A History of Soviet/Russian Meteorological Satellites

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This paper provides an overview of the 40-year history of the Soviet/Russian weather satellite programme, making use of new information that has become available in recent years. It has also benefited greatly from the help of Yuriy V. Trifonov, one of the leading designers of Soviet meteorological satellites [1].

Keywords: Soviet meteorological satellites, Meteor, Elektro, VNIIEM

1. Introduction

The first experimental Soviet meteorological satellite was not launched until 1964, more than four years after the launch of the first US weather satellite. As most other practical applications of satellites, weather monitoring from orbit was not seen as a major priority in the early days of the Soviet space programme, which initially focused mainly on man-related and deep space projects. Eventually, growing pressure from the military to broaden the scope of Soviet space activities seems to have led to a decision in late 1961 to build the Meteor weather satellites, which were to be used both for civilian and military purposes. A number of international agreements on the exchange of weather satellite data signed in the early 1960s sped up this effort. Between 1964 and 1994 the Russians launched three generations of weather satellites (Meteor, Meteor-2, Meteor-3), with the launch rate gradually decreasing as the satellites' lifetimes became longer. After a spectacular number of delays, Russia also fielded its first geostationary weather satellite (Elektro) in 1994. After this the Russian economic crisis caused a major hiatus in the meteorological satellite programme, which was not resumed until 2001 with the launch of the first 4th generation satellite (Meteor-3M). Nevertheless, the days of regular weather satellite launches are long gone and the future of the programme remains very uncertain.

2. A Slow Start

A brief look at the US and Soviet launch record for the first four years of the Space Age shows a remarkable difference both in the number and diversity of objects placed into orbit. By the end of 1961 the United States had logged 64 successful launches covering virtually the entire spectrum of satellites launched today, from scientific satellites and deep space probes to manned spacecraft and a plethora of civilian and military satellites for communications, meteorology, navigation and reconnaissance. By contrast the Soviet Union had orbited only 14 objects, which, leaving aside the first three Sputniks, had been either man-related or targeted for the Moon, Venus and Mars. It was not until early 1962 that the Soviet space programme entered the domain of practical military and civilian applications with the launch of a broad range of satellites, most of them using the all-embracing "Kosmos" cover name.

This stark contrast reflects some basic organisational and policy differences in the early history of the US and Soviet space programmes. The US space programme was initially driven by competing proposals from the various branches of the armed forces and then split into well-defined military and civilian components with the formation of NASA in October 1958. Manned spaceflight did not emerge as a major priority until Kennedy took office in 1960. In the Soviet Union the initiative for the early space projects came exclusively from the OKB-1 design bureau, the major proponents being the legendary Chief Designer Sergey P. Korolyov and his associate Mikhail Tikhonravov. Perhaps it was Tsiolkovskiy's vision of orbital stations serving as places of research and the basis for piloted interplanetary missions that inspired people like Korolyov and Tikhonravov to concentrate their early efforts on manned and deep space exploration. Although some considerable work was done on photoreconnaissance satellites,

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OKB-1's space-related activities continued to focus on these two cornerstones as the 1950s drew to a close. At the same time, much of the bureau's workforce continued to be absorbed by work on the R-7 and R-9 intercontinental missiles. Some studies of applications satellites (including weather satellites) *were* performed in 1956-1958 both at OKB-1 and a military institute known as NII-4. While these may have laid the foundation for later work on such satellites, they do not seem to have resulted in any concrete proposals [2].

Initially, there seems to have been little or no pressure from the upper echelons of power to expand early space activities beyond the ongoing deep space and manned programmes, maybe because these were exactly the two areas of space exploration that captured people's imagination most and grabbed headlines around the world. Aside from showing the world that the Soviet Union had a powerful ICBM, the propaganda benefits of the early space shots were probably the only thing that made the space programme worthwhile from the viewpoint of the country's leadership. As the official history of the Military Space Forces rather bluntly puts it:

> "The great attention given to prestigious scientific [programmes] compared to applications and defence tasks meant that the creation of space systems for observation, communications and meteorology went at a much slower pace than in the US" [3].

Then, in early 1960, there was a sudden change in strategy, with Khrushchov ordering a major expansion of space activities. Fearing that the Soviet Union was losing its leading position in the space arena, he convened a meeting with Korolyov, Keldysh, Glushko and Pilyugin on 2 January 1960 and told them that space should be considered as important as missiles [4]. The meeting is also said to have marked a sharp turn towards the militarisation of the Soviet space programme, a move which according to one respected Russian space historian may have been related to statements about the military uses of space made in 1958-1959 by Lyndon B. Johnson, who at the time was Democratic Senate Majority Leader and the chairman of the Senate Aeronautical and Space Sciences Committee [5]. Moreover, the US had already started launching CORONA reconnaissance satellites (under the cover name "Discoverer") in February 1959, while the Soviet equivalent was still only on the drawing boards.

This shift in policy resulted in a major government decree issued on 23 June 1960 that formulated a 7-year plan for the Soviet space programme, placing special emphasis on the development of heavy rockets and various military space projects. This and a number of follow-on decrees released the following months laid the foundation for the military and applications satellites that began flying in 1962. The decrees were also significant in that they marked the entrance of two other major players in the Soviet space programme, namely Vladimir Chelomey's OKB-52 and Mikhail Yangel's OKB-586.

Not only would these organisations build their own satellites, they were also tasked to develop their own rocket families to launch them into space, expanding the range of masses that could be placed into orbit. In fact, the monopoly of the R-7 based rockets in the early years of the space age was another factor that had contributed to the low diversity of Soviet satellites. Originally designed to launch heavy nuclear warheads over intercontinental distances, the R-7 had much more muscle than any US rocket available at the time, but at the same time was suited to launch only relatively large satellites. While less powerful, the missile arsenal of the US armed forces was much more diversified and better tailored to launch satellites for a broad variety of practical applications. Moreover, Vandenberg had become available in early 1959 to expand the inclinations that could be reached, whereas the Soviet Union's sole launch site in Baikonur offered only a narrow range of launch azimuths.

This last restriction may have been one reason why meteorological satellites in particular were a long time in coming. The high-inclination orbits most suited for such satellites were unattainable from Baikonur due to range safety restrictions. The problem was not solved until early 1963, when the Soviet government decided to use the northern missile base of Angara (later called Plesetsk) for satellite launches, although it took another three years before it was ready for that.

More fundamentally though, there may have been scepticism among meteorologists about the need to build weather satellites at all. Despite the seemingly obvious benefits of having satellites patrol the weather from space, it took a long time for weather satellites to be accepted by the international meteorological community as useful tools in weather prediction, and this was probably no different in the Soviet Union. While satellites could detect visible and infrared radiation coming from the Earth, they could not make direct in-situ measurements of the meteorological parameters so badly needed by computer modellers to predict the atmosphere's behaviour (things like temperatures, pressures, wind speeds and moisture contents). It wasn't until the technology needed to extract such data from satellite observations matured that weather satellites gained broader acceptance among meteorologists [6]. Actually, the initial decision to build weather satellites seems to have been driven more by military than civilian needs, both in the US and the Soviet Union.

3. The Origins of US Space Meteorology

The United States pioneered space-based meteorology with the launch of NASA's Tiros-1 (Television and Infrared Observation Satellite) on 1 April 1960. Built by RCA, it was placed into a 700 km orbit inclined 48° to the equator and remained operational for over three months, sending back almost 23,000 photographs. Although Tiros was a NASA satellite, it had its roots in a 1956 proposal by RCA to develop a photoreconnaissance satellite under the Air Force's "Pied Piper" competition. When RCA's project was turned down, it was taken over by the Army Ballistic Missile Agency (ABMA) under the name JANUS, with the emphasis shifting from photoreconnaissance to strategic weather reconnaissance. Actually, the US military had recognized the importance of space-based meteorology long before that. The Air Force had been studying weather satellites since the early 1950s, both to provide weather reconnaissance behind enemy lines for strategic bombing campaigns and to ensure that photoreconnaissance satellites did not waste precious film photographing cloud-covered targets. In 1959 NASA inherited JANUS from ABMA and redesigned it for civilian needs as Tiros.

In 1961 NASA was instructed to develop a single National Operational Meteorological Satellite System (NOMSS) to satisfy both civilian and military requirements. Expecting that this would take a very long time to develop, the newly formed National Reconnaissance Office (NRO) decided to adapt NASA's Tiros design for an interim series of dedicated military weather satellites in Sun-synchronous orbits. The first film returned by the CORONA spy satellites in 1960 had 40 to 50 percent cloud cover obscuring the images, underlining the urgent need for military weather reconnaissance from space. The first launches under this programme took place in 1962, with the Air Force taking over responsibility from NRO in 1965. Eventually, NOMSS was downscaled to an experimental civilian programme (Nimbus) and the military and civilian weather satellite programmes remained independent. However, all the civilian polar-orbiting weather satellites built after Tiros (ESSA/TOS, ITOS, Tiros-N/NOAA) borrowed many design features from their military counterparts developed under the Defence Meteorological Satellite Programme (DMSP). Over the years the cross-fertilisation between the two programmes has been greater than between any other NASA and DoD undertakings, undoubtedly because of the less sensitive nature of meteorology. The NOAA and DMSP programmes have now been merged as the National Polar-orbiting Operational Environmental Satellite System (NPOESS), with the first launch expected in 2010, almost 50 years after the initial NOMSS proposal [7].

4. The Birth of Meteor

Although weather satellites seem to have been part of the early satellite studies performed at OKB-1 and NII-4 in 1956-1958, the first known concrete reference to a Soviet weather satellite system came in Korolyov's draft proposals for the 7-year space plan, which he outlined on 30 May 1960 in a letter to the Military Industrial Commission (a government body managing the defence industry) and the State Committee for Defence Technology (the ministry overseeing the missile and space programmes in the early 1960s). Perhaps not coincidentially, this was just two months after the launch of Tiros-1. In the first point of the draft decree Korolyov summed up various thematic directions on which planning and design work were to be conducted in 1960-62. Among these were:

> "Systems for solving defence-related goals by creating navigation systems, objects to perform reconnaissance, refine geophysical data, to ensure distant communications and to receive data for weather forecasts".

Expanding on the meteorological systems later in the draft decree, Korolyov mentioned the following objectives:

> "The design and development of aerodynamic satellites (one-two variants) for meteorological services in order to carry out photography and send back to Earth information about the cloud cover and other data necessary for weather forecasting."

What exactly Korolyov meant by "aerodynamic" satellites is not entirely clear, although he may have been referring to low-orbiting satellites using the tenuous upper layers of the atmosphere for passive attitude control.

The plan was to carry out the project in two stages. Experimental satellites were to be launched using R-7 based rockets in the 1961-1963 timeframe, while an operational system was to be set up in 1962-1964 using the heavy-lift N-1 rocket, which at that time was expected to have a payload capacity of 40-50 tons to low Earth orbit. Korolyov proposed an identical philosophy (both in terms of launch vehicles and timelines) for the development of communications satellites. He left open the question as to which design bureau would be responsible for meteorological and communications satellites, a possible sign that he was not eager to further increase the workload of OKB-1 [8].

It appears that only some of Korolyov's proposals were included in the 7-year space plan when it was taken up in the government decree of 23 June 1960. A recently declassified official document drawn up only days before the decree indicates that meteorological satellites were *not* approved in the final version of the plan. The decree merely assigned a body known as the Interdepartmental Scientific-Technical Council for Space Research (MNTS-KI) to start working in October 1960 on concrete plans for developing and launching "satellites for astronomical, astrophysical, meteorological and geophysical observations and research" [9]. The MNTS-KI was an advisory body under the aegis of the Academy of Sciences to oversee long-range space goals. Headed by the Academy's president Mstislav Keldysh, it included senior officials from the design bureaus, the scientific community and the military.

Formal approval for the development of weather satellites had to wait until the release of another government decree on 30 October 1961, indicating they were seen as relatively low-priority objectives. The decree (nr. 984-425) seems to have encompassed a wide range of projects mainly related to military uses of space. Among the satellites sanctioned by the decree apart from the Meteor weather satellites were the Molniya communications satellites and two small military communications satellites known as Pchela and Strela. While Molniya went to OKB-1, the Meteor, Strela and Pchela satellites were assigned to Mikhail Yangel's OKB-586. The decree also ordered the Yangel bureau to develop a new rocket to launch these three satellites. Based on the bureau's R-14 intermediate range ballistic missile, it was called 65S3 or 11K65 and was later retrospectively dubbed the "Kosmos-3(M)" rocket (Western designations SL-8 and C-1). It was to be capable of launching satellites with masses ranging from 100 to 1500 kg into circular orbits (between 200 and 2000 km) or elliptical orbits [10].

5. VNIIEM Enters the Scene

For Yangel's OKB-586 bureau in Dnepropetrovsk, the government decree of 30 October 1961 added more work to an already full plate. The main task of Yangel's bureau was to develop various missiles for the Soviet Union's so-called "missile shield" (the R-12, R-14, R-16 and R-36). In addition to that, the bureau was beginning to work out plans for a heavy-lift launch vehicle called the R-56 and was also busy working on the small DS satellites and converting the R-12 missile to place them into orbit. In order to somewhat relieve the pressure on OKB-586, early design work on the R-14 based space rocket and the Strela and Pchela satellites was transferred in 1962 to the OKB-10 design bureau near Krasnoyarsk, which had already been put in charge of the serial production of Yangel's R-14 missile. It was agreed, however, that OKB-586 would remain the lead organisation for these projects [11]. Several years later OKB-10 would also take over the Molniya programme from OKB-1 and it became the sole manufacturer of Russian communications satellites until the 1990s. It is now known as NPO PM (Scientific Production Association of Applied Mechanics).

Fig. 1 Andronik Iosifyan, the founder of VNIIEM and the chief designer of the Meteor and Meteor-2 satellites. (source: Russian Space Agency)

The Meteor programme followed suit and was transferred to a Moscow-based organisation called VNIIEM, which had maintained close ties with Yangel's bureau for several years. The origins of this bureau can be traced back to the autumn of 1941, as German troops were closing in on Moscow. It was officially founded on 26 September of that year as

Plant nr. 627 by Professor Andronik G. Iosifyan (1905-1993), who before that had worked at a secret department within the All-Union Electrotechnical Institute (VEI) in Moscow. The plant's main task was to supply electric equipment such as communications gear, power supply sources and various special types of armaments to Soviet troops. On 5 May 1944 a Scientific Research Institute called NII-627 was set up on the premises of this plant.

The institute became involved in the Soviet Union's embryonic missile programme in late 1945 when a team of NII-627 was sent to Germany to take part in studying captured V-2 technology. The institute was given responsibility for the development of electric equipment for the first ballistic missiles (such as DC-to-AC converters, electric motors, trimmers, polarised relay switches etc.). The R-7, the Soviet Union's first ICBM, was literally stuffed with electric equipment made under the supervision of Iosifyan, who Korolyov jokingly called "the chief electrician of rocket technology". On 29 September 1959 the institute was renamed VNIIEM (All-Union Scientific Research Institute of Electromechanics).

VNIIEM also became involved in the early missile efforts of Yangel's OKB-586, among others the R-16 ICBM. Iosifyan and Yangel narrowly escaped death when they and several others had gone down for a smoke in an underground bunker when the first R-16 exploded on the launch pad at Baikonur on 24 October 1960, killing nearly 100 people. Having faced death together, the two men became friends for life [12].

It was also in 1960 that Iosifyan proposed to enter the satellite arena by developing two technology demonstration satellites to test an electromechanical attitude control system and various other components that could be used in later satellites. Certainly, building satellites was no obvious line of work for an institute like VNIIEM, where many greeted Iosifyan's plan with scepticism. However, Iosifyan, a man with numerous inventions under his belt, had always been keen to turn ideas into practice and for him this was just another challenge he wanted to take on [13].

Since Iosifyan was on good terms with Yangel, the latter agreed to launch these satellites with the two-stage 63S1 rocket, based on the Yangel bureau's single-stage R-12 intermediate range ballistic missile (this launch vehicle later got the Western designators B-1 and SL-7). On 8 August 1960 the Soviet government issued a decree that gave the go-ahead for the development of the 63S1 and a number of small satellites to be orbited by the rocket, namely some of OKB-586's DS satellites and two OKB-1 satellites called 1MS and 2MS (the latter were ultimately never flown). There is conflicting information as to whether VNIIEM's technology demonstration satellites were also mentioned in this particular decree, but development of the satellites did get underway in 1960. They were initially known as KEL (*Kosmicheskaya elektrotekhnicheskaya laboratoriya* or Space Electrotechnical Laboratory), although the designers later referred to them as Omega [14]. The launches took place in 1963 (see section 9).

Although the October 1961 government decree constituted the *formal* approval for the Soviet Union's weather satellite programme, it would appear that engineers at the Yangel bureau had started working on a design for such a satellite almost a year earlier. Their proposal was based on a passive stabilisation system using the Earth's gravitational field to keep the satellite aligned in the desired direction. This so-called gravity gradient stabilisation is achieved by the use of a long boom with a mass at both ends. The mass nearest to Earth is in a slightly stronger portion of the gravity field and thereby naturally maintains the vertical orientation of the spacecraft. In the Yangel bureau's Meteor proposal those two masses would be the second stage of the 65S3 rocket on one end and a container with batteries and solar panels on the other end. The boom between the two would be deployed after orbit insertion, although gas thrusters were to be used for initial orientation towards the Earth. The solar panels extending from the container could be individually oriented towards the Sun. The meteorological instruments were to be mounted in a section mounted on top of the rocket stage. The television images were to be transmitted to the ground using a parabolic antenna to be deployed after launch [15].

VNIIEM also started displaying interest in meteorological satellites long before the October 1961 government decree. Delegations from VNIIEM began visiting OKB-586 sometime in late 1960 or early 1961 to study the Yangel bureau's Meteor proposal. VNIIEM's engineers had reservations about the gravity gradient stabilisation system proposed by OKB-586 and suggested to use an active electromechanical stabilisation system similar to the one being developed at the time for KEL/Omega. It should be stressed though that originally Omega had nothing to do with the weather satellite programme and that the idea to incorporate some of its systems into Meteor emerged only at a later stage.

Apparently, Yangel, preoccupied with ICBM work and not a strong supporter of building his own satellites in the first place, privately agreed with Iosifyan

even before the October 1961 decree was adopted that the Meteor programme would be transferred to VNIIEM. Preliminary approval for the transfer was given by the Military Industrial Commission (VPK), a top government body overseeing the defence industry, probably in late 1961 or early 1962. However, because VNIIEM was a newcomer to the satellite business, the VPK did order that both the OKB-586 and VNIIEM Meteor proposals be studied on a competitive basis, with one to be selected for further development. This task was again assigned to Keldysh's Interdepartmental Scientific-Technical Council for Space Research [16].

Eventually, the choice fell on the VNIIEM design and although the reasons for this are unknown, one can make some educated guesses. First, the OKB-586 concept undoubtedly looked much more exotic than VNIIEM's. A rocket stage was certainly not an ideal platform for installing meteorological instruments and gravity-gradient stabilisation systems generally provide little variation for pointing instruments to the Earth and are susceptible to torques caused by the tenuous upper layers of the atmosphere and solar radiation. Second, VNIIEM, benefiting from its long-standing relations with the OKB-1 bureau, could rely on an R-7 based booster to put its satellites into orbit. This was a more capable launch vehicle than Yangel's 65S3 and in contrast to the yet-to-be-flown 65S3 was a flight-proven rocket [17]. There are indications that the Yangel bureau at one point also suggested to launch weather satellites using a rocket based on the R-16 missile, but even this launch vehicle had relatively modest characteristics and it was ultimately never developed [18].

Sources associated with Yangel's bureau tend to omit any mention of the competition, saying merely that the Meteor project was handed over to VNIIEM because of OKB-586's heavy workload [19]. The transfer of Meteor-related technical documentation to VNIIEM began in May 1962 and this process continued until at least November of that year [20]. Various specialists from Yangel's bureau were invited to VNIIEM to offer advice and some of them eventually decided to stay at the institute to work full-time on Meteor. Given the fundamental differences between the OKB-586 and VNIIEM Meteor designs, the technical documentation obtained from the Yangel people was not of much use and VNIIEM basically had to start building the satellites from scratch [21]. However, it does appear that VNIIEM benefited from some of the contacts that OKB-586 had already laid with potential subcontractors. For instance, the meteorological instruments that eventually flew aboard the first-generation Meteors seem to have been selected when OKB-586 was still formally in charge of the programme [22]. VNIIEM, reporting to the State Committee for Electronics, was the first design bureau *outside* the traditional missile and aviation industry to be given full responsibility for a satellite project [23]. The bulk of the credit for this undoubtedly goes to Iosifyan, who took the initiative to enter the satellite business with the KEL/Omega satellites in 1960.

6. Military/Civilian Role

Clearly, Meteor was not going to be used solely for civilian purposes. The military importance of weather satellites had already been unequivocally stated in Korolyov's May 1960 draft for the 7-year space plan, which reflected the expansion of military space activities ordered by Khrushchov earlier that year. Moreover, as pointed out earlier, the 30 October 1961 decree that approved Meteor seems to have mainly covered military space projects. The official history of the Military Space Forces says that a Soviet meteorological satellite system was required because of "*the need to have instant knowledge of the hydrometeorological situation not just locally, but also on a global scale because of the appearance of global combat means*".

The specifications for Meteor were laid out by both the Chief Directorate of the Hydrometeorological Service (GUGMS) and the Ministry of Defence. GUGMS was created in 1936 under the Council of Peoples' Commissars (renamed the Council of Ministers in 1946) as a central organ coordinating the work of the country's meteorological and hydrological services. In 1978 it was reorganised as the State Committee of the USSR for Hydrometeorology and Environmental Control (GKGM) and after the collapse of the Soviet Union in 1992 it became the Federal Service of Russia on Hydrometeorology and Monitoring of the Environment (abbreviated in Russian as "Rosgidromet"). Bearing responsibility for Meteor on the military side was a branch of the Strategic Rocket Forces known as the Third Directorate of the Chief Directorate of Reactive Armaments (GURVO). This was the early precursor of the later Russian Military Space Forces and it handled all launch, tracking and communications operations for Soviet spacecraft. Since GUGMS was a newcomer to the field of satellite operations, most of the specification work for Meteor was done by the Third Directorate of GURVO in co-operation with the Ministry of Defence's NII-4 research institute [24].

In short, military applications of space-based weather observations were an important, if not crucial factor in the Soviet decision to press ahead with a meteorological satellite system. All indications are that

Meteor was a combined civilian/military undertaking from the very beginning. At first sight, this would lead one to conclude that the Soviets achieved in the 1960s what the US has been unable to accomplish until the present day. However, the combination of military and civilian tasks on a single satellite was more likely a natural result of the organisational background of the Soviet space programme rather than a conscious money-saving effort. With no central organ like NASA to run civilian space affairs, the space programme essentially remained an arm of the defence industry and the distinction between military and civilian space projects was much more blurred than in the United States. The Molniya communications satellite programme evolved along similar lines as Meteor, being used for both civilian and defence tasks [25].

