The US-A program (Radar Ocean Reconnaissance Satellites - RORSAT) and radio observations thereof

Sven Grahn

Summary - a controversial space program lasting 30 years

The first inklings of a new Soviet space system came at the end of 1967 with the launch of Kosmos-198 that puzzled observers. After having spent only 21 revs in a low orbit at 265-281 km at i=65 degrees it moved up to an orbit at 894-952 km. It was announced to have transmitted on 19.365 MHz, a hitherto unknown frequency. Similar flights followed, with the period in low orbit becoming progressively longer. (See table below).

The first indication of what these satellites could be intended for came in 1973, when Dr Peter Waterman, acting assistant secretary of the U.S. Navy for R&D testified before the Senate Armed Services Committee that the Soviet Union possessed ocean surveillance satellite based on highly maneuverable satellites. Initially, it was thought that the two orbits (low and high) were related to two different purposes. Anyway, we can now understand the series of launches leading up to the fully operational Radar Ocean Reconnaissance Satellite system, called US-A (Upravlenniye Sputnik Aktivny) in Russian and RORSAT (Radar Ocean Reconnaissance Satellite) in western terminology.

At the very end of the 1950's Chief Designer Vladimir Chelomei's "firm" (currently NPO Mashinostroyeniya [Machine Building Scientific Production Association]) in the Moscow suburb Reutov, began studying [in the words of **(4)**]

"... a whole family of unmanned spacecraft, dubbed Kosmoplans, that would be built using modular elements. One variant of the Kosmoplan would conduct naval radar and signals reconnaissance, launched by the UR-200 rocket. In 1959, as Chelomei laid out these plans, he knew a tremendous struggle would be required to wrest a piece of the space program from Chief Designer Korolev. But Chelomei had stacked the deck against Korolev by hiring Khrushchev's son as a lead engineer at his OKB. By 30 May 1960 Korolev presented to the Soviet leadership a plan that now included participation of Chelomei. One project allocated to Chelomei was theme US - Upravlenniye Sputnik - a naval reconnaissance satellite using a P6 nuclear reactor for active tracking and targeting American warships. This was to be developed in 1962 to 1964. Chelomei was authorized by Decree 715-296 of 23 June 1960 'On the Production of Various Launch Vehicles, Satellites, Spacecraft for the Military Space Forces in 1960-1967' to complete a draft project on unpiloted Kosmoplans..."

The reason for the initiative by Chelomei's design bureau was probably that they were developing cruise missiles for the Soviet Navy that could be launched from small vessels such as patrol boats, subs and destroyers. However, these missiles needed targeting data to get close enough to U.S. capital ships to permit the terminal guidance radar or IR sensors to lock on the target. Chelomei's OKB-52 had developed the P-5 "Pyatyorka" missile (SS-N-3c Shaddock in NATO parlance) that was declared operational on 19 June 1957 **(1)**. For Chelomei it must have seen logical to try to propose space systems to provide a complete targeting and attack system.

Nikita Khrushchev was ousted from power on October 13, 1964. This deeply affected the US-A program which was the brainchild of Khrushchev's favorite Chelomei. Chelomei's launch vehicle the UR-200 was canceled and the US program was assigned to KB-1.

"Shaddock" cruise missile

Manager for the system at KB-1's subordinate department OKB-41 was Anatoli Ivanovich Savin (b. 6 April 1920), who was the head of KB-1 (then renamed TsNII Kometa) after 1973. The spacecraft was redesigned for launch by the Tsyklon 2 version of Yangel's R-36 rocket. KB-1 was also responsible for the IS co-orbital anti-satellite program. It was under Savin's management that the US-A system reached the flight test stage.

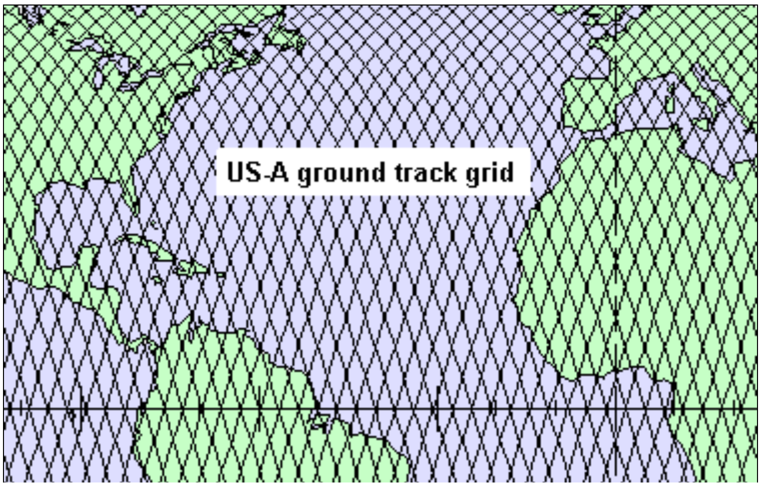
In May 1969 overall management of the US-A program was transferred to KB Arsenal in St. Petersburg. KB Arsenal was made responsible for series production and development of new variants. KB-1 was still the subcontractor for radio controls and spacecraft control systems. Under Arsenal's management the first research and development spacecraft was ready for launch at the end of 1970. The US-A was accepted for military service in 1975.

So, the US-A system was conceived and designed by Chelomei in 1959-1964; redesigned and flight tested by Savin in 1965-1969; and finally completed and put into service by KB Arsenal in St. Petersburg from 1969 and onwards.

Satellite	**L/V**	**Launch date**	**Days in LEO**	**Separation (min)**	**Remarks**	**Announced fx**	**Received signals** (nr of passes)
Kosmos-102	Vostok 11A510	27 Dec 1965	-	-		19.735 MHz	-
Kosmos-125	Vostok 11A510	21 Jul 1966	-	-		19.735 MHz	-
Kosmos-198	Tsyklon-2A, 11K67	27 Dec 1967	1	-	First to be boosted to 900 km orbit	19.365 MHz	-
Kosmos-209	Tsyklon-2A, 11K67	22 Mar 1968	1	-	Carried reactor simulator as K-198	-	-
Kosmos-367	Tsyklon-2, 11K69	3 Oct 1970	< 3h	-	First flight of BES-5 nuclear reactor	19.542 MHz	-
Kosmos-402	Tsyklon-2, 11K69	1 Apr 1971	< 3h?	-	In high orbit at rev 5	-	-
Kosmos-469	Tsyklon-2, 11K69	25 Dec 1971	9.5	-	First flight of radar?	-	-
Kosmos-516	Tsyklon-2, 11K69	21 Aug 1972	32	-	Last flight of S/C by Savin KB. Full radar gear	-	-
Kosmos-626	Tsyklon-2, 11K69	27 Dec 1973	45	-	First flight of updated S/C by KB Arsenal.	-	-
Kosmos-651	Tsyklon-2, 11K69	15 May 1974	71	**25**	First paired flight	-	-
Kosmos-654	Tsyklon-2, 11K69	17 May 1974	74	**25**	First paired flight	-	-
Kosmos-723	Tsyklon-2, 11K69	2 Apr 1975	43	**27**	Orbital plane 23 deg from K-724, n=5	-	166 MHz (16), 19.542 MHz (1)
Kosmos-724	Tsyklon-2, 11K69	7 Apr 1975	65	**27**	n=5	-	166 MHz (31), 19.542 MHz (2)

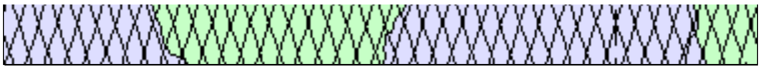
Kosmos-785	Tsyklon-2, 11K69	12 Dec 1975	< 15h	-	Boosted to high orbit on rev 10?	-	-
Kosmos-860	Tsyklon-2, 11K69	17 Oct 1976	24	**38**	Co-planar, n=3	-	-
Kosmos-861	Tsyklon-2, 11K69	21 Oct 1976	60	**38**	Co-planar, n=3	-	166 MHz (21)
Kosmos-952	Tsyklon-2, 11K69	16 Sep 1977	21	**26**	Co-planar, n=2	-	-
Kosmos-954	Tsyklon-2, 11K69	18 Sep 1977	43	**26**	Reactor landed in Canada.Co-planar, n=2	-	166 MHz (2)
Kosmos-1176	Tsyklon-2, 11K69	29 Apr 1980	134	-	Redesigned reactor safety features	-	166 MHz (14)
Kosmos-1249	Tsyklon-2, 11K69	5 Mar 1981	105	**26**	Co-planar, n=2	-	166 MHz (14), 19.542 MHz (12)
Kosmos-1266	Tsyklon-2, 11K69	21 Apr 1981	8	**26**	Co-planar, n=2	-	166 MHz (1), 19.542 MHz (8)
Kosmos-1299	Tsyklon-2, 11K69	24 Aug 1981	12	-		-	166 MHz (3), 19.542 MHz (11)
Kosmos-1365	Tsyklon-2, 11K69	14 May 1982	135	**51**	Co-planar, n=4	-	166 MHz (8), 19.542 MHz (6)
Kosmos-1372	Tsyklon-2, 11K69	1 Jun 1982	70	**51**	Co-planar, n=4	-	166 MHz (6), 19.542 MHz (2)
Kosmos-1402	Tsyklon-2, 11K69	30 Aug 1982	120	**26**	Co-planar, n=2. Fuel burned up S Atlantic	-	166 MHz (9), 19.542 MHz (6)
Kosmos-1412	Tsyklon-2, 11K69	2 Oct 1982	39	**26**	Co-planar, n=2	-	-
Kosmos-1579	Tsyklon-2, 11K69	29 Jun 1984	90	-		-	166 MHz (13)
Kosmos-1607	Tsyklon-2, 11K69	31 Oct 1984	93	-		-	166 MHz (8)
Kosmos-1670	Tsyklon-2, 11K69	1 Aug 1985	83	**26**	Co-planar, n=2	-	166 MHz (5)
Kosmos-1677	Tsyklon-2, 11K69	23 Aug 1985	60	**26**	Co-planar, n=2	-	166 MHz (1)
Kosmos-1736	Tsyklon-2, 11K69	21 Mar 1986	92	-		-	166 MHz (9)
Kosmos-1771	Tsyklon-2, 11K69	20 Aug 1986	56	-		-	-
Kosmos-1818	Tsyklon-2, 11K69	2 Feb 1987	-	-	Test flight of new reactor	-	-
Kosmos-1860	Tsyklon-2, 11K69	18 Jun 1987	40	-	Last flight tracked by the Kettering Group	-	166 MHz (4)
Kosmos-1867	Tsyklon-2, 11K69	10 Jul 1987	-	-	Test flight of new reactor as 1818	-	-
Kosmos-1900	Tsyklon-2, 11K69	12 Dec 1987	120	-	6-day repeat pattern. To high orbit 30 Sept.	-	-
Kosmos-1932	Tsyklon-2, 11K69	14 Mar 1988	66	-		-	-

In the low-orbit phase the side-looking radar, operating at 8.2 GHz, monitored US fleet movements with power coming from a nuclear reactor. The CIA estimated **(31)** that the US-A system had a "high probability of detecting carrier-sized ships in fair weather" and "detection of destroyer-sized ships highly probable, but only under the best of conditions (illuminated length-on in calm seas)". This report also stated that the system "cannot detect any ships in high seas or rain". The width of the area observed parallel to the orbital track was given as approximately 450 km (250 nm) by the CIA **(32)**.



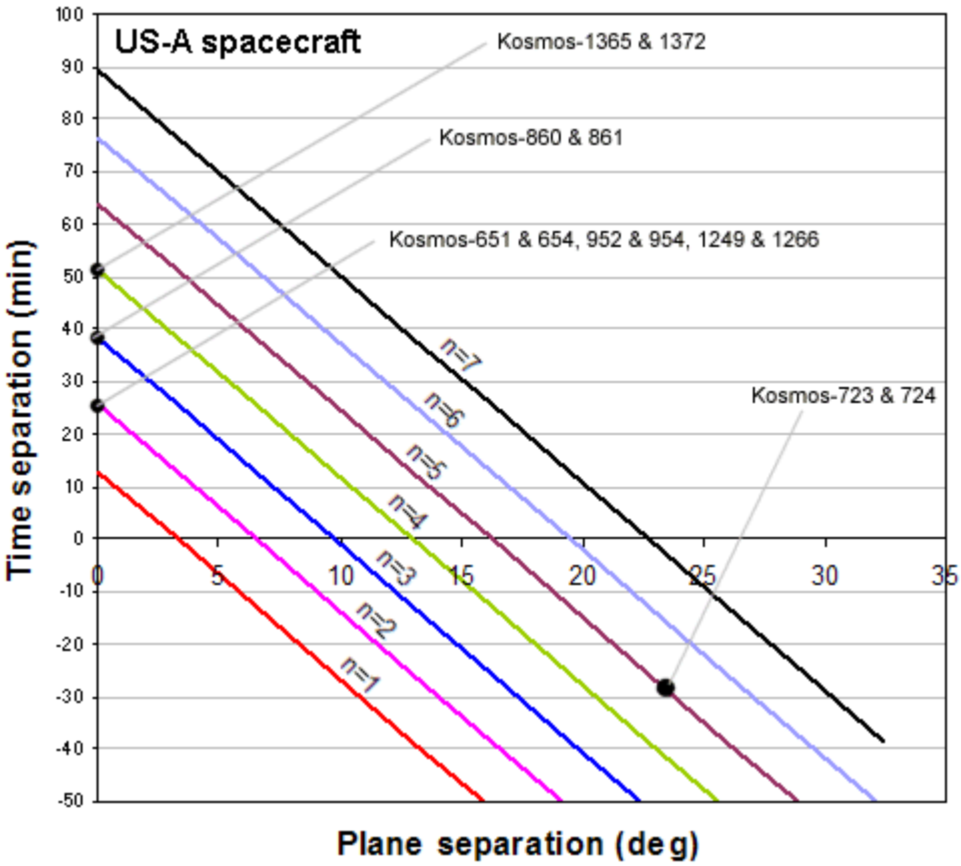
The high orbit was a "disposal orbit" for the spent reactor where radioactivity would decay to less lethal levels. The reason for using a nuclear reactor was that solar arrays would need to be very large to power the radar and the high drag in the low orbit would have made the attitude control and drag make-up problems insurmountable.

The real operational configuration became evident with the flight of Kosmos-651 and Kosmos-654 that entered the same orbital plane with a phase difference of 25 minutes in the 89.65 minute orbit. Constant small maneuvers, or rather thrusting, kept the orbit from decaying and the phase difference constant. These two satellites stayed in the low orbit phase for 71 and 74 days respectively.



The US-A program appears to have been a high-priority system in the Soviet arsenal. Despite several setbacks, failures and public embarrassment the program was pursued for almost thirty years. The program will be remembered for its originality, its disasters (Kosmos-954 and Kosmos-1402), its pollution of earth orbit with space debris and its interference with gamma-ray observatories in orbit!

Repeating orbit



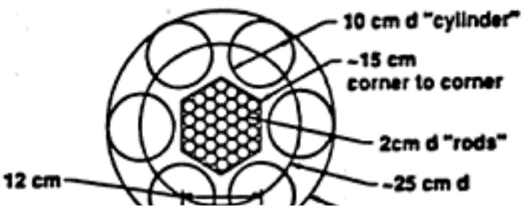
The US-A satellites were placed in an orbit that repeated its ground track every 111 revolutions. Repeating ground track patterns are described in a separate article. The parameters used to describe the US-A orbit are N,M,Q=16,-1,7. The resulting orbit has an average altitude above a spherical earth of 255.3 km and a nodal period of 89.651 minutes. Each satellite traversed a pattern of ground tracks on the globe that formed a grid on the earth's surface (see map on the right). When two satellites operated in a pair, both satellites followed the same set of ground tracks as shown by Nicholas Johnson **(6)**. In addition, the satellites entered the typical repeating pattern orbit almost immediately upon orbit insertion, so that the grid on the globe was the same for all US-A satellites. The grid size was 3.243 degrees in longitude. Presumably, this fixed grid made it easier for military planners to issue tasking orders for imaging by the US-A spacecraft.

