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IDENTIFICATION AND RESOLUTION OF AN ORBITAL DEBRIS PROBLEM WITH THE PROTON LAUNCH VEHICLE

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ABSTRACT

On at least six occasions during 1983-1992, operational debris released from the fourth stage of Russian Proton launch vehicles fragmented, creating up to 60 new trackable debris in Earth orbit after each event. Surprisingly, these fragmentations occurred 18-96 months following successful Proton missions. One month after the fifth incident in September, 1992, Kaman Sciences Corporation (USA) and the Center for Program Studies (Russian Academy of Sciences) carried out an investigation of these problems of space debris and its catalogization. In the course of work, the data on breakups of the fourth stage of the Proton were analyzed, and the probable cause of its disintegration was determined. The Russian experts proposed possible measures to prevent the fragmentation of this hardware in the future. The unprecedented Russian-American cooperation leading to the resolution of this environmental issue should serve as a model for future investigations.

THE PROTON LAUNCH VEHICLE

The Proton launch vehicle has earned a reputation for very high reliability during its 25-year history of operations and has supported a variety of very important space science and applications programs, including the deep space Luna, Mars, Venera, and Zond probes, the Salyut and Mir space stations, and the Astron and Granat astrophysical observatories, as well as geostationary communications satellites and mid-altitude navigation satellites. To date, over 200 Proton vehicles have been launched in both 3-stage and 4-stage variants.

The original 3-stage Proton (designated UR-500) was developed by Chief Designer Vladimir N. Chelomei in the early 1960's. The first stage engines (RD-253) were designed by Valentin Glushko at GDL-OKB (now known as the Energomash NPO), while the second and third stage engines (RD-465, RD-468, RD-473) were created by Semyon A. Kosberg's design bureau (now known as the Khimavtomatika Design Bureau). The Salyut Design Bureau of the Experimental Machine Building NPO (a descendent of the Chelomei Design Bureau) jointly with the Energiya NPO (a descendent of the Korolev Special Design Bureau) currently has overall responsibility for the manufacture and launching of Proton vehicles.

In the mid-1960's, a decision was made to mate an upper stage of Sergei Korolev's N1-L3 manned lunar landing vehicle to Chelomei's 3-stage Proton. This stage which became a 4th stage of the Proton was originally developed as the 5th stage of the much larger N1-L3. Hence, this stage was designated Block D, following the Russian tradition of naming stages alphabetically (the English language "D" is the fifth letter of the Cyrillic alphabet). The 4-stage Proton variant, known as the Proton UR-500K, was first flown in 1967.

Since 1974, an improved version of the Block D, the Block DM, has been used by 4-stage Proton launch vehicles (Figure 1). The stage is approximately 3.7 m in diameter and 6.3 m in length with a dry mass of 3.4 metric tons. The main engine, designated 58M and designed by the Korolev Special Design Bureau, employs liquid oxygen and kerosene or hydrocarbon fuel as propellants and develops a thrust of 85 kN. This restartable engine has a total burn time of more than 600 seconds.

TYPICAL OPERATION PROFILE OF THE 4-STAGE PROTON LAUNCH VEHICLE

The 4-stage variant of the Proton launch vehicle is the more commonly used configuration. Since 1980, the average flight rate has been nine missions per year (Figure 3). During a typical launch sequence, the first and second stages are sub-orbital. The third stage carries the fourth stage and its payload to a low-Earth parking orbit, typically with a mean altitude of less than 200 km. Once in this parking orbit, the spent third stage is separated.

Normally, about one hour later the Block DM is ignited for the first time to enter an elliptical transfer orbit. When the first apogee of this new elliptical orbit is reached (as much as five hours later), the Block DM is restarted for the purpose of circularizing its orbit and making any required inclination changes. The payload is released very shortly after the final shutdown of the Block DM engine. Approximately 15 minutes later, all Block DM residual propellants are vented to space to de-energize the stage.

