SKYLAB DECAY FOLLOW-UP

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Ce document présente l'expérience vécue au CNES à l'occasion du suivi de la rentrée de SKYLAB. On aborde successivement les causes de la chute de la station, les objectifs de l'intervention et les moyens mis en oeuvre. Puis, on précise les problèmes rencontrés : qualification des mesures, méthodes et logiciels utilisés et les aspects opérationnels.

This document presents CNES'operational activities to track and evaluate SKYLAB'S Orbital Decay. Main topics presented here are the causes of the decay, CNES' operational objectives and means utilized. Difficulties and problems encountered are analyzed : quality of measurement, methods and software used and operational aspects.

SUMMARY

REFERENCES

CNES/MT/MS REPORT N° 208 JULY 1979.

1. INTRODUCTION

1.1 Historical accounts

The 85-TON SKYLAB Space Laboratory has been launched on may 14 1973, and has received 3 teams of astronauts during 172 days. Unutilized for 1974, partly due to some operating incidents, its altitude has decreased a little bit more quickly as expected. This altitude decrease was going greater after 1977, due to a solar activity more greater than predicted (a strong solar activity increases the atmosphere density, that increases the satellites drag and consequently their lifetime is reduced.

Fully aware of the difficulty to control the reentry and concerned to minimize the risk for big vehicle pieces to fall down on Earth, NASA had been planned for 1977 an emergency manoeuver based upon the use of the second orbital flight of the shuttle to fit on SKYLAB a booster of which the firing would allow either to park SKYLAB a booster of which the firing would allow either to park SKYLAB on an upper altitude orbit, either to decay it over an oceanic area.

Unfortunately the Space Shuttle program delay and the important solar activity quickly degrading the orbit led NASA to renounce to this procedure.

From the beginning of 1979 the french, english and american specialists have planned that SKYLAB would decay between mid-1979 and mid-1980. Likely the third of the station, i.e. 30 tons of material wouldn't burn out and would fall down in "showers" (500 pieces) in an 6500 km length and 150 km width area located anywhere along the Spacecraft track.

This trajectory, almost circular and 50 deg inclinated, covered the earth between the 50th North and the 50th South parallels. France and a large part of Europe were consequently located in the possible impact area.

1.2 Follow-up Purposes

The risks of SKYLAB impact over FRANCE being not excluded, the french Government assigned CNES for implementing the appropriate capabilities for predicting the impact date, in order that the concerned french agencies are able to take any actions, safeguard useful, as in France as in French overseas territories.

1.3 The implemented capabilities

Contacts have been established with NASA.

NASA planned to control the Spacecraft orbit with its telemetry stations and with long-range radars.

The whole of these data allowed to have a permanent knowledge of the orbit and

Proc. Int. Symp. Spacecraft Flight Dynamics, Darmstadt, FRG, 18-22 May 1981 (ESA SP-160, Aug. 1981)

of the satellite status in order to determine the control possibilities of reentry.

The United States were so trying to minimize the risks of impact on inhabited areas.

The current CNES orbitdetermination capabilities (interferometry) couldn't be used, SKYLAB being out of the 136/138 Mhz frequency range.

Only the radars being able to work in skintrack mode and with a sufficient power (type Bretagne, Bearn, Artois) were able to acquire the spacecraft. As oomplement the optical capabilities could provide an acquisition aid.

The corresponding radars for this king of tracking were available on the following civilian and military launch pads :

- CENTRE SPATIAL GUYANAIS (CSG)
  (GUIANA SPACE CENTER)

This launch pad is using radars located in Guiana and an other one located in NATAL (Brazil). (These radars are currently used for ARIANE flight sequence followup).

- CENTRE D'ESSAIS DES LANDES (C.E.L)
  (LANDES TEST CENTER)

Using radars in Landes, in Azores Islands and aboard the Henri Poincare ship.

- CENTRE D'ESSAIS DE LA MEDITERRANEE (CEM)
  (MEDITERRANEAN SEA TEST CENTER)

Using radars on the Levant Island.

The optical capabilities were as follow :

. BORDEAUX OBSERVATORY (ASTRO 1)
. CERGA OBSERVATORY (ASTRO 1)

1.4 Operations scheme

For the first time in France a whole of radars depending upon different agencies have to be coordinated and implemented in order to collect the maximum of measures allowing to perform an orbit computation on a regular basis. The TOULOUSE Space Center (C.S.T.) has been assigned for providing the radar stations with the satellite acquisition data, to collect the tracking data for a retransmission to NASA, to issue orbital parameters, and to compute a decay window. The initialization of the procedure has been done using the NASA orbit.

To allow the informations exchange a cooperation has been implemented with the U.S. Agency :

. NASA will provide CNES on regular basis with the orbital parameters, the decay predictions, as well as the informations on the manoeuvers strategy.

. CNES will provide NASA, in near-realtime the radar data of some radar stations as well as the computed decay predictions.

During the CNES/NASA meeting, the planned solutions for controlling the SKYLAB decay were presented.

The planned orbit for the satellite decay was the one which passed over the minimum of inhabited lands. This orbit was passing over Pacific, Atlantic and Indian Oceans (see fig. 1).

The control of this orbit could be done by modifications of the drag force, modifying consequently the attitude of the spacecraft. The different possibilities were the following :

- a controlled attitude with the solar panels directed towards the sun.

- a balance attitude between couples of gravity gradient and the aerodynamic couples.