Johnson **(6) also** showed that, even when satellites were co-planar, the temporal spacing in the orbit was chosen so that the two satellites followed parallel grid lines, with 1,2 3,... grid sizes spacing. the picture below shows the relationship between temporal and orbital plane spacing for various values of n, where this parameter denotes the number of days between passes of two spacecraft along the same grid line.

Not only did the US-A spacecraft work in pairs. Their orbits were also closely linked with the passive ELINT ocean reconnaissance satellite system denoted US-P which also used a repeating pattern with a fixed grid over the Earth. The US-P spacecraft are still in use and they have operated in pairs in coordinated orbital planes. However, they have always maintained orbits with a well defined repeating pattern. These spacecraft use an orbit at i = 65 degrees and a nodal period of 93.30 min, which corresponds to an average altitude of 434 km. This turns out to be an orbit with the parameters (N,M,Q)=(15, 1, 4) which corresponds to a ground track that repeats every 61 orbits.

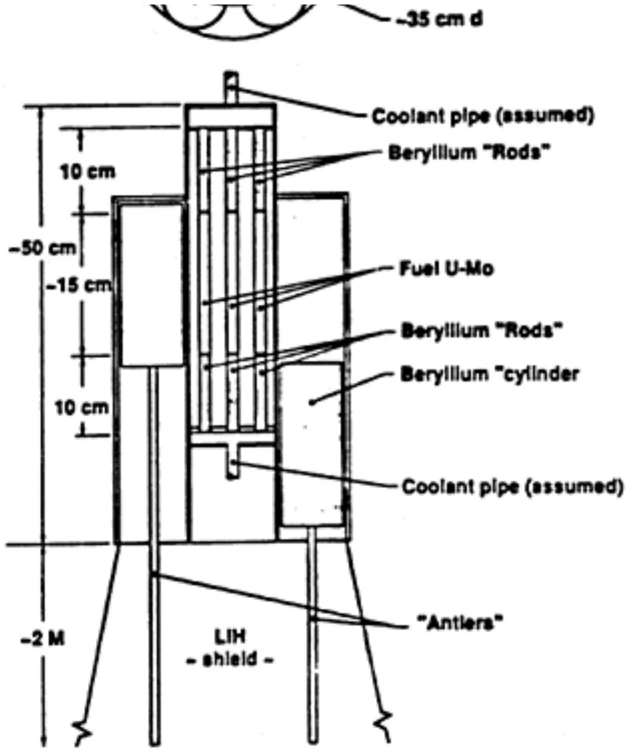
The reactor

The Buk reactor on the US-A spacecraft was a fast neutron reactor that used a uranium-molybdenium alloy as

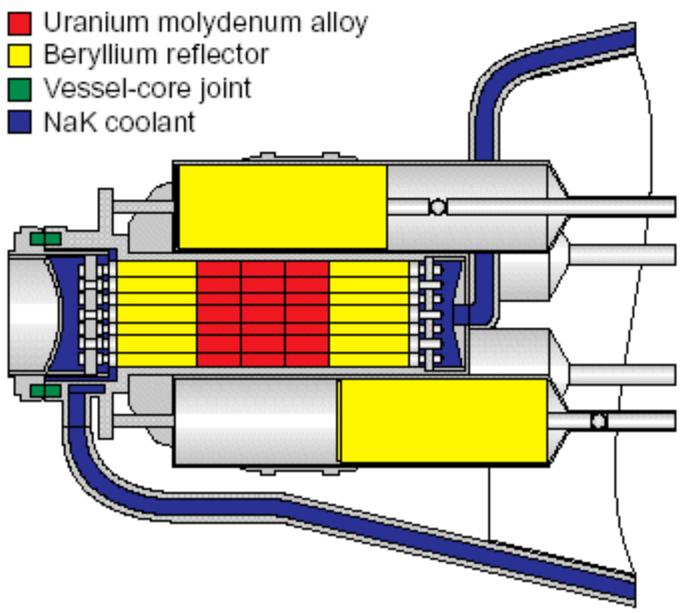


fuel contained in 37 steel clad rods about 0.6 m long. The fuel core of the reactor was 0.2 m in diameter, 0.6 m long and weighed, as an assembly, 53 kg **(37)**. The 30 kg of uranium was more than 90% enriched U235 **(39)**. It generated 3 kW of electrical power **(38)** created by thermoelectric conversion of 100 kW of thermal output. The reactor weighed 385 including the radiation shielding. The radiation shield consisted of LiH and stainless steel supplemented by tungsten and uranium alloys **(39)**. The reactor itself, including the fuel weighed 130 kg **(35)**. The reactor was controlled by six cylindrical control elements made of beryllium that could reciprocate along the reactor axis. The rods (racks, "antlers") that drive the control cylinders are filled with reactor poison BC_2 to prevent a "leakage" of radioactivity through the radiation shield (**41**). It is interesting how much scientists outside the Soviet was able to deduce about these technical details by examining the pieces falling to earth as a result of the Kosmos-954 accident (see below). The top sketch **(40)** on the right was put together by scientists at the Lawrence Livermore National Laboratories which turned out to be quiter accurate when comapring it to later sketches provided by Russian authorities **(37).**

Reactor sketch made by the Lawrence Livermore National Labs based on debris from Kosmos-954



Reactor drawing derived from several sources by Carsten Wiedemann



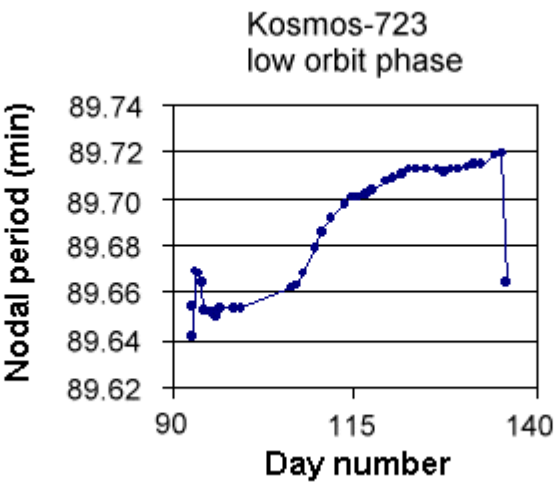
The main propulsion system, was there an ion thruster?

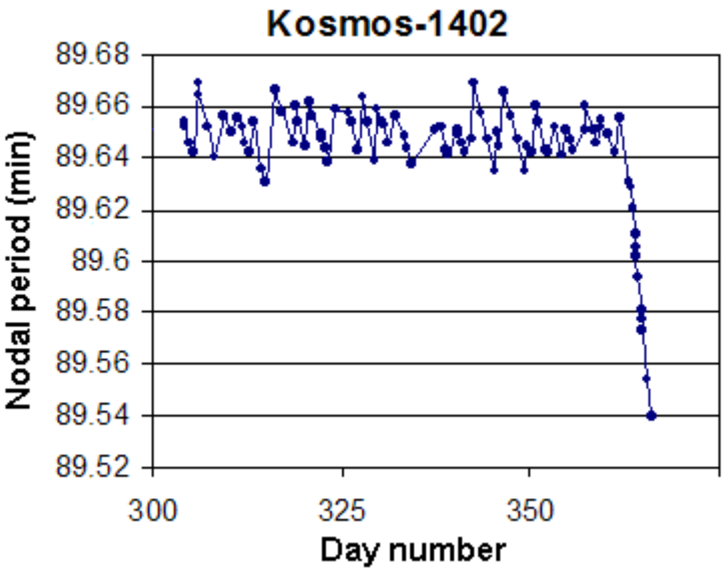
In **(1)** the on-orbit propulsion system of the US satellite type (both the radar -equipped and the ELINT version) is described as consisting of a relatively powerful engine for orbital insertion medium thrust engines for orbital corrections and motion, and very economical low-thrust stabilization engines.

The main propulsion unit for orbit insertion, orbit maintenance and attitude control was the 4E18 propulsion system using N_2O_4 and UDMH as propellant. It was designed by the Soyuz Turayev Machine-Building Design Bureau. Its overall mass including propellant was 910 kg. The 4E18 propulsion system is the green section on the right-hand part of the spacecraft as shown in the figure above. It is 1300 mm in diameter and measures 1332 mm long **(33)**. The propellant mass can estimated by the data given in **(33)**. As a space tug weighing 1000 kg and with no payload the tug can raise its orbit from a circular orbit at 200 km to an orbit ranging between 200 km and 23000 km. This requires a delta-V of 2150 m/s. By using an Isp for $UDMH/N_2O_4$ of 316 sec one can compute the propellant mass to be 500 kg.

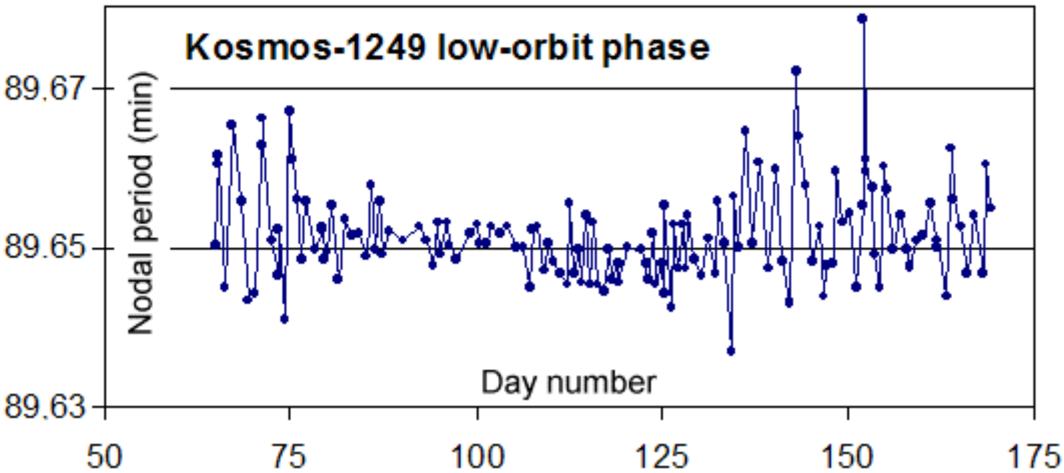
In **(2)**Geoff Perry (leader of the Kettering Group) describes how he found a lower limit on the continuously operating engines that he found could explain the motion of US-P satellites. He gives a figure of $8.5 \cdot 10^{-7}$ N/kg. With a mass of 3000 kg this corresponds to 2.6 mN, which is quite a small engine. For the US-A a much more powerful engine would be needed due to the higher drag. Ion propulsion has been assumed to provide continuous thrust. It is interesting to analyze the motion of US-A satellites to try to find evidence showing which propulsion regime that was used for the US-A. It turns out that there is evidence for both continuous and impulse maneuvers to keep the orbit at a very precise period.

the graph on the left shows the orbital period for Kosmos-723 and the increase in period is monotonic. There is absolutely no sign of a downward motion. However, the orbit of Kosmos-1402 drops in orbital period for a couple of days before an impulse raises the orbit. It seems that two different propulsion systems were used.

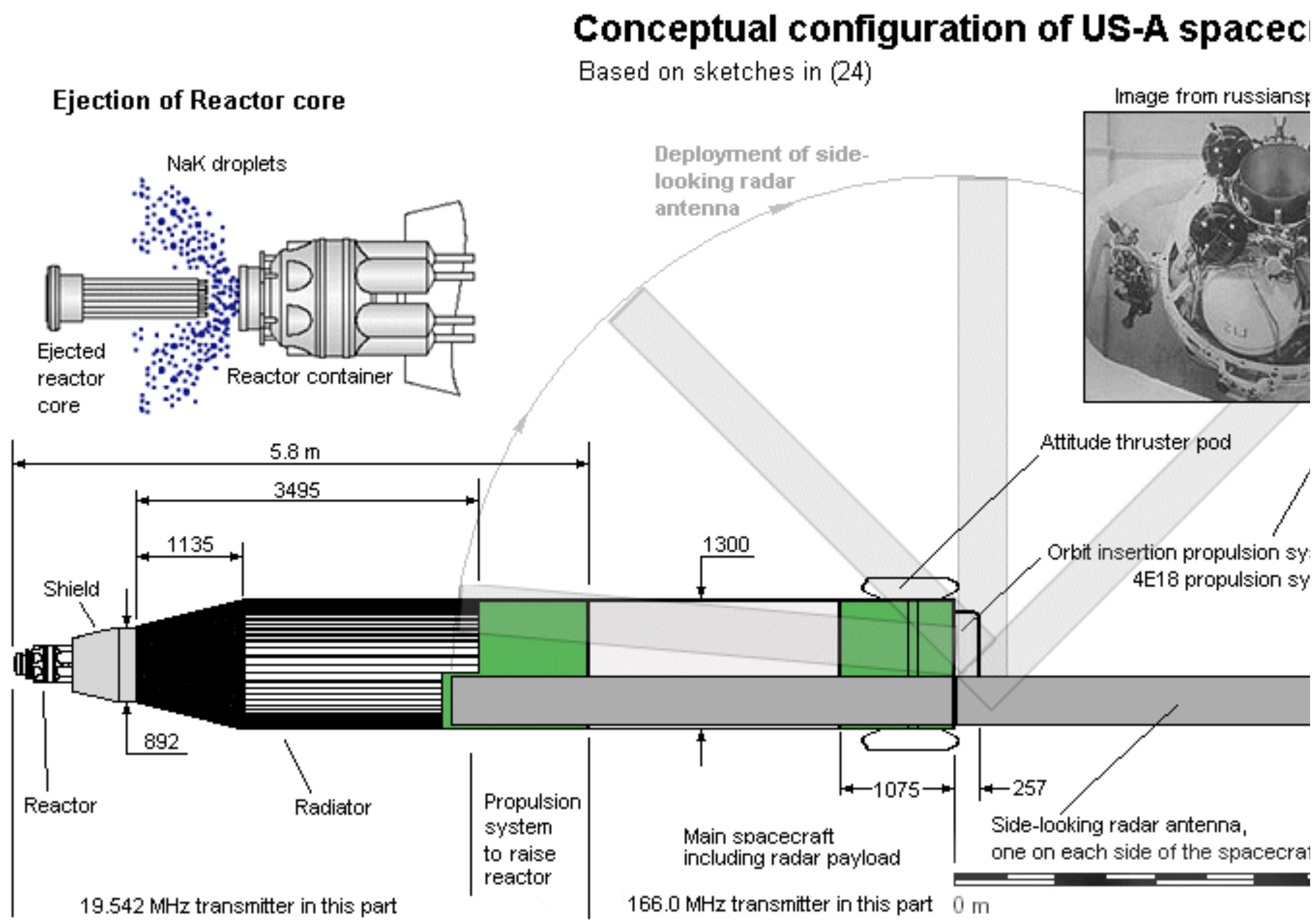




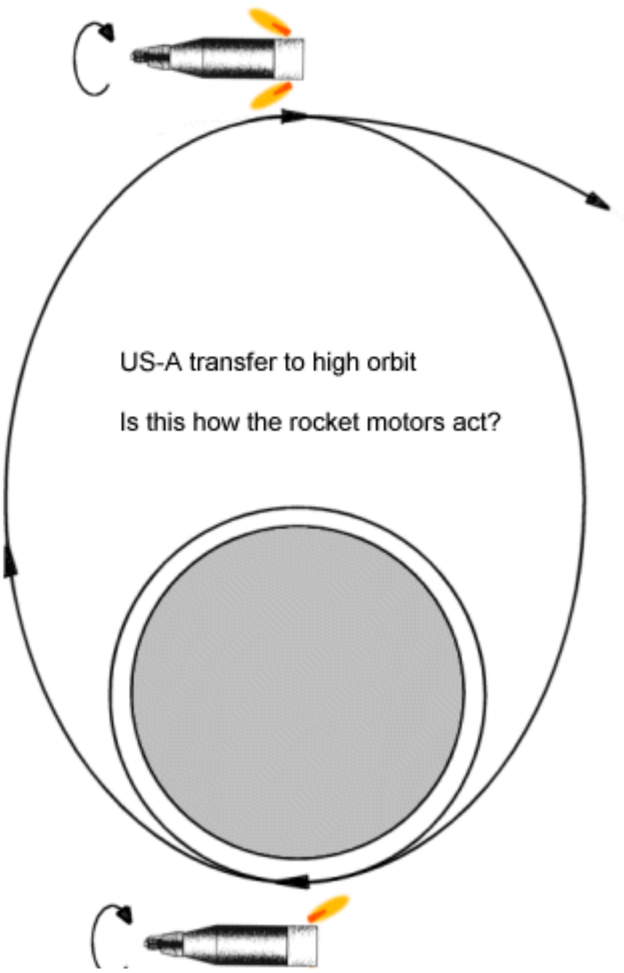
In another case it seems that both types of propulsion may have been used. The figure below shows also the interesting affect that the precision if the control of the orbital period changed with time, from lower precision to high precision and then back to lower precision. This could be a result of the orbit determination process of the United States space tracking network, but his is difficult to determine so long after actual events.



