δ spin rate (r.p.m.) |  | Calibration factor |  | Fuel expended (kg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  | Initial |  | Final predicted |  | Final determined |  | Predicted | Observed | Thrust efficiency | Centroid |  |
|  |  |  |  |  | R.A. | Dec. | R.A. | Dec. | R.A. | Dec. |  |  |  |  |  |
| INJA to ANFA Leg. 1 | 77.8.26 | 5.20.00 | Sun | 34 | 60.90 | — 4.70 | 66.80 | — 3.79 | 66.78 | — 3.73 | 0.12 | 0.15 | 0.81 | 0.920 | 0.048 |
| INJA to ANFA Leg. 2 | 77.8.26 | 5.35.23 | Sun | 113 | 66.78 | — 3.73 | 61.99 | 20.89 | 61.84 | 20.95 | 0.49 | 0.64 | 0.94 | 0.94 | 0.192 |
| ANFA to TRIM | 77.8.27 | 0.50.00 | Sun | 7 | 61.84 | 20.95 | 61.67 | 22.03 | 61.88 | 22.03 | 0.02 | 0.03 | 0.88 | 0.87 | 0.010 |
| ANFA to SAA Leg. 1 | 77.8.28 | 14.00.00 | Sun | 31 | 61.69 | 22.52 | 54.71 | 21.06 | 54.50 | 21.30 | 0.13 | 0.18 | 0.963 | 0.94 | 0.050 |
| ANFA to SAA Leg. 2 | 77.8.28 | 14.15.23 | Sun | 90 | 65.50 | 21.30 | 59.09 | 0.93 | 59.10 | 0.90 | 0.41 | 0.54 | 0.963 | 0.94 | 0.146 |
| SAA to INTA | 77.9. 7 | 17.59.49 | Sun | 475 | 59.26 | 1.25 | 42.02 | — 77.47 | 41.32 | — 77.41 | 1.67 | 2.20 | 0.975 | 0.918 | 0.588 |
| INTA to NONA Leg. 1 | 77.9. 8 | 18.00.00 | Sun | 47 | 41.32 | — 77.41 | 73.77 | — 79.25 | 73.79 | — 79.25 | 0.14 | 0.19 | 0.970 | 0.94 | 0.055 |
| INTA to NONA Leg. 2 | 77.9. 8 | 18.25.39 | Sun | 75 | 73.79 | — 79.25 | 256.11 | — 89.53 | 255.11 | — 79.25 | 0.24 | 0.01 | 0.974 | 0.94 | 0.088 |
| TRIM to MA Leg. 1 | 77.9.15 | 18.00.00 | Sun | 2 | 270. | — 89.41 | 284.0 | — 89.35 | / | / | 0.01 | 0.33 | 0.88 | 0.94 | 0.002 |
| TRIM to MA Leg. 2 | 77.9.15 | 18.15.02 | Sun | 4 | / | / | 311.0 | — 89.64 | 312.0 | — 89.64 | 0.01 | 0.01 | 0.88 | 0.94 | 0.004 |