An examination of a Russian geosynchronous mission profile illustrates this sequence well. Approximately ten minutes after launch from the Baikonur Cosmodrome, the Proton upper stages and payload enter a 200 km orbit with an inclination of 51.6 degrees. As the Block DM crosses the equator on its first northbound pass, the engine ignites for 450 seconds, placing the stage along with its payload into a geosynchronous transfer orbit of 200 km by nearly 36,000 km at an inclination of 48 degrees. Five hours and 20 minutes later as the stage reaches apogee once again over the equator (now southbound), the Block DM fires for a second time for 230 seconds to enter a nearly geosynchronous orbit (mean altitude about 35,800 km with an inclination of less than two degrees).

GROWING RECOGNITION OF AN ORBITAL DEBRIS PROBLEM

The first hint of any problem with the Proton Block DM occurred on 3 September 1984 when a small piece of operational debris from the Astron mission (23 March 1983) brokeup in its elliptical Earth orbit. The unusual Astron mission required the Block DM to enter first a transfer orbit of 230 km by 2,000 km and then to place the Astron spacecraft into an operational orbit of 2,000 km by 200,000 km (Figure 3). Following a pattern set by all Proton geosynchronous missions, two small (~1 m^2) objects designated by the United States as operational debris were left in the transfer orbit. At the time the nature of these objects was unknown outside of the Soviet Union.

During the 18 months since launch, the original transfer orbit of the operational debris had decayed to 220 km by 1230 km. The breakup event occurred at 400 km, very close to perigee. The U.S. Space Surveillance Network (SSN) estimated as many as 21 new fragments had been created (five of these may have originated in a second breakup six days after the first). Unfortunately, none of the debris were officially cataloged before they decayed. An unusual feature of the debris cloud was that all debris were ejected in retrograde directions (lower orbital periods), indicating a highly unusual asymmetric fragmentation.

Not until early 1988 was a second breakup of a Block DM operational debris object noticed. On 5 January of that year a piece associated with the Kosmos 1656 mission (30 May 1985) fragmented into eight observable debris. Of these, five new debris were eventually cataloged. Kosmos 1656 was a rare low Earth orbit (LEO) Proton mission. The Block DM utilized two different transfer orbits, firing for a total of three times within two hours. The two operational debris were released after the second burn of the Block DM and were found in an orbit of 810 km by 860 km at an inclination of 66.6 degrees.

The breakup event occurred near apogee, and the trackable fragments which resulted were less numerous than those from the Astron incident. Moreover, the debris were thrown in both retrograde and posigrade directions. In fact, the ejection energy of one fragment was sufficient to increase its apogee by almost 300 km.

While the breakups associated with the Astron and Kosmos 1656 missions were out of the ordinary, so were the missions themselves. Therefore, since relatively few fragments were observed, members of the orbital debris community did not at the time ascribe any particular importance to the events. This attitude changed in 1991 when two more related events occurred, this time associated with standard Proton flight profiles.

In February and December, 1991, Block DM operational debris from two different GLONASS (Kosmos 1519-1521 and Kosmos 1710-1712) missions brokeup in their transfer orbits of a few hundred km by more than 18,000 km. Also curious was the fact that the objects had been dormant in space for seven and six years, respectively. The relatively close timing of the events and the fact that these were the third and fourth breakups linked to Block DM operations appeared to eliminate the possibility that the satellites were the victims of accidental collisions with natural or man-made objects.

Another disturbing feature was an increase in the number of fragments detected. For the February event, approximately three dozen debris were observed; but due to the low perigee (~340 km) of the parent satellite and breakup near apogee, the debris decayed rapidly, and only four were cataloged by the U.S. Following the December breakup, 26 new debris were seen by the U.S. SSN, and of these only nine have been officially cataloged. Small debris in highly eccentric GLONASS transfer orbits can be extremely difficult to track, particularly when perigees are in the Southern Hemisphere.

