COLLISION OF CERISE WITH SPACE DEBRIS

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ABSTRACT

The 24th of July 1996 at 9h 48 mn UT, a sudden loss of attitude has been observed by the control centre of the french microsatellite Cerise. The first investigations based on telemetry analysis have rapidly concluded that an important change in the moments of inertia of the satellite had occurred. As all the subsystems were found in good health, the only possible explanation was that the gravity gradient boom or a part of it had been lost leading to a tumbling motion of the satellite which is normally stabilized by this boom and pointed towards the Earth.

As no other explanation has been found for the fracture of the boom, the hypothesis of a collision with a space debris has been quickly considered and a detailed analysis of the trajectories of all the objects catalogued in space has been undertaken. The purpose of this paper is to present the main stages of the analysis which have been performed and led to confirm the hypothesis of a collision:

-study of collision opportunities between Cerise and all the objects catalogued in data bases around the date of the attitude anomaly.

-search of unexplained changes in the trajectory evolution of Cerise and of the suspected debris: as both objects have no propulsion system these changes could be due to a collision.

-a new object appears in the data bases after the 27th of July: the trajectory of this object has been analyzed to verify that it could be the result of the collision between Cerise and the debris.

-the geometry of the encounter has been deduced from the trajectories analysis and related to the attitude movement just after the collision which has been determined through telemetry.

-determination of the collision probability between the two objects.

-estimation of further collision risk between Cerise and the same debris or the new created object.

1.INTRODUCTION

The purpose of this paper is to either confirm or refute the hypothesis that Cerise collided with space debris, on the basis of information characterising the trajectories of the different objects. Following a description of the data available for the study and its degree of precision, the logic behind the approach will be discussed, followed in turn by the detailed results of step by step analyses. Finally the section will describe any conclusions which can be drawn.

This analysis is only based on trajectory data, the informations concerning the platform and the mission being classified.

2.INFORMATION AVAILABLE

Any debris larger than about 10cm are tracked by the US Space Command: their orbital elements (2 line elements) are stored in a data base which is regularly updated and distributed by NASA. This data base, which only contains information for the general public, currently lists more than 8000 objects. It is the only available source of information for analysing the trajectories of objects in space.

Objects less than 10cm in size are much more numerous but are not inventoried. They are only represented by mathematical models in the form of flux (number of impacts per m^2 and per second on a given orbit).

It is difficult to calculate the precision of the 2 line elements since they depend on the number and quality of the measurements which have been taken, on the orbit extrapolation model and on how recent the information is. Comparisons which have been made with known satellites reveal an uncertainty of the order of a few kilometers after a few days, typically between 5 and 10 km after 5 days of extrapolation. In the particular case of Cerise, reference 1 indicates an error increased by 2.5 km, using the 2 -line bulletins extrapolated to between 24 and 48 hours. This moreover seems to be consistent with the security volume around the Shuttle during operations: this volume measures $\pm$ 5 km along the track, $\pm$ 2 km along the normal and radial directions. When debris which has been catalogued is likely to penetrate this volume, an avoidance manoeuvre is performed (reference 2).

In this data base the Cerise satellite is registered under the number 23606 and the object 18208 catalogued as debris resulting from the explosion of the 3rd stage of Ariane V16.

Since the 27th of July 1996 a new object has been listed under the number 23994 and with the comment "Cerise debris".

3.APPROACH USED

The aim of investigations in the field of trajectories is to answer the following main questions :

- Was there any possibility of a collision between Cerise and catalogued debris on the date of the observed incident ?
- if yes, is it possible to point to an unexplained change in the trajectories of both Cerise and the debris, corresponding to the date of the incident, (which would be the case if there had been a collision).
- Does the trajectory of the new object listed in the data base from 27/7/96 on, under the name of "Cerise debris" pass through the site of the presumed collision? (could the new object have come from Cerise?)
- what was the geometry of the encounter ?
- what was the likelihood of a collision occuring ?
- what is the risk of Cerise colliding with the initial debris and the new object later ?

