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OLYMPUS END OF LIFE ANOMALY - A PERSEID METEOROID IMPACT EVENT?

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Summary-On August 11, 1993 at 23:32 Zulu (UT), the OLYMPUS satellite lost earth pointing and began spinning, leading to a chain of events which culminated with the satellite's demise. The spacecraft automatic control system attempted to despin and reorient the spacecraft but was unsuccessful. These manoeuvers caused significant fuel depletion. During reacquisition under manual control, it was determined that insufficient fuel remained to return to station. The decision was made to take OLYMPUS out of service, removing the spacecraft as far as possible from the geosynchronous orbit.

The morning of August 12 was predicted to be the peak of the Perseid's meteoroid shower. There was the possibility that the meteoroid stream might reach storm conditions with relatively fresh material released during the last appearance of Comet Swift-Tuttle returning near the Earth. Assessments of the situation had indicated that it was unlikely to be a problem, but an on-board micro-accelerometer package was operated to record impacts, and operators and support staff were put on special alert in case of operational difficulties.

This paper will describe the spacecraft, the sequence of events, tests and analysis, and make operational and design recommendations. While an impact by a meteoroid could not be proven, it is a possible scenario. The impact by a small meteoroid may have generated a plasma triggering a discharge of charged surfaces entering the grounded spacecraft via the umbilical and an external sensor. Such a scenario is particularly interesting for other spacecraft since the Perseid shower is likely to be worse for the next few years.

OLYMPUS - THE LAST ANOMALY

INTRODUCTION

On the night of 11/12 August 1993, the European Space Agency's experimental communications satellite, OLYMPUS, was automatically driven into Emergency Sun Acquisition (ESA) mode after shutdown of the controlling gyro. This was the night of the predicted peak of the annual Perseid meteor shower. Although the entry conditions into ESA mode were benign, the spacecraft failed to acquire the sun, resulting in a spin about the roll axis. This report describes the results of the investigations into the anomaly events. Investigations were conducted jointly by ESTEC, ESOC, Telespazio, BAe Space Systems Ltd., GEC Marconi Avionics, and the University of Kent at Canterbury.

The Director of Telecommunications asked the Communications Satellites Department to lead an investigation into the causes of the anomaly and make recommendations. The team was composed of specialists from the European Space Agency and industry. The industrial side was led by British Aerospace, the OLYMPUS prime contractor. The Team reviewed the design of the Attitude Control System and Emergency Sun Acquisition electronics, the potential reasons for the anomaly in a systematic manner, and the telemetry records. In addition, simulations were performed and reported on. Hardware tests were also conducted with the assistance of GEC Marconi Avionics, the supplier of the gyro. The University of Kent Space Sciences Group was brought in to analyse the potential effects following a meteoroid hit. In addition, the experience of ESTEC with similar problems on Giotto and other missions were reviewed. This paper summarises the results of the investigation.

OLYMPUS BACKGROUND

OLYMPUS was launched in July 1989 to promote and conduct experiments in many areas of communications including direct broadcasting and video conferencing. Among its many uses, OLYMPUS has been instrumental in the development of distance learning satellite applications with over 100 organisations in twelve countries using OLYMPUS to develop training courses which have become part of the established satellite-based educational infrastructure. In the broadcasting field, OLYMPUS was the initial test bed for satellite broadcast programmes such as RAISAT and the BBC Enterprise channnel. The latter was an important precursor to the BBC World TV Service. Demonstration transmissions of High Definition Television were also conducted.

During late 1992 and the first part of 1993, the satellite was used in establishing a data relay link with data being transfered from the experimental Inter Orbit Communications (IOC) terminal on-board the Eureca satellite in low earth orbit to OLYMPUS and then to the earth control and receive stations. This was the first interorbit link demonstrated in Europe and the first use of data relay in the world using the Ka frequency band. For further information, a more complete payload description can be found in Caswell(1994). An exploded view of the OLYMPUS satellite is shown in Figure 1.