THE BREAKUP EVENT OF SEPTEMBER, 1992, AND THE RUSSIAN-AMERICAN INVESTIGATION

While the significance and possible common cause of the aforementioned breakups were still being examined, a fifth even more serious event occurred. On 5 September 1992, an eight-year-old piece of Block DM operational debris brokeup in LEO. This event was quickly detected by the space surveillance systems of both the United States and the Russian Federation. The satellite was associated with the Kosmos 1603 mission which was identical to that of Kosmos 1656 noted above. From a nearly circular orbit near 850 km, a total of 62 identifiable debris were created, spanning an altitude regime from 700 km to nearly 1,100 km. Although the number of debris thrown in the posigrade and retrograde directions were about equal, a distinctly asymmetric ejection pattern was evident in a plot of debris inclination versus orbital period. In general, lower period pieces were thrown into higher inclinations, while higher period fragments were found in lower inclinations. The magnitude of the inclination spread is slight due to the far southern latitude of the event, but the relationship between inclination and orbital period is highly regular and linear (Figure 4).

A month after the breakup event, a team of scientists from Kaman Sciences Corporation traveled to Moscow for a series of space environment meetings arranged by the Center for Program Studies (CPI) of the Russian Academy of Sciences. Dr. Grigoriy Chernyavskiy, Director of CPI, hosted the Kaman Sciences delegation of Dr. Edward Conrad, Dr. Darren McKnight, and Mr. Nicholas Johnson. Following a preliminary analysis of the latest breakup event, the topic of the Block DM was quickly added to the Moscow agenda. To bring expert opinion to bear on the problem, Dr. Chernyavskiy invited to the discussions Dr. Boris Cherniatiev, Energiya NPO deputy Chief Constructor, who was Chief Constructor for the Proton Block DM at the time.

After reviewing the history of the Block DM-related breakups, the five scientists were quickly able to identify a probable cause of the fragmentations. Dr. Cherniatiev described the two pieces routinely ejected from the Block DM as small auxiliary SOZ (stabilization and launching provision) motors designed for the Block orientation and stabilization control on coast phases of flight, when the main motor does not operate, and also for producing axial acceleration prior to the main motor ignition.

The motors, which have a dry mass of 56-60 kg, are released shortly after the main motor ignition of the final phase of Block DM operation. At this time an average of 10-40 kg of residual propellants remain on-board each of the motor units. These hypergolic propellants are held in a single tank but separated by a thin interior wall and by two pressurization cavity diaphragms. The design is partially similar to that used for the second stage of U.S. Delta launch vehicles which were the source of high intensity explosions during the period 1973-1991. The U.S. problem was remedied by implementing a restart and subsequent burn to depletion for the Delta second stage after payload release.

REMEDIAL ACTIONS

According to Dr. B. Cherniatiev, a number of options of remedial actions are now being evaluated to remove all sources of energy for future Block DM auxiliary motor breakups. The problem is complicated by the fact that SOZ motors do not have a programming device and power sources, which make their control after separation from Block DM impossible for the present.

Russian specialists are evaluating some remedial actions aimed at:

- decreasing the amount of residual propellants at the time of separation by introducing an alternative fueling depending on flight schedule requirements,
- introducing into SOZ motor hardware a programmable (mechanical or electrical) actuator that would breakup the cavities of fuel and pressurization gas tanks at some time after separation of the SOZ motors from the Block DM,
- introducing a complete burn of SOZ motor propellants before separation at the final phase of the main motor operation, and
- introducing a combination of the above options.

Whereas the first option can be introduced in the near future, the implementation of the subsequent options will require a rather large volume of design works and experimental tests. These works could be implemented during 1994-1995 depending on their funding.

STATUS AND CONCLUSIONS

Two months after the October, 1992, meeting in Moscow between the Russian and American specialists, a new dimension to the Block DM problem was realized. During 17-18 December, one of the SOZ motors used on the Gorizont 17 mission (launched in January, 1989) broke up into as many as 100 detectable pieces while in a decayed geostationary transfer orbit (GTO) of 190 km by 17,580 km. Although geosynchronous missions represent the primary use of the Block DM (as many as eight missions per year), the SOZ motors normally decay within 6-12 months of launch due to solar-lunar perturbations (Figure 5). However, up to 20% of the SOZ motors have remained in orbit for several years, long enough to meet the apparent requirement for sufficient deterioration of the motor unit to permit propellant-induced fragmentation. To date, two more SOZ motors in GTO have been tentatively associated with breakup events; these events would bring the total SOZ motor breakup count to eight.