- an attitude obtained by a fast tumbling on one of the three axis of the satellite.

On april 4th French Government will give its authorization for using the whole french available radar, CNES being assigned to direct this operation.

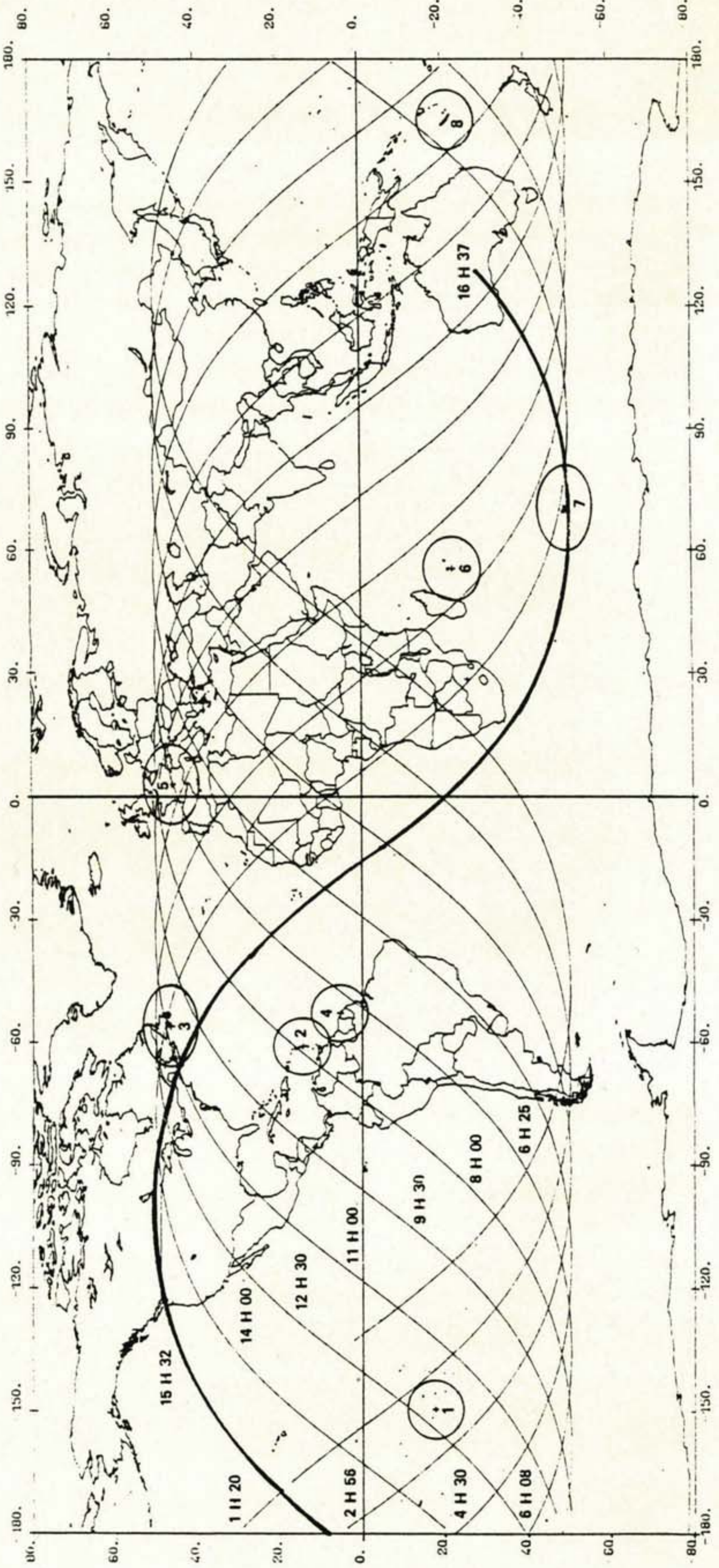
The first radar measures have been performed on april 10th and the whole stations were operationnal on june 1st 1979. The first orbit computed by the CNES was issued on june 19th 1979.

More than the radar measures, the Bordeaux and CERGA optical capabilities provided a certain amount of data. Unfortunately, in the latest phase, for which these informations would have been more useful, the satellite was not in optical visibility of these sites forbidding any measure.

As soon as the service has been implemented, the decay window computation has been performed using NASA orbital parameters until the CNES orbit is available june 30 st).