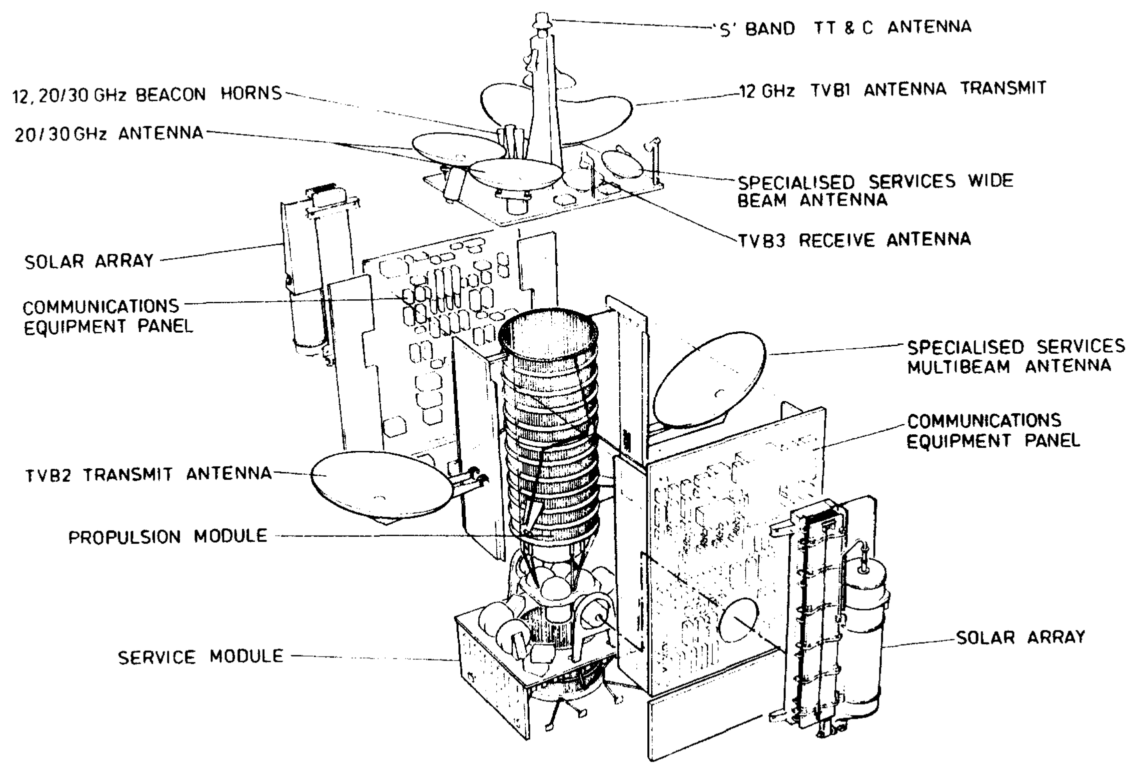

Figure 1 OLYMPUS Exploded View with Stowed Solar Arrays
X-Axis through side antennas (Roll) East/West panels
Y-Axis through deployed solar arrays (Pitch) North/South panels
Z-Axis through apogee engine and forward antennas (Yaw) Aft/Earth panels.

LAUNCH AND OPERATIONS

The OLYMPUS spacecraft was launched on 12 July 1989 by the last of the Ariane 3 vehicles. Early transfer and orbit operations were conducted from ESOC in Darmstadt, Germany. The in-orbit operation at 19 degrees west longitude, was conducted by Telespazio in Fucino, Italy with payload operations conducted from ESOC in Redu, Belgium and ESTEC in Noordwijk, The Netherlands. OLYMPUS proved to be a hardy survivor, demonstrated with a recovery following a trip around the world after an operational and hardware problem in 1991. During this anomaly, the spacecraft was exposed to temperatures much lower than it was designed for, but it suffered only minor damage following a careful thawing and return to full operation. With the unexpected use of large amounts of propellants due to this problem, it was necessary to carefully monitor and conserve the amount of remaining fuel and oxidiser during the rest of the mission.

Major reprogramming of the control microprocessor with new algorithms saved significant fuel. Also, the earth sensors were operationally replaced by the gyroscopes for six hours a day for the generation of an earth reference, to overcome an earth sensor anomaly. North/south stationkeeping was also stopped at the end of 1991 in order to save fuel which had a small impact on communications performance as the inclined orbit increased in inclination.

ANOMALY EVENTS

Prior to the anomalous events of August 11, operations had been proceeding normally. The daily entry into Skew Pack Earth Attitude Reference (SPEAR) gyro control had been undertaken. This control mode provides an earth attitude reference utilising the skew pack gyros in order to overcome the intermittent loss of Infra Red Earth Sensor(IRES) earth reference which was occuring during some seasons around local midnight. A design fault resulted in a sticking scanning mirror under some direct solar conditions. Automatic momentum dumping (SHIELD mode) had also been entered. This mode desaturated the wheels in an efficient manner as a result of the fixed south array, saving fuel.

At 23:40 Zulu (UT) on August 11 1993, the roll attitude appeared to diverge and at 23:53, earth presence was lost on IRES B which was in a monitor mode. By 00:20, an Automatic Reconfiguration Mode(ARM) was undertaken when the angular failure detection limit of 15 degrees, the normal hourly angular rate, was exceeded. For ARMs generated during spear control, the onboard logic would reconfigure directly to Emergency Sun Acquisition (ESA) mode. This was also entered at 00:20.

On call personnel at Fucino (Telespazio, ESOC and BAe) were contacted in addition to personnel at both ESTEC and BAe. All supported the subsequent activities. Everyone had been on alert due to the predicted meteoroid activity. Because the ESA mode did not capture, efforts were made to maintain power levels and regain control of the spacecraft. The spacecraft was eventually configured in a stable state spinning about the roll axis.

Subsequent analysis of telemetry has indicated that there were two major anomalous events, i.e.,

1) The roll gyro had spun down and stopped at 23:32(estimated). This had resulted in the ARM and entry into ESA mode. There was no gyro performance degradation prior to or after this event.
2) Despite the successful reconfiguration and benign body rate entry conditions, the ESA mode had failed to acquire the sun.

In addition, three other apparently minor anomalous events were identified, i.e.,

3) An anomaly in the north solar array position telemetry. The north solar array is automatically slewed to the -Z(aft) position as part of ESA mode automatic operations. Telemetry initially indicated that the array had acquired that position but subsequently it was shown that it was not at that orientation.
4) A small change in the pitch wheel speed of about 4 rpm in 1500, concurrent with the stopping of the roll gyro. No change was observed in the yaw wheel speed. Subsequent analysis also revealed that the average change in roll reaction wheel speed, from each momentum dumping pulse, had changed.
5) There was a loss of telemetry in Fucino for seven minutes. Additional shorter losses of telemetry were experienced due to fringing effects in the antenna pattern during spinning mode.

Investigations were undertaken to establish the cause of these events. Subsequent analysis showed that the change in pitch wheel speeds(4) was due to spindown of the roll gyro. The seven minute loss of telemetry(5) was an independent ground station problem in Fucino. The remaining events(1)-(3) manifested themselves within a short time of each other and investigations attempted to establish if these events had a common cause or were in some way related to each other. Apart from these anomalous events, all other spacecraft subsystems performed normally.