At the start of 1993, nearly 70 SOZ motors were still in Earth orbit, and there is a great possibility that some of them will break up. Moreover, 6-10 additional SOZ motors are expected to be left in semi-synchronous and geosynchronous transfer orbits annually for the remainder of this decade. All these factors will have a detrimental effect on the overall near environment. Therefore, implementation of timely measures to prevent breakups of the Proton launch vehicle upper stages is quite a pressing task indeed.

The authors are extremely satisfied with the open and sincere manner in which this issue was addressed by the Russian Federation and the United States of America. We are hopeful that this example of international cooperation will serve as a model for future investigations.

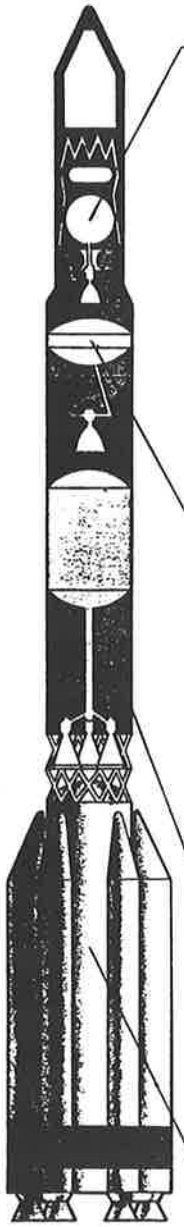

Figure 1. Diagram of 4-Stage Proton Launch Vehicle.

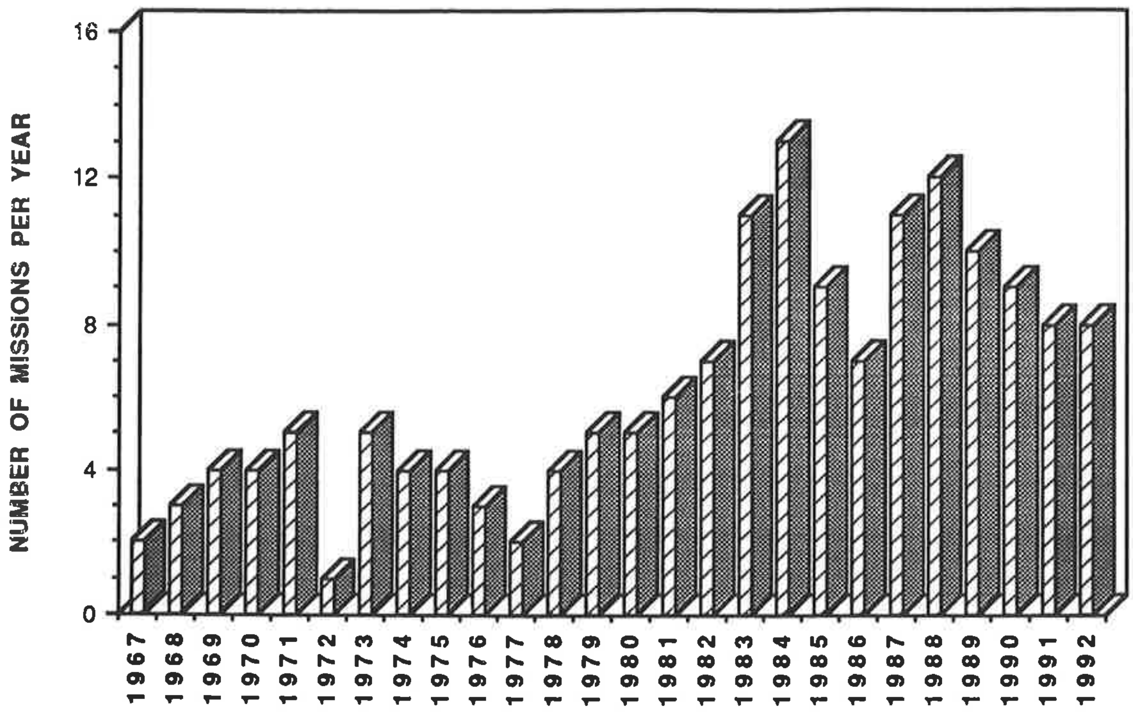

Figure 2. History of Proton 4-Stage Earth Orbit Missions.