Configuration



The ascent to high orbit

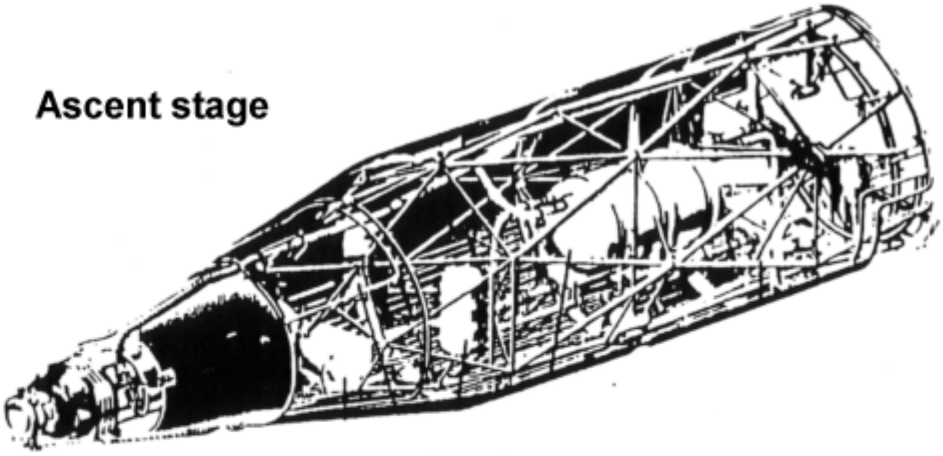


The propulsion system used to raise the reactor to the high orbit provided two impulses. The first put the reactor assembly on a transfer orbit to the high orbit and amounted to about 198 m/s. The second maneuver "circularized" the orbit at the high altitude and amounted approximately to 175 m/s. So, the total delta-v provided by this propulsion system was 373 m/s. If one assumes a very modest specific impulse of 2.7 km/s the mass fraction needed to provide this impulse is about 1.15, i.e. 15% of the mass of the vehicle that ascended to the high orbit was propellant. The overall dry mass mass of ascent stage was 1250 kg **(35)**. Thus, the propellant mass can be computed to be 101 kg for the first impulse plus 89 kg for the second impulse. The total propellant mass amounted to approximately 190 kg.

The vehicle that ascends to the high orbit must have its own attitude control system that is independent from the rest of the vehicle. It seems that Soviet designers chose spin stabilization **(34)**. The ascent stage would have been spun up immediately after separation from the main vehicle. Solid propellant rockets at the rear of the ascent stage would the fire to raise apogee and half an orbit later rocket motors located in the same part would have fired again. However, the spin axis of the ascent stage would remain fixed in inertial space during the ascent to apogee, so the rocket motors that fired at apogee had their direction of action in the opposite direction compared to the first set of motors. The sketch on the right shows how the situation could have looked.

The example of Kosmos-1900 (see below) is interesting. Even though radio contact was lost with the craft in April of 1988 its reactor and attitude control system operated until 30 September of that year when stabilization was lost triggering the ascent to high orbit ( ). Aerodynamic forces seemingly caused the longitudinal axis to deviate too much from the direction of flight. That triggered separation, spin-up and ignition of the first set of solid rocket motors.

The ascent vehicle is 5.8 meters long and 1.3 m in diameter **(35)**. The picture below is of Soviet origin and was shown in **(36)**. The radiator was a 0.4 mm thick copper sheet with embedded copper tubes with 8 mm diameter and 0.5 mm thickness. There were 120 such tubes around the perimeter of the satellite body aligned with the longitudinal axis of the spacecraft and spaced at 34 mm distance. The radiator was supported by a framework as seen in the picture below.



The sketch shows the total length of the ascent vehicle, it seems. However, there is no sign in the sketch above of the propulsion system used to raise the orbit.

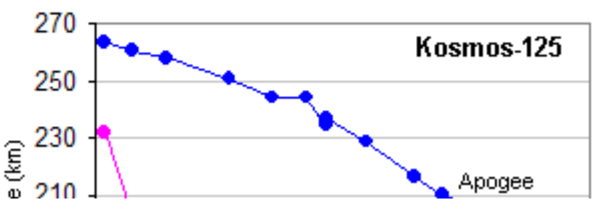
Telemetry systems

The **Kettering Group,** to which I have belonged since 1966, initially had difficulties finding the signals from the US-A system, (see separate article), but in 1975 two factors contributed to success. First, my friend Dick Flagg purchased a 55-260 MHz telemetry receiver with a spectrum display unit for me and had it shipped to Sweden. This was a powerful tool in finding new signals. Within months of bringing that receiver in operation I had identified PPM-AM telemetry on **166.0** MHz from US-A satellites. The second factor was the launch of Kosmos-723 and Kosmos-724. These satellites transmitted extensively including on short waves. Therefore the Kettering Group finally found also the **19.542** MHz FSK-PDM telemetry from the US-A system when I succeeded in picking up this signal from Kosmos-723 on 26 April 1975. As time went by we were able to determine that the 166 MHz transmitter was in the main spacecraft bus that remained in low orbit and the 19.542 MHz transmitter was placed in the part of the spacecraft that was raised to the "storage" orbit (see Kosmos-1299 below). Observations of many US-A missions showed that the short-wave signals were very rare during the low-orbit phase of the mission, but much more frequent in the high orbit, "storage" phase of the flight. Perhaps the HF beacon was used to monitor the status of the reactor. More details about telemetry receptions and formats will be given below when each mission is examined.

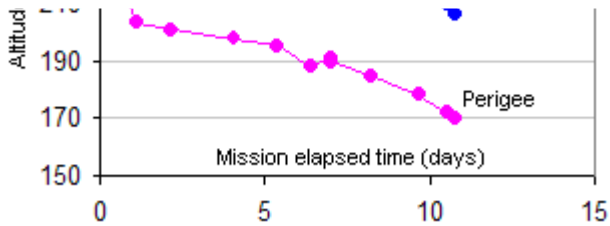
	Word number														
Satellite	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Kosmos-723 (26 April 1975)	2	19	18	19	18	2	21	2	1	21	21	18	2	14	2
Kosmos-1249 (26 April 1981)	2	22	22	22	22	2	22	22	1	22	22	22	22	22	22
Kosmos-1266 (1 May 1981)	2	15	14	14	14	2	15	7	3	3	7	15	21	22	22
Kosmos-1266 (5 May 1981)	3	15	15	15	15	3	16	8	3	3	8	16	22	23	23

Kosmos-102 & Kosmos-125

Kosmos-102 was launched at 2219 UT on 27 December 1965 from site 31 at Baikonur by a version of the R-7 rocket **(1)**. No two-line element sets are available for this satellite, but the RAE Table of Earth satellites gives the orbit as 203-269 km, i=64.97 with a lifetime of 17 days. In a letter to the editor of Flight magazine Geoff Perry pointed out that Kosmos-102 did



not transmit on its announced frequency and noted that it was unlike reconnaissance Kosmos satellites because of its uncharacteristic launch time, natural decay and lack of upper stage in orbit **(19)**.



Kosmos-125 was launched at 0907 UT on 20 July 1966 using the same type of launch vehicle and the same launch pad as the previous satellite of this type. It decayed after 13.23 days. The initial orbit was 205-258 km. Orbital data for the entire life of the satellite are available (see figure). Contact was maintained with the spacecraft until the 52nd orbit **(1)**.

The CIA's National Intelligence Estimate 11-1-67 was handed to President Johnson in March 1967 and read concerning Kosmos-102 and Kosmos-125:

> *"... Another propulsion system was probably used to effect minor changes in the orbit. A probable mission of these satellites was to evaluate the injection and orbit-adjust maneuver propulsion engines and the vehicle attitude control system. Such systems may be incorporated into an improved manned spacecraft ..." **(18)**.*

So, it seems that at this early stage **the CIA did not have a clue**! However, it is possible that the plot of apogee and perigee shows signs of orbit changes for Kosmos-125, especially the jump in perigee at almost constant apogee height at the beginning of the flight. Such a maneuver would be performed near the northern apex since the perigee was over the southern hemisphere (argument of perigee approximately 270 degrees). The rest of the data for Kosmos-125 is suggestive of natural decay.

The purpose of these two flights could be to test the spacecraft's own propulsion system that was used to insert the spacecraft into orbit. Probably, onboard systems such as attitude control were tested. Neither the nuclear power source nor the radar were installed.

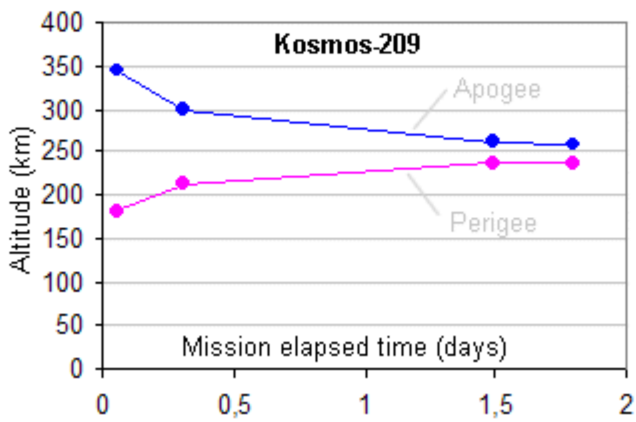
Kosmos-198

The first US-A spacecraft that looked reasonably like the final system was Kosmos-198 that was launched from Baikonur LC90/19 at 1128 UT on 27 December 1967 by a version of the operational rocket for the system, Tsiklon-2A. It entered an orbit at 266-270 km with a period of 89.86 minutes and moved to the high orbit late on 28 December after 21 revolutions **(2)**. So, this was the first flight that included the attitude control and two-impulse propulsion system to bring the spacecraft to the high orbit. It is unclear if there were maneuvers made during the first 21 revolutions. Only one element set exists for the low orbit. The spacecraft carried chemical power sources only. The first available element set for the high orbit is valid for the afternoon of 29 December with altitudes 895-951 km. This spacecraft caused a lot of confusion in the Kettering Group since the TASS announcement said it transmitted on 19.365 Mhz, the same frequency given for the failed lunar probe Kosmos-111, launched in the spring of 1966. We heard no signals from either of the, but because of the frequency similarity, we thought Kosmos-198 was related to the lunar program, and we were nor alone in thinking so, but the problem of Kosmos-198 continued to bother us.

Kosmos-209

Kosmos-209 was launched from Baikonur at 0930 UT on 22 March 1968. The Kettering Group instantly spotted this satellite to be similar to Kosmos-198. Here is what Geoff Perry wrote **(21)**:

> *"...Cosmos 209 has turned out to be another Cosmos 198, changing its orbit after 17 revs. The initial period of 89.5 minutes is now 103.05 minutes and the orbit is near circular between 893.3 and 945.6 km.*



Geoff Perry was right except that it changed its orbit later than he thought. The first element set for the higher orbit appears after 29 revolutions. However, there is a fragment fragment B (cat nr 3160) in the low orbit with its epoch at day 83.82248, which is 1.4267 days after launch which is rev 23. There is a C object in low orbit (cat nr 3161) at epoch 84.25439 which is 1.859 days after launch or on revolution 30. So, the maneuver took place at some time **between revolution 23 and 29**.

The evolution of the apogee and perigee of the spacecraft is shown on the right. It seems that the apogee and perigee converge while the orbital period drops. If this convergence is a real effect of maneuvers or an artifact caused by better and better estimate of the eccentricity is hard to determine this long after the event.

Kosmos-367

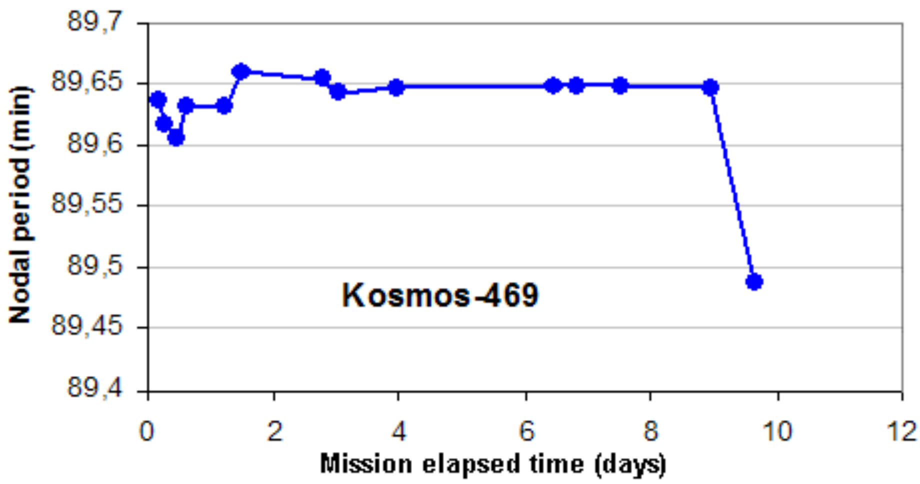
Kosmos-367 was launched 1026 UT on 3 October 1970. An object was logged in an orbit at 241-267 km already 0.367 days after launch. The high orbit was logged even earlier at 0.339 days mission elapsed time (corresponds to rev 5) at 910-1031 km. It is therefore not so strange that TASS announced the high orbit in its communiqué about the mission. The two earlier flights (Kosmos- 198 and -209) that had moved up were announced with their low orbit parameters. This flight is widely regarded as the first flight with a live reactor (1). However, it seems that something went very wrong, so the reactor was immediately boosted to high orbit. TASS announced a transmission frequency for Kosmos-367 at 19.542 MHz, a frequency that was used through much of the future program up until at least Kosmos-1402. For some reason Soviet authorities wanted the world to know this frequency, which is a bit strange considering the otherwise very secret nature of the US-A program..

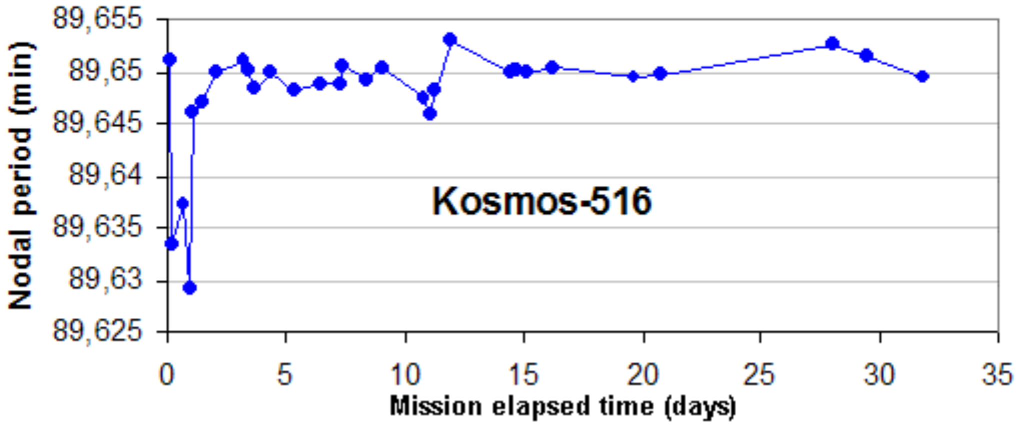
Kosmos-402

Kosmos-402 was launched at 1129 UT on 1 April 1971. There was an object (cat nr 5105) in the high orbit already 0.332 days after launch in an 951-1035 km orbit. There were B and C object in the lower orbit. The first C-object epoch was 0.492 after launch and the orbit was 240-264 km. The short time in low orbit indicates that this was not a particularly successful flight.