The study will therefore involve a 6 stage approach focussing on:

. opportunities for a collision to occur,

. observed changes in trajectory,

. the trajectory of the new object,

. the geometry of the encounter,

. the likelihood of a collision,

. the later evolutions of the orbits.

4.ANALYTICAL RESULTS

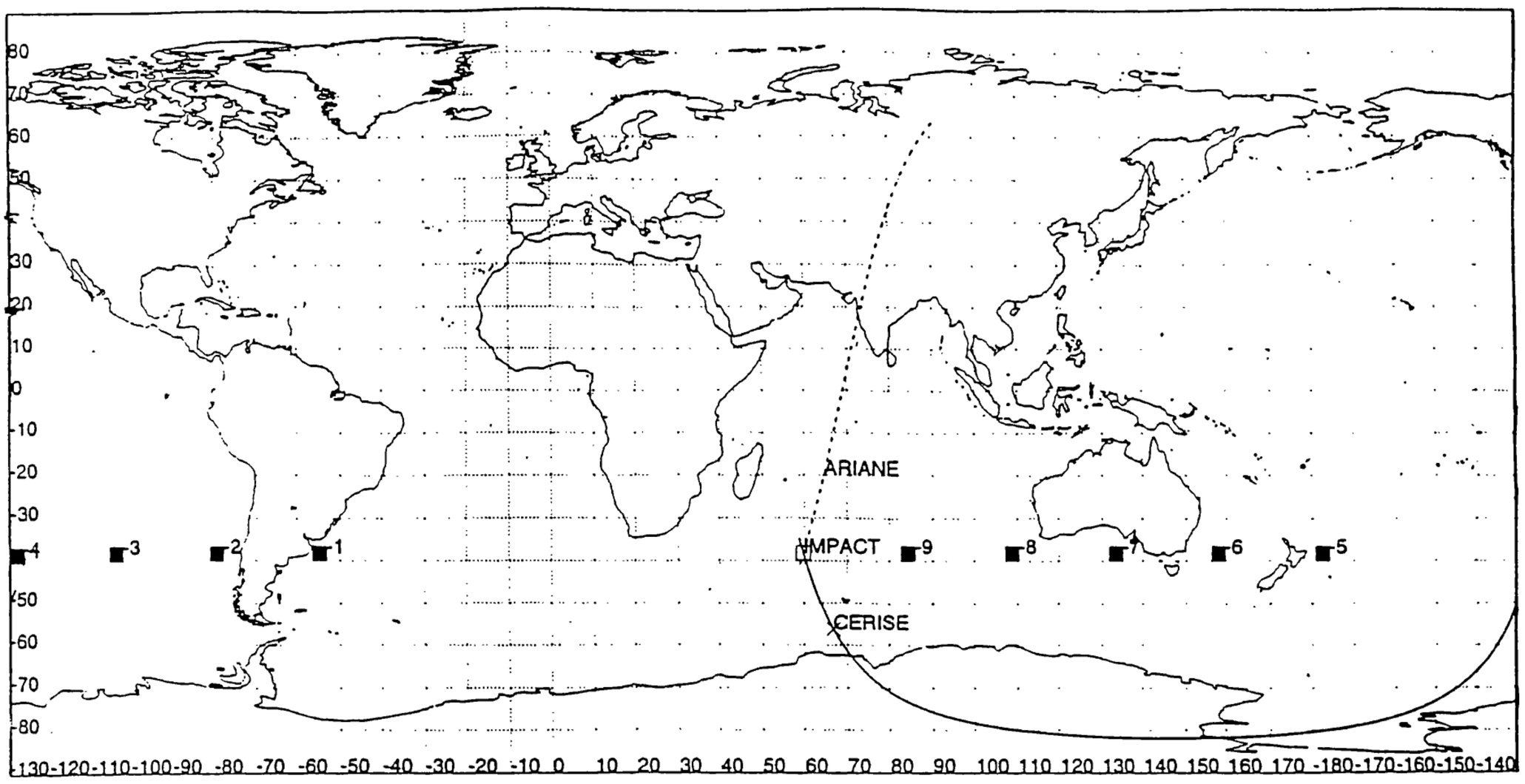
4.1 - opportunities for a collision to occur