7. International Cooperation

Since weather phenomena transcend borders, meteorology was seen as an ideal field for international space cooperation from the early years of the Space Age. Still, the Soviet Union on several occasions proved to be reluctant in taking part in joint undertakings in space-based meteorology. One reason may have been the combined civilian/military nature of the Meteor programme and the organisational structure behind it, which made the Russians wary of sharing any information about the Meteors with outsiders. More fundamentally though, the Soviet Union had a policy of not announcing its space plans in advance, irrespective of whether they were civilian or military, and any internationally coordinated effort in space-based meteorology would have required them to do just that. However, with the Soviet Union being the only satellite launching country besides the United States in the early years of the Space Age, calls from the international meteorological community for the Soviet Union to contribute its share to the space-based weather watch do seem to have pressured the Russians into speeding up their efforts in this field. Without this, the Meteors may have started flying even later than they did.

7.1 The Soviet Union and the World Weather Watch

The launch of the first artificial satellites in the late 1950s sparked interest in the prospects of space-based weather monitoring in at least some circles of the international meteorological community. In early 1958 the executive committee of the World Meteorological Organisation (WMO), a United Nations body set up in 1951, decided that the WMO should engage in some coordinated effort in satellite meteorology and set up a Panel of Experts on Meteorological Satellites. Aside from two WMO representatives, it included Harry Wexler, Director of Research at the US Weather Bureau, and Viktor Bugayev, who at the time headed the Soviet Central Institute of Forecasts. The panel met for the first time in November 1959, but as one of the WMO representatives later recalled “Russian authorities were obviously doubtful about the wisdom of having Viktor Bugayev exposed to situations in which he might reveal Russian plans, for he was not permitted to attend the first meeting” [26]. Actually, as pointed out earlier, the Soviet Union was still almost two years away at this point from committing itself to the development of a meteorological satellite system.

This is not to say that people within the Soviet space and meteorological communities were not *willing* to cooperate. For instance, as early as March 1960 Korolyov mentioned meteorology as a possible area of international space cooperation in a letter to Keldysh [27]. However, this did not result in any concrete Soviet proposals.

The major impetus for international cooperation in satellite meteorology seems to have come from the Kennedy Administration. In his first State of the Union on 30 January 1961 President Kennedy announced his intention to promptly explore all possible areas of cooperation “to invoke the wonders of science instead of its terrors” and among other things invited all nations, including the Soviet Union, to join the US in developing a weather prediction programme. Addressing the United Nations on 21 September 1961, Kennedy called for extending the UN charter to space and again proposed cooperative efforts between all nations in “weather prediction and eventually in weather control”. Two months later, however, the Soviet Union once again showed its reluctance by turning down an invitation to take part in an International Meteorological Satellite Workshop organised jointly by the US Department of Commerce’s Weather Bureau and NASA and attended by meteorologists from 27 countries [28]. Although the Soviet government had just given the official go-ahead for the development of a meteorological satellite system with its decree of 30 October 1961, it clearly was not intent on trumpeting this around.

On 20 December 1961 the United Nations General Assembly adopted Resolution 1721 on international cooperation in space. Among other things the resolution called on the UN Member States and the WMO to study measures to advance the state of atmospheric science and technology so as to provide greater knowledge of basic physical forces affecting climate and the possibility of large-scale weather modification. It also urged them to develop existing weather forecasting capabilities and to help Member States make effective use of such capabilities through regional meteorological centres. Finally, the resolution ordered the WMO to consult with appropriate governmental and non-governmental organisations to submit a report to the UN regarding appropriate organisational and financial arrangements to achieve those ends.

Soon after the 1961 UNGA Resolution was passed, the Secretary General of the WMO requested the two satellite launching countries to second scientists to prepare the report. The choice fell on Viktor Bugayev and Harry Wexler, the two members of the WMO Panel of Experts on Meteorological Satellites. The resulting report (called the *First Report of the WMO on the Advancement of Atmospheric Sciences and Their Application in the Light of Developments in Outer Space*) laid the foundations for the establishment of the World Weather Watch and was formally transmitted from the WMO to the UN in June 1962. In December 1962 the General Assembly adopted Resolution 1802, requesting WMO to develop an expanded progamme to strengthen meteorological services and a programme of research placing particular emphasis on the use of meteorological satellites. The Fourth Congress of the WMO in April 1963 formally endorsed the Bugayev/Wexler report and prompted a third UNGA resolution that approved "efforts towards the establishment of a World Weather Watch under the auspices of the WMO to include the use of satellite as well as conventional data." The goal of the World Weather Watch was to provide all member states of the WMO with timely weather information by combining observing systems, telecommunication facilities and data processing centres all over the world. Accordingly, the WWW comprises a Global Observing System, a Global Telecommunication System and a Global Data Processing System. Weather satellites are the space-based component of the Global Observing System, which now consists of a constellation of both polar-orbiting and geostationary meteorological satellites.

One of the first concrete results of the WWW was the creation of three so-called World Meteorological Centres, one near Washington, a second in Melbourne and a third in Moscow. The Moscow centre was established under the auspices of GUGMS in 1964 and several departments of the Central Institute of Forecasts were transferred to it. In late 1965 the Moscow World Meteorological Centre and the Central Institute of Forecasts were united to form the Hydrometeorological Scientific Research Centre of the USSR (*Gidrometsentr SSSR* and now *Rosgidrometsentr)*, performing the functions of both a Regional and a World Meteorological Centre [29].

7.2 Bilateral US-Soviet Cooperation

Against the background of these developments, the United States also took the initiative to propose a number of bilateral cooperative ventures with the Soviet Union in satellite meteorology. In September 1959, about five months after NASA had assumed control of Tiros, NASA Administrator T. Keith Glennan suggested to the White House that space-based meteorology was one potential area of cooperation with the Soviet Union. Just days after Tiros-1 was launched on 1 April 1960, Glennan actually met with President Eisenhower to discuss his proposed "Project Comet", in which the US and the USSR would each launch a weather satellite and share the data. Eisenhower showed willingness to discuss the idea with Nikita Khrushchov during an upcoming summit, but that was called off when Gary Powers' U-2 was shot down over the Soviet Union on 9 April [30].

By the time President Kennedy entered office in early 1961, tensions between the two superpowers had eased enough for the US to make another proposal. In an apparent response to Kennedy's January 1961 call for increased international space cooperation, the US State Department drew up draft proposals in April 1961 for US-USSR space cooperation. These proposals fell into three categories:

(a) The employment of existing or easily attainable ground facilities for exchange of information and services in support of orbiting experiments.

(b) The coordination of independently-launched satellite experiments so as to achieve simultaneous but complementary coverage of agreed phenomena.

(c) Coordination of or cooperation in ambitious projects for the manned exploration of the moon and the unmanned exploration of the planets."

The exchanges proposed in (a) had already been sought at government agency and scientific society levels since the beginning of the International Geophysical Year, but had produced little or no result. They were included "because of their inherent desirability" and also "because [of the] somewhat greater chance of acceptance ... if initiated at higher levels". The programmes in categories (b) and (c) had not yet been proposed to the Soviet Union.

Exchange of meteorological satellite data was part of the first category:

> "When either nation launches a meteorological satellite, the other would carry out routine and special (airborne, balloon-borne, all-sky camera)

> weather observations synchronized with the passes of the satellite, analyze the data from both sources, and participate in scientific exchanges of the results."

Weather satellites figured prominently in category b):

> "Weather satellites promise broad near-future benefits as a meteorological tool. Equal participation by the U.S. and the USSR in coordinated launching of experimental satellites capable of providing typhoon warnings, etc., would have great impact.
>
> One specific proposal is that the U.S. and the USSR each place in polar orbit a meteorological satellite to record cloud-cover and radiation-balance data, such that
>
> - The two satellites have reasonably overlapping lifetimes (at least three months).
> - The satellites orbit in planes at right angles to each other, providing at least six-hour coverage of the earth.
> - The data characteristics permit reception and analysis interchangeably, if possible.
> - Each country may receive telemetry from the other's satellite through continuous readout if power sources permit or by command if otherwise.
> - Camera resolutions are appropriate only for the objective—photographs of cloud cover.
> - The results are to be made available to the scientific community (World Data Centers and WMO).
>
> ... While the USSR has not yet done anything in this field, it has on one occasion indicated at the highest scientific level that space meteorology is favorably viewed as an area for cooperation. A generous timescale (or offer to provide instrumentation) might moderate the negative factor."

It was underlined in the draft that the proposals made in category (a) and (b) were for *coordinated* rather than *interdependent* efforts and thus would avoid difficulties which could have been associated with the latter type of cooperation with the USSR. The proposed cooperative ventures were chosen such that they would require comparable contributions by the US and the USSR and that there would be "minimal grounds for Soviet suspicions of US motives (access, surveillance, etc.)" [31].

Unfortunately, after the Bay of Pigs fiasco in April 1961 the international climate was not conductive to formally presenting these proposals to the Soviet Union any time soon. By early 1962 US-Soviet relations had once again thawed enough for the Americans to make another overture. Responding to a congratulatory letter from Khrushchov after John Glenn's mission, Kennedy forwarded a series of proposals to the Soviet leader on 7 March 1962 which included the establishment of an operational world weather satellite system:

> "Perhaps we could render no greater service to mankind through our space programs than by the joint establishment of an early operational weather satellite system. Such a system would be designed to provide global weather data for prompt use by any nation. To initiate this service, I propose that the United States and the Soviet Union each launch a satellite to photograph cloud cover and provide other agreed meteorological services for all nations. The two satellites would be placed in near-polar orbits in planes approximately perpendicular to each other, thus providing regular coverage of all areas. This immensely valuable data would then be disseminated through normal international meteorological channels and would make a significant contribution to the research and service programs now under study by the World Meteorological Organization in response to Resolution 1721 (XVI) adopted by the United Nations General Assembly on December 20, 1961."

Khrushchov responded favourably on 20 March:

> "It is difficult to overestimate the advantage that people would derive from the organization of a world-wide weather observation service using artificial earth satellites. Precise and timely weather prediction would be still another important step on the path to man's subjugation of the forces of nature ; it would permit him to combat more successfully the calamities of the elements and would give new prospects for advancing the well-being of mankind. Let us also cooperate in this field." [32]

In late March 1962 NASA Deputy Administrator Hugh L. Dryden and Anatoliy A. Blagonravov of the Soviet Academy of Sciences began a series of talks that resulted in an initial bilateral space agreement signed on 8 June of that year. Aside from cooperative ventures in satellite communications and the exchange of magnetic field data, the agreement called for a two-step approach to cooperation in satellite meteorology. In the first and experimental phase (1963-1964) a joint working group would set up a conventional full-time communications link between Washington and Moscow for the two-way exchange of selected weather data obtained by satellite. The cost was to be shared between the two countries and the link initiated when the US and the USSR were able to exchange data of approximately equivalent interest. In the second and operational phase (1964-1965) the two countries would each launch weather satellites on a coordinated basis, exchanging data in real-time and disseminating it further according to recommendations made by the World Meteorological Organisation [33]. After several delays caused by the Cuban missile crisis in October 1962, the agreement was announced to the United Nations on 5 December 1962 and formally announced to the world on 16 August 1963.

Progress was slow. In an internal memo dated 17 September 1963 Dryden discussed the results of a luncheon with Blagonravov in New York on 11 September to discuss the progress that the Soviets had made in implementing the agreement. Blagonravov indicated that he was having some difficulty with the Soviet Ministry of Communications, which had been too occupied with establishing a so-called “hot line” between the White House and the Kremlin, agreed to in 1963 to reduce the risk of war by miscalculation or accident. This had left little time to deal with the problems of the communications link for the exchange of weather satellite pictures. Blagonravov hoped that the Soviet Union would still meet the mid-1964 date for the exchange of weather pictures, but he admitted that there were problems. Without specifying if these were of a technical or political nature, he did say that “industry was not greatly interested in meteorological satellites” [34].

It was not until 14 January 1964 that Blagonravov informed Dryden that information would be forthcoming shortly detailing their plan for cooperation in meteorological studies. A memorandum of understanding signed in Geneva on 6 June 1964 included a protocol for the establishment of a direct communications link between the World Meteorological Centres in Moscow and Washington. Eventually, the transmission of weather data got underway in October 1964. The link was informally referred to as the “cold line”. Unfortunately, plans for coordinating launches of Soviet and American weather satellites never materialised.

8. Experimental Meteorological Payloads

Even as the first Meteors began flying, the Soviet Union launched various meteorological payloads on other satellites. However, there are no clear indications that there was any relation between these programmes or that any of the instruments were later flown operationally on the Meteors. Therefore these payloads were probably of a purely experimental nature.

8.1 Zenit

In 1962 and 1963 the Soviet Union launched four satellites in the Kosmos series (Kosmos-4, 7, 9, 15) that transmitted video signals to Earth, some of which were picked up by US intelligence services and turned into recognisable pictures. Since cloud cover was readily identifiable in the pictures, CIA experts consulted representatives of the US Weather Bureau’s National Meteorological Satellite Centre and came to the conclusion that the pictures had most likely been made by experimental meteorological satellites. NASA was briefed on the apparent capabilities of these satellites prior to the December 1962 announcement of its agreement with the Soviet Academy of Sciences on the exchange of meteorological satellite data and also prior to the formal implementation of this agreement in August 1963. Only in recent years has it become clear that these were Zenit-2 spy satellites that not only returned developed film to Earth, but also carried a read-out device called Baikal which scanned some of the film in orbit and transmitted the images to Earth electronically. The resolution of the images was found to be unsatisfactory for reconnaissance purposes and the system was dropped from subsequent Zenit-2 satellites. There are no indications that the images were used for meteorological purposes [35].

Experimental meteorological payloads *were* installed aboard several other recoverable spy satellites in the Zenit series. Basically, these were payloads to study the lower atmosphere with applications in meteorology. They were probably flown in addition to the standard reconnaissance cameras. Kosmos-45, 65 and 92, launched in September 1964, April and October 1965 resp., each carried a set of four instruments:

- a cloud cover photometer to measure the brightness characteristics of clouds (0.6 to 0.85 μm)
- a scanning infrared radiometer to determine the angular, spectral and latitudinal distribution of terrestrial infrared radiation (0.8 to 38 μm for Kosmos-45 and 0.8 to 45 μm for Kosmos-65 and 92)
- a UV spectrophotometer to measure the solar UV radiation reflected and scattered by the Earth’s atmosphere
- a colorimeter to measure the radiation characteristics of the night airglow (0.25 to 0.60 μm)

A scanning infrared radiometer operating between 15 and 28 μm was also flown aboard Kosmos-258 in December 1968. The measurements were made in late winter for comparison with those made in autumn and early spring by the three Kosmos satellites mentioned above.

Kosmos-121, launched in June 1966, carried a high-resolution photometer to measure the intensity of solar radiation reflected and scattered from the Earth's surface and clouds in the 0.6 to 0.8 μm band and determined the spatial fluctuation of the radiation spectrum in the mesoscale range [36].

Three satellites probably belonging to the Zenit-2M series (Kosmos-243, 384 and 669) released into orbit "Nauka" modules equipped with microwave and infrared radiometers for studies of the Earth's surface and lower atmosphere. The microwave instruments, operating between 8 mm and 8 cm, made it possible to determine ocean surface temperatures and also to clearly distinguish between cloud cover areas and snow-covered surfaces. The narrow-angle infrared radiometers provided complementary data between 10-12 μm [37].

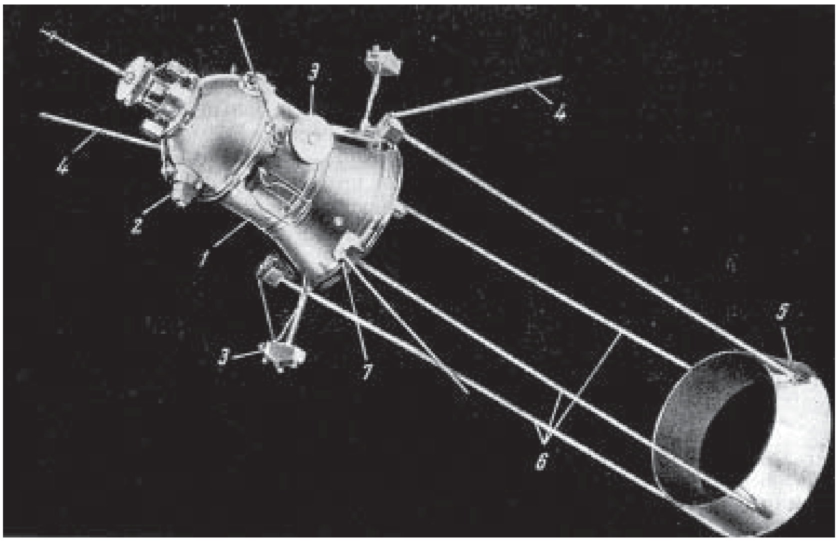

Fig. 2 The DS-MO satellite. Key: 1. satellite body, 2. television equipment, 3. sensors, 4. antennas, 5. aerodynamic stabiliser, 6. boom, 7. boom deployment mechanism. (source: Nauka publishers)

8.2 Molniya

Weather cameras are known to have been flown on several Molniya 1 communications satellites launched in the mid-1960s. They were developed at NII-380, the same organisation that built Meteor's optical cameras, and were used to obtain Earth pictures showing cloud patterns on a global scale as the satellites headed for the apogees of their highly elliptical orbits at about 40,000 km. The first such images were made by Molniya 1-3 on 18 May 1966, well before NASA produced its first Earth pictures from geostationary altitude with the first Applications Technology Satellite (ATS-1) at the end of 1966. The first colour pictures were transmitted in 1967. One source claims that the Molniya pictures were not only used for weather forecasts, but also to find cloud-free zones for Zenit spy satellites, although it is questionable if this was possible from such high altitudes. There was a lot of opposition against the installation of these cameras on Molniya, because some feared that they would interfere with the satellite's communications systems. This may have played a role in the decision to remove the cameras from subsequent Molniya satellites [38].

8.3 DS-MO

Also used for meteorological purposes was one subclass of the Yangel bureau's DS series of light satellites known as DS-MO. The first satellite of this type was launched as Kosmos-149 by a 63S1 booster from Kapustin Yar on 21 March 1967. It carried the following instruments:

- A set of so-called actinometric instruments called Aktin-1, consisting of:
  - two medium-resolution, narrow-angle, three-channel telephotometers (TF-3A and TF-3B) to study the solar radiation reflected back into space by the Earth. The Meteor satellites made similar measurements, but these were spread across the entire spectrum, whereas Kosmos-149 focused on very narrow bands of the spectrum. This made it possible to obtain more detailed information about the composition of the atmosphere and the characteristics of clouds, such as atmospheric water vapour content and cloudtop heights. One of the photometers was mounted in the domed nose section and scanned in a plane perpendicular to the flight path (at 0.34, 0.47 and 0.74 μm), while the other was installed on the left side of the cylindrical centre section and scanned along the flight path (at 0.72, 0.74 and 0.76 μm).
  - a high-resolution, narrow-angle infrared radiometer (SA-2) to study the radiation emitted by the Earth itself. It operated in a part of the infrared band barely absorbed by water vapour in the atmosphere (8-12 μm). This instrument enabled scientists to very accurately determine surface and cloud temperatures and to make independent cloud altitude measurements.
  - a pair of three-channel, wide-angle radiometers (RB-21 and RB-2P) to study the balance between radiation coming directly from the Sun and solar radiation reflected by the Earth (0.3-3 μm, 0.9-3 μm) and to measure radiation emitted by the Earth's itself (3-40 μm). They were attached to booms that telescoped out from the lower and upper sides of the satellite base. The lower unit faced nadir and the upper unit viewed in the zenith direction.

- A television camera system (Topaz-25M) that provided images of the local vertical and of the border region between the atmosphere and space. This was mainly used to provide cloud cover pictures for correlation with the radiation data. It was housed in the side of the domed nose section and its optical axis was directly along nadir.

All the instruments were considered experimental and were not used in actual weather forecasting, although it is not impossible that the data obtained were correlated with those of the Kosmos-144 Meteor satellite launched just about three weeks earlier.

The satellite was intentionally placed into a very low orbit (245 x 285 km, 48.4° inclination) in order to test a passive orientation system that used the tenuous atmosphere present at those altitudes to stabilise the satellite in three axes. For this purpose Kosmos-149 had an annular aerodynamic stabiliser which was mounted on four 6.5 m long bars extending from the main body of the satellite. Deployed after separation from the rocket's upper stage, it was capable of providing an orientation in space with an error less than five degrees relative to the three coordinate axes. The orientation was also controlled using the measurements made by the scientific instruments themselves. The satellite's external appearance earned it the nickname "Space Arrow". It is possible that DS-MO was an outgrowth of the gravity-gradient stabilised Meteor system put forward by the Yangel bureau in 1961-1962.

Given the low orbital altitude Kosmos-149 re-entered the atmosphere a mere 17 days after launch and judging from the relatively broad coverage in the Soviet media was considered a success. However, it was later revealed that the stabilisation system developed problems early in the flight, causing the satellite to roll about its longitudonal axis, as a result of which the data acquired was relatively limited. One other DS-MO satellite (Kosmos-320) was launched on 16 January 1970. It carried the same instrument suite as its predecessor plus a so-called manometer (RIM) to study streams of neutral molecules. Some of the optical devices flown on these satellites were later used by the Soviet Mars-2 and Mars-3 probes to study the atmosphere of Mars [39].

9. Omega

Although Soviet-era publications usually described VNIIEM's Omega satellites as technology demonstrators for Meteor, recent evidence has shown that they were conceived before the Meteor programme was given the green light and were originally intended as general technology demonstrators to increase the lifetime of future satellites. However, it is possible that some modifications were made to the original Omega design to make it more applicable to Meteor.

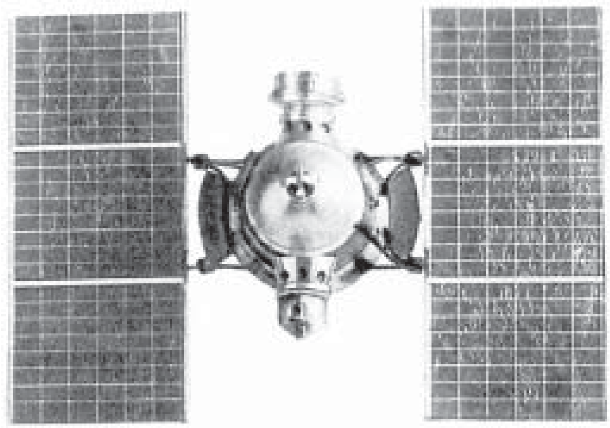

Fig. 3 The Omega satellite.
(source: Sovetskaya Entsiklopediya Publishers)

The two Omega satellites were launched from Kapustin Yar as Kosmos-14 on 13 April 1963 and Kosmos-23 on 13 December 1963. Weighing about 300 kg, the satellites had the form of a cylinder with two hemispherical ends and were about 1.8 m long and 1.2 m in diameter. They were launched into 49° inclination orbits by Yangel's R-12-based 63S1 launch vehicle. Because of the relatively low orbital altitudes (252 x 499 km and 240 x 613 km resp.) they had orbital lifetimes of 4.5 months and 3.5 months respectively.