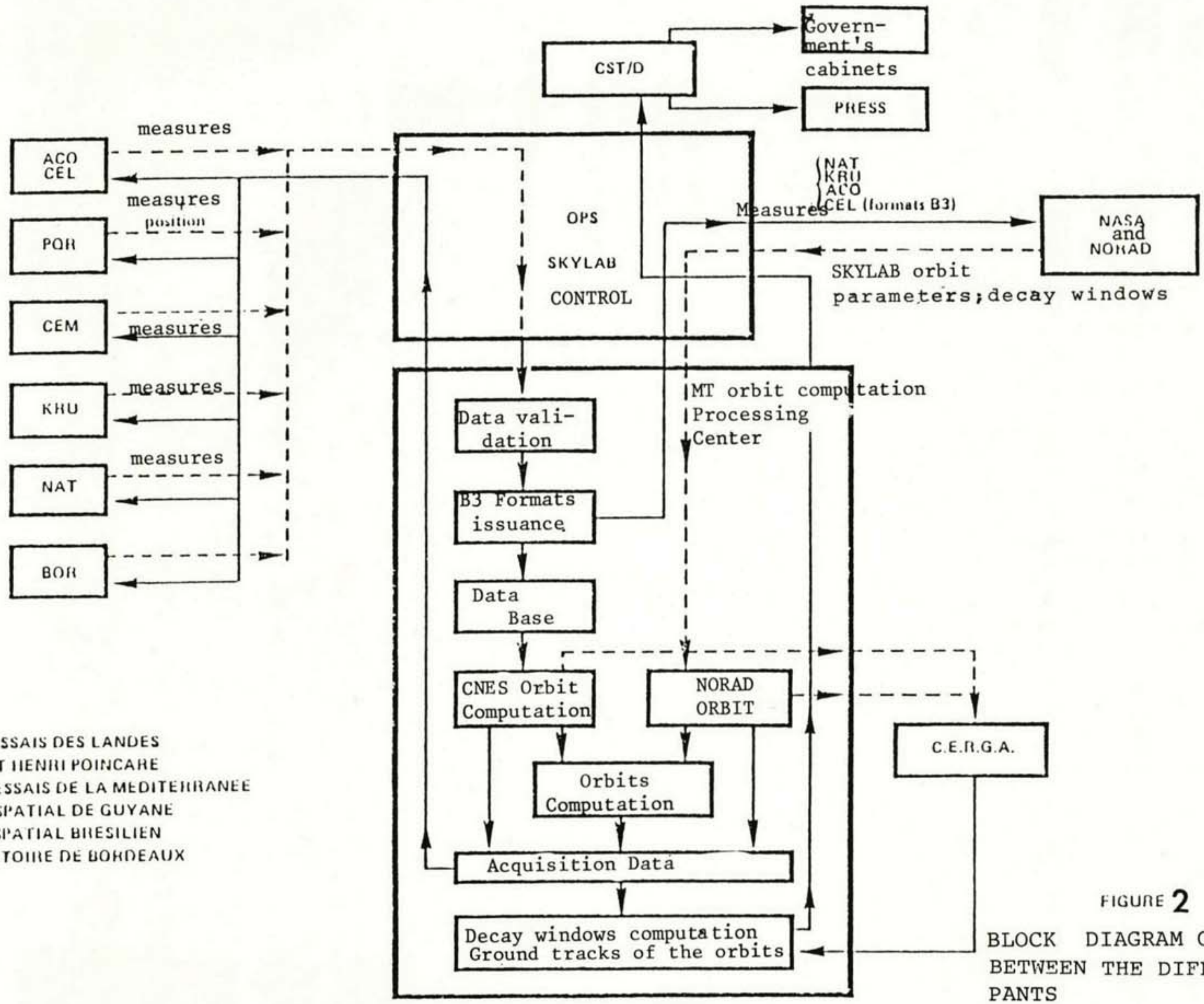
Figure 2 provides a block diagram of the links implemented between the different operations participants.

FIGURE N° 1 - SKYLAB GROUND TRACK OVER FRENCH OVERSEAS TERRITORIES JUL 11, 1979 PASS



STATIONS :

1 - POLYNESIE FRANÇAISE
2 - GUADELOUPE - MARTINIQUE
3 - ST PIERRE ET MIQUELON
4 - GUYANE
5 - FRANÇE
6 - REUNION
7 - ILES KERGUELEN
8 - NOUVELLE - CALEDONIE



ACO : ACORES
CEL : CENTRE ESSAIS DES LANDES
POR : BATIMENT HENRI POINCARE
CEM : CENTRE ESSAIS DE LA MEDITERRANEE
KRU : CENTRE SPATIAL DE GUYANE
NAT : CENTRE SPATIAL BRESILIEN
BOR : OBSERVATOIRE DE BORDEAUX

FIGURE 2

BLOCK DIAGRAM OF THE LINKS BETWEEN THE DIFFERENT PARTICIPANTS

2. ORBIT DETERMINATION

2.1 Obtaining the first orbit

In order to qualify the orbit computation we have waited for the convenient period for which the whole capabilities would have acquired a sufficient measures density (1 to 2 passes per day).
The dates of june 12-13-14 were convenient for these criteria. From the orbit parameters issued by NORAD, we tried to obtain a first orbit with the KOUROU data previously used.

Quickly it happened non-useful and dangerous to use data obtained under 10 deg of elevation (errored points or poor link budget, propagation problems).

In the future this procedure was applied for all the stations. On the other hand, in the last days, NASA required passes untill 3 deg of elevation. We tried then to use the whole measures.

Knowing not the surface/mass ratio computation was initialized with the following value : 5.7×10^{-3} m2/kg. By successive tests, it happened that a multiplier coefficient of about 0.5 had to be applied for obtaining realistic residues. The S/M adjusted coefficient was consequently 2.58×10^{-3} (m^2/kg).

This orbit validation was obtained by comparison with NORAD orbit and a verification of its good quality by extrapolation, quality which has been maintained until the decay, by comparison of the computed acquisition data with the true acquisitions of the radars.

2.2 Orbit determination

The validated radar data were stored in a data base under the form of elevation azimuth and range. The possible pick-up criteria are :

- the date
- the pass
- the station
- the elevation

A numerical integration software was used in order to be able to take into account rather accurately the atmospheric drag.

The modelization of the forces acting on the satellite were so performed :

- terrestrial potential model GEM 10. The whole model has been used for taking into possible resonances (mean motion of about 16 rev./day).
- atmosphere model JACCHIA 65 modified by F. BARLIER for taking into account some systematic errors.