OLYMPUS END OF LIFE ACTIVITIES

With the spacecraft spinning, it was not possible to fire the thrusters in a normal manner because the monomethyl hydrazine (MMH) fuel was spun away from the outlet of the tank with the propellant management device screened channel becoming deprimed. However, the nitrogen tetroxide (NTO) propellant liquid was still available to its outlet and could be expelled. After considerable discussion, it was decided that the only course open was to operate the system in a cold gas manner to despin the spacecraft until the MMH again wetted the screens in the Propellant Management Device and normal thruster activity could commence. Thruster firing was also required to reorient the spinning spacecraft towards the sun and produce sufficient power to keep the satellite platform operational. All thruster firing generally caused nutation buildup of the spinning system. This was periodically removed by a phased thruster firing.

The cold gas propulsion system worked very well and the spin rate was reduced from about 2.1 revolutions per minute about the roll axis which is through the East and West faces of the spacecraft at right angles to each of the earth pointing face and the axis through the solar arrays. Initially the spin axis was about 50 degrees out of the orbital plane and about 50 degrees back from the sun. Although the power and thermal situation was stable initially, regular adjustment of the spin axis relative to the sun was required as the satellite/sun angle gradually changed due to the normal earth/sun movement.

It was estimated that there were at most three kilograms of MMH in its tank. At least 4 kilograms of NTO were thought to be available. In addition, there was a small amount of bipropellants, about 250 grams left in the redundant propellant branch. It was clear that recovery for normal spacecraft operations would not be possible. Also reorbiting into the higher than nominal geostationary orbit was impossible because the perigee was already about three hundred kilometers below due to the spacecraft deorbiting during the failed ESA mode. The only possibility was to lower the apogee hopefully with the biprop system after despin. The thruster burns were timed to reduce the apogee and could only be performed optimally during four to five hours of the day. The spin rate was reduced from about 15 degrees per second (equivalent to 2.1 revolutions per minute) about roll to 5.4 degrees per second when the liquid MMH reprimed and full biprop performance was attained. Further despin of the spacecraft to about 1.8 degrees per second was performed with some of the redundant line fuel. Then a long burn of several minutes was planned to deorbit the apogee. However, after 38 seconds of burn, it was clear that the NTO liquid was completely expelled from its tank.

A simple quick thermal gauging test had been performed just prior to the last firing which indicated that there were about 3 kilograms of MMH and almost no NTO. The gauging accuracy was very high as only a fraction of a kilogram was proven to be left for the NTO. Only the helium gas together with the remaining MMH could be used for further deorbiting. This was thought to have about 1/50th of the normal bipropellant thrust. Fortunately, the efficiency of the cold gas system turned out to be better than anticipated probably due to NTO and MMH vapour contributing propulsively. Roughly speaking, about twice the delta V or velocity change was obtained than expected. By the end of August, the point of diminishing return had been reached with the pressure in the tanks being for NTO, 1.8 bar and for MMH, 1.2 bar. The satellite was electrically safed and the S-band transmitter was switched off with the spacecraft more than 200 kilometers below the geostationary orbit.

Prior to electrical switchoff, a short series of tests were performed to determine the final status as best as possible. The south solar array was successfully driven between the same anomalous stops on the slip ring as experienced in 1991. The south array deployment electronics were powered and the wiring was shown to be open as expected, verifying the results of the failure investigation from January 1991 when a major short occured in the drive and track of the south array, eventually interrupting power supply to the spacecraft from that array. The array was stopped from rotating for the rest of the mission after January 1991 due to concerns of possible internal bus shorts.