The major innovation tested on Omega was an electromechanical attitude control system using rapidly spinning electric flywheels to provide stabilisation. It also included Earth and Sun sensors together with accelerometers to generate the necessary commands to the flywheels. The big advantage of such a system is that it doesn't require the use of propellant, which is often a limiting factor in satellite lifetime. Omega did carry some small gas thrusters, but these were only needed to regularly dump the momentum built up by the flywheels. Another objective of the Omega missions was to see how the satellite's silicon solar cells and other systems responded to prolonged exposure to sunlight and to repeated temperature fluctuations as the spacecraft passed in and out of the Earth's shadow.

The principles of an electromechanical orientation system were first described by the great Soviet spaceflight theoretician Konstantin Tsiolkovskiy as early as 1902. Theoretical studies of both passive and active attitude control systems for future spacecraft were conducted at two Soviet research institutes under the supervision of Academician Keldysh in 1955-1956 and some of these focused on electromechanical systems. These were considered for use in one of the “Oriented Satellites” (OD) studied by the Korolyov design bureau in the mid-1950s, but were ultimately not incorporated into the Vostok piloted spaceships that evolved from the OD conceptual studies. Results of the OD studies were sent to various organisations, including VNIIEM, and Iosifyan may well have been inspired by these when he proposed the Omega satellites in 1960 [40]. It *is* known that one of the people who had specialised in these matters during the studies in the mid-1950s, Yevgeniy N. Tokar (an associate of Boris Raushenbakh), later provided advice to VNIIEM in developing the electromechanical orientation system for the Meteors [41]. At any rate, there is no doubt that VNIIEM receives full credit for turning the theoretical principles of such systems into practice. The institute went on to establish a major reputation in this field. As early as 1963, the same year that the Omegas were flown, VNIIEM was ordered to develop a flywheel system for precision-pointing of the Zenit-4 spy satellites, although it was ultimately not flown [42]. VNIIEM also built gyroscopes for the Molniya communications satellites and much later the institute would go on to develop gyroscopes for the Almaz and Mir space stations and for the Zvezda module of the International Space Station.

Due to problems with the Earth sensors, neither of the two Omega satellites was able to achieve the planned three-axis stabilisation. However, the solar panels, which did not have an autonomous pointing mechanism, were permanently aimed at the Sun by spinning the satellite around its solar-oriented axis. Even though the two satellites did not meet all their objectives, they gathered important information for the design of the Meteor satellites [43].

10. Evolution of the Ground Segment

The introduction of the Meteor weather satellites required the establishment of an elaborate ground network to control the satellites and receive, process and distribute the data received from them. Little is known about the early network, only that there were three receiving stations, a central one in Obninsk in the Kaluga region south of Moscow and two regional ones in Novosibirsk (set up in 1968) and Khabarovsk. The latter two covered Western Siberia and the Soviet Far East respectively. These receiving stations relayed the information to the World Meteorological Centre in Moscow, from where it was disseminated to national customers and to the World Meteorological Organisation in the framework of the World Weather Watch programme. The same receiving stations were used for the Soviet non-recoverable remote sensing satellites (Meteor Priroda/ Resurs-O and Okean) that began flying in the mid to late 1970s. An additional station was set up in Tashkent in Uzbekistan in 1986, but this was disbanded after the collapse of the USSR. Plans for building receiving stations in Murmansk and Petropavlovsk-Kamchatski were never realised.

Fig. 4 Meteor receiving station in Novosibirsk. (source: Gidrometeoizdat)

In 1989 the whole organisational structure and infrastructure for remote sensing and meteorological satellites was consolidated under a single organisation known as NPO Planeta, subordinate to the GKGM and later Rosgidromet. It was responsible among other things for developing concepts for remote sensing instruments, collecting orders for observations and planning the observations, coordinating the work of the central and regional receiving stations and processing, storing and distributing the data. Headquartered in Moscow, it operated the receiving station in Obninsk and owned a scientific research centre (GosNITsIPR) and data storage centre in Dolgoprodnyy near Moscow, where another receiving station was built later. GosNITsIPR (the Scientific Research Centre for Studies of Natural Resources) had already been set up in 1974 and actually took the initiative to set up NPO Planeta.

Sometime in 1997 NPO Planeta was reorganised as the Scientific Research Centre of Space Hydrometeorology Planeta (NITs Planeta), although its functions seem to have remained largely unchanged. It now operates three receiving stations in the Moscow area, namely one in Obninsk, another in Dolgoprudnyy and a third in Moscow itself. The regional receiving stations in Novosibirsk and Khabarovsk also remain operational and are known respectively as the West Siberian and Far Eastern Regional Data Acquisition and Processing Centres (ZS RTsPOD and DV RTsPOD). All these stations receive data not only from Meteor, Resurs-O and Okean satellites, but also from non-Russian weather satellites such as NOAA, Meteosat and GMS. NITs Planeta is responsible for distributing the data to the various organisations of Rosgidromet and also to other clients such as the Ministry of Defence and the Ministry of Emergency Situations. Aside from the five receiving stations mentioned above, there is now also a network of some 60 so-called Autonomous Information Acquisition Points (APPI). Used by local weather stations, airfields and Ministry of Defence units, these can pick up low resolution imagery from Meteor, Okean, Resurs-O and NOAA satellites in real time [44].

It is not clear from where the Meteors were controlled during the first years of operations. Between 1972 and 1995 this was the responsibility of the so-called Mission Control Centre for Space Apparatuses for Scientific and Economic Purposes (TsUP KA NNKhN), more simply known as Rokot. Owned and operated by the Military Space Forces, it was located on the premises of the Academy of Sciences' Institute of Space Research (IKI) in Moscow and was responsible for controlling all of Russia's remote sensing satellites as well as most scientific and deep space missions. Due to cutbacks in the military, the centre was officially closed down on 1 December 1995 and its responsibilities were transferred to the main Russian military control centre Golitsyno-2 in the Moscow suburb of Krasnoznamensk [45]. In an effort to streamline their space-control infrastructure, officials of the Russian Aviation and Space Agency and the Strategic Rocket Forces (which temporarily reabsorbed the Military Space Forces in 1997) agreed in 1999 to gradually transfer control of all civilian satellites to the Mission Control Centre (TsUP) in the town of Korolyov, beginning with the launch of an Okean-O oceanographic satellite in July 1999 [46]. This is the same control centre that has been used to monitor manned flights since 1975. Meteor-3M was the first weather satellite to be operated from TsUP-Korolyov.

11. The First-Generation Meteors

11.1 Description

The first-generation Meteor (index 11F614) weighed about 1,280 kg and consisted of an upper cylinder

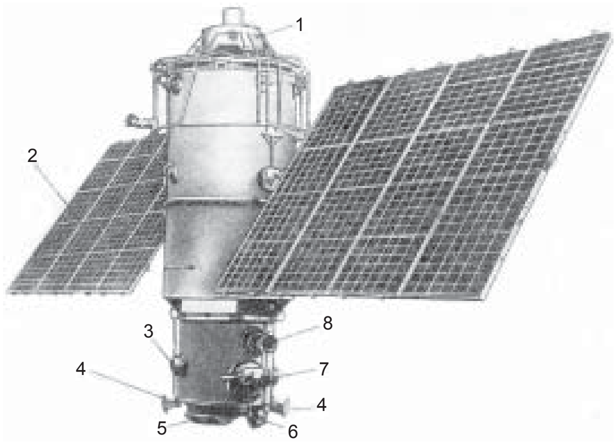

Fig. 5 First-generation Meteor (Kosmos-144). Key: 1. solar panel orientation system, 2. solar panel, 3. orbit control equipment, 4. antennas, 5. MR-600 television camera, 6. magnetic sensor, 7. receiver of actinometric equipment, 8. Lastochka infrared radiometer. (source: Mir Publishers)

containing the support systems and a somewhat thinner lower cylinder carrying the instrument packages. Both cylinders were pressurised. The satellites used a three-axis electromechanical stabilisation system not unlike that flown aboard the Omega satellites. In other words, Soviet engineers elected to "skip" the spin-stabilised design that their American counterparts had used for the first Tiros satellites. Three electric flywheels ensured that one axis was directed earthward along the local vertical, a second oriented along the orbital velocity vector and a third oriented perpendicular to the orbital plane. Also part of the system was an Earth horizon infrared sensor that detected any deviations from the local vertical and generated commands to change the spin rate of the flywheels if needed. As on Omega, excess momentum built up by the flywheels was dumped with small gas thrusters, but part of this task was also accomplished with so-called magnetorquers, electric coils which interact with the Earth's magnetic field in such a manner as to produce a magnetic torque around the satellite's centre of gravity. Magnetometers determined which impulse the coils needed to generate and at which point in the orbit this needed to happen. However, the system was still experimental and the need to regularly use the gas thrusters was one of the main factors that limited the lifetime of the first-generation satellites.

Extending from both sides of the upper cylinder were solar panels that were permanently pointed to the Sun with an autonomous steering mechanism. Such a mechanism had first been developed at OKB-1 for small solar panels ("Luch") carried by some unmanned precursors of the Vostok spacecraft and the technology was reportedly transferred to VNIIEM. A special flywheel was used to compensate for the kinetic moment affecting the spacecraft

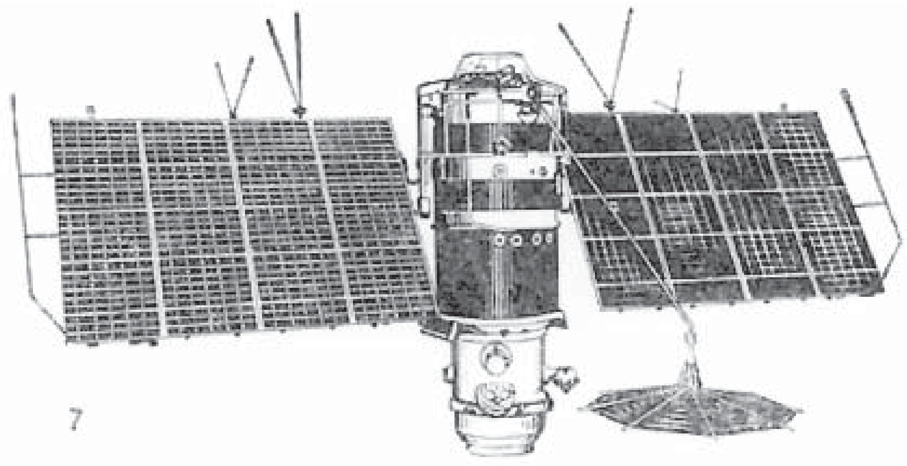

Fig. 6 Drawing of Kosmos-156, showing location of parabolic antenna. (source: Sovetskaya Entsiklopediya Publishers)

during the operation of this mechanism. A special automatic control system was used to prevent the on-board storage battery from becoming overcharged or running low on energy. Extending from a boom on top of the bus was an antenna for returning data to ground stations.

Three main payloads were on board the first-generation Meteor satellites (also see Table 1):

- A vidicon television system called MR-600 to provide mosaic images of clouds and the Earth's surface in the visible part of the spectrum during daylight. The MR-600 consisted of four cameras, two of which were back-ups. The simultaneous use of two cameras made it possible to increase the field of view while maintaining a high angular resolution. One camera would view the left part of the ground track and the other the right part, with a slight overlap between the images. The cameras were activated automatically whenever the elevation of the Sun over the underlying regions exceeded five degrees. For this purpose the satellites carried a special Sun elevation sensor, which could also automatically adapt the cameras' diaphragm settings. If needed, these could also be controlled from the ground. Each imaging cycle lasted 60 seconds.

  Since the satellites obtained information over the entire globe and were within range of Soviet ground stations for a limited period of time, they carried three video recorders, each capable of storing 35 images. When the satellite was out of range for long periods of time, two of the recorders could be activated sequentially to store a total of 70 images. The third recorder was used for simultaneous recording and playback of images. Because of the limited duration of the communications sessions, the images could be played back four times faster than they were recorded. They were relayed to ground stations with a 15 Watt radio transmitter.

  The MR-600 television camera as well as the associated transmitters and reception equipment were developed by NII-380 (headed by Igor A. Rosselevich). Situated in Leningrad, this institute had also been responsible for many other imaging systems used on Soviet spacecraft. It is currently known as NII Televideniya.

- A scanning infrared radiometer called Lastochka to image clouds on the nightside of the Earth. It operated in an area of the infrared band not absorbed by water vapour, and made it possible to determine the temperatures of cloud tops and the underlying surface. The camera could also be used to photograph clouds in daylight, making it possible to compare pictures of the same cloud structures taken by the optical camera. The IR radiometer was able to scan an area up to 40° off-nadir. Its resolution was much lower than that of the optical television camera, but good enough to study large weather patterns such as cyclones, typhoons and atmospheric fronts.

  The infrared radiometer was built by NII-10 in Moscow (headed by Mikhail P. Petelin), an

TABLE 1: *Standard Meteor(-1) Instrument Suite*[1].

Instrument	Number of Spectral Bands	Band Wavelengths μM	Ground Swath km	Ground Resolution km
MR-600 TV camera	1	0.5 – 0.7	1000	1.25 x 1.25
Lastochka infrared radiometer	1	8-12	1100	15 x 15
Actinometric equipment	3	0.3-12	2500	50 x 50

1. These are the data as given for Kosmos-122.

TABLE 2: *List of Meteor(-1) (11F614) Launches.*

Official name (+ Western digit)[1]	Launch date/time (UTC)[2]	Launch site and vehicle[3]	Inclin.[4]	Perigee/Apogee	Comments
Kosmos-44	28.08.1964 16.19	Baikonur 8A92	65.04	615 x 857	
Kosmos-58	26.02.1965 05.02	Baikonur 8A92	65.00	563 x 647	Re-entered 25.02.1990
Kosmos-100	17.12.1965 02.24	Baikonur 8A92	65.00	630 x 658	First three-axis stabilised Meteor
Kosmos-118	11.05.1966 14.09	Baikonur 8A92	65.00	587 x 657	First experimental pictures. Re-entered 23.11.1988
Kosmos-122	25.06.1966 10.30	Baikonur 8A92	65.14	583 x 657	First announced metsat, first published pictures. Re-entered 14.11.1989
Kosmos-144	28.02.1967 14.35	Plesetsk 8A92M	81.25	574 x 644	First Meteor launch from Plesetsk. Re-entered 14.09.1982
Kosmos-156	27.04.1967 12.50	Plesetsk 8A92M	81.17	593 x 635	Re-entered 23.10.1989
Kosmos-184	24.10.1967 22.47	Plesetsk 8A92M	81.19	600 x 638	Re-entered 02.04.1989
Kosmos-206	14.03.1968 09.34	Plesetsk 8A92M	81.23	598 x 640	Re-entered 22.04.1989
Kosmos-226	12.06.1968 12.50	Plesetsk 8A92M	81.24	579 x 639	Re-entered 18.10.1983
-	01.02.1969 12.11	Plesetsk 8A92M	-	-	Launch failure
Meteor (1-1)	26.03.1969 12.30	Plesetsk 8A92M	81.20	633 x 687	
Meteor (1-2)	06.10.1969 01.45	Plesetsk 8A92M	81.26	613 x 681	Re-entered 20.08.2002
Meteor (1-3)	17.03.1970 11.10	Plesetsk 8A92M	81.18	537 x 635	Re-entered 18.11.1983
Meteor (1-4)	28.04.1970 10.50	Plesetsk 8A92M	81.23	625 x 710	Re-entered 16.03.2004
Meteor (1-5)	23.06.1970 13.19	Plesetsk 8A92M	81.23	831 x 888	First use of higher orbit
Meteor (1-6)	15.10.1970 11.22	Plesetsk 8A92M	81.21	626 x 648	Re-entered 08.01.1999
Meteor (1-7)	20.01.1971 11.24	Plesetsk 8A92M	81.21	629 x 656	
Meteor (1-8)	17.04.1971 11.45	Plesetsk 8A92M	81.24	610 x 633	Re-entered 10.01.1991
Meteor (1-9)	16.07.1971 01.45	Plesetsk 8A92M	81.19	614 x 642	Re-entered 27.08.1991
Meteor (1-10)	29.12.1971 10.50	Plesetsk 8A92M	81.26	845 x 927	First use of APT, test of ion and plasma thrusters
Meteor (1-11)	30.03.1972 14.05	Plesetsk 8A92M	81.23	868 x 891	
Meteor (1-12)	30.06.1972 18.52	Plesetsk 8A92M	81.22	889 x 905	
Meteor (1-13)	26.10.1972 22.05	Plesetsk 8A92M	81.27	867 x 891	
Meteor (1-14)	20.03.1973 11.20	Plesetsk 8A92M	81.27	873x892	

TABLE 2: *List of Meteor(-1) (11F614) Launches (Contd).*

Official name (+ Western digit)[1]	Launch date/time (UTC)[2]	Launch site and vehicle[3]	Inclin.[4]	Perigee/Apogee	Comments
Meteor (1-15)	29.05.1973 10.16	Plesetsk 8A92M	81.22	853 x 896	
Meteor (1-16)	05.03.1974 11.38	Plesetsk 8A92M	81.23	832 x 894	
Meteor (1-17)	24.04.1974 11.50	Plesetsk 8A92M	81.23	865 x 894	
Meteor (1-19)	28.10.1974 10.17	Plesetsk 8A92M	81.18	843 x 907	Test of plasma thrusters
Meteor (1-20)	17.12.1974 11.45	Plesetsk 8A92M	81.24	842 x 897	
Meteor (1-21)	01.04.1975 12.30	Plesetsk 8A92M	81.21	867 x 893	
Meteor (1-22)	18.09.1975 00.20	Plesetsk 8A92M	81.26	838 x 901	
Meteor (1-23)	25.12.1975 19.00	Plesetsk 8A92M	81.26	842 x 902	
Meteor (1-24)	07.04.1976 13.05	Plesetsk 8A92M	81.26	843 x 893	
Meteor (1-26)	15.10.1976 23.00	Plesetsk 8A92M	81.27	857 x 892	
Meteor (1-27)	05.04.1977 02.05	Plesetsk 8A92M	81.25	854 x 897	Test of plasma thrusters

1. All operational Meteor satellites of the first generation were officially announced as Meteor without additional digits referring to the specific mission number. In Western launch lists these have usually been added for clarity and they are included between brackets. Note that Meteors 1-18, 1-25, 1-28, 1-29, 1-30 and 1-31 (also announced simply as "Meteor") were actually Meteor Priroda (11F651) remote sensing satellites based on the Meteor bus and are therefore not listed here.
2. Times for the Baikonur launches are from the Launch Log in Jonathan's Space Report at http://planet4589.org/space/log/launchlog.txt. Times for the Plesetsk launches are from : S. Sergeyev, "Statistics of Launches of Meteor Satellites From the Plesetsk Cosmodrome" (in Russian), on-line at http://www.plesetzk.narod.ru/doc/statis/s_meteor.htm.
3. Orbital data are from "*The R.A.E. Table of Earth Satellites 1957-1989*", Royal Aircraft Establishment, Farnborough, 1990.
4. 8A92 and 8A92M are versions of the Vostok launcher.

organisation that was mainly involved at the time in the development of homing devices for ship-based surface-to-air missiles. It is now known as NII Altair.

- a set of actinometric instruments to see how much of the solar radiation received by the planet is reflected back into space ("earth albedo radiation") and how much thermal energy is emitted by the planet itself ("earth radiation"). These are important factors in the Earth's radiation budget, which to a great extent shapes climate and weather patterns. The actinometric instrument package consisted of two narrow-angle and two wide-angle radiation detectors. The first two were scanning sensors that could watch an area up to 60° off-nadir. They had a ground swath of about 2500 km and a resolution of 50x50 km at the sub-satellite point. The wide-angle sensors could study the entire disk of the Earth visible from the satellite's altitude (about 1 million km²).

The narrow-angle instruments worked in three wavebands : between 0.3 and 3 μm (optical and near infrared) to determine the amount of reflected solar radiation (about 70 to 80 % by clouds, about 30 % by the surface and even less by the oceans), between 3 and 30 μm to find out how much thermal radiation is emitted into space by the surface and the atmosphere and between 8 and 12 μm to measure the temperature of the surface and the cloud tops (which also made it possible to determine their altitude, which is important, among other things, for aviation). The measurements in the two last wavebands were made by one of the narrow-angle instruments, which would make measurements in the 3-30 μm area when scanning in one direction and in the 8-12 μm area when scanning in the other direction.

The design bureau responsible for the development of the actinometric instruments was TsKB Geofizika (headed by Vladimir A.

Khrustalyov). This Moscow-based design bureau specialised in optical and infrared sensors used in spacecraft attitude control systems. It is now called NPO Geofizika [47].

11.2 Test Flights

Prior to being declared operational, the Meteors were to perform a series of experimental flights to test the spacecraft bus and the remote sensing instruments. The test flights were to be carried out under the supervision of a State Commission headed by Kerim Kerimov, who at the same time was the head of the State Commission overseeing test flights of the Molniya communications satellites. Among the members of the commission were Andronik Iosifyan, Yevgeniy Shabarov (one of Korolyov's deputies) and Georgiy Golyshev (deputy head of GUGMS). In 1965 Kerimov was replaced by Maj.-Gen. V.I. Shcheulov after having been named head of the State Commission for the Soyuz manned programme. In order to co-ordinate the work of the different organisations involved in Meteor a special Interdepartmental Council was set up led by Yevgeniy K. Fyodorov, the head of GUGMS [48].

The 30 October 1961 government decree had called for the first test flight of Meteor to be conducted in the second quarter of 1963. As so often with timelines for space projects in Soviet government decrees, these dates were far from realistic and became completely unachievable after the project was transferred from OKB-586 to VNIIEM in 1962. Recently declassified decrees of the Military Industrial Commission show how the launch date for the first satellite kept slipping. In April 1963 the target date was October 1963 and by August 1963 this had slipped to December 1963, with the Council of Ministers criticising VNIIEM and its subcontractors for not delivering components on time. By January 1964 the first launch had moved to March 1964 and in April 1964 the first mission was expected in June 1964.