The drag coefficient was permenently readjusted as it was varying depending upon the altitude. This coefficient adjustement includes in fact the error on the initial S/M, its variation with the attitude, the model and solar activity errors.
The previsional solar activity was transmitted every day by the MEUDON Observatory.

On figures 3 and 4 the evolutions of semi-major axis and inclinaison have been outlined related to the epoch time.

2.3 Radars pointing

Before SKYLAB operations the whole french radars were used only for tracking rockets from their lift-off (no problem of initial lock) . Only the CSG and NATAL radars have been qualified by operational trainings on GEOS-C transponder (ARIANE qualification).

Radar beam being very narrow (about 1 deg) two solutions for locking on the target could be expected :

- either very accurate satellite acquisition data (better than 2 seconds in time)
- either watch on waiting point.

The preliminary tests showed that one or the other of these tracking technics was not sufficiently sure. Consequently each capability has developped its own procedures. The generally adopted solution was to calculate the time shift at the satellite acquisition and to consequently adjust the acquisition data. From this adjustement period most of the passes were followed-up.

During the end of orbital life a real-time computation and an acquisition data update allowed to obtain the expected goal and to provide NASA with data until the last orbit. This is pointed out in the "Aviation Week" editorial dated Jul. 1979.

The first pointing data were obtained from the orbital parameters provided by NASA. These mean parameters (according to KOZAI) have been translated in mean parameters (according to BROVWER) in order to be extrapolated, using the current predicts programs of the service.

In the future, the parameters issued from osculating parameters identified in the orbit calculation, have been used for generating pointing data.

It is important to emphasize on the provided information of time shift : they represent the only effective mean to verify the orbital parameters.

Indeed, knowing the time shift measured by a station with regard to a determined predict, the drift of the semi-major axis is deducted from and corrected for re-computing new predicts. This technic was succesfully used.

It has to be noted that this drift was about 2 to 3 kms/day at D-2 days while the last predicts sent in the morning of july 11 were computed with a 65 kms/day drift and was correct.

Realizing this operation and its good completion was allowed, in our opinion, because it was existing in CNES an operational

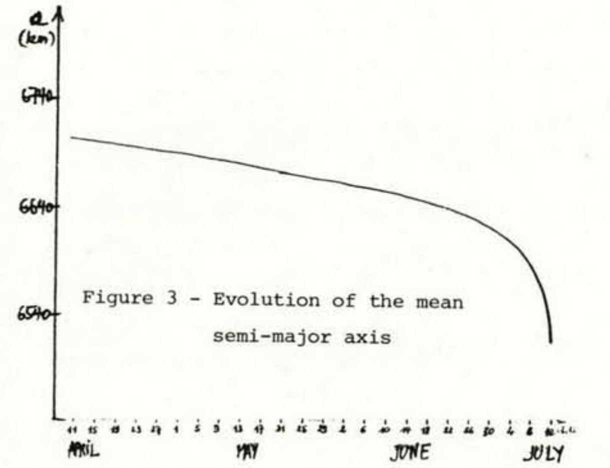


Figure 3 - Evolution of the mean semi-major axis

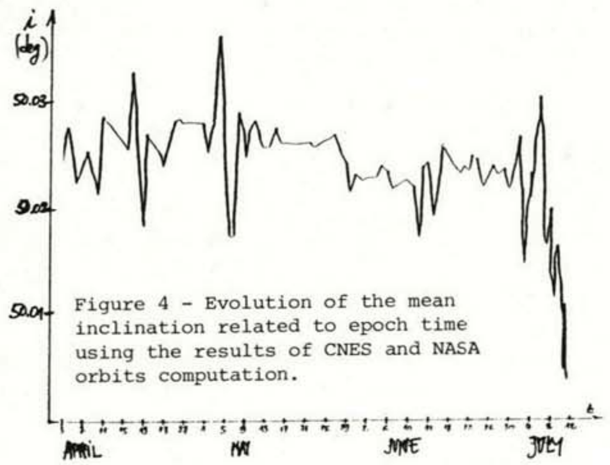


Figure 4 - Evolution of the mean inclination related to epoch time using the results of CNES and NASA orbits computation.

team for orbit computation.

Having the habit to identify very different kinds of orbits (low orbits, transfer and geostationary orbits, ...) and having participated to several launch operations (french and foreign), this team had the necessary ability to adapt itself to this operation.

2.4 Pass predicts

The pass predicts have been issued by means of an orbit extrapolation software , using an analytic method (Brovwer) allowing the predict 5 days prior with a good accuracy the area over which was passing SKYLAB during the latest revolutions. (The maximum error for fixing the track in longitude could be easily evaluated. It didn't exceed 2 to 3 deg.). Then, from july 7 or 8 it was possible to represent the areas covered by the satellite on july 11, date of decay (see fig. 5) indicating the times at which the satellite was passing over each country. As in proportion to the tracking data were allowing to upgrade the knowledge of the decay window, it was possible to have an accurate update the dangerous area being located in the possible decay window.
What is two orbit passing over France were dangerous in the morning of july 11, before the tumble manoeuver. This manoeuver performed at 07.45 UT allowed to diminish the C_a coefficient. The spacecraft lifetime was 2 hours increased. The orbits over France were no more critical. The decay orbit was then located over Atlantic and Indian Oceans.