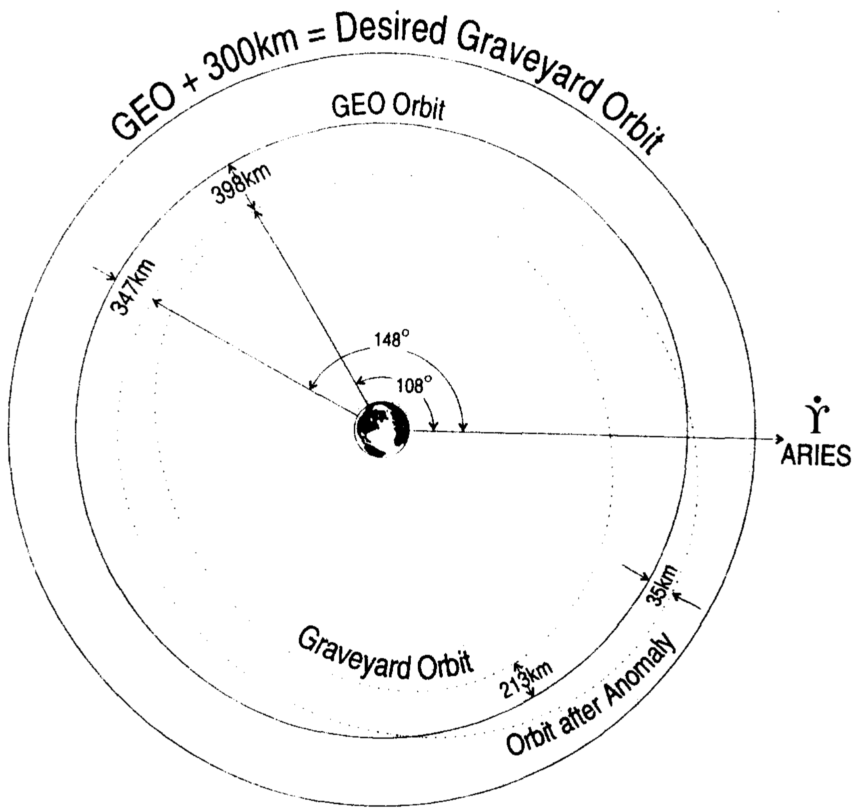

Figure 2 Orbit determination Following Graveyard Orbit Manoeuvers

ROLL GYRO INVESTIGATIONS

The symptoms of the ARM suggested that the problem lay somewhere within the roll control loop. The telemetry format was subsequently changed to examine gyro data. It was noticed that the roll gyro spin motor current was high with erroneous gyro data output. This was consistent with a gyro which had stopped spinning. The effect of the spin down and stopping of the roll gyro would be to introduce a small constant bias input to the roll control loop which would then operate in an open loop manner. This has been verified by simulation, test and inspection of telemetry. The spin down and stopping of the gyro appeared to be temporary as the gyro was later restarted after being switched off and on. The other gyros within the skew pack were apparently unaffected.

The only mechanism that has been identified which would cause the roll gyro to stop rotating is an interruption to spin motor current supply. Investigations were therefore made to identify possible failures or disturbances which would result in such an interruption but, at the same time, not affect the other gyro channels. Disturbances both internal and external to the spacecraft were considered. However several circuits are shared by all channels and therefore a marginal condition would be required for a disturbance to affect only one channel. In addition, no such problem had been observed during gyro equipment level and spacecraft system level tests prior to launch.

The effects of disturbances were investigated by test, both on the flight spare skew pack on its own and in conjunction with the Control Electronics Unit (CEU) engineering model. Power interrupt tests were undertaken with different voltage and pulse widths. In all cases, the CEU tripped out before the skew gyro pack. As the CEU did not trip during the actual spacecraft anomaly, it can be concluded that the problem was unlikely to be due to an interrupt on the 50 volt bus.

The spin motor supplies for all gyros are inhibited by thermistor circuits within the gyro pack at temperatures of less than 50°C. Electrical disturbance pulses were applied to the thermistor lines from the gyro unit to the electronic unit but it was not possible to cause any of the gyros to stop spinning. In any case, all four gyros in the pack would be affected by such an event.

The feasibility of external inputs causing the gyro anomaly was also investigated. AIT (Assembly Integration & Test) test lines allow an electrical path to the gyros. However these were ruled out as they are shielded by electrically grounded thermal blankets. It should also be noted that these pins do not lead directly to the spin motor supplies and electrical jumping between pins would need to occur.

Another possible path was via the main spacecraft umbilical. The skew pack heaters are operated before and during launch; two thermistors are wired from the pack to the umbilical. These wires could provide a possible path for Electromagnetic Interference(EMI) from the external space environment into the gyro package. This connector face is not covered. Tests showed that the gyro heaters alone could be tripped at voltages of 2-3 kV. However no effect was seen on the gyro channels(i.e. spin motors) up to 17 kV. Because of the difficulty of setting up for a full range of voltages, currents and pulse durations, not all possible combinations were demonstrated and the tests were inconclusive.

Telemetry indicated that the skew pack temperatures were constant during the event. However there is no telemetry of the heater status and the heaters are ganged together. It is feasible that half of the heaters could have tripped because there are two circuits, without affecting the temperature of the gyros.

The results of the investigations and tests were inconclusive and the cause of the gyro shutdown remains unknown. Nor is it understood why the roll gyro alone was affected but its condition was probably more marginal. The anomaly was temporary and the most likely cause was a spurious electrical event entering via the umbilical.

INVESTIGATIONS INTO WHEEL SPEED CHANGES

A change in the speed of the pitch wheel was observed concurrent with the stopping of the roll gyro. Analysis also revealed that the average change in roll reaction speed, due to each momentum dumping thruster pulse, had changed. These events were initially thought to be evidence of an external impact. However subsequent analysis showed that this behaviour could be explained as a consequence of the roll gyro run down. The change in pitch was due to the momentum transfer from the roll gyro to the spacecraft as the roll gyro ran down; the roll gyro angular momentum is about the pitch axis. An additional consequence of the stopping of the roll gyro was to effectively put roll control into open loop. The roll wheel speed change was due to a build-up of spacecraft angular momentum resulting from solar pressure torques, which are predominately in roll at this time of day. The momentum was not removed as it normally would be because roll control was in open loop due to the anomaly.

EMERGENCY SUN ACQUISITION (ESA) MODE INVESTIGATIONS

Simulations have shown that for the entry conditions on day August 11, ESA mode should have captured and remained stable. At the time of ESA mode entry, the sun was not in the field of view of the Sun Acquisition Sensor(SAS). Consequently there should have been a series of negative pitch thruster firings. These initialise a rotation of the spacecraft towards the sun and reduce the time to sun acquisition by the SAS located on the aft end of the spacecraft, near the apogee engine nozzle. Analysis has shown that these thruster firings did not occur. It should be noted that even without these thruster firings, simulations have shown that ESA mode should have captured. When the sun entered the SAS field of view, pitch and roll thruster firings did occur but ESA mode failed to capture. Simulations were made varying the tolerances in the ESA mode control loop parameters. In all cases, the ESA mode was still able to capture the sun.