Iosifyan and his team were under tremendous pressure to launch the first satellites as soon as possible because of the international agreements signed in the early 1960s. In order to meet the goal of orbiting the first satellite in 1964, it was decided that the two first satellites would fly a crude attitude control system based largely on that developed for Omega. This meant that engineers knew from beforehand that three-axis stabilisation was unlikely to be achieved on these missions, although they did hope to test the new flywheels and the gas reaction control system. Eventually, the first Meteor satellite was launched on 28 August 1964,

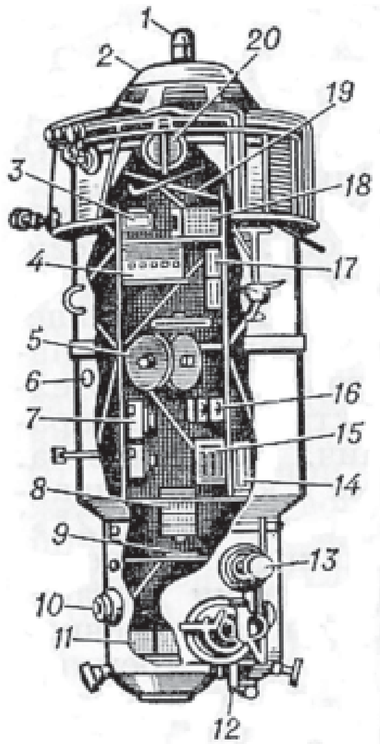

Fig. 7 Cut-away view of first-generation Meteor. Key: 1. star sensor, 2. solar array drive mechanism, 3. television signal commutator, 4. tape recorder, 5. flywheel, 6. electric rocket engine, 7. gyroscopic sensor, 8. electric motor, 9. electric drive for thermal control system, 10. orbit control equipment, 11. television camera, 12. Earth (local vertical) sensor, 13. infrared radiometer, 14. recording and replay system, 15. stepping motor, 16. angular velocity sensor, 17. rotary converter, 18. relay-contactor equipment, 19. magnetorquer, 20. pneumatic valve of gas reaction control system.
(source: Sovetskaya Entsiklopediya Publishers)

which by sheer coincidence also happened to be the day that the United States launched its first Nimbus weather satellite, the first three-axis stabilised American meteorological satellite. Officially called Kosmos-44, the satellite was launched into an elliptical 65.04° inclination orbit from Baikonur by the 8A92 rocket, a modification of the "Vostok" booster originally designed to launch the Zenit-2 spy satellites [49].

A 28 October 1964 VPK decree on the results of the flight stated that Kosmos-44 had allowed engineers to test the electrotechnical and radiotechnical systems of the Meteor bus as well as its on-board automatic control system, thermal control system, power supply system and the ground infrastructure to control the satellite in flight. It also noted that a fault in the rocket's control system had caused the satellite to end up in an unplanned orbit (615 x 857 km, a much higher apogee than subsequent Meteors). Scientific instruments had been able to record changes in "thermal radiation of the Earth's atmosphere", but because of problems with the attitude control system the full programme of the first mission had not been accomplished.

The same VPK decree set the second launch for December 1964, with the third and fourth missions to follow in April and May 1965. A follow-up VPK decree of 16 December 1964 ordered to convert four R-7 missiles into 8A92 boosters for Meteor launches in 1965 and fly one booster per month beginning in August of that year. Again these goals proved to be overly optimistic. The second satellite, Kosmos-58, didn't fly until February 1965 and like its predecessor was a rather crude version of the actual Meteor satellite. It wasn't until the third mission (Kosmos-100) in December 1965 that three-axis stabilisation was achieved, but other problems meant that no weather pictures were returned to Earth. That objective was accomplished by the fourth satellite (Kosmos-118), launched in May 1966, but because of problems with the solar array drive mechanism only a very limited amount of pictures was received and they were never publicly released [50].

In Soviet-era publications none of these four satellites were ever related to the Meteor programme and it was only the similarity of their orbital parameters to those of the first officially announced Soviet weather satellite that betrayed their nature. Since the major goal of these initial flights was to test the Meteor bus itself, not all the satellites may have carried the full instrument suite, although a television camera seems to have been present on all four satellites. A veteran of the NII-380 design bureau claims that the camera system flown on the first four satellites was called MR-300, capable of providing mosaic pictures that could be stored on an on-board recording device for later playback to Earth [51].

The next step in the programme came on 25 June 1966 with the launch of Kosmos-122, which was attended by CPSU General Secretary Leonid Brezhnev and French president De Gaulle, the first Westerner allowed to visit Baikonur. It was not until about two months after the launch that the Russians began providing details about the satellite, the first time that the existence of a Soviet meteorological satellite system was publicly acknowledged [52]. Kosmos-122 is the first satellite known to have carried the full instrument complement described in section 11.1. The satellite remained operational for four months [53].

The successful mission of Kosmos-122 paved the way for the next step in the programme, namely to fly two meteorological satellites in parallel, as would later be the case in the operational system. The first of the pair was launched as Kosmos-144 on 28 February 1967, followed on 27 April by Kosmos-156. There were two notable differences with the previous launches. First, they were staged from the northern cosmodrome of Plesetsk, which had seen its first space launch in March 1966. This made it possible to change the inclination from 65° to 81.2° and thereby provide better coverage of Soviet territory [54]. Unlike US weather satellites, however, the orbit was prograde (not Sun-synchronous) because of range safety restrictions at Plesetsk. The orbital altitude remained unchanged. All future Meteors until Meteor-3M would continue to fly from Plesetsk.

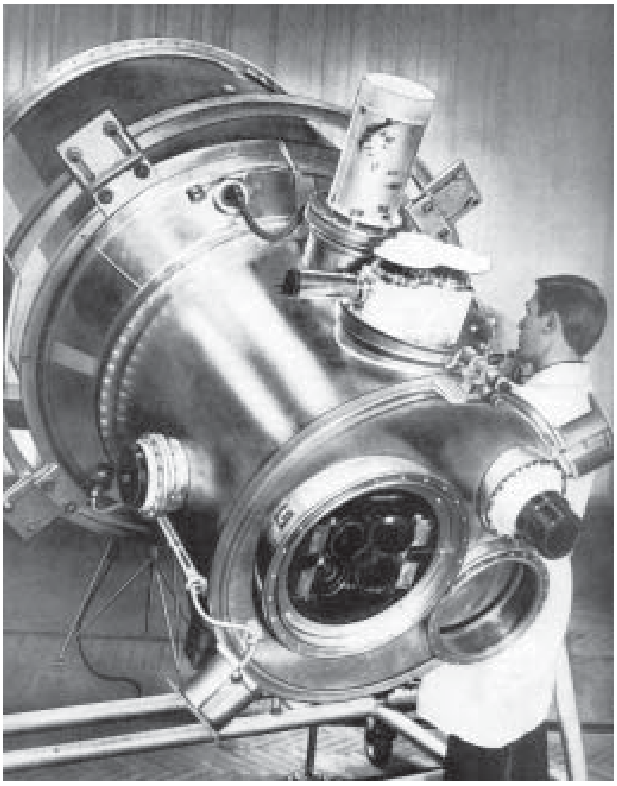

Fig. 8 Meteor payload compartment undergoing testing. (source: Gidrometeoizdat)

Second, the launch of Kosmos-144 marked the introduction of a slightly improved rocket called 8A92M. In 1965 the manufacturer of R-7 based launch vehicles (OKB-1 Branch N°3 in Kuybyshev) had decided to cease the production of the 8A92 since a modernised version of the launch vehicle (the 11A57) had been introduced. However, it turned out that the 8A92 was better suited for launches into near-polar orbits due to its ascent profile and the burn time of the third stage (Blok-Ye). In 1966 it was decided to build the slightly improved 8A92M, which was specially tailored for launches into high-inclination orbits. While the core and strap-on boosters were essentially the same as those of the 8A92 (except for some lighter cables), the third stage carried a new inertial control system that was lighter and more precise than the ones previously used. The rocket also used the nose fairing of the 11A57 launcher, which was 0.4 m longer. In addition, all three stages had improved telemetry systems. The 8A92M would continue to be used for Meteor launches until 1984 [55].

Although the two satellites were launched under the veil of the Kosmos programme, the Soviet media announced in early June that together with their ground stations they formed "the experimental space meteorology system Meteor", which was the first public use of the name. The launch of Kosmos-156 was timed such that its orbital plane was spaced 95° from that of Kosmos-144, meaning that both satellites passed over the same part of the Earth with an interval of six hours. The two satellites enabled meteorologists to obtain data about weather patterns over half of the planet in one day's time. The simultaneous operation of two satellites was a major test for Soviet ground stations, which now had to quickly process telemetric and meteorological information from one satellite before the other one came within range. Of particular interest to meteorologists was the information obtained by the two satellites over regions with few weather stations. For instance, data from Kosmos-144 and 156 were used to determine the position of ice in the Arctic Ocean as the navigation season began [56].

Three more Meteors with Kosmos designations (184, 206, 226) were flown in 1967 and 1968. There was a launch failure on 1 February 1969, when the second stage of the 8A92M launch vehicle malfunctioned. This is the only known complete launch failure in the entire Meteor programme [57].

Despite built-in redundancy, there were repeated failures of electronic systems aboard the first satellites, meaning that the average lifetime was only about 6 to 8 months. This implied that replacement satellites had to be launched on a regular basis to replenish the Meteor constellation. Since VNIIEM did not have the capability to serially produce the satellites, the manufacture of the satellites was turned over in 1966 from VNIIEM to the factory aligned with the Yangel bureau in Dnepropetrovsk, where all the remaining first-generation Meteors were built [58]. Yangel's bureau had been renamed KB Yuzhnoye in 1966 and the plant was called the "Yuzhnoye Machine Building Plant" or simply "Yuzhmash". Ironically, the design bureau that had transferred Meteor to VNIIEM only a few years earlier would now build the satellites, although VNIIEM remained in charge of satellite design, delivering the blueprints to the factory in Dnepropetrovsk. Pre-launch check-out of the satellites was performed at a special branch of VNIIEM founded at the Plesetsk cosmodrome in December 1967. In November 1971 a research institute called "Novator" was set up on the basis of this branch [59].

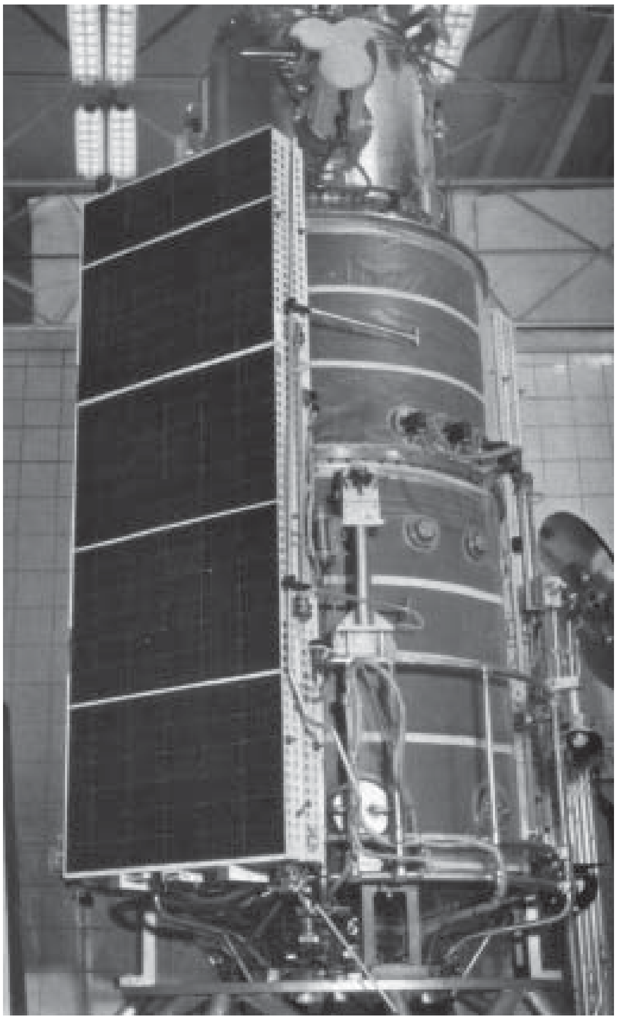

Fig. 9 Meteor satellite in final assembly. (source: Gidrometeoizdat)

11.3 Operational Flights

The first satellite to be officially announced as Meteor was orbited on 26 March 1969, marking the beginning of operational flights. In the following years a number of changes were made both to the orbits and the satellites themselves. Meteor 1-5, launched on 23 June 1970, was the first to fly in a roughly 900 km orbit, which gave the satellite a broader field of view, although it meant that the resolution of the pictures became slightly lower. Beginning with Meteor 1-10, orbited on 29 December 1971, all the satellites would orbit at this altitude.

Meteor 1-10 was also innovative in two other ways. It was the first Soviet weather satellite to use Automatic Picture Transmission (APT), enabling it to downlink pictures in real time to both Soviet and Western ground stations equipped with small receivers (at 137 MHz). Using this system, the ground stations could reproduce images just 5 to 10 minutes after the satellite passed overhead. APT was first tested by the American Tiros-8 satellite, launched in December 1963, and was introduced operationally on the ESSA/TOS satellites in 1966. For the transmission of images in APT mode NII-380 in Leningrad developed a scanning radiometer called MR-900, which would become a standard feature on the later Meteor-2 and Meteor-3 satellites. Radiometers use a system of lenses, moving mirrors and image sensors and have a far better performance than vidicon TV cameras like the MR-600.

Meteor 1-10 also tested two different types of solar electric propulsion systems for orbit maintenance, one an electrostatic and the other an electromagnetic system. The electrostatic system, known as Zefir, consisted of a pair of ion thrusters developed by the Kurchatov Institute for Atomic Energy (IAE) under the leadership of Professor P.M. Morozov. The overall mass of the system was 53.4 kg and it used a 1.56 kg supply of mercury as its fuel. The mercury was bombarded with electrons to ionise it and was then electrostatically accelerated out of the rear of the engine. The engines required 550 W of power and the expected thrust was between 6 and 8 mN. Performance of the thrusters was close to the expected values (around 7 mN), but a failure in the ion acceleration system meant that the tests could not be completed [60]. This probably explains why the use of these engines was not announced by the Russians at the time. They were never flown again on later Meteors. US experience showed that mercury was difficult to work with, since it first had to be turned into a gas before being ionised and also because the atoms would cool after exiting the engine and condense on the exterior of the spacecraft. Later ion engines would usually use xenon.

More successful (and reported in the Soviet media at the time) were tests of an electromagnetic system consisting of a pair of stationary plasma or “Hall” thrusters. Identified as SPD-60 or Eol-1, they were designed and built jointly by Professor Morozov’s team at IAE and OKB Fakel in Kaliningrad near the Baltic Sea. Measuring 108 x 114 x 190 mm, they weighed 32.5 kg and had a supply of 2.4 kg of compressed xenon to create a plasma. Each was supposed to produce between 18-23 mN of thrust and consume 500 W of power. Between 14 and 22 February 1972 the plasma engines of Meteor 1-10 worked for a total of 170 hours, raising the satellite’s orbit by 16.9 km. They ensured that the satellite made exactly 14 revolutions around the Earth in 24 hours time and thereby repeated its ground track every day. Actual thrust was between 16-19 mN and they consumed between 420-460 W of power.

The SPD-60 thrusters were tested again by Meteor 1-19 in 1974 (operating for a total of 600 seconds) and a Meteor Priroda remote sensing satellite launched on 15 June 1976. A different version (SPD-50), which provided less thrust (about 20 mN) but was more power-efficient, was flown on Meteor 1-27 in 1977. All in all, the tests of the plasma thrusters on the first-generation Meteor satellites do not seem to have been entirely satisfactory. All remote sensing equipment aboard the satellites had to be shut off when the thrusters were working and even then the 500W of power available did not turn out to be enough to use the full potential of these thrusters. Solar electric propulsion was not reintroduced on Soviet meteorological satellites until the Meteor-3 generation, which used yet another type of electric engine, namely electrothermal thrusters [61].

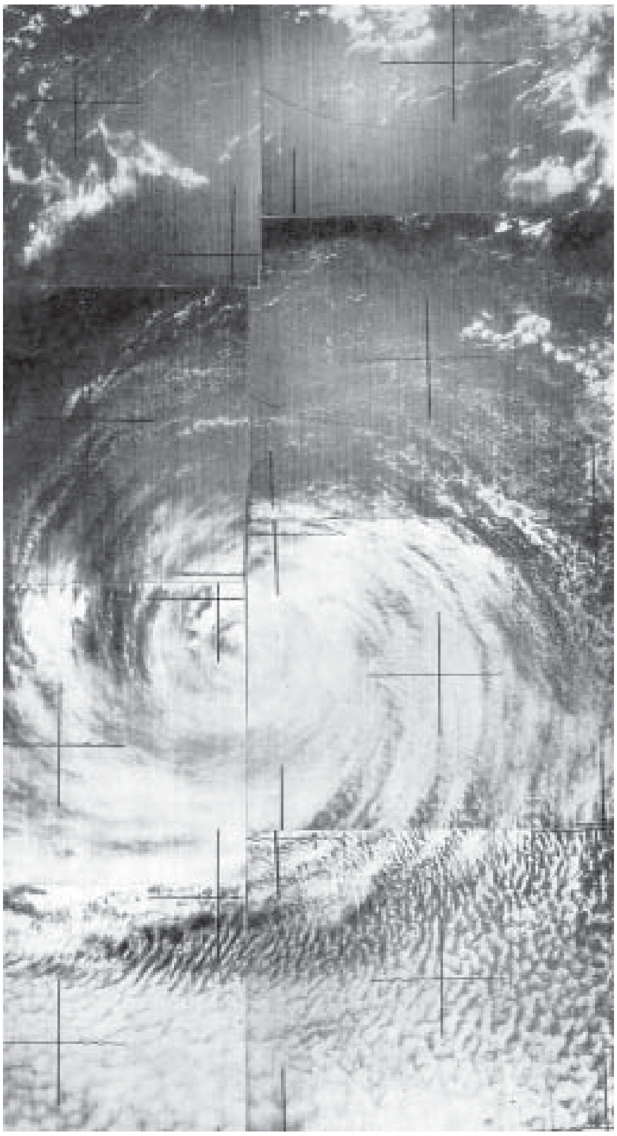

Fig. 10 Picture taken by Meteor 1-5 on 26 October 1970. (source: Gidrometeoizdat)

Apart from the introduction of the MR-900 scanning radiometer, the instrument suite flown by the first-generation Meteors is believed to have remained largely similar to that introduced by Kosmos-122, although some experimental instruments may have flown on some of the satellites. For instance, Meteor 1-8, launched on 17 April 1971, is known to have carried spectrometric equipment to compile a vertical temperature profile of the atmosphere [62]. On several occasions observations from Meteor satellites were coordinated with those performed by orbiting cosmonauts. This was the case on the Soyuz-9 and Soyuz-11 missions and similar experiments were also conducted in later years. The final first-generation Meteor was launched on 5 April 1977.

The first-generation Meteor bus served as the basis for building the Soviet Union's first Earth resources satellites, known as Meteor Priroda (index 11F651). The go-ahead for building these satellites was given by a government decree on 21 December 1971, which may have come in response to the impending launch of America's first remote sensing satellite Landsat. The decree not only approved the Meteor Priroda satellites, but also the Fram (11F635) satellites, which would draw upon the well-proven design of the Zenit spy satellites to return high-resolution pictures to Earth in recoverable descent capsules [63].

A total of five first-generation Meteor Priroda satellites were launched between 1974 and 1981, the first two into Meteor-type orbits from Plesetsk and the last three into Sun-synchronous orbits from Baikonur, where range safety restrictions for retrograde launches had been lifted. At least some of these were built on the basis of Meteors that had been placed in storage at Yuzhmash. Confusingly, all but the last one were officially announced as Meteor. They were equipped with two multi-channel scanning radiometers developed by the design bureau headed by M. Ryazanskiy (now called the Russian Research Institute for Space Device Engineering or RNIIKP), more particularly in a department headed by Arnold Selivanov. MSU-S was a medium resolution camera (240 m resolution from 650 km altitude, swath width 1400 m) and MSU-M a low-resolution camera (1 km resolution from 650 km altitude, swath width 1930 km). Some of the first-generation Meteor Priroda satellites also carried microwave radiometers and the Lastochka-65 infrared imaging system, which had characteristics similar to that of the Lastochka device flown on the Meteors. Although some of the Meteor Priroda data were used for meteorological purposes, these satellites will not be discussed in detail here [64].

Also based on the first-generation Meteor bus was an experimental satellite called Kosmos-1066, launched into a Meteor type orbit in December 1978. This was long believed to be a Meteor that became crippled shortly after reaching orbit, but it is now known that this satellite had a different index (11F653) and was unofficially called "Astrofizika". Instead of the traditional meteorological instrument package, the satellite carried a series of optical instruments to detect various artificially induced light sources on the ground. Two SPD-50 stationary plasma thrusters were installed on the satellite to make sure that the satellite passed over these light sources at the correct moment. The mission may have had military objectives [65].

12. Meteor-2

12.1 Origins and design

Even as test flights of the first-generation Meteors were still underway, plans were being drawn up for a more capable follow-on system. In 1967 the objectives for the Meteor-2 (11F632) system were outlined, with the initial goal being to increase the average lifetime of the satellites from 0.5 to 1 year. In 1969 the technical requirements for the system were approved jointly by GUGMS and the Ministry of Defence. Meanwhile, the five-year plan for 1971-1975 called for Meteor-2 to become part of a "Global Meteorological Space System" (GMKS), which was also to consist of the Meteor-2M satellites. Built on the basis of the Meteor-2 bus, Meteor-2M was to be equipped with instruments to pick up data from buoys scattered over the world's oceans. On 4 June 1970 the Military Industrial Commission gave the go-ahead for setting up the GMKS. A draft plan for such a "unified hydrometeorological space system" was worked out at VNIIEM in 1972, but later that year the Meteor-2M plan was rejected due to what one source describes as "a number of circumstances and subjective reasons". Yuriy Trifonov attributes the cancellation of Meteor-2M to the fact that it was expensive and overweight and was to solve tasks not directly related to meteorology. Moreover, the buoys, which he says were to be used for "a wide variety of tasks", would have to be very heavy. At any rate, the development of Meteor-2 continued, with the draft plan being finished in 1971 [66].

The introduction of Meteor-2 coincided with some major organisational changes at VNIIEM. The institute was not happy with the quality of the Meteors rolling off the assembly line at Yuzhmash and therefore decided to regain responsibility for the manufacture of the satellites. It would also take over the design and assembly of various systems from subcontractors. Given VNIIEM's limited production capabilities, the task of serially producing the satellites was assigned to a branch of VNIIEM set up by Iosifyan in the Moscow suburb of Istra in 1960. The actual design took place at VNIIEM, with Iosifyan

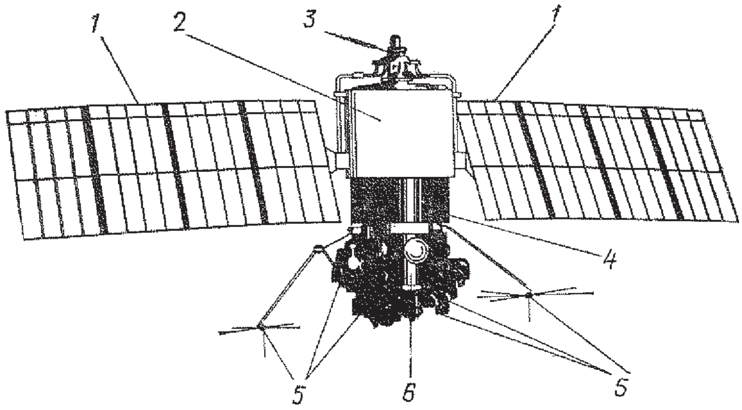

Fig. 11 Meteor-2. Key: 1. solar panels, 2. thermal control system, 3. sensors of solar array orientation system, 4. equipment compartment, 5. antennas, 6. payload compartment.
(source: Znaniye publishers)

being the chief designer. In 1974 Iosifyan resigned as VNIIEM's general director and was replaced in that capacity by Nikolay N. Sheremetyevskiy, one of his deputies and another 30-year veteran of the institute. A test model of Meteor-2 was built and tested at VNIIEM in Moscow, with serial production getting underway at the Istra branch sometime in the mid-1970s. Eventually, the Istra branch would be put in charge *both* of the design and the production of the Meteors, while VNIIEM's central design bureau in Moscow shifted its attention to geostationary weather satellites and the Meteor Priroda and Resurs-O remote sensing satellites [67].