On the basis of the 2 line bulletins, an analysis of the risk of collision between the Cerise satellite and all of the catalogued objects, for the morning of 24/7/96 shows that there was a succession of passes with a very small distance between Cerise and object n° 18208 :

time	**distance**	**relative velocity**
01h37mn02.0s	2.6 km	14.769 km/s
03h15mn14.1s	2.3 km	14.769 km/s
04h53mn26.1s	1.8 km	14.769 km/s
06h31mn38.2s	1.8 km	14.769 km/s
08h09mn50.2s	1.6 km	14.769 km/s
09h48mn02.3s	1.5 km	14.769 km/s

The following figure shows the tracks of the orbits of the two objects as well as the positions at which they were separated by less than 3 km.

OPPORTUNITIES FOR COLLISION BETWEEN CERISE AND ARIANE DEBRIS
24 HOURS BEFORE INCIDENT, DISTANCE LESS THAN 3 KM



Given the uncertainty already referred to, these passes at a distance of less than 2 km might possibly correspond to a collision.

It may be observed that once every orbit (with an orbital period of 98 min) Cerise passes close to object n° 18208 with a very high relative velocy of 15 km/sec.

	Cerise	**object n° 18208**
perigee altitude	656.5 km	652.8 km
apogee altitude	681.5 km	685.3 km
inclination	98.1 deg.	98.5 deg.
right ascension of the ascending node	142.2 deg.	335.2 deg.

Object n° 18208 has the corresponding comment "Ariane 1 deb" in the data base. It is one of 489 pieces initially inventoried and tracked by the US Space Command following the explosion of the 3rd stage of Ariane V16 (SPOT1 launch) of which 58 pieces are still in orbit.

More refined analyses were then performed to eliminate the relative lack of precision of the 2-line bulletins (cf. references 3 and 4). The principal stages were as follows :

- filtering of several successive 2-line bulletins for Cerise and object n° 18208 in order to obtain more precise orbital bulletins for the 2 bodies ;
- precise extrapolation of the motion of the 2 bodies with modelling of the atmospheric drag, while taking into account the actual solar activity observed for the period;
- computing of the distance between the 2 bodies.

This analysis determined a minimum distance of 917 m (reference 3) or 687 m. (reference 4) between Cerise and object n° 18208 on 24/7/96 at 9h 48 min. 2.5 sec.