The various failure mechanisms of ESA mode circuits were investigated. The only credible mechanism identified that could give rise to the observed effects in-orbit was a failure somewhere in the pitch feedback path within the ESA mode control loops. This can account for both the non-execution of the negative pitch bias thruster firings and the subsequent non-acquisition of the sun. The observed pitch thruster firings would have been commanded by signals generated only by the pitch loop forward path. Failure in the roll feedback path could also lead to non-capture but not account for the lack of the negative pitch bias thruster firings. The most likely single failure is a short circuit in a capacitor within the pitch feedback loop. Failure of a resistor (open circuit) or solder joint is also possible. CEU simulations with the failed capacitor have given similar but not identical results to those observed in orbit.

It is worth noting that the ESA mode equipment was exposed to low temperatures following the May 1991 operations anomaly after which the spacecraft drifted around the world. However freezing effects are thought to be unlikely because the capacitors have a self healing mechanism with use and the ESA mode was successfully used twice during the final stages of recovery from that earlier anomaly. The ESA mode components are also robust to ESD/radiation effects. However, random component failure is always possible. In conclusion, although there is some evidence that the ESA mode components may have failed, the exact cause of the failure remains unknown.

NORTH ARRAY POSITION TELEMETRY INVESTIGATIONS

As part of the nominal ESA mode sequence, the north solar array is driven to the -Z(aft) pipper to align the array's cell covered surface normal to the spacecraft aft panel(-Z axis) which will be rotated and held orientated to the sun. Initially, telemetry indicated that this rotation had occured with the north array at the pipper; subsequently it was determined that the array was not at that orientation. A problem could have been present in the SADM(Solar Array Drive Mechanism) but this was successfully used later. A more likely cause is that the telemetry bit was in error; particularly as a similar anomalous effect was observed on August 15 with acquisition being simultaneously indicated at both -Z and +X pippers. Single bit errors can occur.

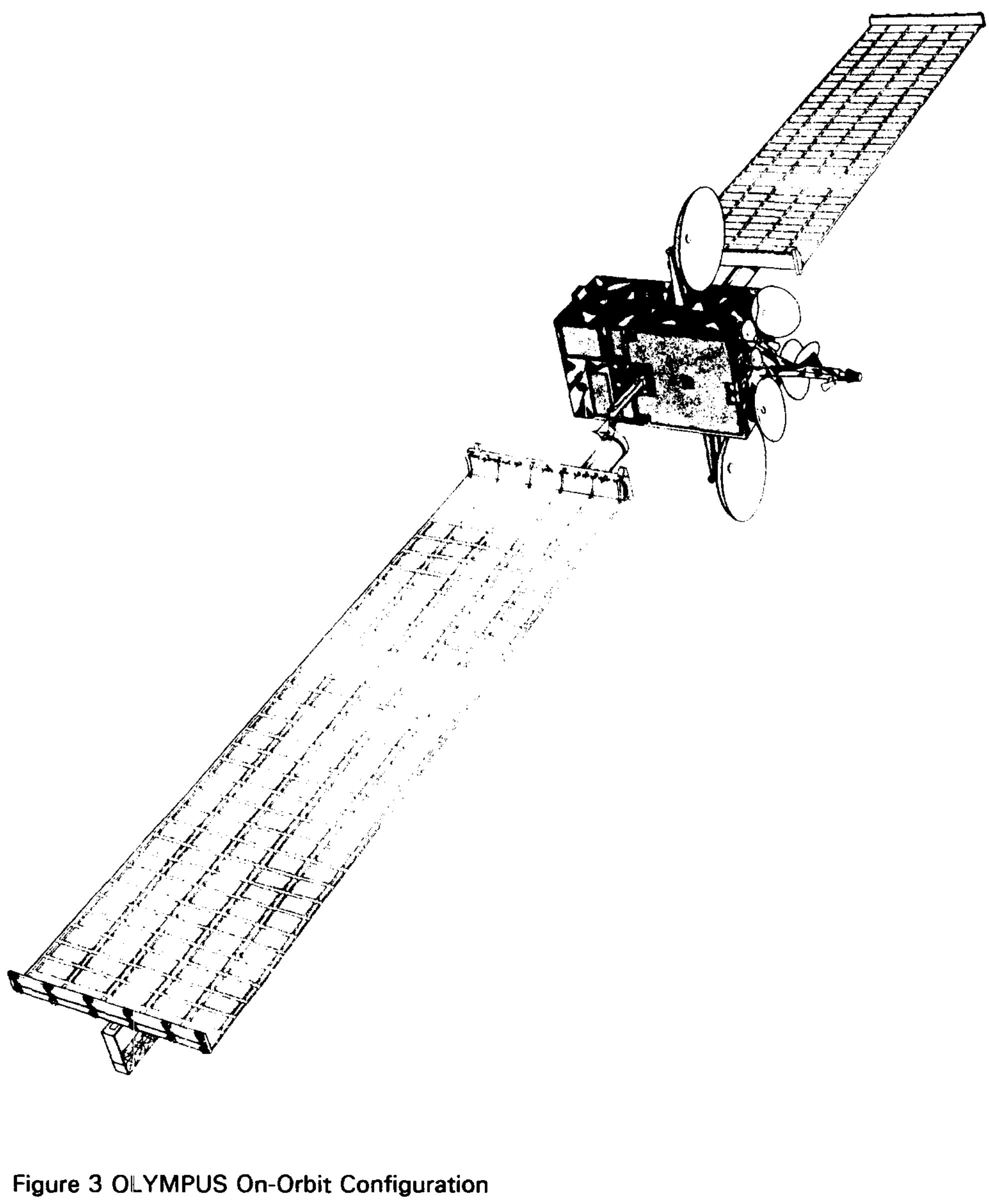

Figure 3 OLYMPUS On-Orbit Configuration

LOSS OF TELEMETRY RECEPTION INVESTIGATIONS

During the anomaly, spacecraft telemetry was lost during a seven minute period. This was later identified to be a ground station problem rather than a spacecraft problem. Antenna pointing wrongly used old pre-set data for ground antenna repointing which did not include the inclined orbit information when the spacecraft drifted from the ground antenna coverage as a result of the anomaly. Reception was reacquired when the ground antenna was pointed with the correct angles. This loss of data was quite disturbing to the support team in real time occuring during the critical moments. Other short term telemetry interruptions were experienced which resulted from the spacecraft antenna pattern fringing in spinning condition. This fringing effect caused by interference between the forward and aft spacecraft antennas had been experienced during other spinning spacecraft anomalies.