With Meteor-2 VNIIEM introduced a new computer-based system called AIST (Automatic Testing System) to thoroughly check out the satellites both at the plant and at the launch site (probably at the 'Novator' branch of VNIIEM at Plesetsk). Compared to the earlier manual and semi-automated techniques, this was a much more reliable system that curtailed development time and required less intervention from Space Units personnel in preparing the satellites for launch at Plesetsk. It placed emphasis on carefully testing the satellites on the ground rather than going through a gruelling series of test flights, as had been the usual practice in the Soviet space programme until then. It was largely thanks to AIST that the lifetime of the Meteor-2 satellites was significantly increased, far beyond the initial one-year goal. The AIST equipment at Plesetsk was also used to check out the 2nd generation Meteor Priroda satellites, which were first shipped to Plesetsk for pre-launch check-out and then flown over to Baikonur to be mated with the launch vehicle. VNIIEM later also supplied similar satellite testing systems to other satellite manufacturers [68].

Apart from the organisational changes and the introduction of AIST, other measures were taken as well to increase the lifetime of the satellites. While the first-generation satellites had still used gas thrusters for momentum dumping, Meteor-2 now relied entirely on magnetorquers to accomplish this task, meaning that depletion of the gas supply was no longer a constraint for its operational lifetime. Meteor-2 also had more precise orientation and stabilisation than its predecessor and an automated timing device to control the meteorological sensors. Although externally similar to Meteor-1, it basically was a new satellite. The overall mass was about 1500 kg.

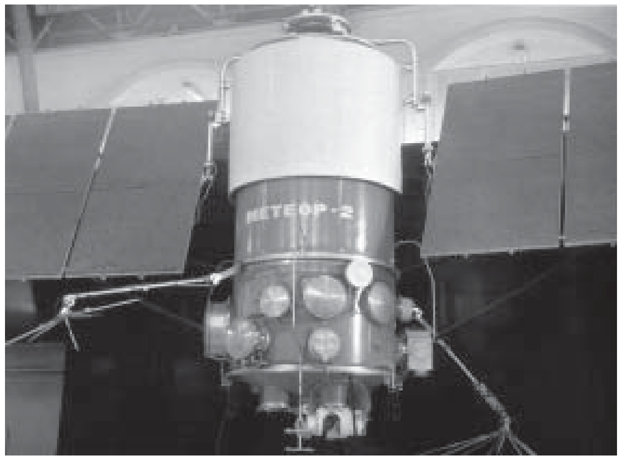

Fig. 12 Meteor-2 on display.
(source: Mashinostroyeniye Publishers)

The payload truss was wider than that of Meteor-1 and the meteorological sensor package, which accounted for 30 percent of the total mass, was virtually entirely new. Aside from the MR-900 APT system introduced on Meteor-1, the Meteor-2 satellites flew a new scanning radiometer (MR-2000, also built by NII Televideniya) to provide global data about cloud patterns, snow and ice fields in daytime. In addition to that there were two infrared scanning radiometers, one (BCh-100 or "Chayka") to furnish global data about cloud patterns, surface temperature, altitude of cloud tops in both daytime and nighttime and another to send back global data on vertical temperature profiles up to an altitude of 40 km in daytime and nighttime. Data for these instruments are listed in Table 3. At least some of the satellites carried the actinometric instruments flown by the first-generation Meteors, but later TsKB Geofizika decided

TABLE 3: *Standard Meteor-2 Instrument Suite.*

Instrument	Number of Spectral Bands	Band Wavelengths μM	Ground Swath km	Ground Resolution km
MR-900 scanning telephotometer	1	0.5 – 0.7	2100	2
MR-2000 scanning telephotometer	1	0.5 – 0.7	2600	1
BCh-100 scanning IR radiometer	1	8 – 12	2800	8
scanning IR radiometer	8	11.1 – 18.7	1000	37
RMK radiation measurement system		no data available		

to stop their production. Also on board was a non-meteorological payload called the Radiation Measurement Complex (RMK) to monitor streams of particles in near-Earth space, among other things to ensure the safety of cosmonauts orbiting the Earth [69].

While it is safe to assume that the Meteor-1 series had a dual civilian/military role, there is positive confirmation that this was the case for the Meteor-2 satellites. Three military objectives have been identified for Meteor-2: meteorological reconnaissance of areas to be photographed by spy satellites, providing local and global meteorological data to the various branches of the armed forces for operational purposes and determining the radiation situation in Earth orbit. A novelty of Meteor-2 was that the information could be directly relayed to about 50 military autonomous receiving points spread across the Soviet Union, the socialist countries and the world's oceans. The information reception points were developed by the NII Televideniya. The data could be used to make 1 to 3 day weather forecasts [70].

12.2 Flights

The Meteor-2 programme was inaugurated on 11 July 1975 with a launch announced with the same name. One source claims the launch was significantly delayed because of problems with the development of TsKB Geofizika's actinometric instruments [71]. The satellite reportedly operated successfully for over two years, although it was not until the second launch in January 1977 that Meteor-2 was actually used "for the Weather Forecasting Service and the economy" [72]. The State Commission in charge of the Meteor-2 test flights was headed by Maj.-Gen. V.I. Shcheulov, who had also headed the State Commission overseeing the first-generation test flights. The programme was not officially declared operational until 21 June 1982, which did not correspond to the actual launch date of a satellite [73].

The first Meteor-2 satellites were placed into almost identical orbits as their predecessors (roughly 900 km circular orbits inclined 81.2° to the equator) and used the same 8A92M launch vehicle. A major development in the programme took place on 25 March 1982, when the eighth officially announced Meteor-2 was launched by KB Yuzhnoye's R-36 based three-stage 11K68 rocket (retrospectively called Tsiklon-3), marking the first time that a Soviet meteorological satellite was launched by a booster *not* based on the R-7. This switch of launch vehicles had been in the works since the late 1960s. The use of an R-36 based rocket to launch "Kosmos and Meteor" satellites was first mentioned in a government resolution issued as early as July 1967 [74]. Final approval for the development of the 11K68 came with a government resolution on 2 January 1970, which mentioned Meteor and the Tsikada electronic intelligence satellites as the intended payloads [75]. However, work on the 11K68 moved to the background as KB Yuzhnoye was too preoccupied with its ICBM projects and did not resume in earnest until 1975 with the release of yet another government decree [76].

On 24 June 1977 the 11K68 began a series of six test flights with what appear to have been mock-up satellites. One of these, Kosmos-1045, launched on 26 October 1978, was a mass model of a Meteor-2 satellite, carrying two piggyback radio amateur satellites (Radio 1 and Radio 2) and an additional radio amateur instrument package that remained attached to the main payload [77]. The 11K68 was officially declared operational for use in the Meteor and Tselina-D programmes by a government decree in January 1980 [78].

The reasons given for the switch to the Tsiklon-3 were that it would "provide a maximum automatisation and safety of pre-launch preparations, ensure a higher precision in orbital insertion ... and create a mass reserve" [79]. The move to the Tsiklon translated into a slightly different orbital regime, with the inclination shifting from 81.2 to 82.6° and the average altitude increasing from 900 to 950 km. In the late 1970s it was considered to use the Tsiklon for

TABLE 4: *List of Meteor-2 (11F632) Launches*.

Official name (+ Western digit)[1]	Launch date/time (UTC)[2]	Launch site and vehicle[3]	Inclin.[4]	Perigee/Apogee	Comments
Meteor 2 (1)	11.07.1975 04.15	Plesetsk 8A92M	81.29	858 x 891	
Meteor 2 (2)	06.01.1977 23.18	Plesetsk 8A92M	81.27	890 x 906	
Meteor 2 (3)	14.12.1977 09.30	Plesetsk 8A92M	81.22	856 x 894	
Kosmos-1045	26.10.1978 07.00	Plesetsk 11K68	82.55	1689 x 1710	Meteor-2 mass model. Test launch of Tsiklon-3.
Meteor 2 (4)	01.03.1979 18.45	Plesetsk 8A92M	81.22	893 x 897	
Meteor 2 (5)	31.10.1979 09.25	Plesetsk 8A92M	81.21	873 x 890	
Meteor 2 (6)	09.09.1980 11.00	Plesetsk 8A92M	81.25	848 x 894	
Meteor 2 (7)	14.05.1981 21.45	Plesetsk 8A92M	81.27	855 x 893	
Meteor 2 (8)	25.03.1982 10.50	Plesetsk 11K68	82.54	942 x 964	First use of the Tsiklon-3 rocket for a standard Meteor launch
Meteor 2 (9)	14.12.1982 22.30	Plesetsk 8A92M	81.25	812 x 892	
Meteor 2 (10)	28.10.1983 09.00	Plesetsk 8A92M	81.17	754 x 890	
Meteor 2 (11)	05.07.1984 03.35	Plesetsk 11K68	82.53	945 x 962	
Meteor 2 (12)	06.02.1985 21.45	Plesetsk 11K68	82.54	939 x 961	
Meteor 2 (13)	26.12.1985 01.50	Plesetsk 11K68	82.54	939 x 962	
Meteor 2 (14)	27.05.1986 09.30	Plesetsk 11K68	82.54	941 x 960	
Meteor 2 (15)	05.01.1987 01.20	Plesetsk 11K68	82.47	942 x 961	
Meteor 2 (16)	18.08.1987 02.27	Plesetsk 11K68	82.56	944 x 960	
Meteor 2 (17)	30.01.1988 11.00	Plesetsk 11K68	82.55	938 x 961	
Meteor 2 (18)	28.02.1989 04.05	Plesetsk 11K68	82.52	941 x 960	
Meteor 2 (19)	27.06.1990 22.30	Plesetsk 11K68	82.55	940 x 961	
Meteor 2 (20)	28.09.1990 07.30	Plesetsk 11K68	82.53	943 x 962	
Meteor 2 (21)	31.08.1993 04.40	Plesetsk 11K68	82.55	938 x 969	Carried Temisat piggyback satellite. Shut down 05.08.02

1. All Meteor-2 satellites were officially announced as Meteor-2 without additional digits referring to the specific mission number. In Western launch lists these have usually been added for clarity and they are included between brackets.
2. All times for the Plesetsk launches are from: S. Sergeyev, “Statistics of Launches of Meteor Satellites From the Plesetsk Cosmodrome”, op. cit.
3. 8A92M is a version of the Vostok launcher, 11K68 is the Tsiklon-3.
4. Orbital data are from “*The R.A.E. Table of Earth Satellites 1957-1989*”, op. cit.

launches into Sun-synchronous orbits from Plesetsk (probably for Meteor as well), but the idea was rejected [79b]. After two more flights using the older 8A92M the Meteor-2 constellation definitively switched to the Tsiklon beginning in 1984. Various combinations of orbital planes were used, usually with 2-3 satellites giving passes at 6-8 hr intervals.

The programme concluded on 31 August 1993 with the launch of Meteor 2-21, which was also the first Meteor to carry a small piggyback satellite, the 30 kg Italian Temisat, which was separated from the Meteor about 11 hours after launch. The launch was also dedicated to the memory of A. Iosifyan, the founder of VNIIEM, who had died earlier that year [80]. The Meteor-2 bus proved to be a very sturdy design. This was demonstrated in 1995 when a Meteor-2 which had not been actively used for 10 years was successfully switched back on in a test of the longevity of its subsystems. Although its scientific instruments were no longer operational, the power supply system still worked and temperatures and pressures on board were normal [81]. Meteor 2-21, the last satellite in the series, was not definitively shut down until August 2002, although only the MR-900 instrument had been providing data during the final years of its operational lifetime. In most cases, not the satellite bus, but the meteorological instruments seem to have been the limiting factors in the lifetime of the Meteor-2 satellites. Especially susceptible to failure were the infrared radiometers, which reportedly worked for only 6 to 12 months on the average [82]. According to one source the Meteor-2 satellites gave an economic effect of 500 to 700 million rubles per year, but these numbers are difficult to verify [83].

The Meteor-2 bus was used as the basis for developing the second generation of Meteor Priroda remote sensing satellites (11F651), two of which were launched (in June 1980 and July 1983, announced resp. as Meteor (1-30) and Kosmos-1484). It also served as the platform for a satellite known as Interkosmos Bulgaria 1300, launched in August 1981 with a series of Bulgarian instruments to study the Earth's ionosphere and magnetosphere (although the solar panels installed on the satellite were built by NPO Kvant and were of the same type as those used on the Soviet-French Oreol-3 satellite).

13. Meteor-3

13.1 Origins and design

The first ideas to develop a third generation of Meteor satellites emerged in the early 1970s and were closely linked to plans to deploy a network of geostationary weather satellites. On 16 December 1972 the Military Industrial Commission proposed the deployment of a "3rd generation hydrometeorological support system" consisting of the Meteor-3 satellites and a series of geosynchronous satellites known as Elektro [84]. However, work on both programmes did apparently not start in earnest until 1981, when a government resolution combined the two efforts into the "Unified Space System for Hydrometeorological Support" (Russian acronym EKS GMO), also known as Planeta [85].

Fig. 13 Vladimir Adasko, chief designer of Meteor-3. (source: Russkiy Kupets)

The design and manufacture of Meteor-3 (index 17F45) was completely entrusted to the Istra branch of VNIIEM. The satellite's chief designer was Vladimir I. Adasko, who at the time was the director of the Istra branch [86]. Adasko would go on to become VNIIEM's general director in 1991 (taking over from Sheremetyevskiy), but died just two years later, being replaced by Stepan A. Stoma, who continues to lead VNIIEM today. Meteor-3 benefited from the experience gained in the Meteor-2 and Interkosmos Bulgaria 1300 programmes and also inherited some design features from the Resurs-O remote sensing satellites being developed simultaneously at VNIIEM's central design bureau in Moscow. The purpose was to build a satellite with a guaranteed lifetime of at least 2 to 3 years, twice that of Meteor-2. The mass of the Meteor-3 satellites varied between 2,150 and 2,250 kg with a payload of 500-700 kg in a volume of 0.7 m^3.

Re-introduced on Meteor-3 was a solar electric propulsion system. After the less than satisfactory performance of the electrostatic and electromagnetic thrusters flown aboard some of the first-generation satellites, engineers now opted for an

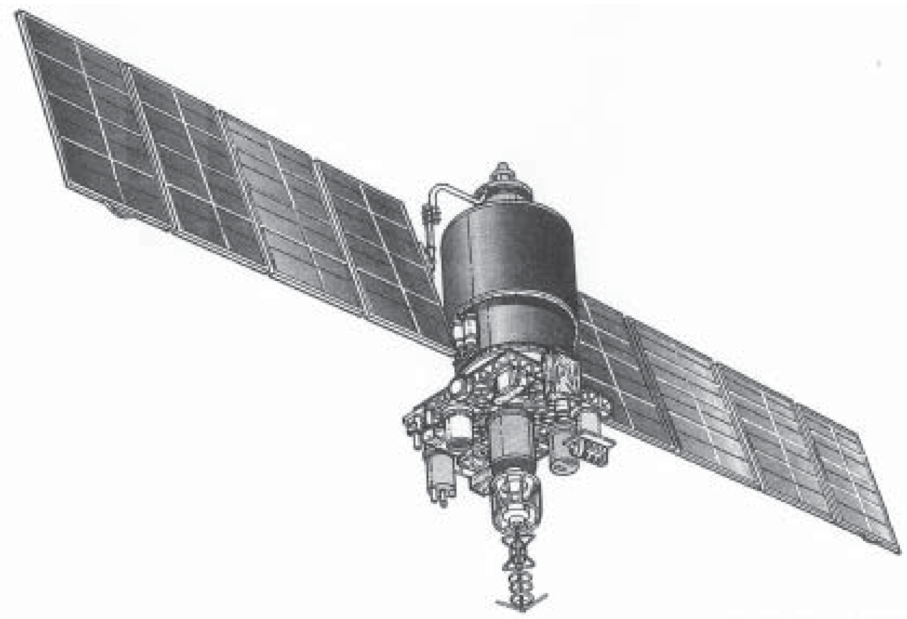

Fig. 14 Meteor-3. **(source: N. Johnson/Teledyne Brown Engineering)**

electrothermal system built in-house at the Istra branch. Designated DEN-15, it operated by heating liquid ammonia to high temperatures (about 1200°C) and then ejecting the resulting constituent gases (hydrogen and nitrogen) at high velocity through an expansion nozzle. Thrust was about 150 mN with a power consumption of no more than 500 W. These thrusters were to pave the way for similar engines to be installed aboard the Elektro geostationary weather satellites for orbit correction and momentum dumping [87]. The three-axis attitude control system provided a pointing accuracy of 1°. The satellites' two movable solar panels (about 1.5 m tall by 3.5 m wide) had a total power output of 500 W.

TABLE 5: *Standard Meteor-3 Instrument Suite.*

Instrument	Number of Spectral Bands	Band Wavelengths µM	Ground Swath km	Ground Resolution km
MR-900B scanning telephotometer	1	0.5 - 0.8	2600	1.0 x 2.0
MR-2000M scanning telephotometer	1	0.5 – 0.8	3100	0.7 x 1.4
Klimat scanning IR radiometer	1	10.5 – 12.5	3100	3 x 3
174-K scanning IR radiometer	10	9.65 – 18.7	1000	42
RMK radiation measurement system		0.15-3.1 MeV (electrons) 1-600 MeV (protons)		

The standard instrument suite for Meteor-3 is listed in Table 5. A novelty on the satellites was a special truss structure at the base of the satellite designed to accommodate additional payload packages with experimental instrumentation or even small piggyback satellites. Additional experiments flown on some of the satellites were the BUFS, Ozon-M and SFM ultraviolet spectrometers to measure total ozone content and vertical ozone distribution in individual regions [88]. Ozon-M operated in 4 spectral bands with wavelengths ranging from 0.25 to 1.03 µm. SFM provided data about the vertical distribution of ozone in the polar regions between altitudes of 35 and 80 km. An initial version (SFM-1) was flown on a Meteor Priroda remote sensing satellite in 1983 and a Meteor-3 satellite in 1988. An upgraded model (SFM-2) was carried by three more Meteor-3 satellites and operated in 8 spectral bands with wavelengths ranging from 0.25 to 0.38 µm [89]. The final satellite in the series also carried a solar radiation monitor called ISP. Some of the satellites also flew international payloads, which will be detailed later.

According to documents filed with the World Meteorological Organisation, the objectives of the Meteor 3 programme were:

- **to obtain, on a regular basis, global data on the distribution of cloud, snow, and ice cover and surface radiation temperatures once or twice daily at times close to the synoptic times**
- **to obtain, on a regular basis, regional data on the distribution of cloud, snow, and ice cover**

TABLE 6: *List of Meteor-3(M) (17F45) Launches.*

Official name (+ Western digit)[1]	Serial Number	Launch date/time (UTC)[2]	Launch site and vehicle[3]	Inclin.[4]	Perigee/Apogee	Comments
Kosmos-1612	17F45 N°1	27.11.1984 14.22	Plesetsk 11K68	82.60	141 x 1217	Meteor-2/3 hybrid. Useless orbit due to Tsiklon upper stage failure. Re-entered 31.01.1985
Meteor 3 (1)	17F45 N°2	24.10.1985 02.30	Plesetsk 11K68	82.55	1227 x 1251	Meteor-2/3 hybrid
Meteor 3 (2)	17F45 N°3	26.07.1988 05.01	Plesetsk 11K68	82.54	1186 x 1208	First regular Meteor-3. Shut down 14.10.93
Meteor 3 (3)	17F45 N°4	24.10.1989 21.35	Plesetsk 11K68	82.56	1188 x 1213	Shut down 22.12.93
Meteor 3 (4)	17F45 N°6	24.04.1991 01.37	Plesetsk 11K68	82.55	1187 x 1213	
Meteor 3 (5)	17F45 N°5	15.08.1991 09.15	Plesetsk 11K68	82.56	1188 x 1206	Carried NASA's TOMS spectrometer for ozone studies. One instrument still operational as of August 2002.
Meteor 3 (6)	17F45 N°7	25.01.1994 00.25	Plesetsk 11K68	82.56	1186 x 1208	Carried French SCARAB instrument, Tubsat-B piggyback satellite
Meteor 3M N°1	17F45 N°101	10.12.2001 17.19	Baikonur 11K77	99.65	996 x 1016	First Meteor launch using Zenit. Launched with four piggyback satellites.

1. All Meteor-3 satellites were officially announced as Meteor-3 without additional digits referring to the specific mission number. In Western launch lists these have usually been added for clarity and they are included between brackets.
2. All times for the Plesetsk launches are from : S. Sergeyev, "Statistics of Launches of Meteor Satellites From the Plesetsk Cosmodrome", op. cit.
3. 11K68 is Tsiklon-3, 11K77 is Zenit..
4. Orbital data are from "*The R.A.E. Table of Earth Satellites 1957-1989*", op. cit. and "Satellite Digest" in *Spaceflight.*

- to obtain, during each communication session, global data on the vertical temperature and humidity distributions in the atmosphere
- to observe, on a regular basis, information on radiation conditions in near-Earth space globally once or twice a day, and for each orbit in storm conditions [90].

13.2 Flights

A development schedule for Meteor-3 was approved in June 1983 and the draft plan was finalised in 1984 [91]. The first two satellites in the series were experimental and were actually hybrids of Meteor-2 and 3, weighing only 1750 kg. The first one was launched on 27 November 1984, but it got stranded in a useless orbit after the Tsiklon upper stage failed to reignite and was given the cover name Kosmos-1612. The second one was successfully orbited on 24 October 1985 and was the first to be officially announced as Meteor-3. It was not until 26 July 1988 that the first regular Meteor-3 was placed into orbit. There would be four more launches between October 1989 and January 1994 [92]. Despite the higher mass, a more fuel-efficient launch profile of the Tsiklon-3 booster enabled the satellites to be placed into slightly higher orbits than Meteor-2 (1200 km circular), which provided a wider ground swath for the same angular field-of-view and prevented coverage gaps in the equatorial regions.

Two Meteor-3 satellites were notable for the foreign payloads they flew. A Meteor-3 launched on 15 August 1991 carried the American Total Ozone Mapping Spectrometer (TOMS) to study the distribution of ozone across the planet. A deal on this was reached in late 1990 after almost two years of negotiations. Actually, the spectrometer had been built fifteen years earlier as an engineering model for an identical instrument flown on the Nimbus-7 satellite, launched in 1978 [93]. By flying it on Meteor, NASA wanted to ensure there

Fig. 15 Meteor-3/TOMS launch. **(source: NASA)**

would be no gap in ozone data once the TOMS on the ageing Nimbus-7 failed. TOMS operated by comparing solar radiation received and reflected by the Earth in six wavelengths between 0.312 and 0.380 µm. Meteor's TOMS ceased functioning on 27 December 1994 after providing a wealth of information on the condition of the ozone layer [94]. It marked the first major Soviet/American cooperative space venture since the Apollo-Soyuz Test Project in 1975.