Kosmos-469

Kosmos-469 was launched at 1130 UT on 25 December 1971. This was the first US-A flight confirmed by Russian source to have had the BES-5 nuclear reactor (4). This is in contradiction to (1) where Kosmos-367 is regarded as the first craft with the reactor. This spacecraft carried an active radar, perhaps for the first time. It moved up to the high orbit on 4 January 1972. It seems that Kosmos-469 may have been the spacecraft where the tight orbit control worked for the first time.





Kosmos-516

Kosmos-516 was launched at 1036 UT on 21 August 1972. Sources say that this was the first US-A to carry complete radar system into orbit (1). The spacecraft moved to the high orbit on 21 September after 514 revolutions, i.e. 31.8 days. The plots of orbital data on the right for this and the previous flight seems to indicate rather sparse tracking of the satellites. Perhaps those in charge did not fully comprehend what these satellites were or how they operated. For later missions much more dense tracking information is available.

Kosmos-626

In his diary for 28 December 1973, Geoff Perry wrote:

> *"... news of Cosmos 626 from TASS. 65 degree, 89.7 min, 257-280 km. Is this a new two-tone? Probably not since perigee is high. Other satellites with this inclination and orbit have been C.402, 469 and 516 - the type that suddenly maneuver up to a 104 min period after varying times in low orbit? Perhaps this is another engine test like these? ..." **(17).***

Kosmos-626, the first US-A satellite to carry out a nominal mission was launched at 2019 UT on 27 December 1973. Interestingly enough, in an national Intelligence Estimate published on 20 December 1973 the CIA had been able to use previous launches to correctly identify the purpose of these satellites **(1)**. Probably the appearance on the two previous vehicles (K-469 & K-516) of an operating radar must have given analysts a firm clue to the character of the system. The general public was still in the dark as the quote from Geoff Perry's diary shows. The satellite was boosted to the high orbit on 11 February 1974 after 45.3 days.

Kosmos-651 & Kosmos-654

Only 139 days after Kosmos-626 another US-A satellite was launched on 15 May 1974 when Kosmos-651 took off from Baikonur at 0730 UT. A mere two days later a surprise took place. This is what Geoff Perry wrote:

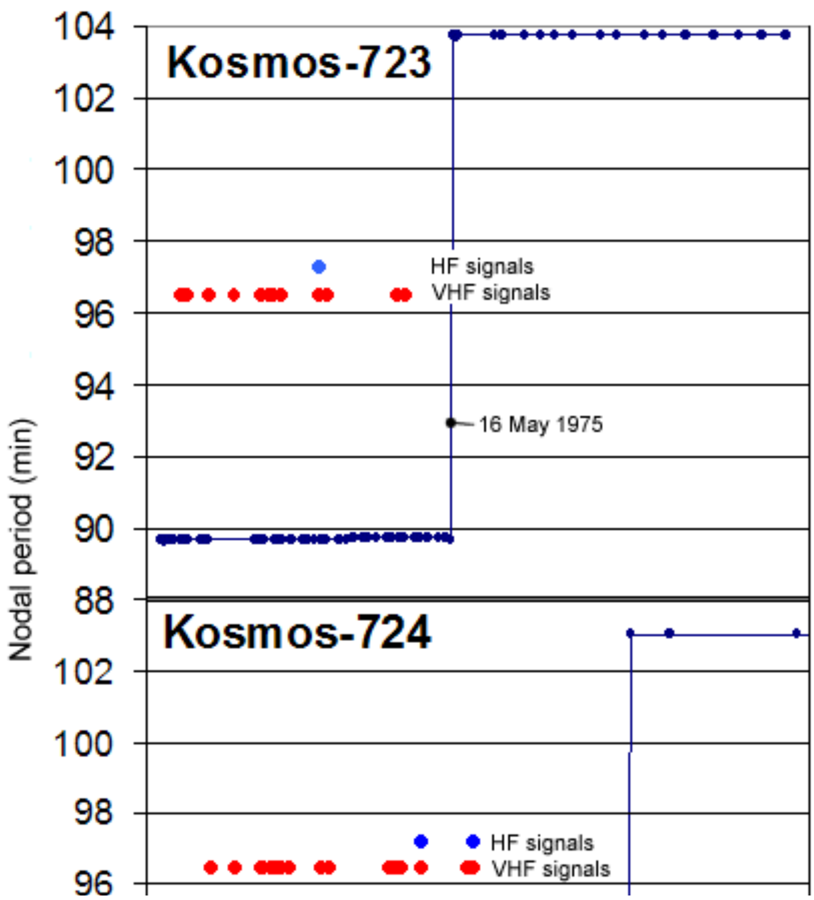
> *"..yet another launch. 65 degrees, 89.6 min. Looks like another ocean-surveillance type. New satellite is 25 minutes ahead of of C. 651 and since in same orbital plane, is consequently 6.4 degrees further east in ground track. Is this a replacement or are the two working as a pair? We will have to wait and see..." **(15)**.*

Kosmos-654 had been launched at 0653 UT. At this time, no signals had ever been received from the US-A type of satellite so the assessment of these spacecraft had to be based entirely on analysis of orbital data slowly filtering in from Goddard Space Flight Center. But a few weeks after the launch the situation was clear. Let me quote Geoff Perry again:

> *"... C.651 and C-654 have BOTH maintained their initial orbital period and track separation. This implies that both are operational and are receiving micro-thrust orbit corrections..." **(16)**.*

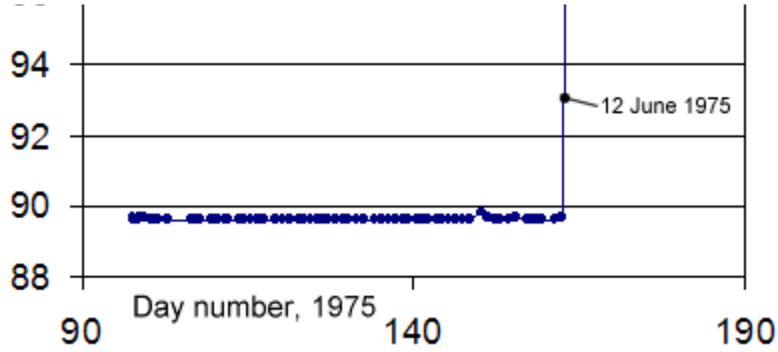
Kosmos-651 moved to the high orbit on 25 July 1974, after 71 days, and Kosmos-654 performed this maneuver on 30 July 1974, i.e. after 74 days.

Kosmos-723 & Kosmos-724



Kosmos-723 was launched from Launch Complex 90 at Baikonur at around 1100 UT on 2 April 1975 **(4)**. The launch vehicle stages were all suborbital and the satellite put itself into an initial orbit at 247.3-268.3 km above a spherical Earth. Its companion spacecraft Kosmos-724 was launched from from the same site at around 1100 UT **(4)** on 7 April 1975. The initial orbit was at 248.0-266.2 km, very close to that of Kosmos-723.

Again there was a 27-minute difference in passing the equator with Kosmos-723 leading. However, the orbital planes of the two craft were displaced by 23 degrees in longitude. In **(2)** Geoff Perry describes how he, as Senior Science Master at the Kettering Grammar School, gave the plotting of orbital data of these two spacecraft to two pupils, Stuart Ganney and John Kellet. They quickly found that both spacecraft were making small maneuvers to maintain the 89.65 minute period and that it seemed that these maneuvers were made in unison



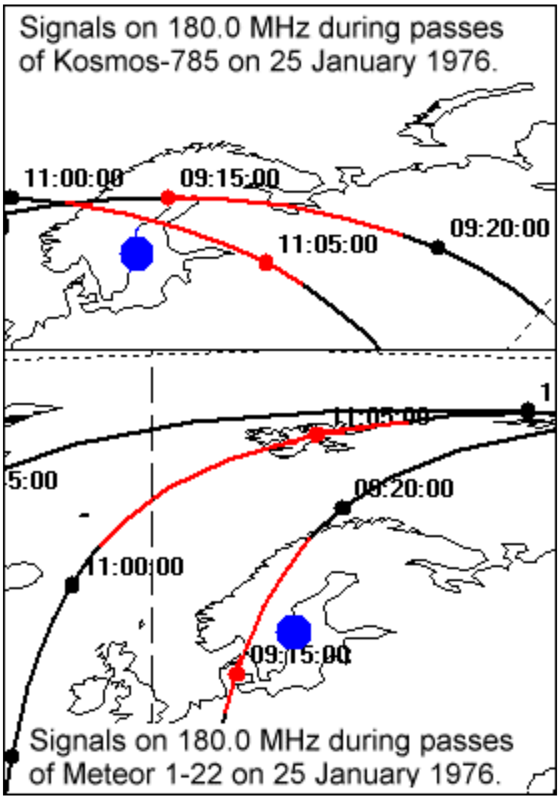
as if stationkeeping. However, Kosmos-723 gradually increased its orbital period (see "ion thrusters" above) and this led to the decrease in time difference at the equator. By early May the time difference was close to zero.

Four days after the launch of Kosmos-723, I was able to pick up PPM-AM telemetry on 166.0 MHz from the spacecraft on three passes. It seemed that the spacecraft was commanded from a site to the east of Moscow, because signals started when the craft was over the Baltic, far above the radio horizon of Moscow. In general Kosmos-724 transmitted more during passes further to the east than Kosmos-723 **(3)**.

The launch of the US-A spacecraft coincided with a surge in Soviet reconnaissance satellites and large-scale Soviet naval maneuvers. The Okean 75 naval war games were conducted 15-17 April in the Atlantic, Mediterranean, Pacific and the Indian Ocean. At one point there were three reconnaissance satellites in orbit, Kosmos-720 (two-tone signals on 19.995 MHz received by the Kettering Group), Kosmos-721 area survey satellite (FSK-PDM signals on 19.994 MHz picked up), and Kosmos-722 close-look spacecraft (two-tone signals on 19.989 MHz).

On 26 April 1975 I was able, for the very first time, to pick up signals on short-waves from a US-A spacecraft, Kosmos-723, on 19.542 MHz. This frequency had been known during eight years but eluded us. Upon hearing the signals I immediately phoned Geoff Perry and he tuned it on his radio as were were speaking! The spacecraft was still in low orbit and had not moved up to the high storage orbit. Kosmos-724 also transmitted on 19.542 MHz a few times on the low orbit. The first time was on 11 May 1975. Kosmos-723 was launched to high orbit on 16 May and Kosmos-724 on 12 June. In October of 1975 the system was declared operational (1**)**.

Kosmos-785



This satellite appears to be somewhat of a mystery. It moved very quickly (after rev. 10) to the high orbit after its launch at 1245 UT **(4)** on 12 December 1975. The move to the higher orbit was probably commanded from Kamchatka as it came into view from Soviet soil again early on 13 December 1975 after having left the zone of visibility over Western Russia the evening before.

There have even been doubts as to it being a US-A spacecraft. I am the the source of this doubt. I picked up PPM-AM signals twice on 25 January 1976 on 180.0 MHz. The signals were brief but strong. The signals matched the passes (0914-0919 UT, 1101-1106 UT) of Kosmos-785 very well (see map below). However, these signals also match the passes of Meteor 1-22 very well. Since signals on 180 MHz were quite common from the Meteor-1 series, I think that one can safely say that Kosmos-785 did not transmit on 180 MHz that day in January 1976.

The reason I thought that they came from Kosmos-785 was more the result of lack of orbital data for other satellites to calculate passes. remember, this was in the days well before the Internet and getting access to all those element sets to run against a certain set of observations was a very tedious task. Now, with the availability of old element sets via the Internet and easy-to-use software for computing passes, this old mystery can now be cleared up. Probably Kosmos-785 transmitted on the usual frequencies, but we just missed the signals because of the short duration of the mission.

Kosmos-860 & Kosmos-861

After Kosmos-860 moved up late on 10 November 1976 I was unable to pick up any VHF signals from it. I certainly heard Kosmos-861 in the low orbit (as I had done with Kosmos-860?)

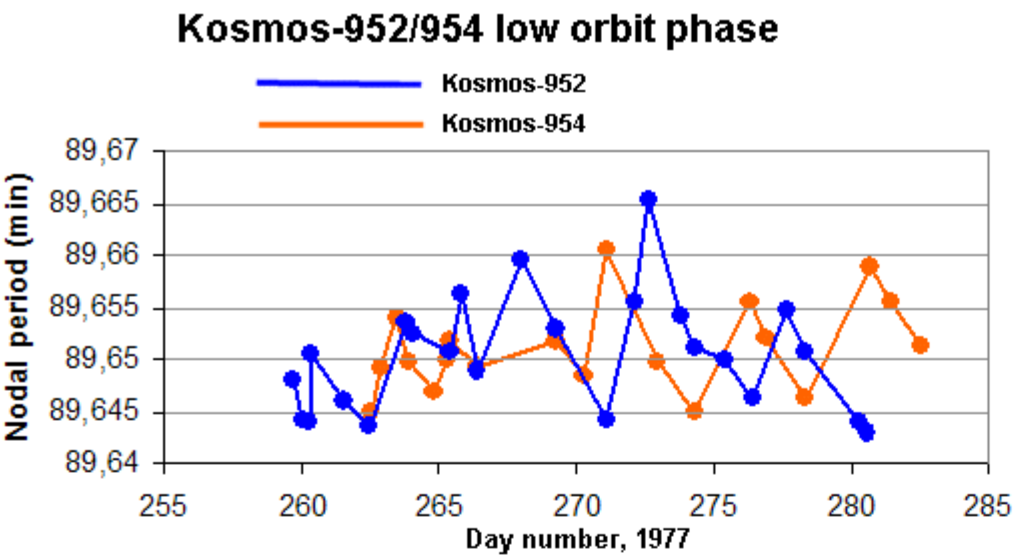
Denys Hibbins in Nunhead outside London picked up signals on 19.542 MHz in the evenings during the period 13-21 November but thought they were from Kosmos-861, which was still in the low orbit. Geoff Perry analyzed the reception log on 23 November and found that signals came 21 minutes later every day. Therefore the orbital period had to be 1440+21 divided by 16, 15, 14, 13 or 12 giving orbital period values of 91.3, 97.4, 104.4, 112.4 or 121.75 minutes. At that point it was obvious that the signals came from Kosmos-860 in the high orbit with a period of 104.33 minutes. So, the short-wave transmitter operated in the high orbit. We had thought that the spacecraft was completely inactivated in the high orbit because of the lack of VHF transmissions. Now it seemed that the short-wave transmitter relayed some sort status information, possibly about the status of the deactivated reactor. Denys Hibbins picked up no more short-wave signals from Kosmos-860 after 23 November.