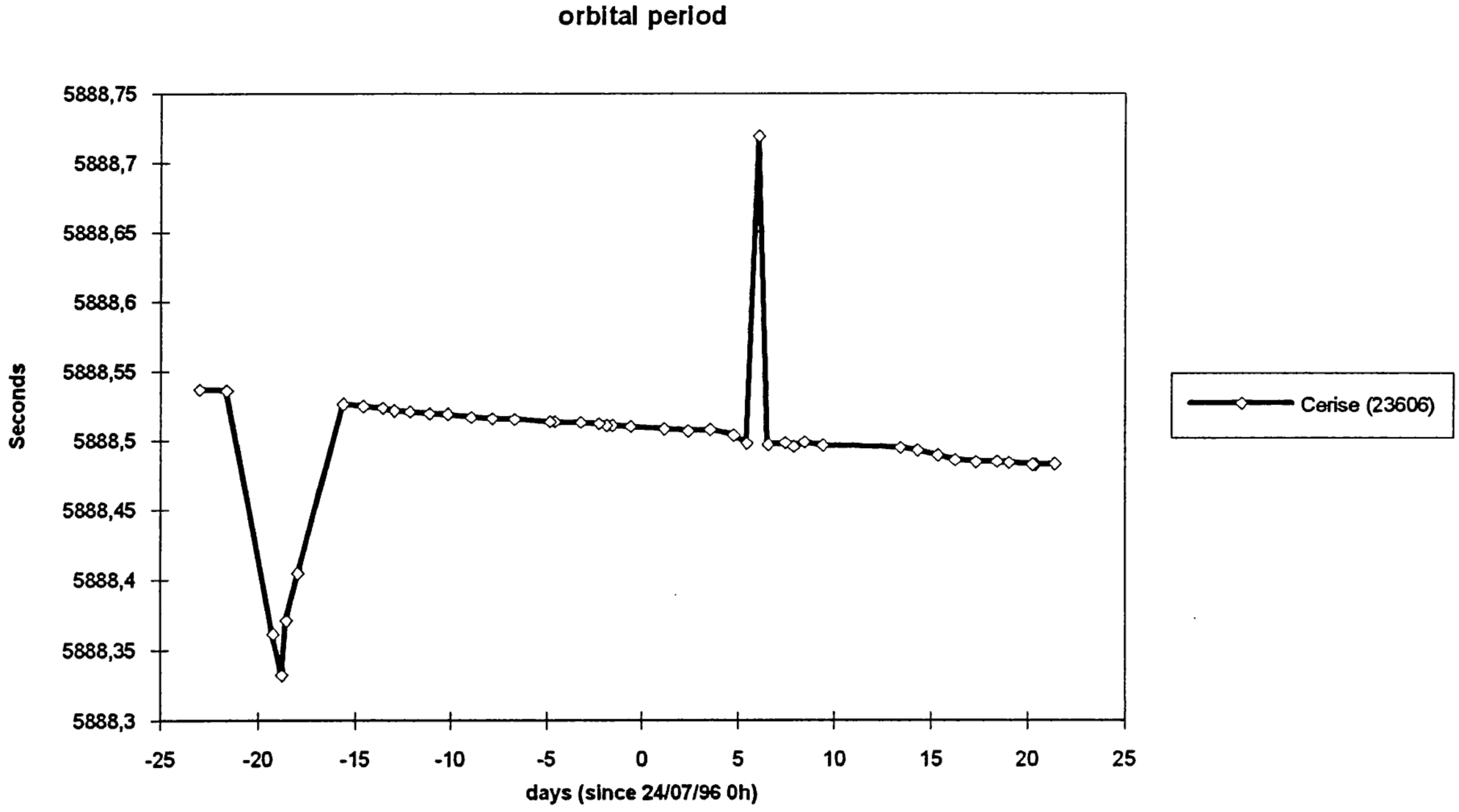
To sum up, this first stage revealed a succession of passes during which Cerise was not far from object n° 18208 on the morning of 24/7/96. Given the uncertainty due to the data used the hypothesis of a collision seems plausible (i.e. cannot be excluded) but has not been verified at this stage of the analysis.