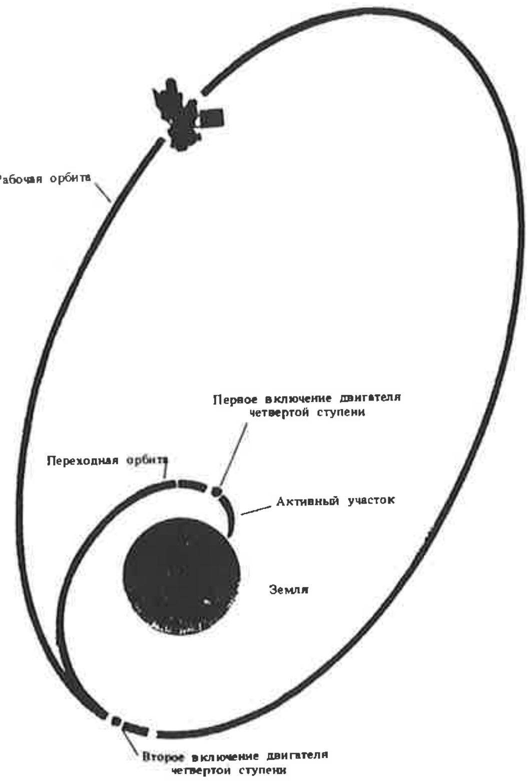

Figure 3. Astron Launch Profile.