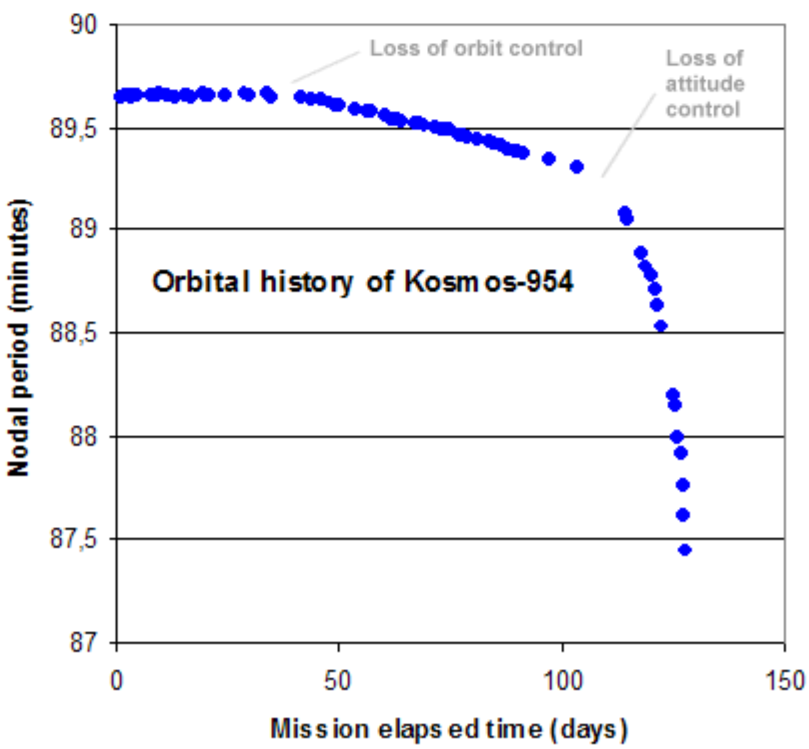
Denys Hibbins again picked up FSK-PDM signals on short-waves, this time on 19.545-19.547 MHz on 22, 28, 29 and 30 December 1976. Geoff Perry also picked "weird" signals on 19.547 MHz on 31 December at 0023-0028 UT and on 1 January 1977 at 2319-2323 UT. These turned out to have come from Kosmos-861 which moved to the high orbit on 20 December 1976. Geoff Perry speculated in his day-to-day log on 1 January 1977 that **"these signals are used to check out the payload in the high orbit prior to its eventual shut-down".**

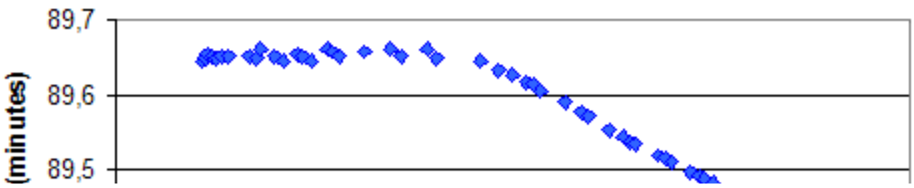
Kosmos-951 & Kosmos-954, a near-disaster

Kosmos-952 was launched at 1425 UT on 16 September 1977. Kosmos-954 was launched at 1348 UT on 18 September 1977. The three lower graphs on the right show the evolution of the orbit of Kosmos-954 in three views: the entire mission, up until loss of attitude control and up until loss of orbit control and maintenance. The top graph shows the evolution of the orbital period of both spacecraft during the low-orbit phase of Kosmos-952. A quick examination of the graph gives the impression that the maneuvers of the two spacecraft were coordinated, but with a short delay. Interestingly, while the orbit of Kosmos-954 was being controlled and Kosmos-952 was still in the low orbit the orbital period was kept at the same average. But after the loss of Kosmos-952 the period of Kosmos-954 appears to have increased slowly.

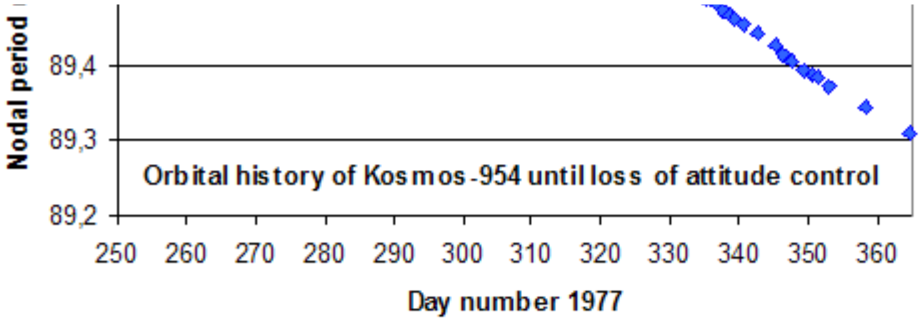
It seems that orbit control lost in the period 23-29 October 1977. The last point in the bottom graph still does not show that the spacecraft had complete lost control, because the reduction in period from the previous available data point was not typical of unhindered decay under attitude control. So, presumably control was lost on that day or the days

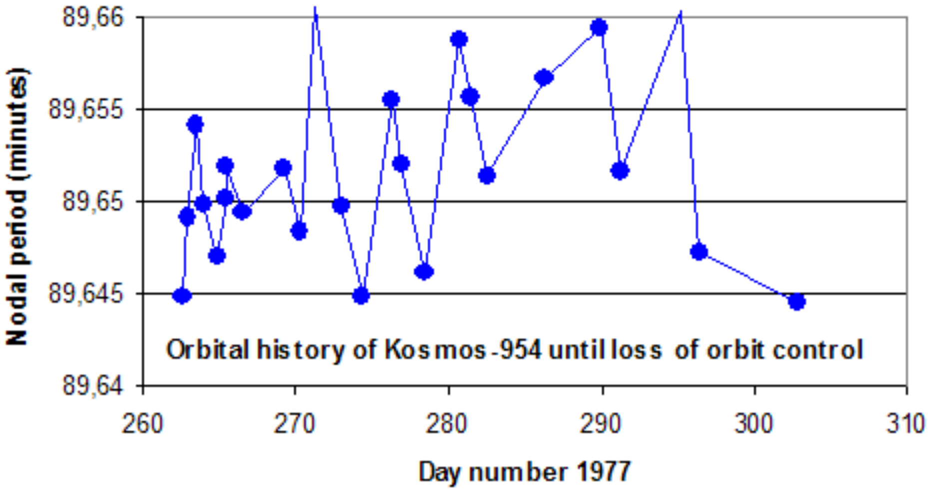






immediately thereafter, perhaps on 1 November 1977.





Weiss **(5)** has given the details of how the Kosmos-954 crisis was handled in the U.S.A. In November 1977 US intelligence sources determined that the Kosmos-954 was experiencing difficulties. On 1 December 1977 the deputy Under Secretary of Defense for Policy (Admiral Murphy) was alerted by his staff. The NSC formed an interagency committee on 19 December 1977 called the Ad Hoc Committee on Space Debris. Kosmos-954 lost its attitude control on 6 January 1978. On that date the NSC briefed its principals and put the re-entry date in April. However, later the same day the Air Defense Command reported the loss of attitude control and that the re-entry would come soon.

The US approached the Soviet Union about the spacecraft on 12 January 1978. The Soviet Union responded on 14 January 1978 and confirmed that the spacecraft was "depressurized" on 6 January and that the reactor fuel was (68 lbs)? 50 kg Uranium-235. Leaders of the US Congress and allied countries with space tracking capability were informed on 17-18 January, More clarifications were requested from the Soviet Union on 17 january. On 18 January the Soviet Union responded that the reactor would not go critical and that it was designed to burn up on re-entry. On 23 January the Soviet Union told the U.S. that the satellite would come down on the 24 th. At 1000 UT EST on 24 January DIA's Current Operations center and told the NSC that re-entry was imminent, within one orbit. The satellite reentered the atmosphere over Queen Charlotte Island at 1153 UT and landed just east of the Great Slave Lake.

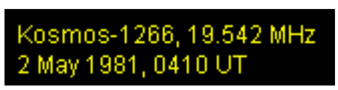
It is interesting to note that Soviet Air Defense Forces Center for Monitoring Cosmic Space (TsKKP) started continuos monitoring of Kosmos-954 starting 20 December 1977, which suggests that something further went wrong around that date **(1)**. The same organization also is said to have predicted re-entry to take place at 1212 UT on 24 January 1978 **(1)**. I have tried to locate information about the exact time of impact. Of course this may be inappropriate as the vehicle was split into many parts. I have found indications that the crash occurred at 1200 UT +/- 10 minutes and 1158 UT.

Kosmos-1176

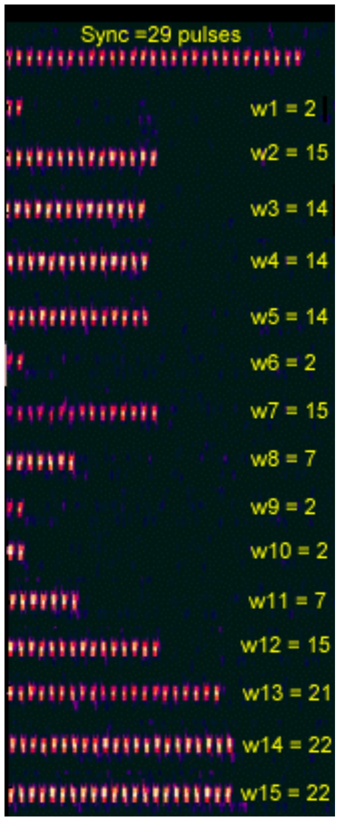
The next US-A satellite, Kosmos-1176, was launched at 1140 UT on 29 April 1980, the same day that the International Herald Tribune carried an article about Geoff Perry and the Kettering Group under the headline *"Another gifted British Hobbyist. UK Amateur Monitors Russians in Space".* The resumption of US-A flights was a big enough event to prompt the U.S. Department of State to issue a communiqué about Kosmos-1176 on 2 May 1980 **(14).** The first orbital data were relayed to me by Geoff Perry at 1130 UT on 3 May 1980. I picked up first signals from Kosmos-1176 at 1421.30-1428.05 UT on 3 May 1980 on 166.0 MHz (PPM-AM). I kept listening to signals from the satellite until 16 May 1980.

Kosmos-1176 was exceptionally long-lived. It was moved to the high orbit on 10 September 1980 after 133.7 days - almost twice the previous record duration - 74 days for Kosmos-654. The main body, object 11788, was detected in an orbit at 873-970 km, while the other object (11971), which we now know is the fuel core, was found in an orbit at 870-943 km. It seems that the fuel core was ejected "backwards" from the main vehicle. At the time, we did not pay attention to this new object or understand what it could be. In fact, initially the Kettering Group thought that 11971 was just a re-designation of 11788.

Kosmos-1249 & Kosmos-1266



Kosmos-1249 was launched from Baikonur at 1809 UT on 5 March 1981 and its companion satellite took off at 0345 UT 21 April 1981. The orbits of the two spacecraft were chosen to be co-planar with an initial phase difference time separation of 25.9 minutes, which is close to the theoretical value for co-planar orbits with n=2, i.e. 25.6 minutes. Kosmos-1249 moved to the higher orbit on 19 June 1981 and Kosmos-1266 did the same on 29 April 1981.



Signals were picked up on 166.0 MHz and 19.542 MHz from both spacecraft. Interestingly, the short-wave telemetry from Kosmos-1266 was not of the normal FSK-PDM type. All telemetry words in the frame were "pulsed" in the style of the synchronization pulse train. Instead of try to measure the length of these tones relative to the synchronization pulse train, it is only necessary to count the number of short pulses in each word to determine the measured value. The telemetry is illustrated by the figure on the right which shows each telemetry word below the one before it. **By clicking on the figure the telemetry signal in the figure can be heard**. My radio log shows that the short-wave telemetry from Kosmos-1266 was of the pulsed type described above, while the signal from Kosmos-1249 (listen **here)** was of the normal FSK-PDM type, but sometimes switching over to the "pulsed" mode. I was lucky to be able to catch short-wave telemetry from Kosmos-1249 in the low orbit on 26 April 1981.

Kosmos-1299

Kosmos-1299 was launched at 1637 UT on 24 August 1981. On 5 September 1981 the reactor was raised to the high orbit. There is a two-line elements set for a "B" object that is generated at the time of boost to the high orbit with the epoch day 248.88785098, i.e. at 2118 UT. Therefore the maneuver must have occurred before this time. There were five pieces generated by the maneuver as shown in the table on the right. I picked up very strong, but deeply and regularly fading PPM-AM signals on 166.0 MHz in the evening of 5 September 1981 at 1706.14-1709.05 UT and 2141.55-2147.53 UT. By comparing with passes of the various pieces it it is obvious that the **166.0 MHz signals only could have come from the pieces left in low orbit.** It is impossible to determine which one because the reception times match all three pieces in low orbit. Also, the second reception took place after the first epoch of object B, so the boost maneuver had indeed taken place. Interestingly during both receptions the signals was fading deeply indicating that the spacecraft transmitting the signals was tumbling. Therefore the boost maneuver must have taken place before my first observation at 1706 UT. I did not hear any more signals on this frequency from Kosmos-1299. After deactivation of the reactor the batteries for powering onboard systems in the low orbit object probably quickly depleted. They were, one can suppose, dimensioned to handle short interruptions in power from the reactor.

In the high orbit	
Catalog nr 12783 = 1981-81A	The boost rocket with the reactor casing
Catalog nr 12808 = 1981-81D	The ejected reactor fuel core
In the low orbit	
Catalog nr 12784 = 1981-81B	Rocket?
Catalog nr 12807 = 1981-81C	Rocket?
Catalog nr 12809 = 1981-81E	Platform?

On 6 September 1981 picked up extremely strong short-wave telemetry on 19.542 MHz from Kosmos-1299 of the pulsed type described above. The signals were received at 1730.45-1738.20 UT and 2103.54-2119.24 UT and were typical of over-the-horizon receptions. During these receptions object A (cat nr 12783) was always above the horizon, while object D (cat nr 12808) was well below the horizon at the end of the second reception. This indicates that **the short-wave transmitter is in the main object in the high orbit, i.e. the boost rocket with the empty reactor casing**. This was confirmed a little more than a year later during the flight of Kosmos-1402 (see below). Last signals on 19.542 MHz from Kosmos-1299 were picked up by myself on 13 September 1981.

The text above is the result of hindsight. At the time of the US-A flights in 1981 it was not known what the additional piece in the high orbit (such as 1981-81D) really was. That it was the ejected fuel core only became evident in connection with the Kosmos-1402 accident. It is instructive to read what e very knowledgeable analyst such as Nicholas Johnson wrote at the time **(13)**:

> *"...A new characteristic of the post-Kosmos-954 radar satellites was confirmed in 1981. When the nuclear power supply is transferred to the higher storage orbit, a second fragment is now ejected with a relative velocity of 6 to 7 meters/sec. Speculation has arisen that this extra piece may be a potential destruct package. If the spacecraft malfunctions at a low altitude, the satellite could be blown up, widely scattering its nuclear fuel and making detection of radioactive debris virtually impossible. If the power supply reaches the storage orbit, the destruct package is separated to prevent an accidental explosion and the creation of long-lived debris..."*

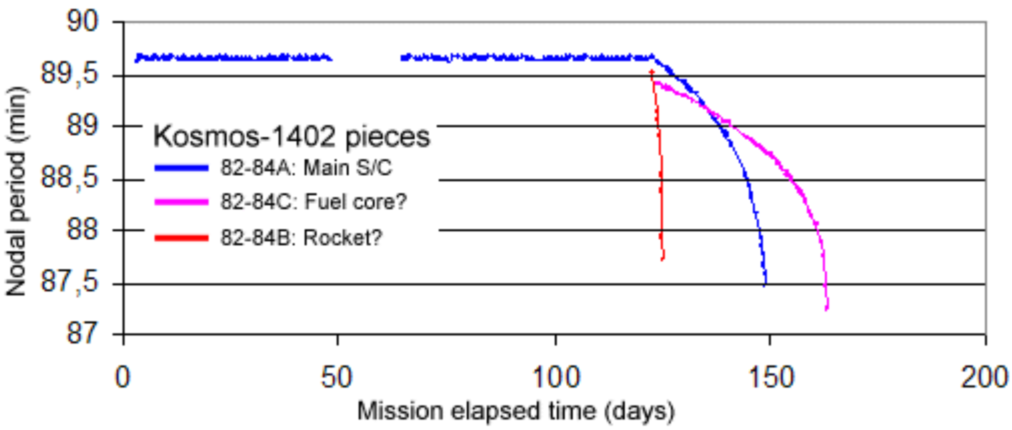
This was wrong, but in a sense not too far off the mark - as we shall see later. Scattering of the fuel core was the idea of the post-Kosmos-954 series but not in the way thought in 1981.