TABLE 2. - *Orbital maneuvers performed with TAA + TAB jets in continuous mode.*

<table>
<tr><th rowspan="2">Maneuver description</th><th rowspan="2">Date (year, month, day)</th><th rowspan="2">Igtime (h, min, s)</th><th rowspan="2">Duration (s)</th><th colspan="2">Δ spin rate</th><th rowspan="2">Spin axis precession (deg)</th><th colspan="6">Convergence parameters semimajor axis</th><th rowspan="2">Thrust efficiency calibration factor</th><th rowspan="2">Fuel expended (kg)</th></tr>
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<tr><td>Station acquisition 1</td><td>77. 8.29</td><td>13.49.25</td><td>59</td><td>−0.18</td><td>−0.07</td><td>0.08</td><td colspan="2">41 809.33</td><td colspan="2">42 090.47</td><td colspan="2">42 089.22</td><td>0.939</td><td>1.047</td></tr>
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<tr><td>Station acquisition 4</td><td>77. 9. 3</td><td>0.42.56</td><td>56</td><td>−0.09</td><td>−0.13</td><td>N.C.</td><td colspan="2">42 092.88</td><td colspan="2">41 846.38</td><td colspan="2">41 846.11</td><td>0.953</td><td>0.864</td></tr>
<tr><td>Station acquisition 5</td><td>77. 9. 4</td><td>12.13.14</td><td>59.5</td><td>−0.08</td><td>−0.08</td><td>N.C.</td><td colspan="2">41 846.00</td><td colspan="2">42 096.70</td><td colspan="2">42 096.39</td><td>0.953</td><td>0.888</td></tr>
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<tr><td>N/S station keeping</td><td>78.10.31</td><td>16.12.33</td><td>165</td><td>−0.39</td><td>−0.35</td><td>0.06</td><td>0.254</td><td>86.24</td><td>0.187</td><td>270.70</td><td>0.185</td><td>273.09</td><td>0.946</td><td>2.208</td></tr>
</table>

TABLE 3. - *Spin axis reorientation maneuvers performed by TAA jet in pulsed mode.*

| Maneuver description | Date (year, month, day) | Igtime (h, min, s) | Sync | Duration (pulses) | Attitude | | | | | | Δ spin rate (r.p.m.) | | Calibration factor | | Fuel expended (kg) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Initial | | Final predicted | | Final determined | | Predicted | Observed | Thrust efficiency | Centroid | |
| | | | | | R.A. | Dec. | R.A. | Dec. | R.A. | Dec. | | | | | |
| INJA to ANFA Leg. 1 | 77.8.26 | 5.20.00 | Sun | 34 | 60.90 | −4.70 | 66.80 | −3.79 | 66.78 | −3.73 | 0.12 | 0.15 | 0.81 | 0.920 | 0.048 |
| INJA to ANFA Leg. 2 | 77.8.26 | 5.35.23 | Sun | 113 | 66.78 | −3.73 | 61.99 | 20.89 | 61.84 | 20.95 | 0.49 | 0.64 | 0.94 | 0.94 | 0.192 |
| ANFA to TRIM | 77.8.27 | 0.50.00 | Sun | 7 | 61.84 | 20.95 | 61.67 | 22.03 | 61.88 | 22.03 | 0.02 | 0.03 | 0.88 | 0.87 | 0.010 |
| ANFA to SAA Leg. 1 | 77.8.28 | 14.00.00 | Sun | 31 | 61.69 | 22.52 | 54.71 | 21.06 | 54.50 | 21.30 | 0.13 | 0.18 | 0.963 | 0.94 | 0.050 |
| ANFA to SAA Leg. 2 | 77.8.28 | 14.15.23 | Sun | 90 | 65.50 | 21.30 | 59.09 | 0.93 | 59.10 | 0.90 | 0.41 | 0.54 | 0.963 | 0.94 | 0.146 |
| SAA to INTA | 77.9. 7 | 17.59.49 | Sun | 475 | 59.26 | 1.25 | 42.02 | −77.47 | 41.32 | −77.41 | 1.67 | 2.20 | 0.975 | 0.918 | 0.588 |
| INTA to NONA Leg. 1 | 77.9. 8 | 18.00.00 | Sun | 47 | 41.32 | −77.41 | 73.77 | −79.25 | 73.79 | −79.25 | 0.14 | 0.19 | 0.970 | 0.94 | 0.055 |
| INTA to NONA Leg. 2 | 77.9. 8 | 18.25.39 | Sun | 75 | 73.79 | −79.25 | 256.11 | −89.53 | 255.11 | −79.25 | 0.24 | 0.01 | 0.974 | 0.94 | 0.088 |
| TRIM to MA Leg. 1 | 77.9.15 | 18.00.00 | Sun | 2 | 270. | −89.41 | 284.0 | −89.35 | / | / | 0.01 | 0.33 | 0.88 | 0.94 | 0.002 |
| TRIM to MA Leg. 2 | 77.9.15 | 18.15.02 | Sun | 4 | / | / | 311.0 | −89.64 | 312.0 | −89.64 | 0.01 | 0.01 | 0.88 | 0.94 | 0.004 |