EXTERNAL EVENTS

The underlying causes of the roll gyro, ESA mode and -Z pipper anomalies are unclear. Their symptoms appeared within a short time of each other and the question arises as to whether there was a common cause. Other systems on OLYMPUS operated nominally and no internal mechanism could be identified that would generate these three anomalous events. Investigations therefore examined the feasibility of the anomalies being due to external events. It was found that no unusual solar effects occured at the time of the event or during the preceeding hours. However the fact that these anomalies occured within a few hours of the predicted peak of the annual Perseid meteor storm cannot be ignored. The operations team were on special alert in case of problems. Meteoroid impact could have several effects such as structural damage, momentum transfer, creation of a plasma cloud, and triggering the discharge of previously charged surfaces.

Telemetry was thoroughly examined for evidence of meteoroid impact. There was no evidence for either momentum transfer nor general electrical effects causing power dropouts. However the 24 second telemetry format update rate may be too coarse for detection of such transient events. In addition, OLYMPUS carried a vibration continuous monitoring unit (the PAX). This had been activated for the Perseids to monitor for any impact. The PAX data was examined in detail with negative results at the time of the event. Several transient events were detected which were not normal, particularly before the gyro anomaly. Seven events in 11 seconds were recorded about two minutes prior to roll gyro shut down. These events can not be correlated with onboard autonomous activities. It should be noted that the PAX would not necessarily have detected an impact on the solar arrays which are the largest spacecraft areas exposed to the meteoroid stream because the frequency response of the array could be outside of the response range of the accelerometers and the amplitude of the impact pulse at the location of the Pax on the spacecraft body would be attenuated by the array and boom support structure. The PAX is on the inboard side of the forward or earth facing panel.

If a plasma were generated by a meteoroid impact, there would have to be electrical routes to the affected subsystems. The possible electrical connection to the gyro is through the spacecraft umbilical which is only used during launch. For the ESA mode electronics failure, it could be through the sun sensor although there is some input protection. Meteoroid impacts can generate plasmas with very high currents. The testing of the effects due to high currents could not be undertaken due to equipment limitations. Testing of disturbance effects was limited to high voltage.

Again the evidence for meteoroid impact and hence a common cause for the anomalous events remains inconclusive. However, the timing of the events leads one to suspect very strongly that this is the common cause. OLYMPUS had experienced no problems for about six months prior to this final fatal anomaly. Roll thruster firings were taking place in order to desaturate the wheels being loaded by solar pressure on the fixed south solar array. A firing took place a few seconds before the estimated time of the gyro spin down. Whether these exhaust gases in the region of the umbilical and the sun sensor could have assisted in the creation of a plasma is unclear but should not be ignored.

POSSIBLE PERSEID IMPACT

When considering whether the OLYMPUS anomaly may have been caused by the impact of an interplanetary meteoroid, it is immediately tempting to suspect the Perseid meteor shower as the source, this shower having its maximum on the night of the satellite failure. Typical activity in previous years has seen the visual Perseid meteor rate maintain greater than 50 an hour for a 2 to 3 day period (peaking at around 100). These visual Perseid meteors (magnitude brighter than 6.5) correspond to stream meteoroids of mass around 1 mg or greater. However since 1988, the shower has shown increased activity with a new peak (lasting a few hours) reaching about 400 meteors an hour. This enhanced activity is thought to be due to material released from the Perseid's parent comet, Swift-Tuttle, at its last perihelion passage in 1862 (see Roggemans 1992 and Wu & Williams 1993). Potential satellite impact due to the Perseid meteor storm conditions were discussed in the paper of Beech & Brown 1993 where it was stated that the meteor rate might reach the order of 10^5 per hour.

The new peak in the Perseid visual meteor rate has been occuring progressively earlier each year. The 1989 peak occured at around August 12 08:00 Z (UT), whereas the 1991 peak was earlier at around 06:00. The 1992 and 1993 peaks have occured at around 03:30. The OLYMPUS failure occured somewhat earlier at August 11 23:32 Z (UT) when the Perseid visual rates were around 100 and rising. The sporadic background meteor rate is around 10 in comparison. It should be noted however that this ratio in visual rates does not give a direct indication of the spatial density of meteoroid stream versus the sporadic background. Crucial in understanding this is the distinction that must be drawn between a meteor shower and the associated meteroid stream. A meteor occurs when a meteoroid particle enters the Earth's upper atmosphere causing the surrounding atmosphere to become highly excited and ionised, producing a long thin 'tube' of photo-luminescing gas which is seen as the meteor trail. A high meteor count rate does not necessarily imply a high meteoroid flux rate at a given mass. The ionisation produced in the meteor trail (and hence its visual magnitude) is proportional to $m^{0.9}v^{3.9}$ (Veriani 1973) where m is the meteoroid mass and v is the meteoroid's geocentric velocity. It is clear then that the visual brightness of meteors is highly velocity-dependent.