Kosmos-1365 & Kosmos-1372

Kosmos-1365 was launched from Baikonur at 1939 UT on 14 May 1982 and its companion satellite took off at 1358 UT 1 June 1982. The orbits of the two spacecraft were chosen to be co-planar with an initial phase difference time separation of 51.1 minutes, which is close to the theoretical value for co-planar orbits with n=4, i.e. 51.23 minutes. Kosmos-1365 moved to the higher orbit on 27 September and Kosmos-1372 did the same on 11 August. Signals were picked up on 166.0 MHz and 19.542 MHz from both spacecraft. An examination of my log reveals that the short-wave telemetry from Kosmos-1372 was of the pulsed type described above, while the signal from Kosmos-1365 was of the normal FSK-PDM type. So, one may speculate that **the two types of transmissions was a way of discriminating between the two reactor packages in "storage" orbit.**

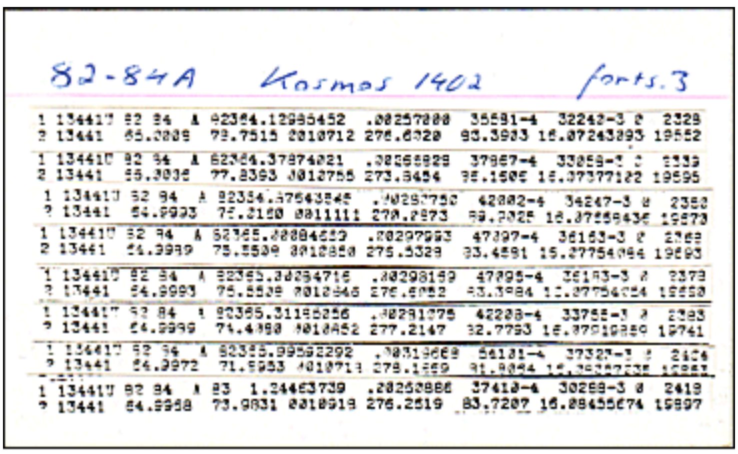
Kosmos-1402 & Kosmos-1412, another international incident

Kosmos-1402 was launched at 1004 UT on 30 August 1982 while Kosmos-1365 was still in operation in the low orbit. Therefore, another launch was not expected immediately. Kosmos-1402 was launched into an orbit co-planar with that of Kosmos-1365 and a time phase difference of 38.63 minutes (38.42 minutes is the ideal value for co-planar orbits with n=3).



When Kosmos-1365 was deactivated on 27 September a replacement for that satellite was promptly launched when Kosmos-1412 was launched at 0000 UT on 2 October 1982. The orbits of these two spacecraft were chosen to be almost co-planar (difference 0.85 deg) with an initial phase difference time separation of 25.52 minutes, which is close to the theoretical value for co-planar orbits with n=2, i.e. 25.6 minutes. However, Kosmos-1412 ended its mission on 10 November 1982 when it moved to the high orbit. Again, despite heroic efforts by Soviet planners, a single US-A spacecraft was left in the operational orbit. Kosmos-1402 "soldiered on" in this orbit until the end of December 1982 when dramatic events occurred. The graph below shows how the spacecraft was split into three pieces that all decayed instead of moving to the high orbit.

By analyzing the relative motion of these pieces it seems that the C object, presumably the fuel core as we shall see later, seems to have separated at high speed (<10 m/s?) from the main A object late (approx. 2200 UT) on 27 December 1982. A sign of this can be seen in the graph above; the fuel core orbital period trace starts at 89.4 minutes - well below the orbital period curve for the main object. The B object, often called the rocket separated from the main object at about 0200 UT on 28 December 1982. The last element set of Kosmos-1402 which shows an increase of period relative to an earlier value is dated at 2250 UT on 27 December 1982. So, it seems that in the hours around midnight of 27/28 December the last orbit-correction maneuver was made, controllers realized that the spacecraft was malfunctioning and the attempt to boost it to higher orbit took place, but failed. However, the relative motion analysis appears strange. One would have thought that the low-density "rocket" would have separated from the vehicle before the fuel core. The main object would have



Before the advent of the Internet and personal computers two-line element sets were distrubuted as Xeroxed sheets. I cut out individual element sets and glued them to index cards like this one.

ascended to high orbit and then discarded the fuel core. Here, events seem reversed. It should be remembered that the relative motion analysis is uncertain. It is based on single element sets that could have errors in them.

It took a few days for the news about the misfortune of Kosmos-1402 to reach the Kettering Group and to trickle into the open domain. Geoff Perry, the senior science master at Kettering Boys' School and leader of the Kettering Group had assigned orbital analysis of Kosmos-1402 to one of his pupils. John Corvesor plotted orbital period vs time and used Xeroxed copies of two-line elements sets printout mailed from NASA's Goddard Space Flight Center. I used the same source myself and we usually got the envelopes at the same time, about five days after they were mailed in the U.S. a couple of times per week (incredibly, this was a free service). Therefore, there was an inevitable time lag in monitoring the status of Kosmos-1402. When Geoff Perry was called by a U.S. journalist on 3 January 1982 about a possible mishap to Kosmos-1402 he could only say that as of 26 December everything was OK. During this period, two-line element sets were received in the U.K. by telex at Aston University and on 4 January, without giving Geoff Perry any orbital data, they told him that Kosmos-1402 had split into three pieces. Geoff called me the following morning (5 Jan) to see if I had had a later mailing from GSFC of elements - and indeed - I had. I had processed (cut and glued) the element sets. In the wastepaper basket I found the element sets for the two new objects, B and C as well as for A. The data showed that the two new objects had appeared early on 28 December, but that there was an element set for the A object in the low orbit for early on 29 December. So, the ascent to the high orbit had indeed failed. So, there was another major international incident in the works. On 5 January I also informed Geoff that space tracker Jan-Ola Dahlberg in Malmö had picked up short-wave signals on 19.542 MHz typical of US-A satellites on 30 December. Based on the element sets I gave him and Jan-Ola's signals Geoff Perry gave the news for publication by ITN at 1435 UT on 5 January 1982.

On 6 January Soviet media denied that anything was amiss with Kosmos-1402 "on a pre-planned course and presented no danger" , but the following day they did admit the the satellite was coming down. At 1700 MT the following statement was issued by Moscow:

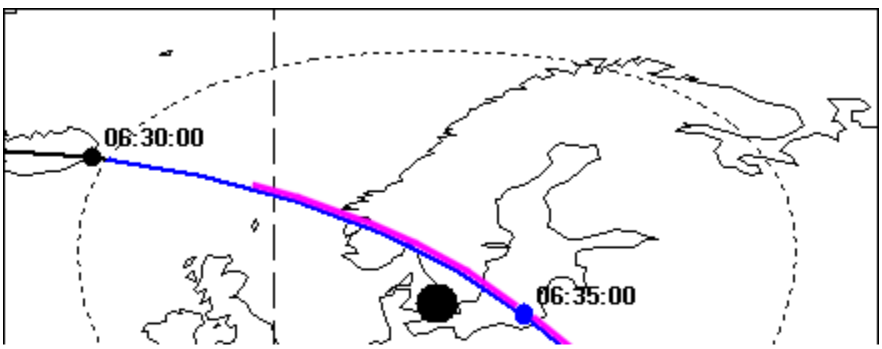
> *"... On Dec 28 the satellite's active mission ended and in accordance with the flight programme it separated into individual fragments upon command from the ground. The purpose of this was to isolate the active part of the reactor so that it would burn in the dense layers of the atmosphere, the radioactivity levels following this remain within the limits of the natural background..."*

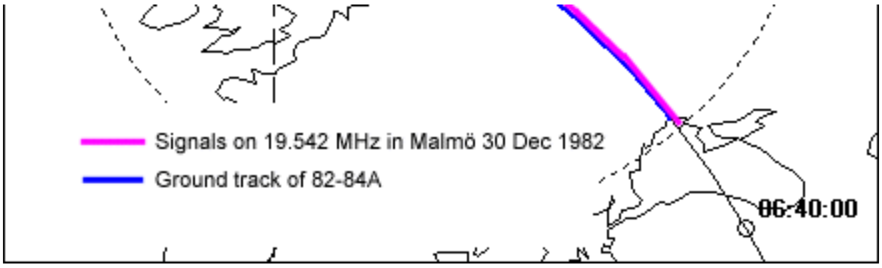
News article in Dagens Nyheter 9 January 1983 describing the demise of Kosmos-1402 and Jan-Ola Dahlberg's reception of signals from it. The picture shows Jan-Ola in front of his Drake receiver.

At the time of this hidden high drama the Kettering Group was trying to find signals from a new type of spacecraft, Kosmos-1426, and we were listening on all known frequency bands. Jan-Ola Dahlberg in Malmö in southernmost Sweden then happened to pick up signals on 19.542 MHz, the typical US-A frequency. He picked up the "pulsed" mode telemetry with the characteristic telemetry words 1, 6 and 9 short. The first brief observation was made on 29 December at 1755.57-1756.14 UT when all Kosmos-1402 pieces were far to the east of Sweden. Two more such observations were made on 31 December 1149.00-1154.30 UT and at 1223.12-1228.00 UT.

However, a most important observation with very strong signals indicating that the spacecraft was over the horizon was made on 30 December at 0631.30-0638.00 UT. This made it possible to determine the origin of these signals. The map below shows that the main piece of Kosmos-1402, 82-84A, was above the horizon when the signals were heard. The "B" piece had passed Malmö ten minutes earlier and the reactor core "C" had passed 20 minutes early so neither of these could be the source of the signals **(7).** Because we suspected that the short-wave transmitter was in the rocket stage that brought the reactor and its fuel core to the high orbit (see Kosmos-1299 above), **Jan-Ola's signals also confirmed the misfortune of Kosmos-1402.** After we had learned about the misfortunes of Kosmos-1402 in early January we tried pick up more signals on 19.542 MHz from Kosmos-1402, but to no avail. Jan-Ola's signals on 31 December were the last from this spacecraft.

The next phase of the public excitement around the Kosmos-1402 mishap was the estimate of the re-entry time. Orbital data were still scarce so people with only public domain information were "fumbling in the darkness". On 10 January doubts as to what the A and C parts were started to appear. Pierre Nierinck, a very skilled satellite observer and orbital analyst based in Dunkirk, had

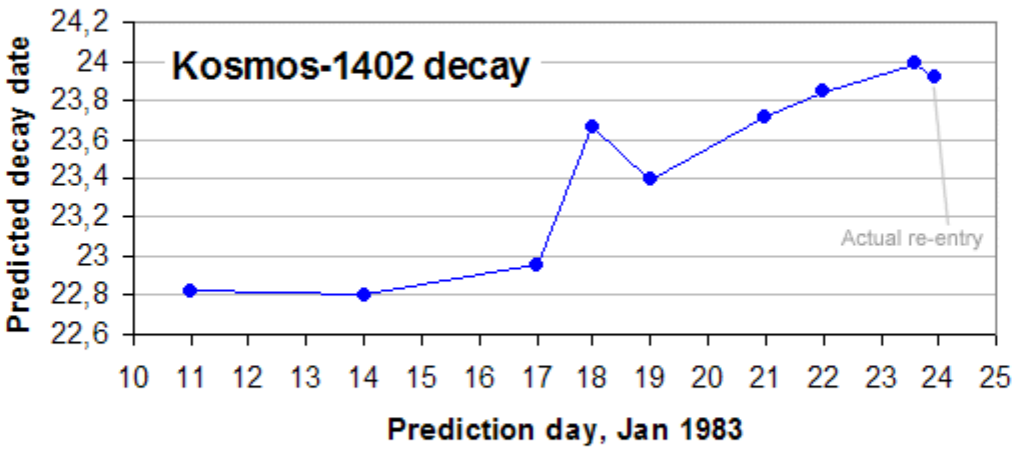




calculated that the densities of the A, B and C objects were related as B,A,C=1,10.2,24.5 showing that C was the most dense objects. Pierre also calculated that the re-entries of the A and C objects would be Jan 23 +/- 4 days for the A object and Feb. 7 +/7 days for the C object **(8)**. This agreed well with the date January 22.82 calculated by Geoff Perry using a method developed by King-Hele **(9).** On 15 January I called Geoff Perry at 0911-0926 UT and argued that the A piece was coming down faster than it should have in case the reactor was attached. I argued that we were concentrating on the wrong object if we wanted to follow the fate of the reactor. Geoff tried to convince me that there always was an object that flew for 20-30 days after separation of all the object. In my diary I can read "I am still skeptical" **(10)**. At 1656 UT Geoff Perry was called by a newspaper ("The Mail on Sunday") who told him that TASS announced that the reactor fuel core would burn up in mid-February. At that moment it was clear that we had been worrying about the wrong object.

The TASS announcement quoted a Dr Belotserkovskiy of the Academy of Sciences. He explained that the fuel core would disperse in the atmosphere and that radioactivity would be well below the natural background. While this was reassuring, it did not calm anyone, and the A object would still contain radiation contaminated material. So, the hunch of Pierre Neirinck to analyze densities showed clearly that the densest object "C" must have been the fuel core. Pierre at that point had recalculated the densities as B,A,C=1,9.23, 19.01. We continued to compute the re-entry date by fitting a second degree curve by the least squares method to find the decay rate (n-dot). This was used in the method **(9)** developed by King-Hele to compute the decay date. The graph shown here displays how the predicted decay date converged nicely to the actual decay date - naturally. The prediction always underpredicted the lifetime of the spacecraft. Not much, but still we always underestimated the lifetime, initially by approximately 7%.

The A piece, the boost rocket and reactor hull entered the Earth's atmosphere at 2210 UT and possibly reached the surface at 2222 UT on 23 January. This corresponds to the epoch 23.92. The reactor core entered the Earth's atmosphere at 1056 UT according to Soviet data and fragments, if any would have reached the earth's surface at 1107 UT according to US sources.



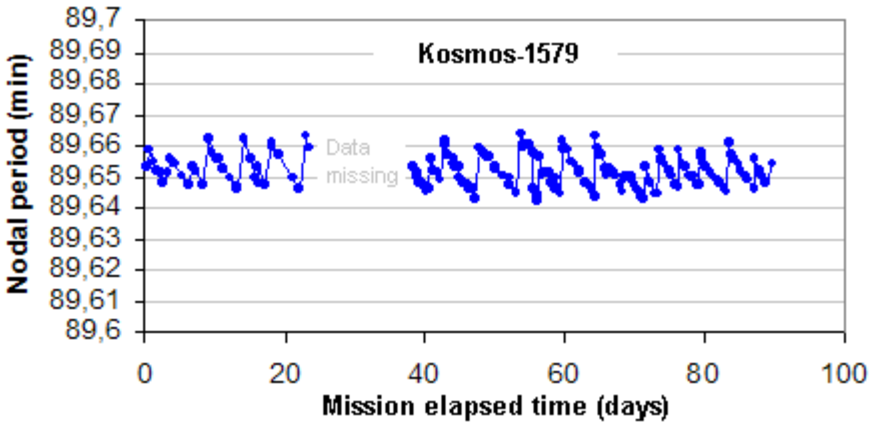
The fact that the reactor fuel core had been separated and that this new safety device had been introduced to handle situation such as the earlier accident with Kosmos-954 was not really known until the Soviet authorities said so in connection with Kosmos-1402. Earlier evidence that an additional object appeared in the high orbit after Kosmos-954 had not been interpreted as ejection of the fuel core. The confusion in connection with Kosmos-1402 also showed that Western intelligence sources had not correctly understood the redesign of the US-A system at this time. In a UN document from 1980 **(12)** there are hints at this method. The document discusses what happens if the structural parts holding the fuel rods melt during re-entry. The radioactive material is then dispersed so that no change in the background radiation can be expected. But the document does not mention intentional ejection of the fuel core - only hints at the existence of a back-up safety system. Evidently, the Soviet authorities also used the ejection of the fuel core as a means of countering the other criticism of the US-A system; that the ascent t the high orbit only postponed the radioactive contamination problem. With the fuel core ejected even in the high orbit, Soviet authorities could argue that when that reentered in a thousand years' time it too would "disappear" in the natural background radiation. In effect the revised design of the US-A system meant that the previous design was ruled as totally unsafe. Let me quote Nicholas Johnson's interesting remarks in **(11)**:

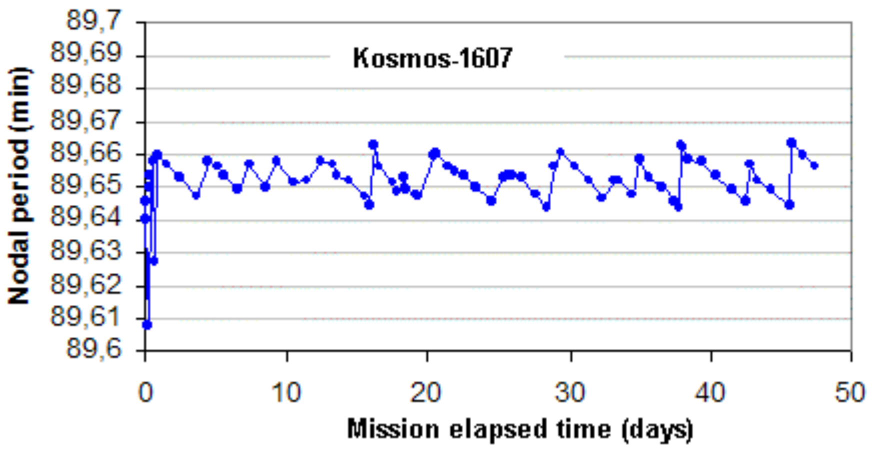
"... The solution finally chosen by the Soviets say as much about their philosophy of spacecraft design as it does their space technology. Instead of incorporating additional redundant features into the propulsion mechanism that failed, the Soviets concluded that no system was perfectly fail-safe and therefore they concentrated on methods to prevent detectable radioactive debris from striking the earth. In the case of Kosmos 954, it was the rugged reactor housing that protected the 'hot' fuel core during reentry and contributed to the contamination of the canadian tundra. The final

Soviet solution was to develop a way to eject the fuel core from the reactor. This technically challenging operation would ensure incineration of the unprotected fuel core during reentry. The remaining reactor housing, which still possessed a lower radiation level, would also be likely to undergo more complete burnup and fragmentation as it reentered the Earth's atmosphere..."