The behaviour of the TAA jet fired in pulsed mode is described in table 3. We think that it is reasonable to assume values of 0.97 for B and zero for A, for thruster efficiency in maneuvers with duration higher than approximately 15 pulses. For shorter maneuvers, the TAA behaviour can be assumed equal to that of TRB. Values of 0.86 for B and 0.008 for A give a good fitting of the results.

The calibration value of 1.03 for the first maneuver performed with the TRB jet might not be reliable for the following reasons:

- the maneuver was performed in ''pulse train'' and in such a way the number of fired pulses has a one pulse incertainty;
- there are no other similar maneuvers to confirm this result;
- the maneuver was performed in earth synchronization mode, so earth sensor instead of sun sensor errors were introduced, thus lacking in homogeneity respect to all other maneuvers.

The centroid calibration factor for the TAA jet can be assumed equal to 0.94 for maneuvers of any duration. Thus, assuming for the nominal centroid the value of 65 degrees (for average spin rate and pressure), the centroid results shifted backwards by approximately 4 degrees.

We used spin axis precession and SMA respectively to evaluate the thrust efficiency of TAA and TRB and in order to obtain centroid calibration factors reported in table 3, we proceeded by nullifying the angle between the predicted and determined spin axis precession paths. In evaluating the calibration factors values shown in table 3, it is necessary to make an evaluation of the attitude determination precision. In the best conditions (that is when data from a consistent part of an orbit is available) the estimated uncertainty is 0.1 degrees ( 3 $\sigma$ value ) that can increase up to two or three times when telemetry data is available for only a few minutes. This happens in the determinations between maneuvers very close in time like the two legs of a single attitude maneuver.

TABLE 4. - *Orbital maneuvers performed with TRB jet in pulsed mode.*
(Centroid calibration factor is assumed to be 0.94)

| Maneuver description | Date (year, month, day) | Igtime (h, min, s) | Sync. | Duration (pulses) | Predicted spin axis precession (deg) | Δ spin rate (r.p.m.) | | Semimajor axis (km) | | | Thrust efficiency calibration factor | **Fuel expended (kg)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Predicted | Observed | Initial | Final predicted | Final observed | | |
| Station acquisition orbit trim | 77. 9.14 | 18.00.00 | Earth | 23 | 0.21 | 0.34 | 0.33 | 42 158.57 | 42 165.21 | 42 165.19 | **1.03** | **0.032** |
| E/W station keeping | 77.12. 1 | 11.20.00 | Sun | 12 | 0.11 | 0.16 | 0.15 | 42 166.81 | 42 164.02 | 42 164.02 | **0.97** | **0.016** |
| E/W station keeping | 78. 5. 2 | 19.11.00 | Sun | 11 | 0.10 | 0.13 | 0.11 | 42 166.47 | 42 163.91 | 42 163.92 | **0.96** | **0.014** |
| E/W station keeping | 78.12.12 | 12.40.00 | Sun | 6 | 0.05 | 0.06 | 0.06 | 42 167.15 | 42 166.04 | 42 166.05 | **0.89** | **0.006** |

Consequently the calibration factors computed for short maneuvers are of low reliability. Furthermore it is impossible to calibrate the thruster centroid for TRB jet since attitude precession induced by TRB are of the same magnitude of the $3\sigma$ precision. The centroid value for TRB jet was then assumed to be equal to that of the TAA jet.

There were three maneuvers performed using the TAB jet in pulsed mode,of 2, 3 and 4 pulses. Because of the short number and the short duration of this type of maneuvers, we did not give any values for TAB calibration factors as they have practically no significance.