The final Meteor-3, launched on 25 January 1994, was equipped with a French scanning radiometer called SCARAB to measure solar radiation reflected back into space by the Earth. Unfortunately, SCARAB was crippled in the spring of 1995 by a failure in the instrument's motorized support structure [95]. The satellite was also outfitted with a German navigation instrument named PRARE and a Russian-built retroreflector array for precise orbit determination. In addition to that, it carried a 40 kg German piggyback satellite (Tubsat-B) that was released from the satellite 9 hours and 16 minutes after launch.

Another SCARAB was supposed to be flown on the final Meteor-3 (serial nr. 8), which in early 1994 was expected to be launched in 1995. However, the satellite never left the ground because of a lack of funds. The financial crisis that followed the collapse of the Soviet Union had hit the Meteor programme especially hard. Even at the time of the Meteor-3/TOMS launch in 1991 VNIIEM deputy general designer Yuriy Trifonov told journalists that funding had ceased and that he expected this to be the last Meteor satellite [96]. It would appear that the final Meteor-3 launch in 1994 was an unexpected bonus. The Meteor-3 programme was never officially declared operational and all the seven satellites launched were considered experimental [97].

Using the same bus as the Meteor-3 series were the third generation Meteor Priroda satellites (11F697), flown between 1985 and 1994. Three of these were launched, the first two by the Vostok-2M booster (Kosmos-1689 and Kosmos-1939) and one by the Zenit booster (Resurs-O1 N°3).

14. Meteor-3M

14.1 Origins and Design

Despite the financial difficulties, planning got underway in the early 1990s for a fourth generation of meteorological satellites called Meteor-3M (index 17F45) with a design lifetime of 3 years. This coincided with a major organisational change at VNIIEM in November 1992, when the Istra branch became an independent entity called NIIEM (Scientific Research Institute of Electromechanics). VNIIEM became officially known as NPP VNIIEM (NPP standing for "Scientific Production Enterprise"). NIIEM comprises several research and development and engineering and test units. The largest unit is the Elkos space equipment division. Aligned with it is an experimental plant, which has become an independent stock holding company called ZAO Novator (not to be confused with the Novator branch at Plesetsk). The director of the Elkos division, Rashid Salikhov, was named chief designer of Meteor-3M.

Although outwardly similar to Meteor-3, Meteor-3M would have much improved capabilities and use a modernised bus also being developed for the next generation of Resurs-O satellites (sometimes referred to as Resurs-O2). It was to become the first Russian meteorological satellite to be placed into a Sun-synchronous orbit, increasing global coverage. Original plans in the early 1990s had called for launch by Tsiklon-3 into an orbit at around 900/950 km and an inclination of 82-83° [98]. By 1993 designers were planning a switch to an uprated Soyuz launch vehicle being developed under the "Rus" programme, allowing the satellite to be placed into a Sun-synchronous orbit at an altitude of 900-950 km [99]. Eventually the choice fell on the Ukrainian-built Zenit rocket, which had also been used for launching a Meteor-3 based Resurs-O remote sensing satellite in 1994. This made it possible to increase the altitude to just over 1000 km. That altitude was to be maintained using the same DEN-15 electrothermal thrusters employed by Meteor-3. The pointing accuracy of the three-axis stabilisation system was increased to 10 minutes of arc. Due to the change of orbital inclination the solar panels would now have a power output of 1200 Watt throughout the satellite's entire lifetime. The use of an on-board computer expanded the satellite's control functions and the spacecraft's position in orbit could be more accurately measured using GPS and Glonass data. With a total mass of about 2,350 kg, Meteor-3M was able to carry a payload of about 1000 kg, about 300 kg more than Meteor-3.

The instrument suite of the first Meteor-3M differs in several ways from that flown on earlier Meteor satellites. In addition to the meteorological payload it also has some of the remote sensing instruments traditionally flown on the Resurs-O satellites. Similarly, the Resurs-O1 N°4 satellite, launched in July 1998, was equipped with an MR-900M meteorological camera. This cross-fertilisation between the Resurs-O and Meteor programmes was undoubtedly dictated by the declining space budgets of the 1990s, which made it necessary to combine as many functions as possible on a single satellite.

The Meteor-3M payload consists of three instrument sets: a meteorological set (MR-700M), a "scientific measurement set" (BKNA) and a natural resources set (BIK-M1). These three instrument sets operate independently from one another, each using their own transmitters to relay data to the ground at different frequencies and transmission speeds.

The MR-700M complex consists of the following instruments:

Fig. 16 Rashid Salikhov, chief designer of Meteor-3M. (source: NIIEM)

- MR-2000M1: an optical scanning telephotometer for daytime meteorological observations. It is made up of two identical sets of equipment, each comprising an optical scanning device (MR-2010M), an automatic timing device, a magnetic tape recorder (MR-2030M) and a communications block. The system is activated by a Sun sensor whenever the elevation of the Sun over the underlying regions is at least five degrees. Mass is about 55 kg.
- Klimat: a scanning infrared radiometer for daytime and nighttime meteorological observations. Mass is about 100 kg.
- SFM-2: two ultraviolet spectrometers to study the vertical distribution of ozone between altitudes of 35 and 75 km by analysing solar light penetrating the atmosphere during sunrise and sunset. SFM-2A operates as the Sun sets above the northern hemisphere (between 45° and 80° northern latitude) and SFM-2B as the Sun rises above the southern hemisphere (between 30° and 60° southern latitude).

The BIK-M1 comprises:

- MSU-E: a high-resolution scanning telephotometer. Mass is 33 kg.
- MSU-SM: a medium-resolution scanning telephotometer. Mass is 7.3 kg.

Built at RNIIKP, these are similar to the devices flown routinely on the Resurs-O satellites and are mainly used for natural resources studies and disaster monitoring. The main users of the BIK-M1 data are the Ministry of Natural Resources and the Ministry of Emergency Situations.

The BKNA contains the following five instruments:

- MIVZA: a microwave radiometer to study the moisture content of clouds and areas of heavy precipitation. Mass is 50 kg.

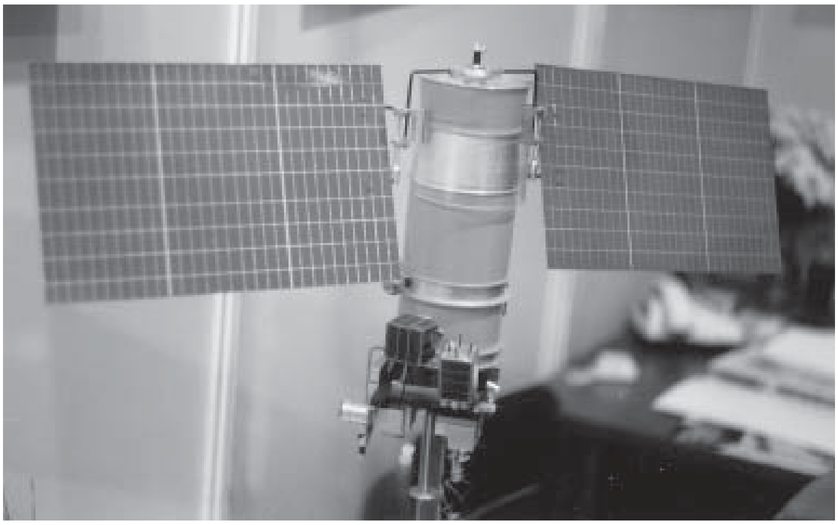

Fig. 17 Meteor-3M model on display at MAKS-2001. (source: Timothy Varfolomeyev)

- MTVZA: a microwave radiometer which for the first time combines the functions of an imager and sounder. It can make vertical temperature and moisture profiles of the atmosphere, measure the overall moisture content in the atmosphere, study the intensity of precipitation, determine wind speed and direction, ocean temperatures and monitor ice and snow fields. The first analogous US-built instrument (SSMIS) was launched on a DMSP satellite in October 2003. Mass is 107 kg.
- KGI-4S and MGSI-5EI: two instruments to measure conditions in the near-Earth space environment (charged particles, state of the magnetosphere and ionosphere). Mass is 16.5 and 7 kg respectively.
- SAGE III: Stratospheric Aerosol and Gas Experiment. This instrument was designed by NASA's Langley Research Centre and relies on flight-proven designs used in the SAM II, SAGE I and SAGE II instruments flown respectively on Nimbus-7 (launched 1978), the Applications Explorer Mission B (launched 1979) and the Earth Radiation Budget Satellite (launched 1984). SAGE III is a grating ultraviolet/visible spectrometer that studies the Earth's atmosphere by watching the Sun and the Moon as they rise or set from the satellite's vantage point. The instrument's main objectives are:
    - to provide longterm monitoring of tropospheric and stratospheric aerosol
    - to provide measurements of mid and high level clouds including thin clouds that are not detectable by nadir-viewing passive remote sensors.
    - to study the global distribution of water vapour, which as the predominant greenhouse gas plays a crucial role in regulating the global climate system
    - to monitor ozone levels in the lower stratosphere and upper troposphere, investigate the relationship between aerosol, cloud and chemical processes affecting ozone concentrations and to study the greenhouse characteristics of ozone

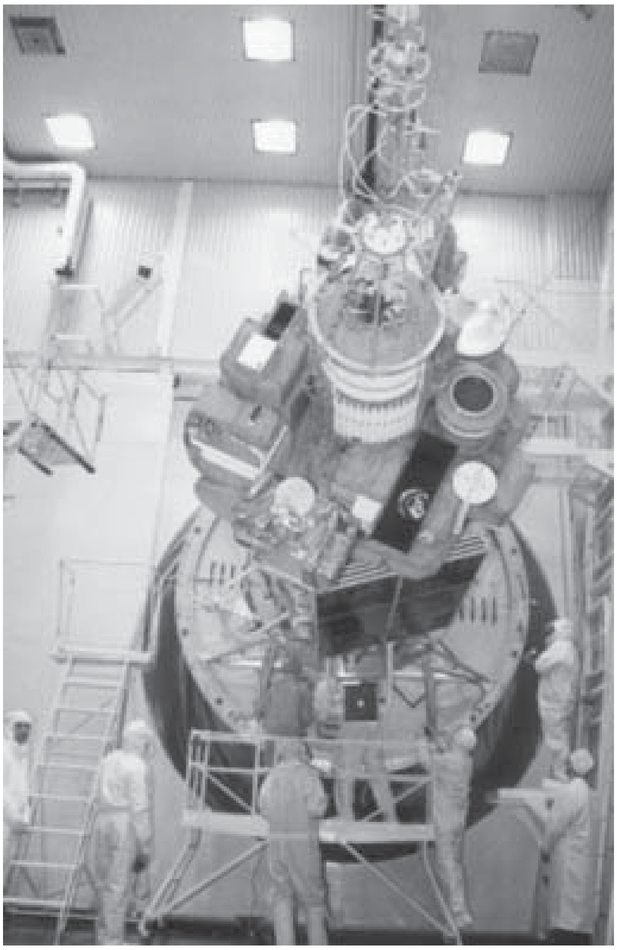

Fig. 18 Meteor-3M being prepared for launch at Baikonur. (source: Russian Space Agency)

    - to detect trends in stratospheric and mesospheric temperature that would be important diagnostics of climate change
    - to study the concentrations of nitrogen dioxide (NO2), nitrogen trioxide (NO3), and chlorine dioxide (OClO), which play crucial roles in stratospheric chemistry and the catalytic cycles that destroy stratospheric ozone

SAGE III is commanded and controlled by personnel at the SAGE III Mission Operations

Centre at Langley Research Centre. Data are downlinked twice daily to Wallops Flight Facility in Virginia and Obninsk in Russia. Two identical instruments are to be launched later, one of which will be installed aboard the International Space Station. Mass of SAGE-3 is 76 kg.

A secondary mission objective is to test a novel type of spherical retroreflector for precise laser ranging. The retroreflector is a 60 mm glass ball installed in a holder fixed to the Meteor-3M spacecraft. Additional data for most of these instruments are listed in Table 7 [100].

TABLE 7: *Meteor-3M Nr. 1 Instrument Suite*.

Instrument	Number of Spectral Bands	Band Wavelengths	Ground Swath km	Ground Resolution km
MR-2000M1 scanning telephotometer	1	0.5 - 0.8 μM	2900	1.5 km
Klimat scanning IR radiometer	1	10.2 – 12.5 μM	3100	1.7 km
SFM-2 ultraviolet spectrometer	4	0.2 – 0.51 μM	-	-
MSU-E high-resolution telephotometer	3	0.5 – 0.9 μM	76	38 x 38 m
MSU-SM medium-resolution telephotometer	2	0.5 – 1.1 μM	2240	225 m
MIVZA microwave radiometer	5	22 – 94 GHz	1700	25 – 110 km
MTVZA microwave radiometer	21	18.7 – 183 GHz	2600	12 – 75 km
SAGE-3 spectrometer	11	0.29 – 1.55 μM	-	-
KGI-4S	5	0.17 – 3.2 MeV (electrons) 5 – 40 MeV (protons)	-	-

14.2 The Mission

Throughout the 1990s promised launch dates for Meteor-3M went by without anything happening, a problem blamed at least by some on the fact that funding of the programme was taken over from Rosgidromet (and presumably the military) by the cash-strapped Russian Space Agency in 1992. In late 1993 plans called for the first Meteor-3M to be launched in 1996-1997, followed by the second satellite in 1997-1998. Both were scheduled to fly SCARAB radiometers. In addition to that, the first one was to carry a German-French-Russian-Suisse device called H-MAZER and NASA's SAGE-III instrument [101]. By 1994 the two launches had moved to 1998 and 2000 respectively, with both now supposed to carry a SAGE and the second one to fly a SCARAB plus a new TOMS spectrometer. In August 1999, by which time Meteor-3M N°2 had already slipped to 2001-2002, NASA decided to withdraw TOMS from the satellite and fly it on a dedicated satellite called QuikTOMS, built by Orbital Sciences [102]. Unfortunately, the satellite was lost when its Taurus launch vehicle failed to place it into orbit on 21 September 2001.

An expected September 1999 launch date for Meteor 3M N°1 slipped to mid-2000 after the Russian Space Agency ordered to install 130 kg of extra equipment on the satellite [103]. There were several further delays, some of them caused by the late delivery of the SAGE-III instrument. Eventually, Meteor-3M left the Earth on 10 December 2001, ending an amazing 7-year gap in launches of Russian meteorological satellites. During the second half of the 1990s Russian meteorologists mainly had to rely on weather data provided by foreign satellites. Two Meteor satellites (Meteor 2-21 and Meteor 3-5) *were* still operational by the turn of the century, but most of their instruments had broken down by that time. Valuable meteorological data were also provided beginning in 1998 by the weather camera on Resurs-O1 N°4.

Although the Zenit rocket had earlier launched two Resurs-O satellites into Sun-synchronous orbit, it was the first such launch profile for a Meteor satellite. Since the first stage and the payload fairing would fall back on the territory of Turkmenistan, a special memorandum had to be signed with that country's Ministry of Defence several days before the launch. A special mobile receiving station developed by the Yuzhnoye design bureau was flown over to Oman to monitor the satellite's separation from the rocket when the two passed over the country about 17 minutes after liftoff. Just two seconds after the separation of Meteor-3M four small piggyback satellites were deployed from a so-called AR-7018 separation platform fixed to the bottom of Meteor's pressurised compartment. Developed by NIIEM, this platform can carry 30-50 kg satellites

and separate them at a speed of 0.6-0.7 m/s. The satellites installed on the platform have no mechanical or electrical interfaces with the satellite or the rocket. The four piggyback satellites carried on the first Meteor-3M launch were Kompass (Russia), Badr-B (Pakistan), Maroc-Tubsat (Morocco) and Reflektor (US-Russia). The total mass of Meteor-3M, the separation platform and the four satellites was 3007.2 kg. Meteor-3M itself (minus the separation platform) weighed 2476 kg at launch [104].

After having waited so long for the launch of another weather satellite, Russian meteorologists were soon to be disappointed again when it turned out that the transmitting equipment for the meteorological payload failed to work properly. Several of the four transmitters soon began failing and the amount of data received was extremely limited and not up to international standards. The transmitter problems affected both the MR-2000M1 and the Klimat cameras. The MR-2000M1 camera was built many years ago at the NII Televideniya and was taken out of storage and slightly modified for Meteor-3M N°1, but it is not clear if this has anything to do with the problems it suffered. There have also been difficulties with the MTVZA and MIVZA instruments, which are limited in their capabilities due to technical problems with their scanning modes. There was a problem with the SAGE-III instrument early on in the mission, when its primary transmitter failed on 2 January 2002. However, this problem was solved by switching to a back-up transmitter and the instrument is now working fine [105]. On 11 December 2003 Russian media quoted Vasiliy Asmus, the director of NITs Planeta, as saying that the meteorological payload of Meteor-3M had failed completely. This once again leaves Russia without any independent weather monitoring capability from orbit.

14.3 Future Plans

For some time it was considered to build the next Meteor satellite on the basis of a new, lightweight platform (UMKP-800) (see section 16.3), but in the summer of 2002 a decision was made to return to the heavy platform used by Resurs-O1 N°4 and Meteor-3M N°1 with some slight modifications. Now identified as Resurs-UKP (UKP standing for "Universal Space Platform"), the bus has a mass of around 1500 kg and can carry a payload of about 1000 kg. The launch vehicle will no longer be the Zenit, but the Soyuz with a Fregat upper stage. Although cheaper, the Soyuz/Fregat has less lifting power, resulting in a lower Sun-synchronous orbit (between 650 and 830 km, depending on the actual payload carried).

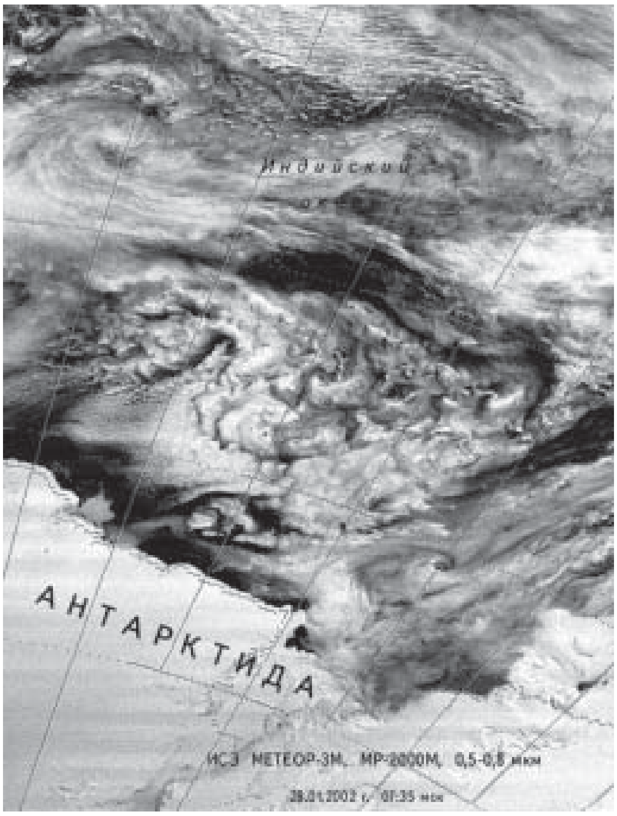

Fig. 19 Picture of Antarctica taken by the MR-2000M1 camera. (source: NITs Planeta)

The next Meteor-3M will not be a specialised weather satellite, but a universal remote sensing platform. At least as early as 1993 there was talk of a single, multipurpose remote-sensing satellite system to combine the functions of a variety of satellites such as Meteor and Resurs-O and the varied instrument suites flown by Resurs-O1 N°4 and Meteor-3M N°1 were the first steps in that direction [106].

Clearly, Meteor-3M N°1 is handicapped by its relatively out-of-date and rather unreliable remote sensing instruments. An effort has been made to upgrade the instruments for the next satellites and bring their performance closer to international standards. The following payload has been announced for Meteor-3M N°2:

- MSU-MR (also called Globus): a cross-track scanning visible/infrared radiometer operating in six channels between 0.5 and 12.6 µm and with a resolution close to 1 km. Its characteristics will be similar to the AVHRR/3 instrument flown aboard the latest US NOAA satellites.
- KMSS: a supplementary optical scanning unit providing imagery in four visible channels (0.45-0.9 µm) with a resolution of about 100 m.
- MTVZA: a microwave sounder/imager similar to the one aboard Meteor-3M N°1. It will operate in 26 channels between 18.7 and 183.3 GHz. Also being considered is an advanced version called MTVZA-OK, which would extend its observations to the visible and infrared parts of the spectrum.

- IRFS-2: an advanced infrared sounder based on a Fourier spectrometer operating in five spectral bands between about 5.0 to 15 µm and designed to study temperature and moisture profiles, cloud properties and ozone levels. This is a modified version of the IRFS that was supposed to fly aboard the originally planned Meteor-3M N°2 and which has been under development at the Keldysh Research Centre for 8 years.
- Severyanin: a side-looking synthetic aperture radar designed to obtain information on the ice situation and the status of the sea surface. Its frequency range is 9500-9700 MHz, the swath band is about 450 km with two modes of spatial resolution, low (0.7 x 1.0 km) and medium (0.4 x 0.5 km). This radar was originally expected to fly on a follow-on Resurs-O satellite known as Resurs-Arktika and later Resurs-RL.
- Radiomet: a supplementary sounding instrument using radio occultation principles
- GGAK-M: a complex of heliogeophysical instruments.

Under Russia's federal space programme for the 2001-2005 timeframe, VNIIEM was tasked to field a universal remote sensing satellite in 2003 [107]. The latest plans are for Meteor-3M N°2 and 3 to be launched in 2005 and 2007, but it remains to be seen if those dates will be met [108]. At any rate, it looks like the venerable Meteor/Resurs platform has been given a new lease of life. Recently, the same platform was even selected for a satellite called Koronas-Foton to study solar-terrestrial relations [109].

15. Going Geostationary: GOMS/Elektro

15.1 Origins

Planning for geostationary weather satellites got underway in the US, Europe and Japan in the early 1970s. On 19-20 September 1972 representatives of the United States, Europe, Japan as well as observers from the World Meteorological Organisation and the Joint Planning Staff for the Global Atmospheric Research Programme met in Washington to set up a committee for the Coordination of Geostationary Meteorological Satellites (CGMS), which was to harmonise the operation of geostationary weather satellites.

Coincidentially or not, it was only three months later, on 16 December 1972, that the Military Industrial Commission issued a decree on the development of a "3rd generation hydrometeorological support system" consisting of Meteor-3 and a series of geostationary weather satellites called Elektro (index 11F652) [110]. The Soviet Union wasted no time in joining the international effort. It became a member of the CGMS during the committee's second meeting, held in Zurich between 18 and 24 January 1973, and announced its intention to orbit its own geostationary weather satellite and place it over the Indian Ocean at 76°E [111]. The Russians later committed to doing this before the end of 1978, by which time the first Global Experiment under the Global Atmospheric Research Programme (GARP) was to get underway. Remarkably, when these initial talks began, the Soviet Union had not yet launched a single geostationary satellite, not even for communications. The first Soviet geostationary satellite (a mass model of a communications satellite) was not placed into orbit until March 1974.