It has to be noted that, from the begining of the operations, NASA announced that the reentry would be controlled in order to have the decay precisely on this Oceanic" orbit. With two manoeuvers one performed on june 20 nd and the other one on july 11st, NASA was able to decay SKYLAB exactly on the planned orbit, using only the evolution of the drag coefficient. This technic, very difficult to control, has been succesfully used by the Americans.

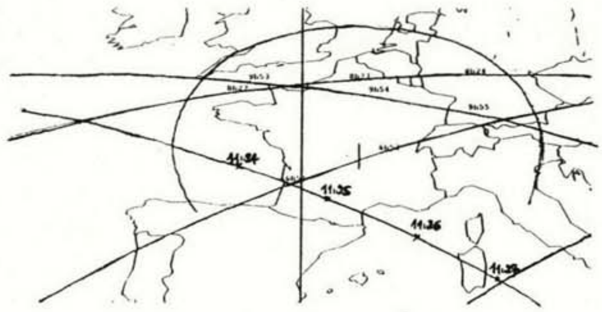


Figure 5 - SKYLAB pass over FRANCE on july 11, 1979 : UT time

3. REENTRY PREDICTS

Each orbit determination improves the knowledge of the spacecraft decay and allows to get more accurate reentry predicts. The nominal date for decay is then computed from assumptions on the evolution of a certain amount of parameters function to the altitude and the motion of the satellite. The uncertainty on this evolution allorws to define a decay window.

3.1 Computation algorithms

SKYLAB decay date was related to the abiloty to forecast the evolution, on one hand of the parameters allowing to calculate the aerodynamic (C_X) and geometric (S/M) coefficients.

This forecast being rather difficult, it was believed necessary to direct our study to a global modelization of the phenomena for describing the perturbations of the Keplerian orbit.

The whole orbit determinations is going to be used to identify the mean aerodynamic coefficient (C_a) showing the best the evolution of the semi-major axis of the orbit. This coefficient will have integrated itself the short-term fluctuation : from the altitude (h), the atmosphere density (ρ), the eccentricity (e), the solar activity

(Kp) and flux (F-$\bar{F}$), the attack surface, the drag coefficient (C_x).

Then the aerodynamic force is as follows :

$$F = -\tfrac{1}{2}\, \rho_{ref}\, k\, \frac{S C_x}{M}\, V^2\, \vec{V}/|\vec{V}|$$

V is the satellite speed related to the atmosphere

$$V^2 = (V_{Sat} - V_{Atm})^2 = V^2_{Sat}\left(1 - \frac{Vatm}{Vsat}\right)^2$$

$|Vatm| \sim 0{,}5$ km/s

$|Vsat| \sim 8$ km/s

Then $\frac{Vatm}{Vsat}$ ratio is small

$$V^2 = V^2_{Sat}\left(1 - 2\,\frac{Vatm}{Vsar}\right)$$

The evolution of the semi-major axis is provided by the following perturbations formula.

$$\frac{da}{dr} = -\,\frac{a\,|\vec{Vsat}|}{E}\;|\vec{F}|$$

a orbit semi-major axis

$\vec{V}_{Sat}$ satellite speed

E Orbit energy

This formula is easily transformed : $\left(E = -\frac{\mu}{2a}\right)$

$$\frac{da}{dr} = \frac{2a^2\,|\vec{Vsat}|\;|\vec{F}|}{\mu}$$

The result is the equation giving the evolution of <u>a</u>.

$$\frac{da}{dr} = -\,\rho_{ref}\, k\, \frac{S C_x}{M}\; \frac{a^2 V^3_{Sat}}{\mu}\left(1 - 2\,\frac{V_{atm}}{V_{Sat}}\right)$$

For a circular orbit :

$$V^2_{Sat} = \frac{\mu}{a}$$

$$\frac{da}{dt} = -\left[\frac{k\, S C_x}{M}\left(1 - \frac{2V_{atm}}{V_{Sat}}\right)\right]\rho_{ref}\sqrt{\mu}\sqrt{a}$$

VSat is sligthly varying function to the altitude then $\frac{Vatm}{VSat}$ can be considered as constant.

Integration of this equation for obtaining the evolution of a

$$\frac{1}{\sqrt{\mu}}\int_{a_0}^{a_f}\frac{1}{\rho_{ref}^{(a)}\sqrt{a}}\,da = -\int_{t_0}^{t_f} k\,\frac{S C_x}{M}\left(1 - 2\,\frac{V_{atm}}{V_{Sat}}\right)dt$$

The second term of the equation defines a mean value of little varying terms included in the integral. If $(t_f - t_o)$ is much greater than an orbit (if $t_f - t_o$ is about one day = 16 orbits) this coefficient is really significative we will call it <u>aerodynamic coefficient Ca</u>.

$$C_a = \int_{t_0}^{t_f} k\,\frac{S C_x}{M}\left(1 - 2\,\frac{V_{atm}}{V_{Sat}}\right)dt$$

The integral equation is reduced to :

$$\frac{1}{\sqrt{\mu}}\int_{a_0}^{a_f}\frac{1}{\rho_{ref}\sqrt{a}}\,da = -\,C_a\,(t_f - t_o)$$

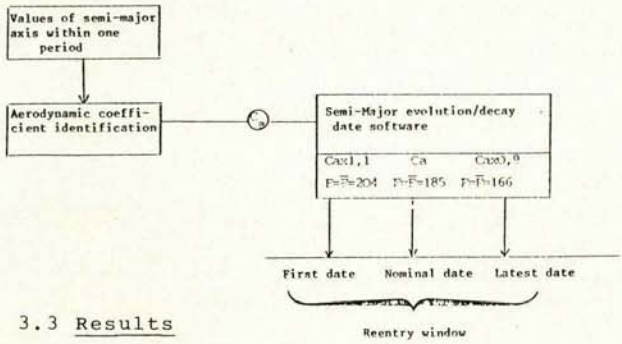
This equation is resolved by numerical integration in order to obtain the semi-major axis value related to the epoch time.