Thus ended the second serious mishap in the US-A series. There would almost be one more before the program ended in connection with the break-up of Soviet power.

Kosmos-1579 and Kosmos-1697, two single spacecraft missions





The US-A program resumed at 0021 UT on 29 June 1984 when Kosmos-1579 was launched . There was a big naval exercise in the Baltic at the time of its launch, but it is unclear if this was significant. the spacecraft remained in operation in the low orbit until 27 September 1984, i.e. 90 days. The orbit maintenance of Kosmos-1579 was very regular as shown by the plot of orbital altitude vs time. Orbit corrections were performed approximately every three to four days.

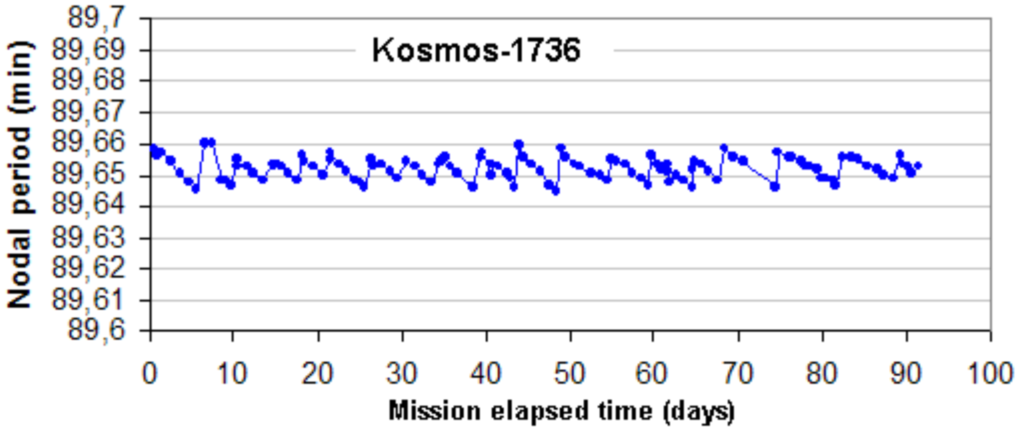
There was no second US-A satellite launched to work with Kosmos-1579. Instead , Kosmos-1579 probably operated in unison with the US-P spacecraft Kosmos-1567. Evidence of this is the typical spacing between the orbital planes of the two spacecraft of approximately 150 degrees. Geoff Perry and I tracked the spacecraft in July 1984 while Geoff was a house guest of myself and my wife Inger on his way to a conference in Sweden. We heard the 166.0 MHz telemetry at 0721-0726 UT on 8 July 1984.

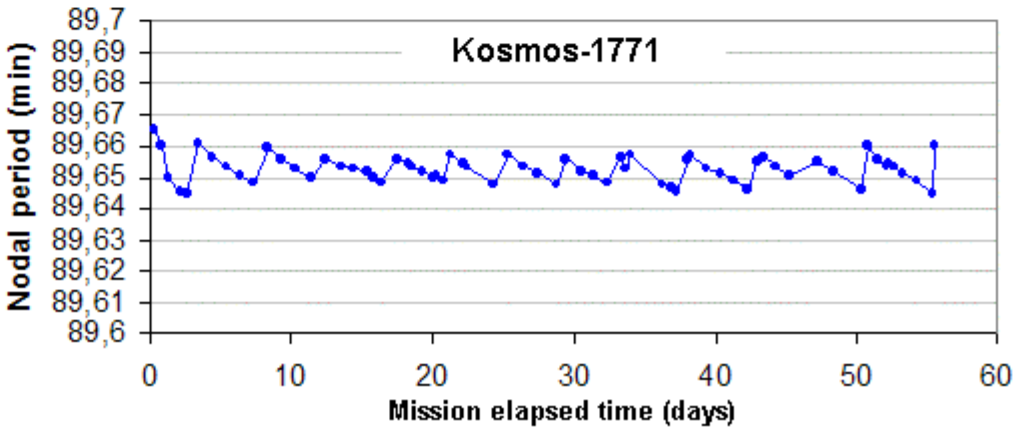
Kosmos-1607 was launched at 1229 UT on 31 October 1984. I picked up signals on 166.0 MHz on eight occasions between 10 November 1984 and 27 January 1985. The spacecraft moved to the higher orbit on 1 February 1985 after 90 days. This spacecraft was also co-ordinated with the orbital plane of the US-P spacecraft Kosmos-1579 and -1588. In the figure on the right orbital data are only available for half of the low orbit phase.

Kosmos-1670 & Kosmos-1677, the last dual spacecraft mission

Kosmos-1670 (catalog number 15930) was launched at 0536 UT on 1 August 1985. Kosmos-1677 (catalog number 15986) was launched at 2233 UT on 23 August 1985. The orbits of the two spacecraft were almost exactly co-planar with an initial phase difference time separation of 25.6 minutes, which is the theoretical value for co-planar orbits with n=2. Kosmos-1670 was raised to the high orbit on 22 October 1985 and Kosmos-1677 performed the same maneuver on 23 October 1985. Initially the two US-A spacecraft operated in coordination with the two US-P spacecraft Kosmos-1567/1646 as shown by the 150 degrees of angular distance between the orbital planes of the two pairs of spacecraft. A third US-P spacecraft was launched on 19 September 1985 to take up its place in the US-P system. Five Soviet ocean surveillance satellites operated at the same time **(22)!**

The timing of the launches seems to have been connected to NATO's largest peacetime naval exercise "Ocean Safari 85" in which some 200 warships from 10 countries participated. Aircraft carriers and the U.S. battleship Iowa took part. Soon after the launch of Kosmos-1677, ships started to leave Norfolk, Virginia, for the rendezvous area off Boston. The "armada" then sailed to Iceland and onwards to Europe to simulate the resupply of Europe in case of war. Mock attacks against the convoy were conducted. The maneuvers continued in the North sea, the Straits of Denmark and the Baltic **(22)**. This must have been a very tempting target for the US-A system. It is therefore understandable that a dual spacecraft mission was flown. As it turned out, because of the ascent of Mikhail Gorbachev, reduced East-West tension and the eventual fall of the Soviet Union, this was the last dual spacecraft US-A mission.





Kosmos-1736

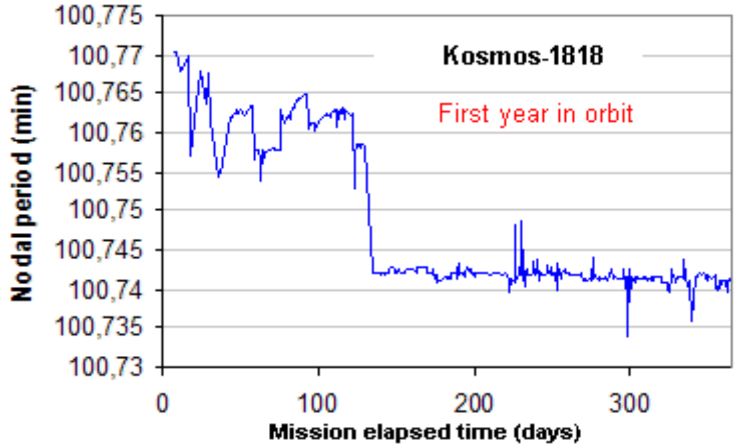
Kosmos-1736 (catalog number 16647) was launched at 1005 UT on 21 March 1986. It moved to the higher orbit on 20 June 1986 after 92 days. Kosmos-1736 entered orbit in a plane 137 degrees (well within the 132-150 degree band established since 1975) from that of Kosmos-1735, a US-P spacecraft **(23)**. Johnson **(23)** also speculated that the timing of the launch had something to do with U.S. naval maneuvers off Libya a few days later.

Kosmos-1771

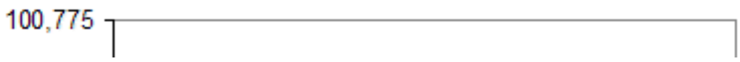
Kosmos-1771 (catalog number 16917) was launched at 1258 UT on 20 August 1986. Again the spacecraft's orbital plane was 150 degrees away in right ascension from that of Kosmos-1735. Thus, it seems that the new US-A satellite was working in conjunction with the same US-P spacecraft as its predecessor. A U.S. armada of some 30 ships, including two aircraft carriers and a battleship, performed maneuvers in the Sea of Japan and the Sea of Okhotsk during September and into early October 1986 **(23)**. As the U.S. naval operation ended two Soviet ocean surveillance satellites, Kosmos-1682 and -1771 were taken out of operation. Kosmos-1771 boosted itself to the high orbit on 15 October 1986.

Kosmos-1818

At 2330 UT on 1 February 1987 a US-A satellite, Kosmos-1818, (catalog number 17369) was launched into an unusual orbit signaling something entirely new in the program. It was put into an orbit at 65 degrees inclination between 789 and 802 km altitude. It seems that the main US-A spacecraft bus was used to insert the spacecraft into the high orbit. In that orbit two large fragments were detached.

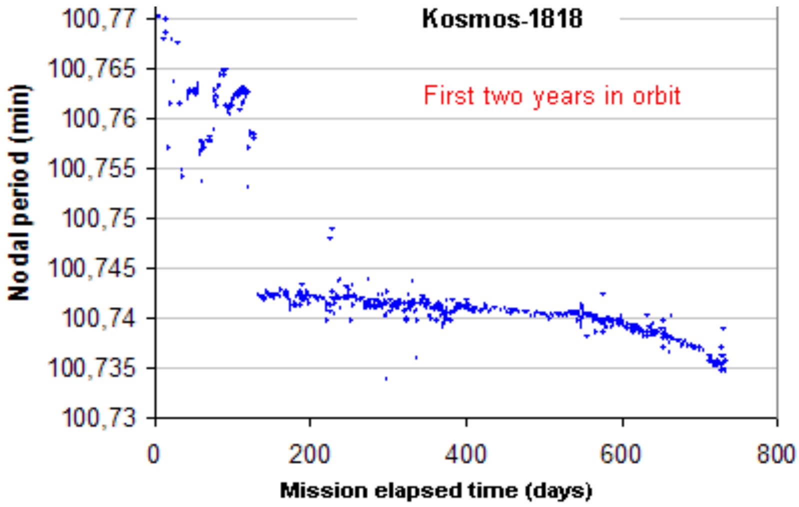


Although not revealed immediately, it later turned out that this spacecraft was called Plazma-A and tested the new TEU-5 Topol **(1)** reactor, ion engines and other systems **(27)**. Sketches of this spacecraft do not show a radar such as on the original system. Perhaps the radar antenna would appear on later operational models of this spacecraft type. But perhaps the higher output of the new reactor type would have made it possible to operate the radar from the higher altitude. The higher altitude would also make it unnecessary to make a maneuver up to a higher orbit to store the deactivated reactor.



Kosmos-1818 was placed in an orbit that

repeated its ground track every 99 revolutions. Repeating ground track patterns are described in a separate article. The parameters used to describe the orbit of Kosmos-1818 are N,M,Q=14,1,7. The resulting orbit has an average altitude above a spherical earth of 792.9 km and a nodal period of 100.76 minutes. As shown in the top graph on the right the spacecraft maintained this period for about 130 days. It then maneuvered down to an orbit with a period of 100.74 minutes after which it started to gradually lower its orbit. (The "spikes" in the orbital period graph are probably artifacts). The lower figure on the right is suggestive of natural decay, but thus is not altogether clear. Up until 400 days mission elapsed time there were variations in period that could be the result of maneuvers. During the period of orbit control near 100.76 minutes there were episodes of monotonic increase of the period indicating the use of ion thrusters. Nothing similar had been seen since Kosmos-723 in April 1975.



Plasma-A spacecraft

Image of Plasma-A from www.skyrocket.de

Actually, making a maneuver down from the repeating pattern orbit makes sense if the spacecraft had been deactivated upon leaving the 100.76 minute level. If left at the higher altitude to decay naturally, it would pose a collision risk, albeit small, for later replacement satellites.

According to Günther Krebs' web site

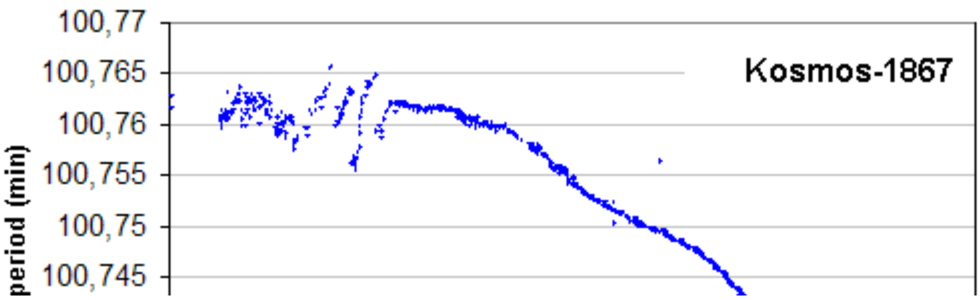
"... The Plazma-A satellites were technological test spacecraft to test out new systems for the US-AM RORSATs. It was based on the US-A RORSAT bus, but was fitted with the new Topaz nuclear rector, which used thermo-emission conversion method to convert heat to electricity. Topaz provided over 10 kW of power and had long endurance and storage in a radiation-safe orbit. Plasma-A did not have the radar of the US-A spacecraft, but tested a number of other systems: electrostatic manoeuvring engines, ion orientation and stabilization engines, solar sensors, magnetic momentum compensators, and multi-channel wave devices. The Plasma-A satellites carried instruments to map the magnetic field of the earth for the development of a magnetic navigation system ..."