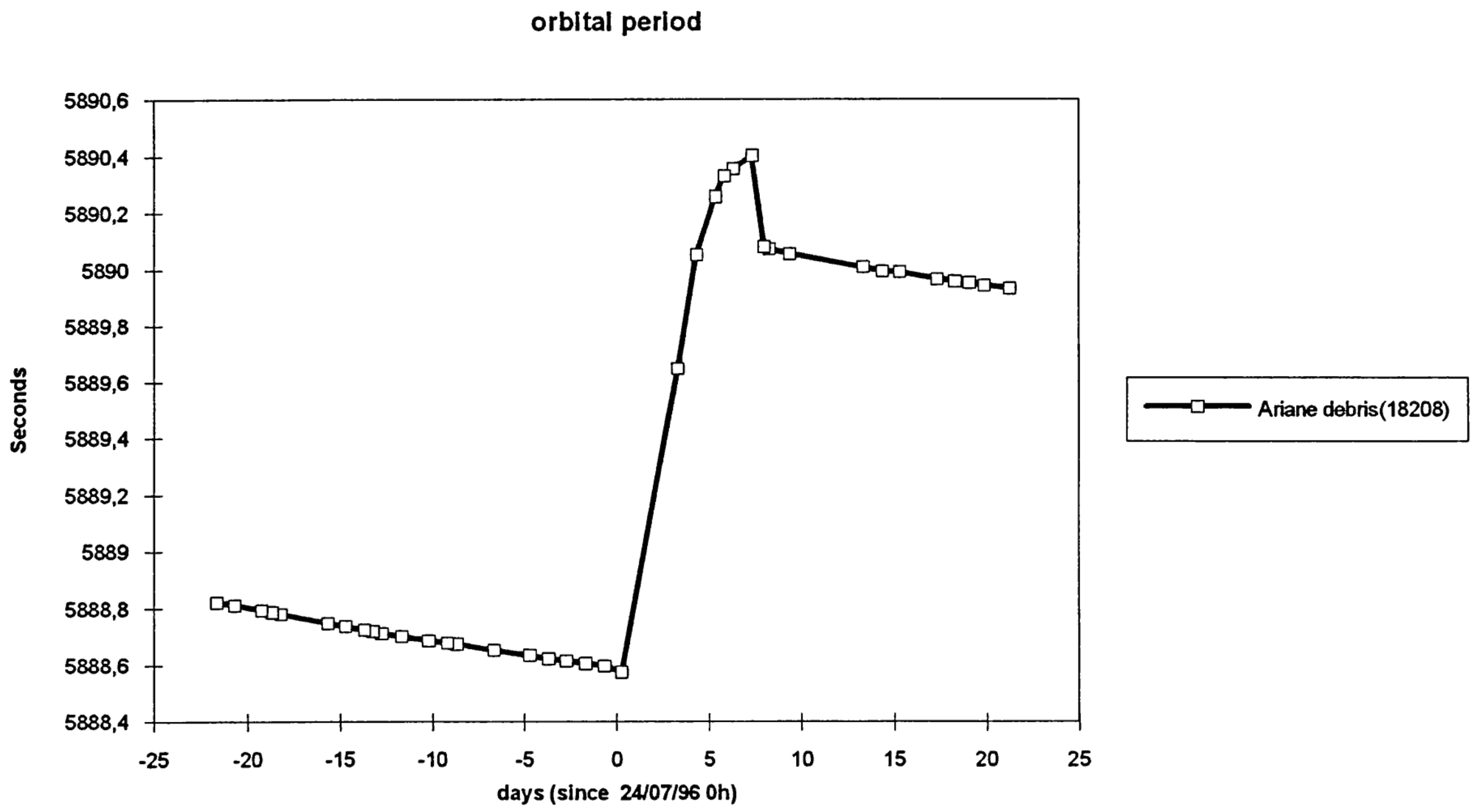
4.2 Observed changes in the trajectories

The orbit of the Cerise satellite is not controlled by a propulsion system; the same is of course true for object n° 18208. Evolution of both of their orbits is only due to natural perturbations and in particular to atmospheric drag which causes a regular decrease of the semi-major axes (and of the orbital period).

The purpose of this section is to analyse the orbits of Cerise and object n° 18208 before and after the date of the incident in order to highlight any possible unexplained change in the evolution of these two orbits.

The following figures show the evolution of the orbital period of the two objects as a function of time and around the date of the incident:





Comments on Cerise data :

- 5 points which may *a priori* be considered to be aberrant measurements (negative values for the atmospheric drag parameters $\dot{n}/2$ and β^* ;

- apart from these 5 points, a constant decrease over time due to atmospheric drag ;

- no trajectory change is revealed by the data in question.

Concerning the data for object n° 18208 :

- 6 aberrant points (negative values for the coefficients $\dot{n}/2$ and β^*) ;

- an increase in amplitude of 1.5 sec. between 24/7/96 and 28/7/96 which corresponds to a variation of 1.2 km on the semi-major axis ;

- apart from the period corresponding to the increase, a constant decrease over time due to atmospheric drag.