3.2 <u>Utilization of the algorithm</u>

The first calculation is used to identify the aerodynamic coefficient C_a, from the evolution of the semi-major axis within several days (value issued from orbit computation).

The C_a coefficient to find is the one minimizing the variations between the computed and the true values.

Not knowing in advance the evolution of C_a coefficient, the most probable decay date is computed considering C_a constant. The limit values of the window are obtained applying a ± 10 % uncertainty on the aerodynamic coefficient and on the knowledge of the solar flux.



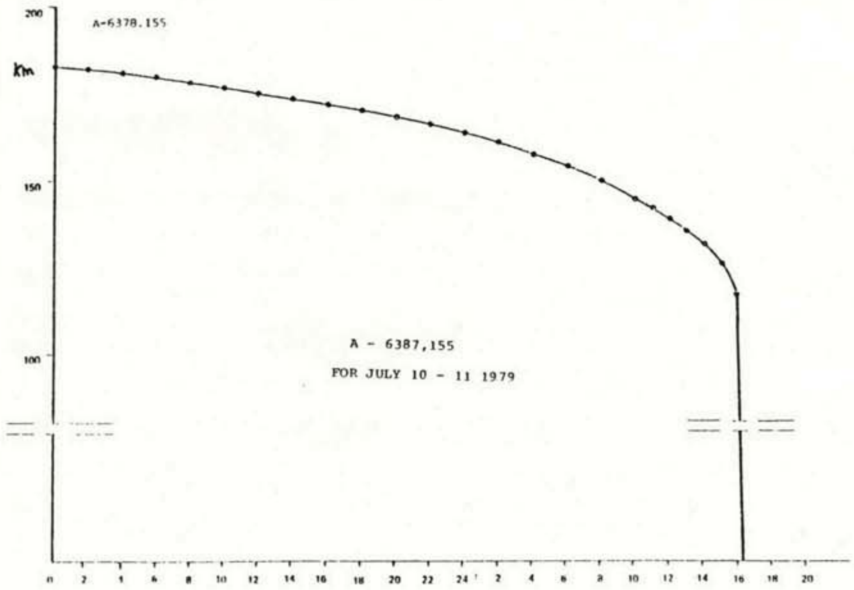
3.3 <u>Results</u>

On the figures are shown the reentry windows issued by CNES and NORAD from mid-may. From 15 to june 6 the CNES windows have been issued only with an uncertainty of ± 10% on the aerodynamic coefficient. If we add to this an uncertainty of ± 10% on the flux, all the issued windows include the effective reentry date (july 11). This date was announced july 2 by CNES and july 5 by NASA.

On the other hand the effective decay time wasn't in the last window issued by CNES (about one hour shift). This shift could be explained as follows :

- The prediction program was based upon the assumption of a slight and non-secular evolution of different parameters.
- The tumble manoeuver, on the last day didn't allow us to identify the new aerodynamic coefficient.
- the atmospheric density is computed for altitude on the equator, assuming that the errors concerning the altitude variation were included in the C_a aerodynamic coefficient.

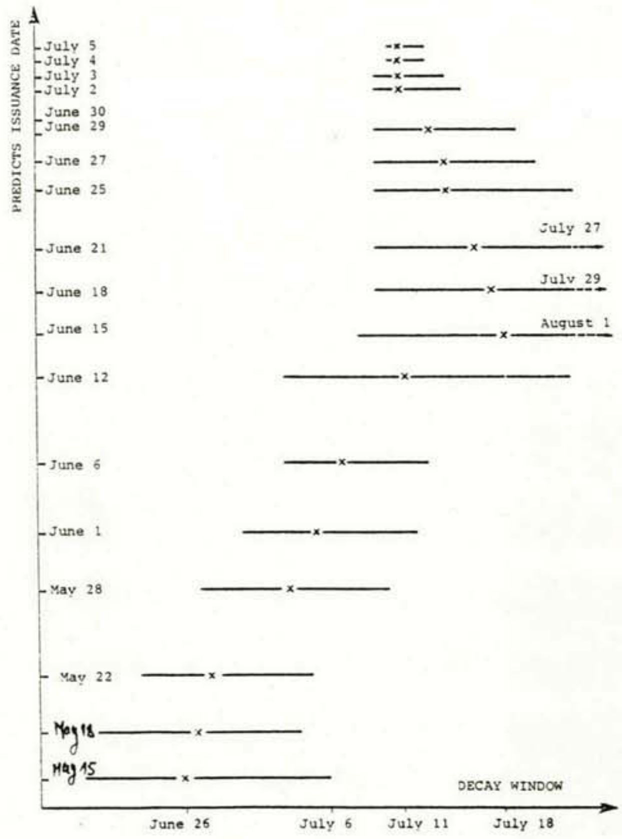
The true altitude of the satellite was 12 kms varying between equator and latitu-



de ± 50 deg. Then this variation was not well taken into account by the aerodynamic coefficient C_a at the end of orbital life. To improve the knowledge of reentry date it was absolutely necessary to use the mean altitude (equator altitude + 6 km) with these new assumptions the decay date is 16.51 UT.