The Perseid stream consists essentially of a 'tube' of meteoroids dispersed around the orbit of comet Swift-Tuttle, and the Perseid shower is seen when the Earth passes through the stream (at heliocentric velocity of 30 km per sec) such that the Perseid meteoroids enter the atmosphere with a geocentric velocity of approximately 60 km per sec. A 'typical' sporadic meteoroid in comparison might have a geocentric velocity of approximately 20 km per sec or lower. For a Perseid and typical sporadic meteor of the same visual magnitude, the sporadic meteoroid is more massive than the Perseid meteoroid by a factor given the ratio of the velocities to the power of 4.3, i.e. about 100.

What is the ratio of the Perseid to sporadic meteoroid flux for a given particle mass at the time of the OLYMPUS anomaly? From above, a sporadic meteoroid is typically 100 times more massive than a Perseid meteoroid producing the same magnitude meteor. By assuming a cumulative mass distribution index, alpha = 1, to scale the flux to equal masses (where the flux of particles with mass greater than or equal to m is proportional to m^{-alpha}) and noting again that the ratio of Perseid/sporadic visual meteor rates at the time of the anomaly was about 10, then it is seen that for the same particle mass, the typical sporadic flux is greater than the Perseid flux by a factor of about 10. When considering the probability of an impact of a given mass particle, the sporadic background is more important than the Perseid stream.

However, when considering the possible damage to OLYMPUS, we do not know what mass particle, if any, impacted the spacecraft. We do know that it was probably very small to be undetectable by momentum transfer to the accelerometers and wheels. One must assess the relative probability of impact by a sporadic versus Perseid meteoroid in terms of an equal damage scenario. Impact damage in terms of penetration depth is approximately related to mv^2 (see for example Love & Brownlee 1993) and so for example a 1 mg Perseid meteoroid would penetrate the same thickness of aluminium as a 10 mg sporadic. Hence the Perseid to sporadic fluxes for equal penetration damage would be about unity. Plasma production however, from a hypervelocity impact is related to approximately $mv^{3.5}$ and so a 1 mg Perseid would liberate as much plasma as a 50 mg sporadic. Hence, the Perseid to sporadic ratio of meteoroid fluxes for equal plasma damage is about 5.

At the time of the observed anomaly then, the 'plasma risk' from the Perseid stream was at least 5 times higher than normal. We use the word at least for the following reasons: The visual meteoroid hourly rates quoted refer to meteors of magnitude greater than 6.5. This corresponds to a limiting Perseid meteoroid mass of about 1 mg, and as such represents a rather 'large' particle. Smaller particles (of order micro-grams) are present in the stream and can be observed with meteor radar techniques (though the recent short-lived enhanced peak has not yet been observed with radar to the authors' knowledge). These smaller particles will be more abundant, although the mass distribution index for the small-particle enhanced flux of recent years is not known. It is possible that there was a greatly enhanced flux of smaller meteoroids released into the stream during Swift-Tuttle's last perihelion passage. Also, we have taken the visual meteor rate as being about 100, whereas the later peak was about 400. If the small particle flux did rise proportionately (but peaked earlier) then the impact 'plasma risk' would have been proportionately higher.

Another point to note is that at the time of the anomaly, the visual meteor rate at Earth was not at it's peak (as stated above), the anomaly occurring about 3.5 hours before the visual peak. Three points are worth consideration in attempting to understand this. Firstly, the descending node of comet Swift-Tuttle is 600,000 km outside of the Earth's orbit, and the spacecraft was 7% closer to the node than the Earth during the period around midnight August 11/12. Secondly, the OLYMPUS satellite crossed the mean orbital plane of the Perseid stream approximately 18 minutes before the Earth. Lastly, the smaller meteoroid particles that are here tentatively linked to the OLYMPUS damage, will have been ejected from the parent comet with larger velocities (greater acceleration by radiation pressure), and this will lead to a greater dispersion in orbital inclination, a slightly thicker stream cross-section and hence a broader peak meteor activity than from larger meteoroids. These points may go some way to explaining the 'early' impact.

OVERALL METEOROID IMPACT RISK

The overall risk of meteoroid impact to a satellite from a typical sporadic meteoroid is not insignificant. For example, the flux of .1 mg particles to earth is about 3.3 X 10^{-10} m^{-2} s^{-1} (Grun et al. 1985) and so crudely, this indicates an expected impact rate to a satellite such as OLYMPUS (with exposed surface area of around 140 m^2) of around 1.5 impacts per year, giving an expected total of about 6 of these impacts over the satellite's mission life of 4 years. This figure is in line with the 3 damaging apparent impact related events that occured during the OLYMPUS mission. Additional impacts may not have been noticed because the damage was minor; in fact, it seems likely that the number of impacts must be higher to have 3 that found three spacecraft operational weaknesses. A typical sporadic impact at 20 km s^{-1} would penetrate to the order of 1 mm of aluminium and so may offer considerable risk to spacecraft systems.

A detailed analysis of the spacecraft orientation to the incoming Perseid meteoroid flux gives the angles between the satellite face normal vectors and the incoming meteoroid relative velocity vector. Resolved area to the stream flux are also calculated for the faces. These angles and areas are given in Table 1. It is seen that the South solar array which was fixed due to an earlier anomaly presented the greatest resolved area to the stream flux, and hence is the most likely place for a Perseid impact; however, it really could be anywhere in the areas of similar magnitude.

Table 1: The incident angle between the face normal vector and the Perseid incoming meteoroid relative velocity is shown with the resolved area to the stream flux.