The changes observed are summarised in the following table :

	Cerise	**object n° 18208**
Δperiod	0	1.5 sec
Δinclination	0	0.006 deg
Δargument of perigee	6 deg	12 deg

Changes in trajectory cannot be precisely dated with the method due to the way in which a new 2-line bulletin is obtained, either :

- through extrapolation of a previous bulletin, thus masking any possible transition ;

- or from the processing of a batch of measurements which may be spread out over several days, which results in a transition period which can be seen on the graphs.

This second stage of the analysis thus shows a sudden change in orbit of debris n°18208 between the 24th and 27th of July. The date cannot be precisely determined due to a lack of data.

The change has a low amplitude which is nevertheless clearly visible on the plots and which cannot be explained by laws of natural motion. A more in-depth analysis of the atmospheric drag parameters confirms this statement. Indeed the 2-line bulletins supplied by NASA for the 6 orbits between the 24th and 31st of July reveal negative values for the parameters $\dot{n}/2$ and β^*, which can only be explained by a violation of the natural motion of the object, due either to internal (e.g. manoeuvre, violent disintegration), or external causes (e.g. a collision).

4.3 -Trajectory of the new object

A new object is mentioned in the data base from 27/7/96 under the number 23994 with the title 'Cerise debris'. The main characteristics of its orbit are as follows :

- perigee altitude : 656.1 km
- apogee altitude : 682.3 km
- inclination : 98.1 degrees
- right ascension of the ascending node : 142.2 degrees.

It was noted that Cerise's orbit was practically unchanged during the incident: the new object which came from Cerise also remained on a very similar orbit.

An analysis of the trajectory of this object extrapolated backwards in time reveals that its trajectory passed close to the site of the presumed collision on the corresponding date: following processing of the successive 2-line bulletins and orbit determination, we then had 5 different trajectories. These were the trajectories for Cerise before and after the incident, the trajectories of the debris before and after and the trajectory of the new object afterwards. Taking the assumed date of the incident, these trajectories correspond to 5 points which are clustered in a sphere with a radius of 600 m (reference 3).

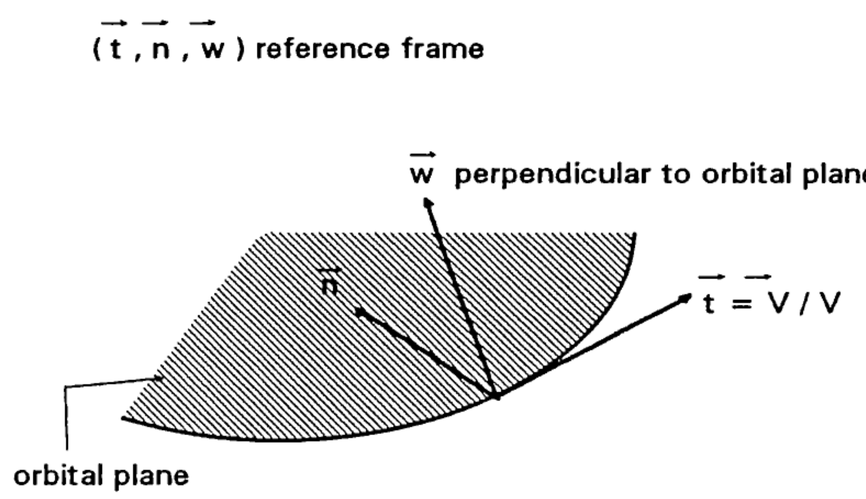
This third stage of the analysis shows that the trajectories of Cerise, of object n° 18208 and of the new object 23994 pass through approximately the same point in space on the 24/7/96 at 9h 48 min 2.5 sec. These observations are therefore consistent with the hypothesis of debris created during the collision in question.