## 4.2 Fuel weight

Tables 2,3, and 4 contain fuel consumption values computed by the OMP program for each maneuver. Table 5 compares the sum of the fuel consumption computed by the OMP for all the maneuvers with the consumption computed by applying Boyle's law using the actual temperature and pressure values for two mission ephochs: at the end of the fourth station acquisition maneuver (STACQ 4) and at the end of the east west station keeping maneuver of Dec. 12,1978.

TABLE 5

| Epoch | Pressure (atm) | | Temperature (°C) | | Fuel remaining (per tank) (kg) | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | OMP calculation | | Boyle's low calculation | |
| | A system | B system | A system | B system | A system | B system | A system | B system |
| After fourth station acquisition maneuver September 3, 1977 | 14.14 | 15.82 | 15.2 | 19.6 | 5.910 | 6.405 | 5.846 | 6.300 |
| After second N/S station keeping maneuvers October 31, 1978 | 11.34 | 12.60 | 20.0 | 26.8 | 4.281 | 5.118 | 4.343 | 4.819 |

From table 5, it appears that there is better agreement between computed data and Boyle's law data in system A; the higher discrepancies reported for system B may be explained by the existence of errors in the system B pressure and temperature measurements.

## 4.3 Spin rate

The spin effects predicted for maneuvers performed using one (TAA) or both axial jets were constantly lower than the actual effects measured after maneuver execution. In an attempt to obtain a better agreement between predicted and obtained spin effects, the TAA jet mounting angle has been modified from the nominal value of 0.75 degrees out of axial direction, to a value of 0.85 degrees. The spin effects computed by the OMP shown in table 2 and 3 are based on this modified mounting angle value. However a discrepancy for continuous mode maneuvers still exists and is higly variable; for pulsed mode maneuvers the observed spin values are constantly higher than the predicted ones by a factor of about 1.3. Since it is evident that the mounting angle has a fixed value, we thus deduced the difference in the higly variable discrepancies found for the spin effects in pulsed mode maneuvers, compared with the much more consistent discrepancy obtained with continuous mode maneuvers, is not caused by a geometric factor but by the nutation damper effects.

As mentioned in paragrapf 1.5, part of the energy dissipated by the dumping fluid sloshing is converted into kinetic energy which produces an increase in the spin rate. The different characteristics of the nutation motion caused by the pulsed mode firing, compared with that caused by continuous mode firing, can explain the different effects on the spin rate. In fact pulsed mode firing should produce regular impulsive motions, and than nutation, on the S/C.

In table 4 it can be seen that observed and predicted spin effects are always found in good agreement for the radial jet (TRB); this fact reinforces our hypothesis that radial jet firing should not induce relevant nutation effects on the S/C.

## 4.4 Spin axis precession in continuous mode firing.

Looking at table 2, which contains orbital maneuvers performed by firing the axial jets in continuous mode, we observe that the spin axis induced precession have a wide range of variability and that some of them have not been computed. The reason of the variability may be explained by the following considerations.

TAA and TAB jets are not started and stopped simultaneously but start and stop firing are shifted two seconds apart for the two jets. We may represent the global perturbation produced by the two jets start firing with a precession vector having a certain intensity and direction. At the end of firing a similar phenomena causes another precession vector having another intensity and direction. The two phenomena pratically cannot be correlated together. In fact, being the mean duration of firing several tenths of seconds, the spin rate not constant during the firing and the time of the actual opening and closing of the valves affected by an uncertainty comparable with the duration of a revolution, the phase relation of the two precession vectors is unpredictable. Therefore, if the two perturbations result to be in phase, the final precession of the spin axis will rise to the higher values; if they are in opposition, the final perturbation on the attitude will result the smallest. We can see that some attitude perturbations resulted to be almost zero; we may thus deduce that in those cases the two precession vectors were in opposition an that generally the amplitude of precession vector at the start and the stop firing is about the same. The largest perturbation was 0.64 degrees; that means, supposing that the start firing and the stop firing perturbations were in phase, that 0.32 degrees is the amplitude of the single perturbation vector.

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