SPACECRAFT FACE	INCIDENT ANGLE TO FACE NORMAL (DEGREES)	RESOLVED AREA OF FACE TO STREAM (SQUARE METERS)
East (+X)	58	1.94
West (-X)	no impact	
South (+Y)	no impact	
North (-Y)	34	2.89
Earth (+Z)	78	1.29
Aft (-Z)	no impact	
South Array	73	8.48
North Array	94	1.73

If the OLYMPUS anomaly was caused by meteoroid impact on the night of the Perseid shower, then from above, it was seen that the equal penetration damage flux from the Perseids was of the same order as the sporadics. If the impact damage was plasma related, then in fact the Perseids offered at least 5 times the equal plasma damage flux. And so, one can conclude that although significant meteoroid impacts (say of the order of 1 mm penetration damage) are relatively rare, they do happen. And if the OLYMPUS end-of-life anomaly was impact and plasma related, then it is highly likely that it was a Perseid impactor.

MISSION IMPACT

Following the events of August 11/12, the decision was taken to end the OLYMPUS mission. There was insufficient propellant to recover and continue with the mission. The amount of propellant was not exactly known but it would be required to return to station and to operate for the rest of the mission with a sufficient amount remaining to allow for a graveyard burn. The decision to end the mission was not based on any equipment failure following the anomalous events. The gyro was not permanently failed and the ESA loop electronics although failed could have been made inoperative for most conditions. Prior to this anomaly there was sufficient propellant for the mission to last until the summer of 1994. There had always been a concern that unexpected propellant consumption in an ESA mode manoeuver would possibly terminate the mission.

If sufficient propellant had been available the mission could have continued using the gyro skew pack for attitude control because the problem was transient. Also the redundant skew gyro was still available. However some different logic would have had to be designed and implemented to provide an emergency sun acquisition mode. One possibility would have been to use the software based sun acquisition mode.

A by-product of the termination of the mission was validation of the Thermal Propellant Gauging Technique(TPGT) The onboard propellant masses had been consistently and successfully estimated by this technique which uses heating of the tank liquid to determine fluid mass. The accuracy was particularly good at the end-of-life. The mass of NTO and MMH was determined within a fraction of a kilogram. This technique clearly has a role in supporting the life of communications satellites in which the last few months of operation can be very valuable.

RECOMMENDATIONS

Although it was impossible to prove that the demise of OLYMPUS was caused by the impact of a Perseid meteoroid, it does seem probable. Many lessons have been learned from the mission; of these, some concern the possibility of impact by meteoroid showers such as the Perseids. It is interesting to note that the loss of the south solar array in January 1991 could have been the result of particle impact on the south array drive and track; the loss of a solar array section in January 1993 was probably the penetration by a particle causing shorting in the north solar array cabling. These two earlier events resulted in the loss of about 65 per cent of the power. Neither of these anomalies caused sufficient momentum transfer to have an effect on the wheel speeds; if these anomalies were due to particle impacts, they were minor particles possibly at low speed. In the south array drive and track anomaly, investigations indicated that debris which could have been internal or external entered the slipring assembly resulting in a massive short. It could have been an external particle hitting the cover which deposited metal on the rings. In the second case, tests prior to launch had shown that a meteoroid impact could penetrate the cabling on the array and result in a local short to the ground plane and anomaly investigations indicated that this was the most likely scenario. Other particle impacts have probably occured in other areas which had no operational effect. However, this final anomaly investigation caused us to consider the impact of very high speed particles, up to 60 times faster than debris material at approximately 1 kilometer per second or three times faster than sporadic at 20 km per second and the effects can be important. Because the Perseids is an annual event and the shower is now fresher with a possibly increased proportion of fine dust than earlier in the space age, some guidelines and prudence are suggested:

1. Minimise the area cross-section as much as possible during the peak period of the shower.
2. Prepare operational contingency plans for recovery from and for observation of impacts/plasmas.
3. Provide total protection from plasmas through external electrical windows such as sun sensors.
4. Ground and cover all interface points such as spacecraft umbilical connections.

CONCLUSIONS

OLYMPUS operated for four years and fifty days until August 31, 1993. It was expected to remain in operation until July 1994 but the mission was terminated prematurely in August 1993 when during the night of 11/12 August, while traversing the Perseids meteoroid belt, the service was interrupted. On that evening, for reasons which could be related to a possible meteoroid strike, the satellite lost its earth pointing attitude and began spinning slowly. This event and subsequent retrieval activities, used almost all of the last few remaining kilograms of propellants.

Given the fuel situation, the agency determined that it would not be possible to reestablish service and decided to reorbit to a lower orbit because the anomaly had already reduced the perigee. There would not have been sufficient fuel to retransfer the spacecraft to a higher orbit beyond the geosynchronous orbit. Once the satellite had reached the lower orbit, some end of life tests were conducted and the pressurant remaining in the tanks was depleted. With the satellite in this safe configuration, OLYMPUS was turned off and the mission ended.

OLYMPUS had been placed in an graveyard orbit more than 200 kilometers below the geosynchronous orbit. While it was disappointing not to achieve the fully planned mission duration, the experience gained and lessons learned are significant and will finally be made worthwhile in their application to other missions. OLYMPUS supported hundreds of communications users in many countries over half the earth right up to its last days, demonstrating new modes of communications and services from spacecraft. It must be said when all is considered that the mission was a great success.

Spacecraft are impacted by orbit debris, man-made and natural; even dust impacts can have a significant effect if the impact is in a critical area. The larger spacecraft receive more impacts in their sweep of space. Meteoroid streams have a greater effect with very high velocities producing substantially more impact plasma. Large spacecraft should exercise caution during showers to minimise the risk and be designed to be robust against this operational hazard.

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