On condition that modification, the method used in this decay date predict program, gave during all SKYLAB follow-up, satisfactory results.

The logical following to get more accurate the short-term predicted date, is a sufficient knowledge of the coefficients related to the attitude and aerodynamism of the spacecraft associated with powerful trajectography capabilities. Then it would be possible to completely take into account the atmosphere model from F. BARLIER which takes of course into account the true altitude.



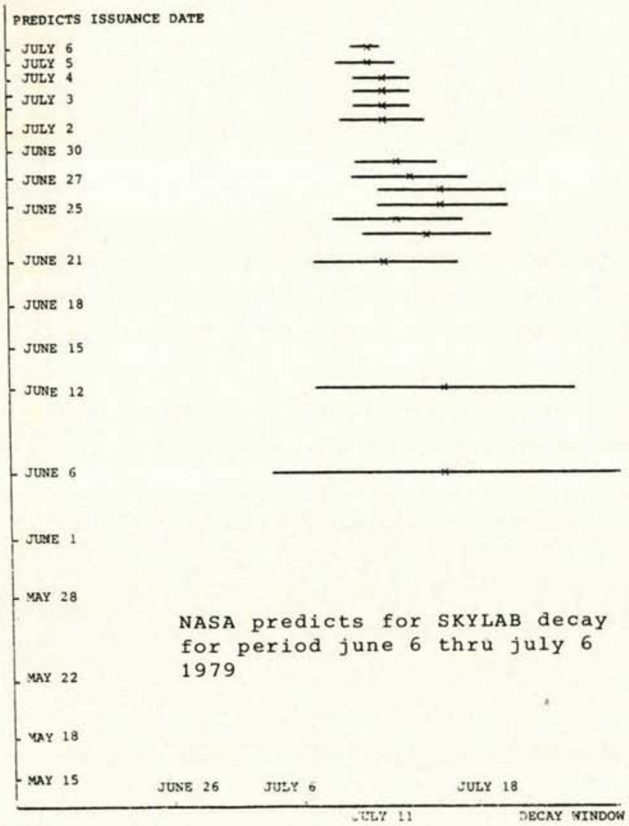
CNES predicts for SKYLAB decay for period may 15 thru july 5

4. OPERATIONAL PROCEDURES

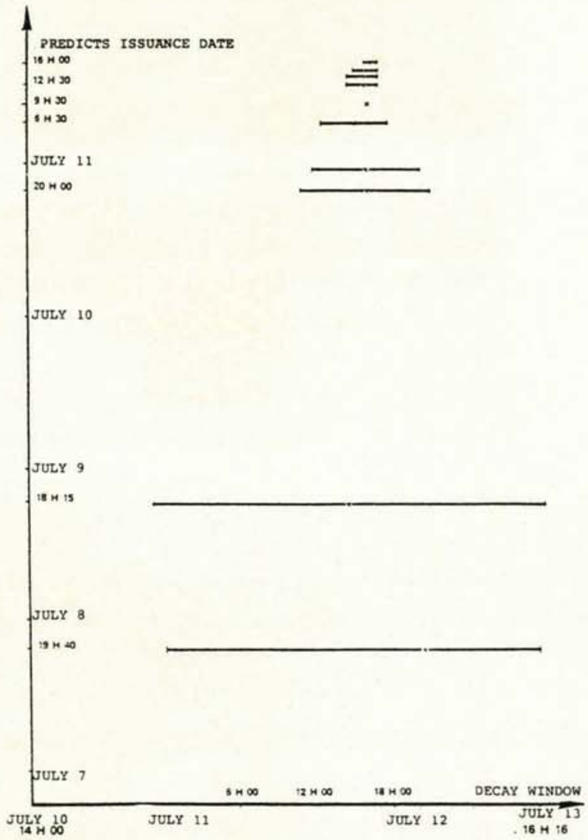
The first implemented software were the ones for obtaining SKYLAB pass predicts over each radar site, from NORAD orbital parameters.

These software have been built-up in proportion to the interfaces definition and stations needs to qualify the acquisition system.

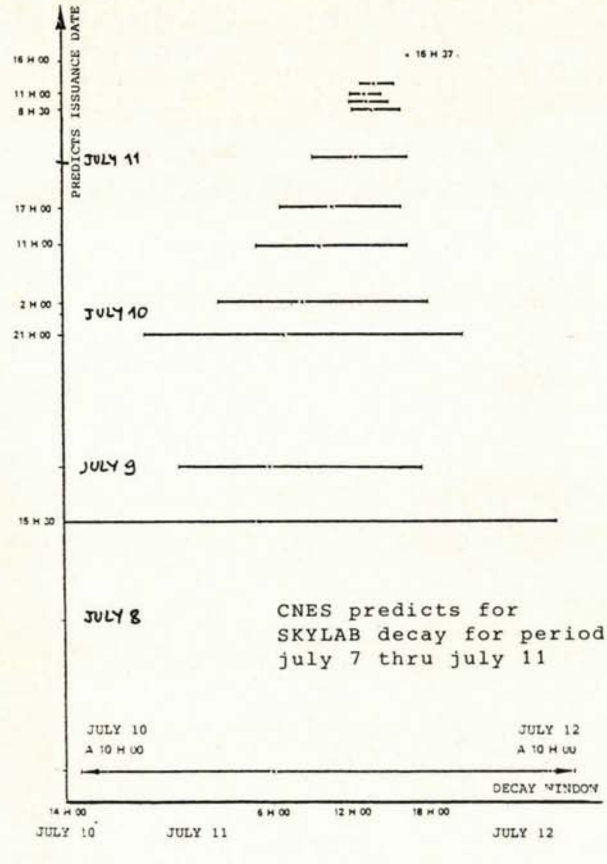
This work and the corresponding operation tasks were performed within the framework of the routine tasks of the orbit determination Operational Section from Department of Orbit Computation.