Fig. 20 Yuriy Trifonov, chief designer of Elektro. (source: Russkiy Kupets)

America launched the world's first dedicated geostationary weather satellite (SMS-A) in May 1974 and Japan and Europe followed suit with Himawari-1 and Meteosat-1 in July and November 1977. The Soviet Union, however, did not deliver. Citing technical difficulties, the Soviets withdrew their pledge to join the international satellite network before GARP started.

Yuriy Trifonov, who was the chief designer of Elektro, says the December 1972 VPK decree did not provide the authority to begin design work on the satellites and that work in the ensuing years remained limited to discussing the technical characteristics that the satellite should have. It was not until the appearance of a government decree sometime in 1977-1978 that VNIIEM was actually authorised to start the design of Elektro, with an initial draft plan being finished in 1979. Subsequently, a VPK decree in 1980 assigned the subcontractors that were to become involved in the project and set a timeline for

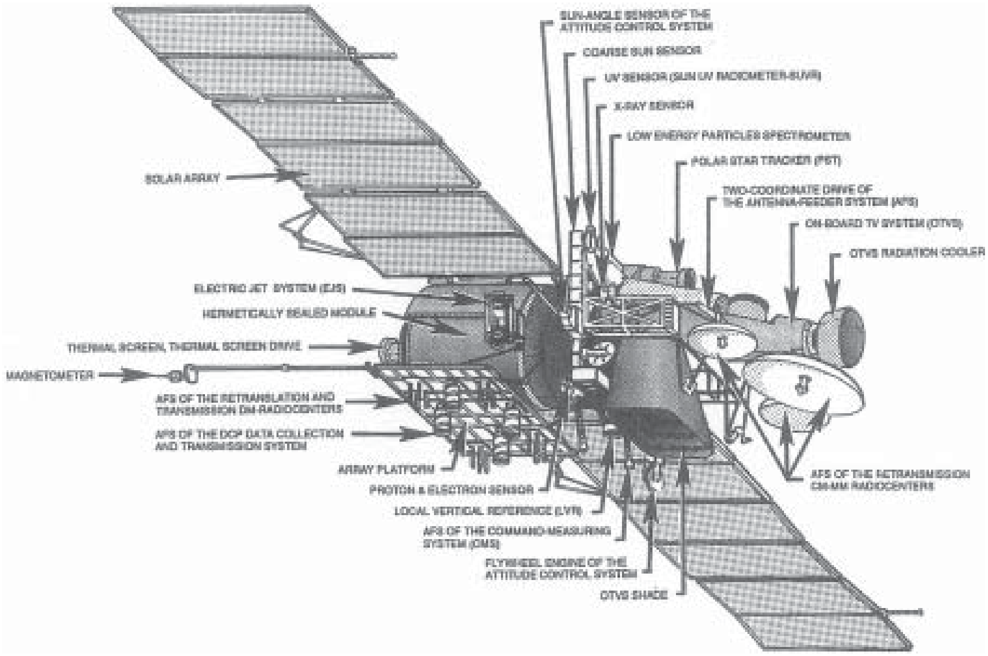

Fig. 21 Main systems of Elektro. **(source: Teledyne Brown Engineering)**

the development of the satellites. As mentioned earlier, the Elektro and Meteor-3 programmes were unified as the “Planeta” programme in 1981, implying that both would use the same ground infrastructure and data processing techniques. The geostationary tier of this system also became known as Planeta-S [112].

Indications are that the initial driving force behind Elektro in the early 1970s was the need to fill the Indian Ocean gap in the international network of geostationary weather satellites, but this was probably not convincing enough to the Soviet government to give the final go-ahead for the project. After all, geostationary weather satellites cannot cover the Soviet Union’s northernmost regions, where many of the nation’s weather patterns are shaped. The idea must have been even less attractive to the military, who had an important say in the approval and financing of *any* space project in the Soviet Union. Ultimately, the military did find some use for these satellites and this presumably was the decisive factor in the approval of the programme in 1977/78. As the official history of the Military Space Forces puts it, Elektro was designed “to increase the efficiency of the hydrometeorological support of the armed forces of the USSR and the national economy” [113].

Eventually, the Soviet Union filed three locations for geostationary weather satellites with the International Telecommunications Union (ITU), which regulates the transmission and receiver frequencies in the geostationary belt. These positions were 76°E (over the Indian Ocean), 166°E (over the Pacific Ocean) and 14.5°W (over the Atlantic Ocean). The satellites were registered with the ITU as the Geostationary Operational Meteorological Satellites or GOMS, the name that was commonly used in the West to refer to these satellites. Only the Indian Ocean satellite was to be included in the international satellite network, with the two other satellites solely being used for national needs.

At first sight it is hard to see what military use GOMS could have had. After all, the military are usually only interested in low-orbiting weather satellites (like Meteor and DMSP), which can provide detailed weather images of strategically important regions. At least one objective the military were eying was for the trio of Elektro satellites to operate entirely autonomously for one month in case of a nuclear conflict and send back images of the Earth to give a large-scale idea of the resulting devastation, assuming anyone was still around to see them. Somehow, the military reasoned that the control infrastructure for the satellites would be destroyed, but that there would still be a capability to receive and process information from the satellites. All this made it necessary to install various computers aboard the satellites and build in as many as two back-ups for critical systems, all of which contributed to the numerous delays that the project suffered. The man behind this idea reportedly was Dmitriy Ustinov, who was the Soviet Defence Minister from 1976 until his death in late 1984 and before that had been the *de facto* head of the Soviet space programme in his capacity as Secretary of the Central Committee of the Communist Party for Defence Industries and Space [114]. In addition to this, the satellites were to have an elaborate communications payload, making it possible to communicate between themselves, with two of them relaying data to the central satellite in the system, which was then to forward it to the ground. It is also possible that the communications payload was to be used to relay military data.

While the military helped to approve the project in the late 1970s, they nearly caused its demise in the 1980s. As the Soviet Union's geopolitical doctrine changed with the arrival of Mikhail Gorbachov in the mid-1980s, the military lost interest in having their own global weather system and cancelled their order for it. As a result, financing for Elektro came to a virtual standstill in 1989-1991. Only the establishment of the Russian Space Agency in 1992 led to its resurrection, although by this time it was planned to use only one of the three slots reserved in the geostationary belt [115].

15.2 Design

Elektro was entirely designed and built at VNIIEM's central design bureau in Moscow. In its final design GOMS was a 2580 kg spacecraft measuring 6.35 x 2.10 x 4.10 m. It was divided into two major sections, with the communications payload in the lower section and the weather imaging equipment in the upper section.

Elektro had two 7.35m long solar panels with a total surface of 30 m², both equipped with an autonomous electromechanical attitude control system. The panels had a daily average capacity of about 1,200 W, up to 700 W of which could be supplied to the payload. Elektro had a three-axis stabilisation system using Sun sensors, a polar star tracker and an infrared Earth (or local vertical reference) sensor. It became only the second geosynchronous weather satellite to be oriented and stabilised along three axes, following in the footsteps of America's second-generation GOES satellites, the first of which (GOES-8) was launched in April 1994. The attitude control actuators were three flywheels and a set of electrothermal ammonia thrusters, similar to the ones used on Meteor-3. The thrusters were not only used for attitude control, but also for stabilising the satellite after separation from the launch vehicle, moving it from its insertion point (at 90°E) to its final parking spot (at 76°E), for stationkeeping and for regularly dumping the momentum built up by the flywheels. There were 16 thrusters in all, two pairs along the X axis for attitude control and six pairs along all three spacecraft axes for momentum dumping. The total thrust of the system was 130 kN and the total mass 130 kg (78 kg dry, 52 kg of propellant). The thrusters were one of the few components of Elektro developed at the Istra branch.

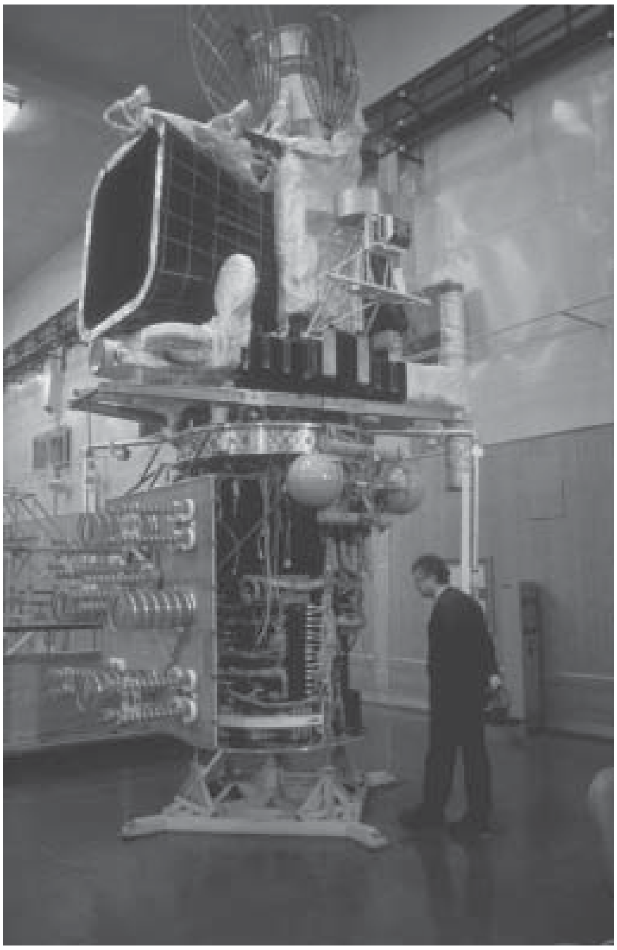

Fig. 22 Elektro during assembly. (source: Eumetsat).

The two computers carried by GOMS (known as On-Board Control Systems or BUS) had their own specific tasks. BUS-1 was responsible for controlling the satellite's housekeeping systems and BUS-2 was in charge of attitude control. GOMS was only the fourth Russian geostationary satellite to use computers (following the Altair and Geyzer data relay satellites and the Oko-1 early warning satellites). According to information released at the time of the launch the computers would enable GOMS to operate without any interference from the ground for 18 days. After each 18-day observation period there would be a 3-day break for ground controllers to load an identical or adapted 18-day programme into the computer, including commands for possible orbit corrections.

The actual payload comprised about 650 kg of the overall mass and consisted of three main parts:

- the On-Board Television Complex (Russian abbreviation BTVK): situated in the upper part of the satellite and consisting of a visible wavelength scanning telephotometer and a scanning infrared radiometer using one spectral band each (data in Table 8). The scanning TV systems used a new electromechanical precision drive with a laser interferometer. Mounted on top of the complex

TABLE 8: *Elektro nr. 1 On-Board Television Complex.*

Instrument	Number of Spectral Bands	Band Wavelengths	Ground Resolution	Scan Lines Per Frame
Scanning telephotometer	1	0.4 - 0.7 µM	1.25 km	8000
Scanning IR radiometer	1	10.5 – 12.5 µM	6.5 km	1400

was a passive radiation cooler for the infrared camera. The complex weighed about 395 kg and was built by the NII Televideniya in St. Petersburg. The official objectives of the camera complex were:

- to acquire real-time television images of the Earth's cloud cover, surface, snow and ice fields within a radius of 60° centred at the sub-satellite point (meaning that in actual fact only a small part of the Soviet Union could be covered)
- to measure the temperature of the ocean surface and cloud tops
- to detect dangerous natural phenomena
- to determine wind speed and direction at various levels

- the Radiation Magnetometric System (RMS): a set of instruments installed in the upper portion of the satellite to study radiation of galactic and solar origin, solar ultraviolet and X-ray radiation and changes in the Earth's magnetic field at geostationary altitude. The data was transmitted 24 times per day (with one-hour intervals) to the Institute of Applied Geophysics. Total mass was 55 kg. The system provided information about:
  - the density of electron fluxes with energies in four bands from 0.04 MeV to 1.7 MeV
  - the density of proton fluxes with energies in four bands from 0.5 MeV to 90.0 MeV
  - the density of alpha particles fluxes with energies from 5 MeV to 12.0 MeV
  - the intensity of galactic cosmic radiation with energies greater than 600 MeV
  - solar X-ray radiation intensity with energies between 3-8 KeV
  - the intensity of solar ultraviolet radiation between 0.3 and 121.6 nm
- the communications payload, consisting of the On-Board Transmitting Radiotechnical Complex (BPRK) and the On-Board Relay Radiotechnical Complex (BRRK). The BPRK was used to transmit the BTVK images, data from the RMS and telemetry to the ground. The BRRK (also known as "Oreol") performed the same task, but was mainly employed to retransmit processed BTVK pictures to users and also to collect and transmit data from Russian and international data-collection platforms on the oceans (both buoys and ships) and in ice-covered areas (only buoys). There were several antennas on the satellite's lower array platform and also three parabolic antennas on top of the satellite.

Pictures provided by the BTVK and data from the Radiation Magnetometric System and from the ground-based data collection platforms were first sent to three receiving and processing centres, the central one in Dolgoprudnyy near Moscow and two regional ones in Khabarovsk and Novosibirsk (the same ones used for Meteor). Originally, GOMS was also to have used a centre in Tashkent, the capital of Uzbekistan, but these plans had to be scrapped when Uzbekistan became independent after the collapse of the USSR. The need to replace this station (apparently by the one in Novosibirsk) contributed to the numerous launch delays. The task of the three centres was to process the raw data downlinked by GOMS and retransmit it back in WEFAX (weather facsimile) mode to the satellite, which in turn relayed the images to so-called autonomous reception stations which had line-of-sight view with the satellite. The communications payload on GOMS also ensured high-speed exchange of data between the three centres. Actual command and control of the satellite itself was in the hands of the Rokot mission control centre at the Institute of Space Research before being transferred to Golitsyno-2 in late 1995. The satellite was also monitored by four ground stations: OKIK-4 (Yeniseysk), OKIK-9 (Krasnoye Selo near St. Petersburg), OKIK-13 (Ulan-Ude) and OKIK-20 (Solnechnyy near Komsomolsk-na-Amure) [116].

15.3 The Mission

By 1989 only an engineering model of the satellite had been built at VNIIEM [117]. A number of launch postponements were caused by a series of software glitches and also by vibration problems resulting from the movement of the scanning mirror in one of GOMS' radiometers [118]. The operational model was completed in the summer of 1991 and was subsequently sent to Baikonur by truck and rail to test its ability to withstand the rigours of transportation before launch. It was later shipped back to Moscow for final testing before being returned to the cosmodrome [119]. It seems to have remained in storage at the launch site for several months, awaiting a launch slot on a Proton rocket. The originally planned launch date of 26 October 1994 slipped five days due to delays in the delivery of fuel for Elektro's Proton rocket. According to some reports this was because the fuel suppliers had not received the required advance payment for the fuel, while others suggested that new restrictions imposed on the storage of rocket fuel meant that no new fresh fuel was available in time for the launch.

Elektro finally took to the skies on 31 October 1994 at 14.30.56 GMT, sixteen years later than originally planned. The Proton rocket and its Blok DM-2M upper stage flew a standard geosynchronous launch profile. At the beginning of the second orbit the DM-2M fired a first time to put the stack into a geosynchronous transfer orbit and 6.5 hours after launch as the assembly reached apogee the upper stage was restarted to circularise the orbit. As soon as the Blok-DM-2M was cast off, the satellite slowly began drifting to its final location at 76°E.

However, the problems that had plagued the satellite before launch kept dogging it in orbit. Elektro's local vertical reference sensor, crucial for the satellite's orientation in space, turned out to be inoperable, although identical sensors had flown on VNIIEM's Meteor and Resurs-O spacecraft without having failed a single time. Analysis showed that the drive mechanism of the sensor's scanning mirror had malfunctioned. While the coarse Sun sensor could be used to turn Elektro's solar panels towards the Sun, it was not possible to stabilise the satellite using the sun-angle sensor and the polar star tracker, meaning it kept spinning around its Z-axis. Elektro's improper attitude was also causing an additional problem. The satellite's electrothermal thrusters were regularly fired to dump the momentum built up by the satellite's flywheels, but because of the incorrect orientation this had the effect of accelerating Elektro's drift to the west. Originally supposed to reach its final location on 20 November, the spacecraft overshot its geostationary parking spot on 10 November and kept drifting further westwards.

Fortunately, engineers on the ground came up with a plan to stabilise Elektro by monitoring the intensity of radio signals transmitted by its array platform. Whenever the signals reached their maximum strength, they knew that the platform and hence the –Z axis of the satellite was pointing towards the Earth and this enabled them to take partial control of

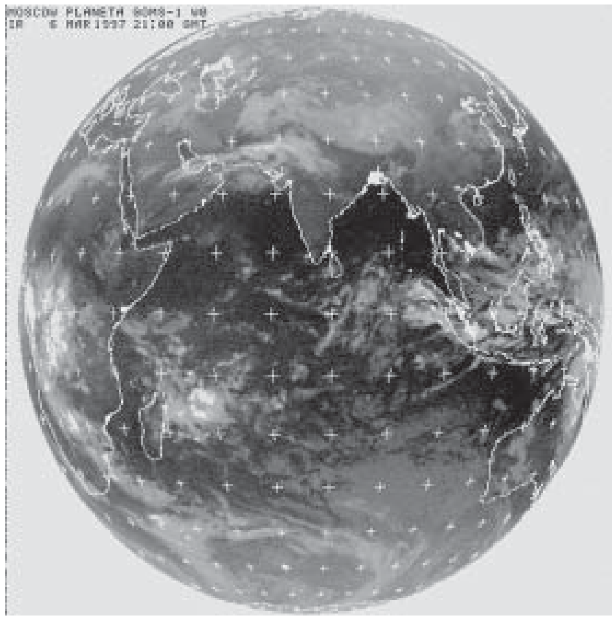

Fig. 23 Picture taken by Elektro. (source: NITs Planeta)

the satellite's orientation. The electric thrusters were now used to reverse Elektro's westward drift, which had taken the satellite 3° beyond its intended parking spot by 13 November. Although Elektro was now being stabilised along two axes, this did mean that one side of the satellite now continuously faced the Sun. While temperatures inside the hermetically sealed module remained within acceptable limits thanks to its thermal protection screen, the radiation cooler mounted on top of the satellite's TV system could not cope with the excess heat. Therefore, engineers were forced to periodically turn the satellite 180° around to prevent its camera equipment from overheating [120].

After a nearly three-week drift back eastward Elektro was finally stationed at 75°46'32" on 6 December. By early February 1995 ground controllers were successful in their attempts to achieve three-axis stabilisation by using the directivity pattern of the array platform and images from the on-board television complex to incorporate the polar star tracker into the orientation system. Nevertheless, orientation continued to be a headache. The central processor of the BUS-2 attitude control system computer malfunctioned once every two to three months on the average, causing the satellite to lose its proper orientation. Each time this happened, the Sun sensor had to place the satellite in a safe solar orientation mode to make sure that the deviation did not become any larger and that the radiation cooler did not become permanently exposed to the Sun. Then, after the necessary mathematical modelling, ground controllers would use either the flywheels or the electric thrusters to guide the polar star tracker back to Polaris. Initially, this whole procedure took one to two days, but as controllers gained more experience, they were able to restore the satellite's orientation in a matter of hours [121].

All in all, Elektro's mission appears to have been a mixed success at best. Orientation problems aside, the visible wavelength scanning telephotometer never worked properly, depriving meteorologists of the much-wanted high-resolution images of the Indian Ocean region. Although the Indian Insat communications satellites have meteorological payloads, their data is not made widely available to the World Meteorological Organisation, which was therefore heavily banking on Elektro to fill this major gap in worldwide weather coverage [122]. Elektro did provide some 20,000 lower resolution infrared images of the region, although reception of those seems to have been intermittent [123]. Several months into the flight tests began of the centimetre band communications system needed to relay data from Russian and international data collection platforms. However, because of the lack of such platforms and the fact that many of the local reception stations were not ready, those tests seem to have remained limited [124]. The geophysical payload appears to have provided useful data about the terrestrial magnetosphere and radiation conditions at geosynchronous altitude.

Having a design lifetime of at least three years, Elektro remained operational well into 1998, with the last infrared images apparently having been sent back on 13 August of that year [125]. By that time it had reportedly consumed just 75 % of the ammonia fuel needed for its electrothermal ammonia thrusters [126]. The satellite began drifting off station in late September 1998 [127]. Indian Ocean coverage for the World Meteorological Organisation was taken over by the European Meteosat-5 satellite, which was relocated to 63°E between January and May 1998 and began sending back data from that spot in July 1998. In the absence of a new Elektro satellite, the data from Meteosat-5 is still being used by Rosgidromet today.

15.4 Future Plans

At the time of Elektro's launch a second, improved satellite was being assembled at VNIIEM, which was to have been equipped with an additional infrared radiometer operating between 6-7 μM. There were also plans to expand its communications payload with two transponders, each having up to 650 communications channels with a data rate of 64 kbit/s when using VSAT ground stations with a 1.6 m antenna or up to 1,060 channels for ground stations with 2.4 m antennas. Given the lack of ground stations for data reception only a minor percentage of these channels was supposed to be used for meteorological purposes. The hope was to lease the bulk of them to paying customers. The only modification required to the satellite for this additional payload (known as "Boomerang") would be to increase its average power supply by 500-600 W, which could be achieved by the use of more efficient solar cells and additional drives allowing the solar panels to completely revolve.

Apparently, the idea was that the improved Elektro-2 would replace its predecessor at 76°E and that the other two GOMS slots at 14.5°E and 166°E would be occupied by two Elektro-based satellites that would *solely* be used for communications. In addition to that, two further standard Elektro satellites with upgraded three-band radiometers would be placed into 24-hour orbits inclined 60° to the equator. With the ascending nodes of their orbits over 76°E, they would collect weather data over a large part of the eastern hemisphere from 20°E to 140°E, providing much improved coverage of the northernmost regions of Russia compared to the geostationary satellites [128]. One additional payload for Elektro studied at the Institute of Space Research in 1999-2001 was a small telescope called GROT (Geostationary Radiation Cooled Telescope) for astrophysical observations in the optical and infrared wavebands and also to observe space debris in the geostationary belt and to spot potentially dangerous asteroids and comets [129]. During the 1990s VNIIEM also studied smaller versions of Elektro based on light spacecraft buses, but these plans never went beyond the drawing boards (see section 16).