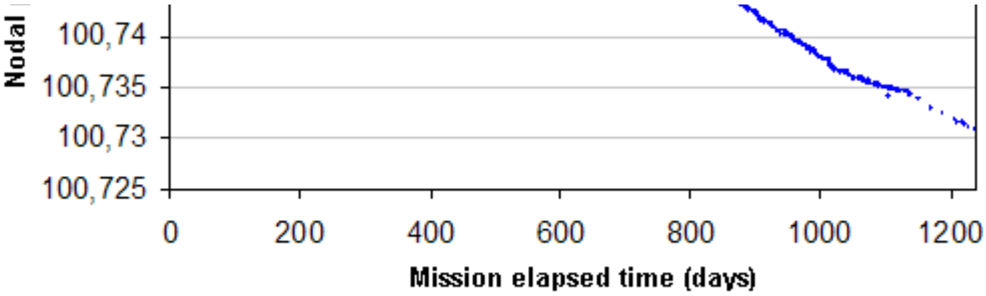
Kosmos-1860, the last US-A spacecraft tracked by the Kettering Group

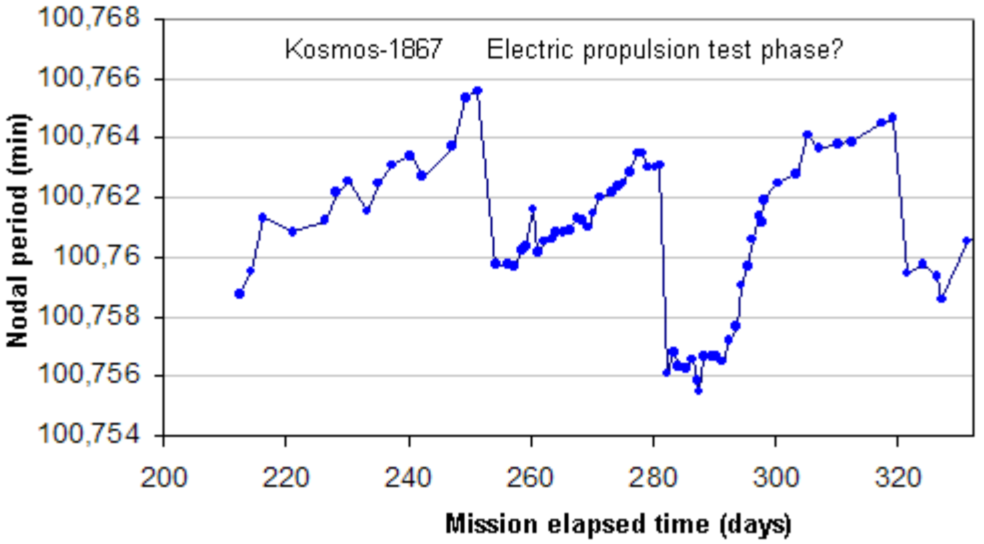
Kosmos-1860 (Catalog nr 18122) was launched at 2133 UT on 18 June 1987. I picked up my first signals from this spacecraft (on 166.0 MHz) on 23 June 1987 and heard it a total of five times before I "dropped track of it" on 26 June 1987. That was the last the Kettering Group ever heard of this type of satellite. The orbital plane of Kosmos-1860 was 142 degrees from that of the US-P spacecraft Kosmos-1834 **(25)**. It seemed that this US-A spacecraft, Kosmos-1860, was launched at a time of some increased tension, just as previous such mission had. In this case the Soviet Union had recently accused the US navy of violation of Soviet territorial waters. Also the U.S. was making a strong naval buildup in the Persian Gulf after the attack on the U.S.S. Stark on 17 May **(25)**. The spacecraft operated in low orbit until 28 July when the boost to the high orbit occurred. The life in low orbit was 40 days and the spacecraft displayed very normal behavior in low orbit with orbit adjustments approximately every five days..

Kosmos-1867, another gamma-ray pollutant

The second Plasma-A test satellite, Kosmos-1867, was launched at 1535 UT on 10 July 1987. It initially repeated the flight pattern of Kosmos-1818 and entered the 100.76 min repeating pattern orbit. The period was maintained near 100.76 minutes for about 520 days.





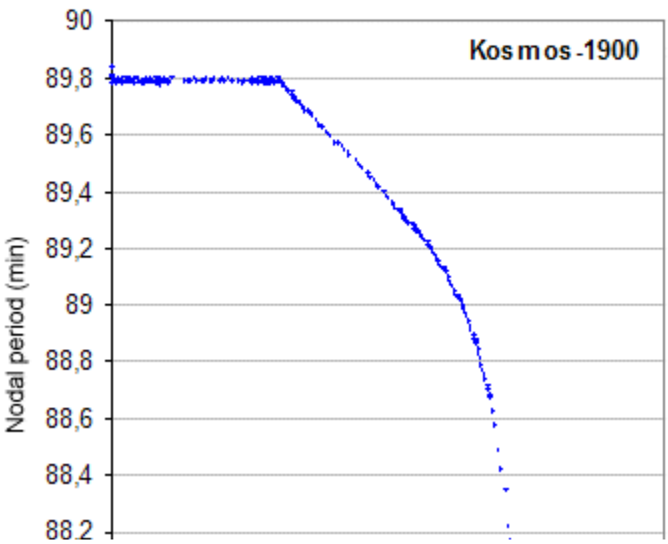


Initially, there were large excursions of the orbital period around 100.76 minutes. During these excursions the period sometimes increased monotonically, indicating continuous thrust by an electric rocket motor. Later the orbit was maintain at rather steady values. During this later phase it seemed as if the electric thruster (Plasma-2 SPT electric engine) was switched on and off. After the 520 days of controlled orbit the natural decay started.

At the time of this flight observers were indeed confused as to the character of the satellite. However, the era of *Glasnost* had commenced and the true character of the Kosmos-1818 and Kosmos-1867 missions was revealed by the Soviet Union at the 6th Symposium on Space Nuclear Power Systems held in Albuquerque, New Mexico, during 8-12 January 1989 **(28).** At that symposium it was revealed that the spacecraft had carried a 10 KW reactor with a thermionic system for conversion of the reactor's power into electric energy. The operation of the reactor in high orbit had also caused interference with scientific space missions such as the Solar Maximum Mission (SMM). It seems that the problem was detected back in 1980 but escalated in February 1987 when Kosmos-1818 put a live reactor for a long period above the altitude of SMM **(26)**. As Allen Thomson explained in a letter to the FPSPACE listserver on 29 March 2004:

"... The interference problems mostly or entirely came from the injection of positrons into the magnetosphere while reactors were operating (gamma rays from the fission reaction interacted with reactor and adjacent material to produce electron-positron pairs, the electrons and positrons were then trapped in flux tubes in the magnetosphere, and when the positrons encountered another satellite they annihilated with electrons in the structure to produce gamma rays). There may have been some direct interference when other satellites got close to the operating reactors, but those instances would have been fairly brief and infrequent. As noted, the RORSATs were too low during their operational lifetime to contribute much to the trapped-positron problem. It was only the two Topaz reactors which operated at a considerably higher altitude that managed to make a nuisance of themselves by interfering with instruments on Solar Max and Ginga (and possibly other satellites) ..."

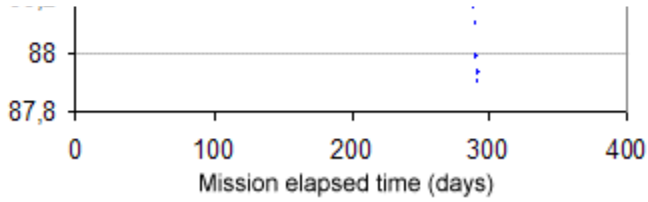
Kosmos-1900 & 1932, a confusing finale



Kosmos-1900 (Catalog number 18665) was launched at 0540 UT on 12 December 1987. The parameters used to describe the orbit of Kosmos-1900 are N,M,Q=16,-1,6, which means that the ground track repeats every 95 revolutions. The resulting orbit has an average altitude above a spherical earth of 262.1 km and a nodal period of 89.79 minutes.

Another US-A spacecraft, Kosmos-1932, was launched at 1421 UT on 14 March 1988. Strangely enough this satellite used the older, traditional orbit with a 7-day, 111 revolution, repeating ground track pattern.

The Kosmos-1900 spacecraft maintained this tightly controlled orbit until mid-April 1988. On 10 April the last orbit correction occurred. After that a steady decay started. Initially it was thought that the spacecraft would descend to the 89.6 minute orbit with a 7-day,



111 revolution, repeating pattern. That altitude was reached on 9 May 1988 and when the spacecraft continued to drop it was obvious that the spacecraft was in trouble.

The news spread forcing TASS on 13 May 1988 to announce that contact with the craft was lost in April, but that there was no danger to the general public because there were "systems ensuring radiation safety on completion of the flight". While this bad news spread Kosmos-1932 terminated its mission and safely boosted its reactor to the high orbit (See below). However, international concern over the flight prompted TASS to give more details about the reactor. In a report to the International Atomic Energy Agency the total mass of radioactive fuel (90% U-235 and the rest U-238) with six beryllium reflector rods measuring 100x250 millimeters and weighing 3.6 kg. The report described the safety features. The boost to the high orbit would be triggered by:

- Command
- Loss of spacecraft pressurization
- Reactor power deviations
- Loss of attitude control

In addition there was a back-up system to triggered at 115-120 km by aerodynamic heating at which occurrence the reactor core would be ejected.

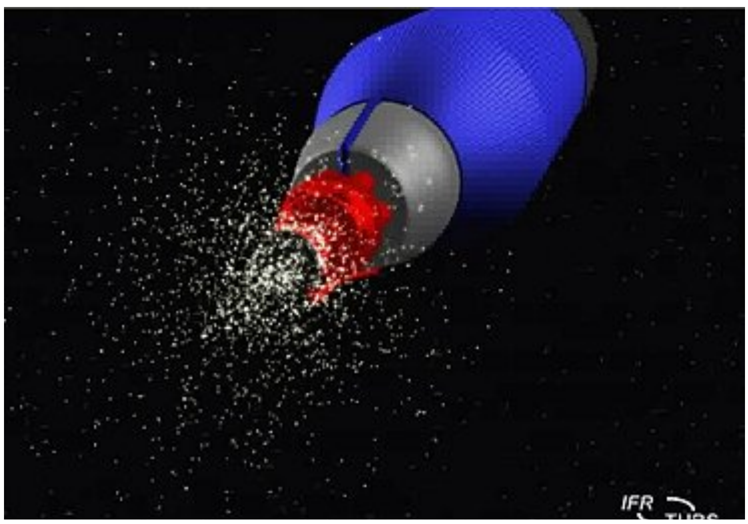
Meanwhile, on 20 May 1988, Kosmos-1832 boosted itself to the high orbit after 66 days. The flight had proceeded in a perfectly normal way with maneuvers every 3-4 days.

On 24 September 1988 Moscow television admitted that the mission of Kosmos-1900 had been to "observe ocean surfaces". Perhaps this admission could be made at this time because the decision to cancel the program had been taken or was imminent.

However, all through the natural decay of the craft its attitude control seems to have been working well. However in the evening hours the spacecraft lost stabilization - due to aerodynamic forces or loss of attitude control propellant - is not known. Also, electric power must have been generated throughout this long period - and the only available source of power was the reactor. It must have performed reasonably well since it did not trigger the ascent to high orbit. But the loss of attitude control immediately triggered the boost to higher orbit - at 2108 UT on 30 September 1988, according to TASS. However, the resulting high orbit was somewhat different from normal, possibly caused by an incorrect initial attitude at separation of the ascent vehicle. If the maneuver started at the equator the yaw error could have been as much as 45 degrees causing a lower apogee of the transfer orbit. The final orbit was about 300 km lower than normal; actually between 695.4 km and 763.4 km at 66.1 degree inclination. So, the improbable happened, at the last moment the safety system actually worked and propelled the Kosmos-1900 reactor into high orbit. TASS could not resist issuing a triumphant message on 17 October 1988. The news agency had earlier reported both the ascent to high orbit and the decay of the main spacecraft left in low orbit which re-entered over the indian Ocean at 2226 UT on 1 October 1988.

So, Kosmos-1932 was the last launch of the US-A program, while Kosmos-1900 was the last US-A craft to "leave the stage".

The final chapter - Sodium/Potassium coolant from US-A satellites found in orbit



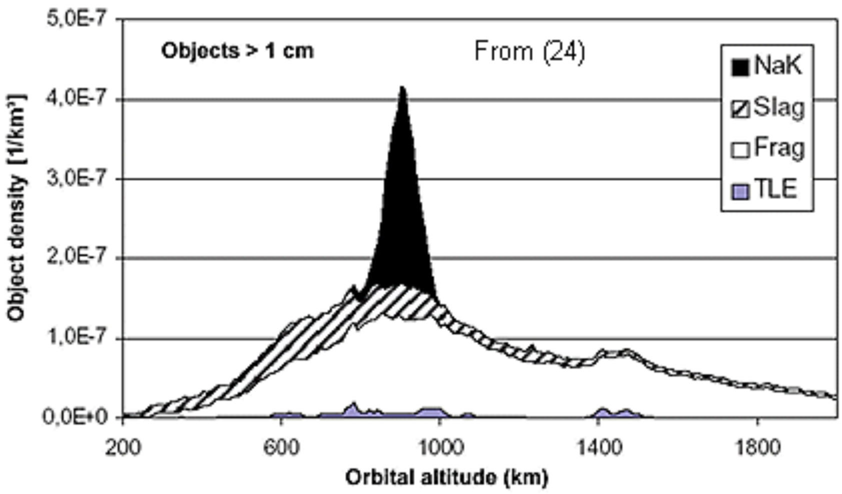
As we have seen there was a significant design change to the US-A satellite after the Kosmos-954 accident. At the conclusion of primary mission at low altitude, the nuclear reactor section was boosted up to an 800-900 km graveyard orbit - as before the Cosmos 954 accident - but with the important difference that the fuel core was there ejected in any case. The fuel core separation was accompanied by a loss of sealing in the primary reactor coolant loop, containing 13 kg of liquid NaK. Therefore, a leakage of NaK droplets occurred. The secondary reactor coolant loop, with 26 kg of liquid

NaK, was designed to maintain, instead, its sealing. The figure on the right shows a computer-generated view of the reactor core ejection and droplet dispersion. This image has been captured from a movie clip gracefully provided by Carsten Wiedemann of the Institute of Aerospace Systems at the Technical University of Braunschweig. A German report to the U.N. summarized the situation **(30)**:

"... the so-called RORSAT droplets, were found in the course of sample measurements with Haystack radar. It detected a large swarm of objects in near circular, 65^{o} inclined orbits at an altitude of about 900 km. A more detailed examination of those objects, using the Millstone Hill and Goldstone radar sites as well as optical observations, showed that they were up to 5.6 cm in diameter, of spherical shape and exhibiting characteristics of specular metals. From decay measurements, a consistency of about 900 kg/m^{3}could be derived. All these facts point in the direction of liquid sodium-potassium (NaK) droplets exhausted from the nuclear reactors of Russian RORSAT satellites that used NaK as a coolant.

Those satellites, which are not in use any more, are dumped in a 950 km storage orbit, where the later version of RORSATs release their fuel rods from the reactor core to ensure complete disintegration during later re-entry. Probably, in the course of this procedure, a large fraction of the NaK coolant is ejected into space. Effects like cavitational bursting within the outflowing stream may result in the generation of an appreciable number of even small droplets. Due to very low evaporation rates, the thus generated droplets form metallic spheres that remain nearly unchanged in size for their orbital lifetime.

The problem here is similar to that posed for the modeling of orbital fragmentations: only the upper end of the diameter spectrum can be made subject to verification by direct measurement. Therefore, any mass or diameter distribution derived from a theoretical modeling of the outflow process suffers from a large margin of uncertainty—especially in this case, where nearly no data on the smaller end of the size spectrum are available.



*Material data for NaK usually is only given for parameter intervals being of some interest for thermodynamic processes, and experiments to examine the effect of liquids spraying into a vacuum have so far only been conducted for water. However, some similarities between water and NaK, especially in terms of consistency, together with the general lack of data, seem to justify adopting at least the basic characteristics of the water droplet diameter distribution data for the NaK problem. This assumption is also supported by the fact that the vapour pressure of hot NaK (753 K) equals that of water at room temperature (293 K) ..." **(30)**.*

Carsten Wiedemann writes in his summary **(24)** of the US-A orbital debris problem that about 2/3 of the 13 kg NaK in the primary cooling loop was ejected at an average speed of 13 m/s. Modeling of the resulting debris population assumed an omnidirectional spreading of the NaK droplets. The coolant is an eutectic alloy of sodium and Potassium with 77.8% (by weight) of potassium. This alloy is called NaK-78. the total mass of NaK ejected by 16 US-A spacecraft was 146 kg, but progressive decay and evaporation caused the maximum amount of NaK droplets in orbit to reach 110 kg at the time of the raising to high orbit of Kosmos-1900. In 1999 this amount had dropped to about 55 kg. Initially, even very small droplets were present. In fact in terms of numbers small droplets dominated. The maximum size of the population was estimated to be about 5 cm. Small particles have a higher drag because the surface to volume ratio is higher than for larger droplets. Therefore, in 1999, there were probably no droplets left with sizes less than 3 mm. The total number of droplets was initially more than half a million, while the corresponding number in 1999 probably was about half that number. The space debris population in general is dominated by small particles, but for objects larger than 1 cm the NaK droplets are a significant contributor to the space debris density between 800 and 1000 km.

Acknowledgments and concluding note

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Much material has also been obtained from Mark Wade's www.astronautix.com - a prime source of astronautics

history on the Internet - which is herewith acknowledged.

This article is a continuing project. There is much more to tell about this fascinating program and so many aspects not yet covered by the text above. Stay tuned!

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