4.4 - Geometry of the encounter

The encounter between Cerise and object n° 18208 took place at the point with the following coordinates, longitude 59.7 degrees and latitude -38.2 degrees.

The geometry of the encounter may be represented in Cerise's local orbital reference frame $(\vec{t}, \vec{n}, \vec{w})$. This reference frame is defined by :

- $\vec{t}$ according to the velocity,
- $\vec{n}$ perpendicular to the velocity, in the orbital plane, oriented towards the Earth,
- $\vec{w}$ completes the trihedron (perpendicular to the orbital plane).



The following table gives the components of the velocity vectors for Cerise in this reference frame, before and after the incident, for object n° 18208 before and after and for object n° 23994 after (in km/sec.):

	for $\vec{t}$	for $\vec{n}$	for $\vec{w}$
Cerise velocity before	7.511354	0	0
Cerise velocity after	7.510921	0.001080	-0.000340
18208 velocity before	-7.008458	-0.005089	2.699582
18208 velocity after	-7.008976	-0.006091	2.701345
23994 velocity after	7.510917	0.000401	-0.000009

The angle between the velocities of Cerise and object n° 18208 is 158.9 degrees which corresponds to an almost head-on collision.

Due to the collision, the two objects, Cerise and n° 18208, underwent a change in velocity. These $\Delta\vec{V}$, expressed in the reference frames $(\vec{t},\vec{n},\vec{w})$ for each object, are shown in the following table (reference 3):

	Cerise	18208
component for $\vec{t}$	-0.43 m/s	1.12 m/s
component for $\vec{n}$	1.08 m/s	-1.00 m/s
component for $\vec{w}$	-0.34 m/s	-1.46 m/s
module	1.21 m/s	2.09 m/s

It is astonishing to note that the period and hence the semi-major axis of object n° 18208 increased during the presumed collision whereas the two objects were going in opposite directions. The $\Delta\vec{V}$ in the trajectory of debris n° 18208 is in the direction of its velocity and not in the opposite direction.

The relative velocity vector of object n° 18208 with respect to Cerise has the following components in the reference frame $\vec{t},\vec{n},\vec{w}$: (-14.519 -0.005 2.700)

4.5 - Analysis of the likelihood of a collision

The aim of this section is to give an order of magnitude for the likelihood of a collision:

-with objects greater than 10cm in size when a possibility of an encounter at a distance of less than 2 km has been predicted using the 2-line bulletins..

-with uncatalogued objects smaller than 10cm in size.

4.5.1 - Likelihood of a collision during a close pass

Once the moments of the closest passing of two objects has been determined it is necessary to evaluate the likelihood of a collision. For this analysis the following parameters have to be taken into account:

-the precision of the orbit determination for the two objects,

-the closest pass distance predicted,

-the characteristic sizes of the satellite and the debris,

This likelihood of a collision depends mainly on the precision with which the positions of the satellite and the debris are known. This information is generally lacking when only 2-line bulletins are available.

In the specific case of Cerise, given a characteristic size of 5 m^2 and a precision for the 2-line bulletins of about 1 km, we then get a likelihood of collision of the order of 2 10^{-6}.

4.5.2 - Likelihood of a collision with objects smaller than 10cm in size

It is also necessary to consider the possibility of a collision with an uncatalogued object. In this case it would be meteorites or debris smaller than 10cm in size, whose flux is given by mathematical models. The following table gives the flux values (in the number of impacts per m^2 and per year), for a Cerise orbit, for particles with diameters greater than a given size:

	d>1 cm	d>0.5 cm	d>0.1 cm
meteorite flux	$0.57\ 10^{-6}$	$0.88\ 10^{-5}$	$0.18\ 10^{-2}$
debris flux	$0.33\ 10^{-4}$	$0.15\ 10^{-3}$	$0.77\ 10^{-2}$
total flux	$0.34\ 10^{-4}$	$0.16\ 10^{-3}$	$0.95\ 10^{-2}$

(sources: Kessler model for debris, Grün model for meteorites)

The likelihood of a collision with debris or a meteorite which are not catalogued, yet which have a sufficiently large size to break the Cerise boom remains very low. Moreover such a collision would not explain the change in trajectory of object n° 18208 which occurred on the day it passed close by Cerise.