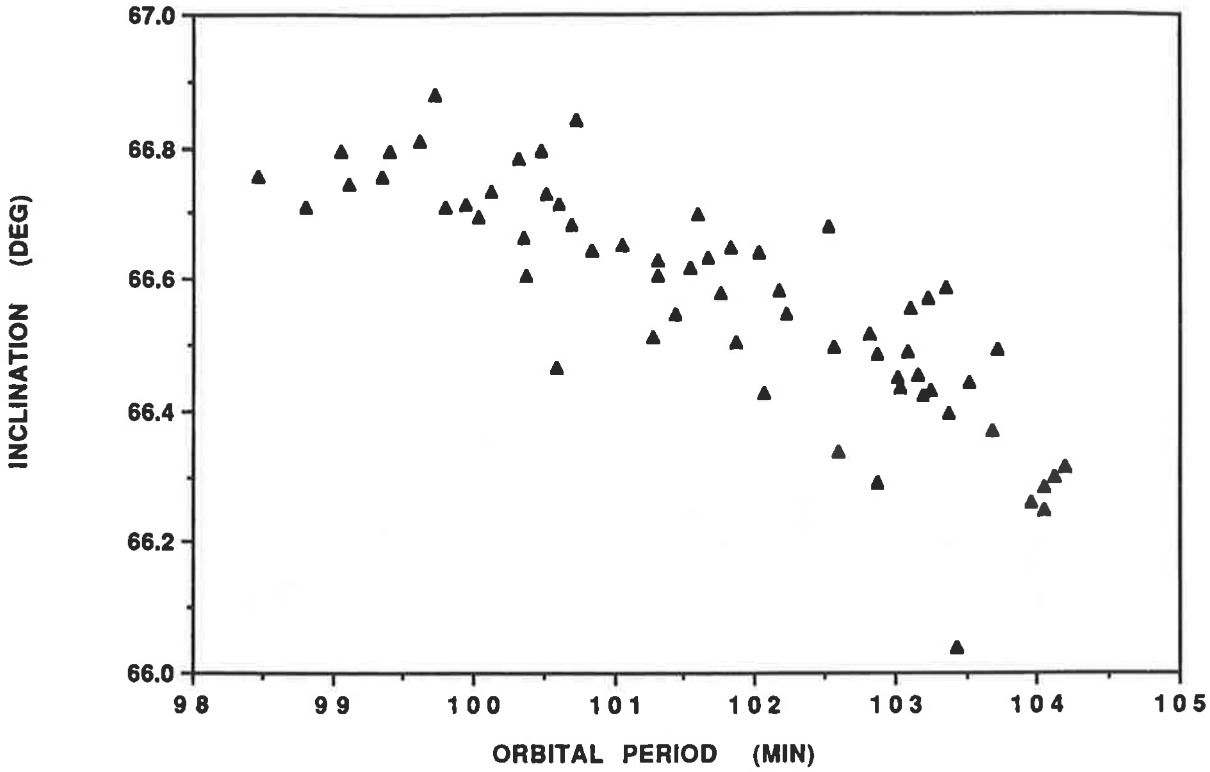

Figure 4. Kosmos 1603 Debris Cloud, Inclination vs. Period.

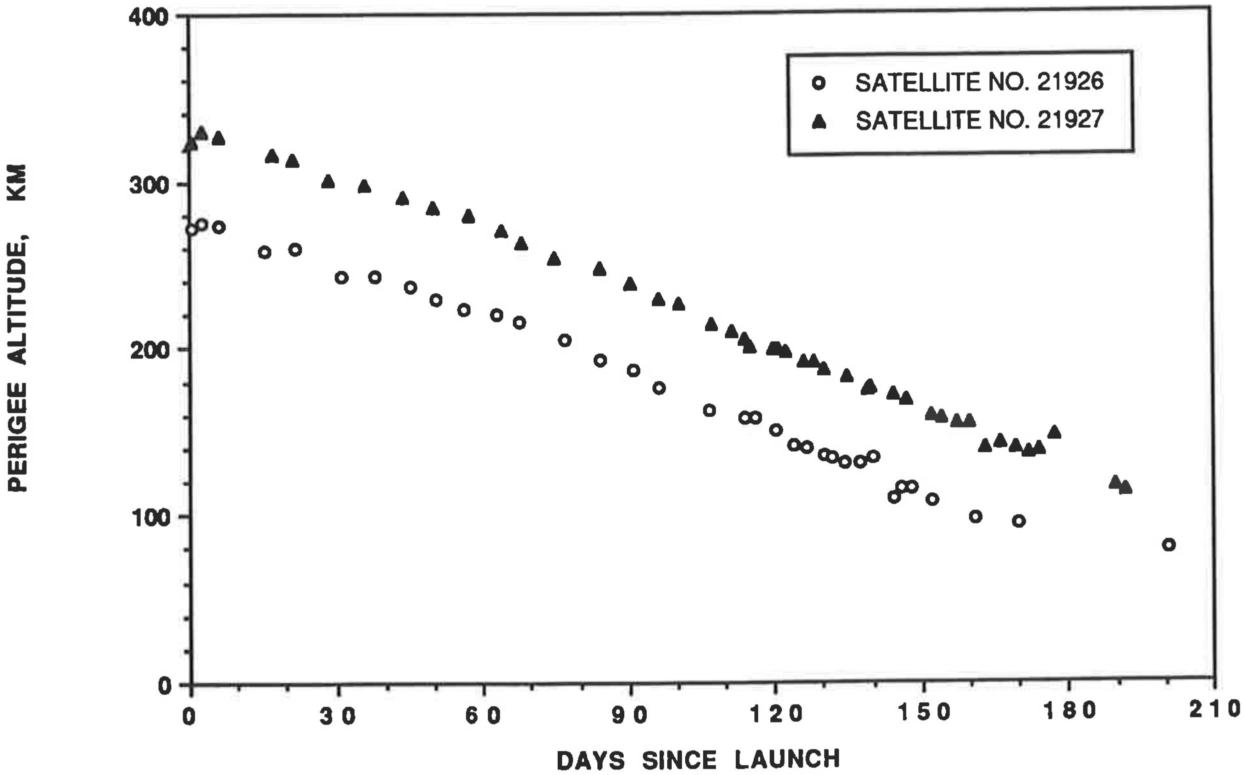

Figure 5. Decay History of Block DM Auxiliary Motors in GTO. (Gorizant 25 Mission)