NASA predicts for SKYLAB decay for period june 6 thru july 6 1979



NASA predicts for SKYLAB decay for period july 7 thru july 11



CNES predicts for SKYLAB decay for period july 7 thru july 11

For data collection we waited for the perfectly defined interfaces with the stations.

Then the problem analysis could be done globally, which allowed to develop coherently the appropriate software.

So, all the translations were programmed under the form of small modules allowing a fast assembling with regard to the stations and an effective intervention in case of modification of data collection mode. This type of modification has been done in order to minimize the station operators (e.g. KOUROU).

In this phase, the first priority was to translate the data in NORAD format for sending to NASA coherent datà. During this time frame NASA emphasized on the fact that only the calibrated stations : (i.e. getting data to be validated in the NORAD orbit determination) could participate in the operations.

In this framework complete transmission tests (Data Collection, B3 format translation, data routing to NORAD via NASA), with near-real-time constraints allowed to determine and to advise NASA, of the necessary and accepted transmission delays for the planned operations in the final phase. These tests were performed in the normal computer working hours.

In parallel, using the same modules the interface with the data base has been performed.

Except during the week-ends for which the predicts update was necessary (passes on Monday morning) and during the near-real-time tests, the predicts, the B3 format translation, data base update, have been normally processed withing the framework of orbit determination operational operating until D-10 days.

From May this job was filed in a log-book.

During this period the software and personnel redundancy aspect was implemented :

- all the software except the orbit determination one have been translated to be runned either on the CYBER or 6214 computer either on the 7614 computer.
- a safeguard and restore procedure was implemented for all the static or no static files used in the whole chair.
- for the personnel, the three operational teams (7 people), planned for ensuring the final phase were trained to use the programs, to input the data and to control the results. On this way this task was aided by the log-book reminding the sotfware inputs and including the list of execution packets.

The data validation and the adjustement of the orbit computation were more difficult.

On june 19 we were able to compute a first orbit using only KOUROU (this capability was used at first to qualify the orbit because the data signification and the coordinates were perfectly known).

From this orbit we have progressively introduced the data coming from the other capabilities except POINCARE. We were able to validate the results by comparison of predicts issued with NORAD orbit and the time shifts measured in station

We have determined the optimum period (3 days) allowing to adjust the whole orbit parameters and the drag coefficient.

During the june 30 week-end we recalculated all the orbits with a 3-day period with a one-day overlap till june 29. This allowed to join with the operational determination. The friction being more and more important, the orbit has been computed every day with a 2-day measurement period.

On july 2, using a good orbit determination with data from june 20 to 22 we validated the june 21 pass performed by the POINCARE of which we didn't take into account till this date (these data introduction being more difficult coordinates in motion).

On D-6 days according to the arrangements with NASA (data Sending in near-real-time except during computers night closure) the operational teams were implemented to be on duty 24/24.

On D-2 days, Monday July 9, the computers were opened 24/24 and the whole Service was provided, each operational team insuring the whole following functions :

- generation of pass predicts
- data collection, validation, Nasa translation
- NORAD orbital parameters and interesting information coming from NASA
- orbit computation
- reentry windows determination
- graphs

At his date the orbit determination was performed each time the measures were received.

The predicts adjustement was provided for every group of passes for which the transmission and in-station computations delays allowed this operation.

5. CONCLUSION

The tasks performed within the framework of SKYLAB reentry allowed to reach the prime goal which was to advise the people of the risk of SKYLAB falling down the FRANCE and French Overseas territories.

This goal was reached : early in the morning of july 11 it was possible to assure that any risk for France was removed. (However there were fears for New-Caledonia and Kerguelen Islands).

We were able to overcome the difficulties concerning the provision of sufficiently accurate acquisition data to the radars, due to an appropriate tracking procedure and due to the implementation in CNES of a 24/24 operational service.

This allowed to follow up SKYLAB untill the last orbit, to perform a good cooperation with NASA and to inform in the imposed delays the Agencies concerned with the risk of SKYLAB falling down. The whole tasks described in this document is the First CNES experience in the framework of atmosphere reentry follow-up for an unmanned satellite. More than the operational aspect and the capabilities coordination we have had to overcome, the CNES experience has been developped in the fields of radar designation, low-orbit determination and decay window predict. The near-real-time reaction aspects, which was capital in proportion to approach the effective date, has been a good training very motivating, for the personnel in charge of the future operations (launches, transfer orbit and placing in position, "rendez-vous", manned reentries).

Of course, these operations will be prepared a long time in advance with more fixed procedures and an adapted personnel training. However we have to plan a flexibility of the processing capabilities which must allow, in this kind of operations, to have very short reaction delays ; this was important in the framework of SKYLAB reentry follow-up.