4.6 - Later evolution of the orbits

Given the proximity of the objects following the collision, further analysis was done in order to evalutate the risk of later collisions in orbit between Cerise and the Ariane debris on the one hand, and between Cerise and the Cerise debris on the other hand (reference 5).

The data used were 2-line bulletins from around 30th July, 14th August and the 30th August in order to evaluate the sensitivity of results to the initial conditions. Likewise different hypotheses were made on the level of solar activity, and hence on the atmospheric drag.

We may conclude that since the Ariane debris has risen by 1.2 km and since its altitude is decreasing quicker than Cerise's, it will cross Cerise's orbital sphere a few months later.

As for the orbits of Cerise and its debris they are extremely close since their semi-major axes differ by only 60 m. In particular, their inclinations are practically identical which results in two coplanar orbits, at least in the beginning. Moreover, since the perigee and apogee of Cerise frame the perigee and apogee of the Cerise debris, there is a potential risk of their orbits intersecting. While it is very difficult today to predict the dates on which they will move closer, since the trajectography based on 2-line bulletins and atmospheric drag models is not very precise, it is nevertheless possible to confirm that Cerise will catch up with its debris in a few months due to its relative velocity of the order of a metre per second. Other later passes at a slight distance are also predictable as long as the differential nodal regression has not separated the two orbital planes.

The likelihood of collision cannot be calculated at the present time but the Cerise debris and the Ariane debris should be tracked in the future in order to calculate the real risks more precisely.

Comment : this analysis has not taken into account those objects in the NORAD catalogue which are likely to pass close by Cerise in the months to come, but the experience of the Cerise incident shows why such an orbitography watch is necessary.

5 - CONCLUSIONS

Analysis of the trajectories of different objects therefore reveals that:

- encounters at a very slight distance (perhaps nil) took place on the day of 24/7/96 between Cerise and the 18208 debris ;
- the time of one of these encounters (9h48min) corresponds to the loss of satellite attitude observed ;
- at the same time on the same day there was a sudden change in the trajectory of debris n° 18208 ;
- The trajectory of the new debris (object n° 23994) which was then listed in the data base pass through the point of intersection of the trajectories of Cerise and object n° 18208 on the date of the presumed collision.

The study reveals that the trajectories of the 3 objects are consistent with the hypothesis of a collision between Cerise and object n°18208. To be absolutely certain one would require a precision in determination of the orbits of less than one metre (order of magnitude of the size of the objects).

To conclude, the simultaneity of these events means that the hypothesis of a collision between Cerise and debris n° 18208 on the 24th July 1996 around 9h48 min is very likely. Moreover debris n° 23994 does appear to have been caused by this collision.

However the increase in period of the Ariane debris following the collision has not yet been explained and should be studied further.

REFERENCES

Reference 1 : Résultats d'orbitographie de le station Cerise (note CNES CT/TI/MS/AM/96-128 du 3/4/96) [Orbit determination results from the Cerise station]

Reference 2 : Interagency report on orbital debris-1995 (The National Science and Technology Council, Committee on Transportation Research and Development)

Reference 3 : Etude de la collision entre le satellite Cerise et un débris Ariane (note CNES CT/TI/MS/IO/96-319 du 29/8/96) [Study of the collision between the Cerise satellite and Ariane debris.

Reference 4 : Etude Incident Cerise, note ONERA n° DES/SA/09-96/1 septembre 96 [Study of the Cerise Incident]

Reference 5 : Etude de l'incident Cerise du 24/7/96 (note ALCATEL ESPACE ATES 96/038/383/PML/0090) [Study of the Cerise incident on 24/7/96]