At the time of the Elektro launch there was talk of orbiting its successor in 1997, but those plans never materialised. A follow-up Elektro was still included in Russia's federal space programme for 2001-2005, with a launch expected in 2002 [130]. According to information released in late 2002 the satellite was to be launched in 2005 and occupy the same spot as its predecessor at 76°E. The satellite's main instrument would be the MSU-G imaging radiometer to provide images in three visible and near-infrared channels and seven infrared channels between about 0.5 and 12.5 μm. Resolution at the subsatellite point was to be 1 km for the visible and near-infrared channels and 4 km for the infrared channels. The radiometer's capabilities should have been comparable to those of the SEVIRI radiometer carried by the European MSG (Meteosat Second Generation) satellites. The satellite's other major objectives were to gather heliogeophysical information and collect and transmit information from some 800 data collection platforms. Elektro-2 was also supposed to have a transponder for the COSPAS/SARSAT rescue system. It should have had the necessary modifications to remain operational for 10 years, more than double the lifetime of its predecessor [131].

Even though Elektro-2 was in an advanced stage of construction at VNIIEM, responsibility for the development of Russia's geostationary weather satellites has recently been transferred to the NPO Lavochkin design bureau, ending VNIIEM's 40-year monopoly in the building of weather satellites. Called Elektro-L, the satellite weighs 1230 kg and is expected to be launched by the Soyuz-Fregat booster, the Fregat being an upper stage developed by Lavochkin. The Lavochkin bureau has earlier developed two other types of geostationary satellites (the Oko-1 early warning satellites and the Kupon communications satellite, both types launched by Proton), but there are no immediate indications that Elektro-L shares any systems with the buses used for those satellites. The solar panels will be able to furnish 1.7 kW and 0.8 kW of this is intended for the payload. The 362 kg payload is to consist of the MSU-GS visible/infrared radiometer (with characteristics very similar to that of the MSU-G for Elektro-2) and the GGAK-E heliogeophysical complex, apparently a modification of the GGAK-M planned for the next Meteor-3M. The latest announced launch date is 2006 [132].

16. Small Satellites

16.1 METON/GOMS-M

Faced with ever tighter budgets, VNIIEM began working out plans around the mid-1990s for a series of small environmental monitoring and weather satellites that would eventually replace the Meteor, GOMS, Resurs-O and Okean satellites. Using a standard unpressurised spacecraft bus, they were to be equipped with modern electronics and computers and rely on relatively inexpensive ICBM-based launch vehicles to be placed into circular polar orbits. Initial plans called for the development of two buses, known as UMKP-1 and UMKP-2 (UMKP standing for "Unified Small Space Platform"). The three-axis stabilised satellites derived from these buses were called UniSat. The UMKP-1 based satellites (weighing between 160 and 240 kg) were to be launched by the four-stage Start-1 booster and the UMKP-2 derived satellites (weighing between 365 and 470 kg) by the more capable five-stage Start rocket. They would be placed into orbits with an inclination less than 98° and between altitudes of 500 and 900 km. It was also considered to use the Kosmos-3M and Rokot launch vehicles to simultaneously orbit two or four UniSats [133].

Somewhat later plans were announced for a so-called Space Environmental Monitoring System (KOMOS), consisting of four types of satellites in Sun-synchronous orbits (METON, ECON, DETON, ARLON) and one in geosynchronous orbit (GOMS-M). METON and GOMS-M would be the meteorological components of this system.

METON was described as a 238 kg satellite to be placed into a 650 km Sun-synchronous orbit by the Start-1 booster, indicating it was to use the earlier announced UMKP-1 bus. Its 91 kg payload would consist of a microwave sounder and visible/infrared radiometer. The microwave sounder was designed to perform vertical sounding of the atmosphere's temperature and humidity and was to study precipitation intensity and determine the boundaries and parameters of snow and ice layers. It was to have 26 channels with a resolution of between 6 and 37 km and covered a swath of 1800 km. The visible/infrared radiometer would provide images in two spectral bands (0.55-0.75 μm – 10.5-12.5 μm) with a ground resolution of between 0.6-1.2 km and it covered a swath of 800 km.

GOMS-M was described as a 550 kg satellite supposed to be launched by a variation of the Soyuz booster with a Fregat upper stage. Being the only geostationary element of the KOMOS constellation, it apparently had a unique configuration. It would essentially perform the same role as the "big" GOMS/Elektro. It was supposed to have a 209 kg payload, consisting of a MSU-GS visible/infrared radiometer (with a total of 13 bands between 0.55 and 12.5 μm) and a radiation magnetometric system (RMS-M). It was considered to place GOMS-M into a 24 hour orbit with a 65° inclination, giving good coverage not only for the tropical and subtropical regions but also for mid and high latitudes [134].

16.2 Moskva-Meteor

In mid-1999 plans were announced for a network of small satellites to monitor the weather and the environment in the Moscow region. Known as Moskva-M, it would feature seven weather satellites (Moskva-Meteor) and two environmental monitoring satellites (Moskva-Eko). The proposal to deploy this system came after the federal meteorological service Rosgidromet failed to forecast a major storm that hit Moscow in June 1998, killing at least four people and causing millions of dollars in damages.

The satellite buses were to be developed jointly by VNIIEM and NIIEM, while the instruments would be provided by RNIIKP. Although the satellites would weigh about 100 kg less than the satellites in the KOMOS series (just 135 kg), it is safe to assume they shared many design features. They could be launched into space as piggyback payloads or separately on converted ICBMs. The Moskva-Meteo satellites were supposed to fly in Sun-synchronous orbits at 700 to 800 km altitude and were to provide data to a ground control centre every hour and a half. Up till then the Moscow Meteorological Bureau, set up by Moscow mayor Yuriy Luzhkov in the wake of the June 1998 storm, received updates only once every four hours.

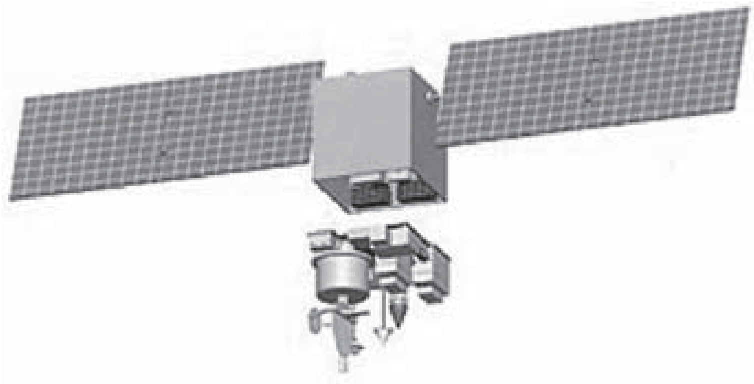

Fig. 24 Meteor-M. (source: VNIIEM)

After full deployment the system was to be able to forecast such storms with a 0.9 probability about two hours before hitting the city. It would also provide much better forecasts of heavy snowfall, making it easier to decide whether it was necessary to send hundreds of snow-clearing trucks onto Moscow's streets. Several false alarms in the past had cost the city millions of rubles. The system would also make it possible to predict temperatures with a precision of 1 degree four hours in advance.

The complete system was expected to cost 110 million rubles ($4.45 million). There was also talk of a scaled-back network of just three meteorological satellites, which would cost 40 million rubles but would provide much less accurate forecasts. The success of the project hinged on the contributions of private investors. It received only lukewarm support from the Russian Space Agency, which insisted that the system be used not only for Moscow, but on a nationwide scale. This is apparently why negotiations were held with several other Russian regions to help shoulder the costs in return for meteorological and environmental data. The Moscow city government was expected to make a decision on the system in September 1999. Nothing has been heard of the proposals since, indicating that Moskva-M has died a silent death [135].

16.3 Meteor-M

The latest smallsat plans released by VNIIEM centre around a spacecraft bus known as UMKP-800. The bus has a mass of 430 kg and the payload attached to it can range in mass from 300 to 450 kg depending on the orbital altitude (either circular Sun-synchronous orbits between 650 and 850 km or geostationary orbits). Launch vehicles can be Strela, Rokot (with a Briz-KM upper stage), Kosmos-3M or heavier rockets.

The polar-orbiting weather satellite that VNIIEM has proposed on the basis of the UMKP-800 bus is called Meteor-M. With an overall mass of 800 kg, it can be launched by the Rokot booster into a circular 835 km orbit inclined 98.68° to the equator and would have a maximum lifetime of 7 years. The payload, weighing 320 kg, would contain several of the instruments now planned to fly on Meteor-3M N°2. VNIIEM also considered to build a geostationary weather satellite (Elektro-M) using the UMKP-800 platform. Other UMKP-800 derived satellites that have been studied are Meteor-O and Resurs-D for ecological and disaster monitoring and the radar-equipped Meteor-R for various remote sensing applications.

For a while it looked like Meteor-M would become the successor of the first Meteor-3M, but, as mentioned earlier, those plans were abandoned in the summer of 2002 in favour of a Meteor-3M using the heavy Resurs-UKP platform. According to Yuriy Trifonov, the payload capacity of the UMKP-800 platform is too small to carry a diverse complement of remote sensing instruments, although he still holds out hope that such satellites will be developed sometime in the future [136].

17. Conclusion

All indications are that Russia's weather satellite programme is not anywhere near recovering from the collapse it suffered in the 1990s. Nikolay Sheremetyevskiy, who headed VNIIEM from 1974 to 1991, summed up his bitter feelings in an interview about two years before the launch of the first Meteor-3M:

> "We are hopelessly behind America. They are capable of developing and launching a modern meteorological satellite once every three years and we once every ten years! And whereas we build a satellite weighing 3 tons, in the West they can build a satellite weighing just 300 kg for the same purpose. There is a revolution going on in microelectronics and we are watching from the sidelines. We are moving into the past much more

> swiftly than we were moving into the future. There is no money, no rockets, no equipment, no self-made electronics, nothing that a "space country" should have..." [137].

Unfortunately, Meteor-3M did not rectify the situation. It was launched with a modest and largely outdated meteorological payload that is now completely crippled, leaving Russian meteorologists to rely entirely on information from foreign satellites. V.N. Dyadyuchenko, the deputy chief of Rosgidromet, admitted in a recent interview that the ratio between data received from Russian and foreign weather satellites is about 1:100 and that the instruments installed aboard Russian weather satellites are still far from living up to international standards [138].

In February 2001 the poor shape of Russia's weather satellite programme even attracted political attention. Deputies of the Russian parliament expressed their concern about the deplorable state of the programme in a joint letter to Prime Minister M. Kasyanov, putting the blame not only on the country's economic crisis, but also on the fact that the Russian Space Agency had taken over prime responsibility (including financing) of the programme from Rosgidromet (and presumably the military) in the early 1990s. In their words the agency had monopolised the weather satellite effort and much of the data reception and processing infrastructure had been unnecessarily duplicated. The deputies called for returning financial responsibility for meteorological satellites to Rosgidromet and setting up an interdepartmental commission to better coordinate the work of the numerous ministries and organisations involved in remote sensing satellite programmes (meteorological, Earth resources and oceanographic satellites). They also voiced support for closer cooperation with foreign partners in developing on-board instruments and increasing the lifetime of weather satellites [139].

So far none of these recommendations have been implemented, but at least a glimmer of hope is provided by an April 2003 decree of the Russian government, which lists the launch of new Meteor and Elektro satellites as one of five priority goals to be accomplished by the Russian Space Agency in 2003-2005 [140]. Whether this promise will actually translate into increased funding is another matter.

18. Acknowledgements

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59. "FGUP NII 'Novator' With Experimental Plant", on-line at the Rosaviakosmos website at http://www.rosaviakosmos.ru/cp1251/org/nii-nov.html
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61. G.I. Golyshev (ed.), "*Kosmos i pogoda*", op. cit., p.72, 76; V. Glushko (ed.), "*Kosmonavtika Entsiklopediya*", op. cit., p.449; Yu. Koptev (ed.), "*50 let vperedi svoego veka*", op. cit., p.116; O. Gorshkov, "[Russian] Electric Rocket Engines Today" (in Russian), *Novosti Kosmonavtiki*, 7/1999, pp.56-58; A. Manushkin, "Plasma Engines for Space" (in Russian), *Krasnaya Zvezda*, 5 January 2002; A.I. Morozov *et. al.*, "Thirty Years in Space: First Tests of Stationary Plasma Thrusters on the Meteor Artificial Earth Satellite" (in Russian), paper presented at the 26th Academic Readings on Cosmonautics in Moscow in January-February 2002. Abstracts on-line at http://www.ihst.ru/~akm/section4(2002).htm
62. G.I. Golyshev (ed.), "*Kosmos i pogoda*", op. cit., p.74.
63. V. Favorskiy and V. Meshcheryakov, *"Voenno-kosmicheskiye sily, kniga 1",* op. cit., pp.233-234.
64. M. Tarasenko, "The National System of Realtime Remote Sensing of the Earth" (in Russian), *Novosti Kosmonavtiki,* 17-18/1998, pp.36-38. In Western launch tables the first-generation Meteor Priroda satellites were listed as Meteor 1-18, 1-25, 1-28 and 1-29. The last in the series, officially announced as Meteor Priroda, is sometimes listed as Meteor 1-31. Meteor 1-30 was a second-generation Meteor Priroda satellite.
65. Trifonov interview; O. Gorshkov, "[Russian] Electric Rocket Engines Today", op. cit.; I. Morozov *et. al.*, "Thirty Years in Space : First Tests of Stationary Plasma Thrusters on the Meteor Artificial Earth Satellite", op. cit. There has been some speculation that the satellite had the capability of detecting atmospheric nuclear blasts, which at the time were expected to be performed by South Africa. Trifonov can neither confirm nor deny that the satellite had military applications. He says the satellite remained operational for about half a year.
66. V. Favorskiy and V. Meshcheryakov, "*Voenno-kosmicheskiye sily, kniga 1"*, op. cit., pp.215-216; Trifonov interview.
67. Trifonov interview; "From the Omega Spacecraft to the Meteorological Systems", op. cit., p.5. Most sources give 1960 as the year that the Istra branch was established, but a commercial leaflet issued by NIIEM says that it was in December 1959. Some sources say the Istra branch was involved in Omega, but Trifonov denies this. According to him the establishment of the Istra branch was not related to space-related tasks and its involvement in the Meteor programme remained limited until the introduction of Meteor-2. Note that VNIIEM also had branches in many other Soviet cities (including Leningrad, Tomsk, Vladimir,Voronezh and Yerevan).
68. V. Favorskiy and V. Meshcheryakov, "*Voenno-kosmicheskiye sily, kniga 1",* op. cit., p.216; "From The Omega Spacecraft To The Meteorological Systems", op. cit., pp.5-6.
69. Meteor-2 payload data compiled from the following sources : P.A. Rumyantsev, "The Space System Meteor", op. cit., pp.20-25; V. Glushko (ed.), "*Kosmonavtika Entsiklopediya",* op. cit., p.244; S.N. Baybakov and A.I. Martynov, "*S orbity sputnika – v glaz taifuna"*, Moscow, Nauka, 1986, pp.109-110; G. Caprara, "*The Complete Encyclopedia of Space Satellites",* New York, Portland House, 1986, pp.28-29; A.I. Lazarev *et. al.*, "*Kosmos otkryvaet tayny zemli"*, St. Petersburg, Gidrometeoizdat, 1993, p.57; V. Favorskiy and V. Meshcheryakov, "*Voenno-kosmicheskiye sily, kniga 1"*, op. cit., p.216; various editions of N. Johnson's *The Soviet Year in Space* and *Europe and Asia in Space;* Trifonov interview.
70. V. Favorskiy and V. Meshcheryakov, "*Voenno-kosmicheskiye sily, kniga 1"*, op. cit., pp.216-217.
71. Ibid, p.216.
72. "From The Omega Spacecraft To The Meteorological Systems", op. cit., p.6.
73. V. Favorskiy and V. Meshcheryakov, "*Voenno-kosmicheskiye sily, kniga 2"*, op. cit., p.21; "From The Omega Spacecraft To The Meteorological Systems", op. cit., p.6.
74. S. Sergeyev, "Tsiklon", op. cit., p.38. Possibly, this was part of a wider ranging government resolution released on 21 July 1967, which also mentioned the use of the two-stage 11K69 ("Tsiklon-2") for launching naval reconnaissance satellites of the US type as well as some other unmanned and manned military programmes. See: A. Siddiqi, "*Challenge to Apollo"*, op. cit., p.949.
75. A. Siddiqi, "*Challenge to Apollo"*, op. cit., p.951; I. Afanasyev, "The Rocket Carrier Tsiklon-3" (in Russian), *Novosti Kosmonavtiki*, 2/2001, p.38.
76. B. Gubanov, "*Triumf i tragediya Energii, tom 2",* op. cit., p.39.
77. A. Kopik, "25th Anniversary of the First National Radio Amateur Satellites" (in Russian), *Novosti Kosmonavtiki,* 12/2003, pp.52-54. Also see: "Statistics of Launches of Meteor Satellites from the Plesetsk Cosmodrome" (in Russian), on-line at http://www.plesetzk.narod.ru/doc/statis/s_meteor.htm. The orbital parameters of the satellite differed significantly from those of Meteor-2. Although the orbital inclination was identical to that of later Meteor-2 satellites launched by the 11K68, Kosmos-1045 orbited at an altitude of about 1700 km, about 800 km higher than Meteor-2. Therefore, its mass was probably not representative of the operational Meteor-2 satellites. The Meteor-2 model carried a small solar panel to feed the batteries for the on-board radio amateur package, which remained operational for about 10 years.
78. I. Afanasyev, "The Rocket Carrier Tsiklon-3", op. cit.
79. V. Favorskiy and I. Meshcheryakov, "*Voenno-kosmicheskie sily, kniga 2"*, op. cit., p.21. Unlike the upper stage of the 8A92M/Vostok-2M, the Tsiklon-3 upper stage was restartable, making it possible to perform a two-stage ascent profile that was more accurate than Vostok's direct ascent profile. Yu. Trifonov says the switch to the Tsiklon-3 was necessary because production of the Blok-Ye upper stage of the 8A92M rocket had ceased.

79b. E. Babichev and V.Kureyev, "Sun-Synchronous

Nadezhda" (in Russian), *Novosti Kosmonavtiki*, 8/2000, p.26. The authors claim the idea was abandoned because such launches could have been misinterpreted by the US as Soviet missile attacks. They would have to be conducted in a northwesterly direction, with the satellites passing over US territory shortly after orbit insertion. Eventually, Plesetsk did not see its first Sun-synchronous launch until June 2000.
80. B. Konovalov, "Flight of Satellite Dedicated to its Creator" (in Russian), *Izvestiya*, 1 September 1993.
81. K. Lantratov, "Russian Low-Orbiting Meteorological Satellites" (in Russian), *Novosti Kosmonavtiki*, 21/1995, p.39.
82. Ibid.
83. V. Favorskiy and I. Meshcheryakov, "*Voenno-kosmicheskie sily, kniga 2*", op. cit., p.217.
84. V. Favorskiy and I. Meshcheryakov, "*Voenno-kosmicheskie sily, kniga 1*", op. cit., p.203, 217.
85. V. Favorskiy and I. Meshcheryakov, "*Voenno-kosmicheskie sily, kniga 2*", op. cit., p.188.
86. "Chief Designer of Weather Satellites Dies" (in Russian), *Novosti Kosmonavtiki*, 23/1993, p.30.
87. Yu. Koptev, "*50 let vperedi svoego veka*", op. cit., pp.116-117; Trifonov interview.
88. These instruments are known to have flown on the following satellites: BUFS-1 on a Meteor Priroda in 1983 and Meteor-3 (1) in 1985, BUFS-2 on Meteor-3 (2) in 1988 and Meteor-3 (5) in 1991, SFM-1 on a Meteor Priroda in 1983 and a single Meteor-3, SFM-2 on three Meteor-3 satellites.
89. "60th Anniversary of the Central Aerological Observatory" (in Russian), article on the website of the Central Aerological Observatory at http://cao-rhms.ru/history.html.
90. N. Johnson, "*Europe & Asia in Space 1993-1994*", op. cit., p.209.
91. V. Favorskiy and I. Meshcheryakov, "*Voenno-kosmicheskie sily, kniga 2*", op. cit., p.188.
92. S. Ivanov, "Meteor-3 Nr. 7 Launched" (in Russian), *Novosti Kosmonavtiki,* 2/1994, pp.33-34.
93. C. Covault, "Long Astronaut Flights on Mir Sought for US-Soviet Summit", *Aviation Week and Space Technology*, 1 July 1991, p.19.
94. "Meteor/TOMS Experiment Finished" (in Russian), *Novosti Kosmonavtiki,* 3/1995, pp.77-78.
95. "French Scarab Failure Spoils Russian Mission", *Space News,* 24-30 April 1995, p.2.
96. Moscow Central Television, 15 August 1991 As translated by *JPRS Report*, 20 September 1991, p.31.
97. K. Lantratov, "Russian Low-Orbiting Meteorological Satellites", op. cit.
98. A.I. Lazarev *et.al.*, "*Kosmos otkryvayet tainy zemli*", op. cit., pp.58-59.
99. I. Sarfonov, "Meteor-3 : Plans and Prospects" (in Russian), *Novosti Kosmonavtiki*, 19/1993, p.27.
100. Meteor-3M data compiled from: I. Lisov and I. Marinin, "Meteor-3M N°1" (in Russian), *Novosti Kosmonavtiki,* 2/2002, pp.36-38; M. Pobedinskaya, "Will the Weather Forecast Be More Accurate ?" (in Russian), *Novosti Kosmonavtiki*, 3/2002, p.27; website of TsUP/Moscow at http://www.mcc.rsa.ru/Meteor/meteor.htm; "Sputnik Server" at http://sputnik.infospace.ru/meteor-3m/engl/meteor.htm ; website of the Scientific Center for Earth Operative Monitoring at http://www.ntsomz.ru/animal/meteor.htm; Langley's SAGE III website at http://www-sage3.larc.nasa.gov/; NIIEM brochures.
101. I. Sarfonov, "Meteor-3: Plans and Prospects", op. cit., pp.26-27.
102. W. Ferster, "Russian Delay Leads to TOMS Deal for Orbital", *Space News*, 23 August 1999, p.3; S. Golovkov, "TOMS Withdrawn From Meteor" (in Russian), *Novosti Kosmonavtiki*, 10/1999, p.41.
103. S. Shamsutdinov, "About Russian Remote Sensing Satellites" (in Russian), *Novosti Kosmonavtiki*, 11/1999, p.43.
104. A. Nikulin, "Meteor in the Zenit" (in Russian), *Novosti Kosmonavtiki*, 2/2002, pp.27-35; I. Lisov and I. Marinin, "Meteor-3M N°1", op. cit., pp.36-37.
105. Short news item, *Novosti Kosmonavtiki*, 4/2002, p.40; "Status of Russian Polar Orbiting Meteorological Satellite System", working paper prepared for the 30th meeting of the Coordination Group for Meteorological Satellites, Bangalore, India, 11-14 November 2002, on-line at the Eumetsat website at http://www.eumetsat.de/; Under the All-Seeing Celestial Eye : Problems of Space Meteorology" (in Russian), interview with Rosgidromet deputy chief V.N. Dyadyuchenko, 23 June 2003, on-line at http://www.mecom.ru/roshydro/pub/rus/publ/public_40.htm; Trifonov interview.
106. V. Kiernan, "Russia Ready To Upgrade Mir for Remote-Sensing Work", *Space News*, 21-27 June 1993, p.17; I. Lazarev *et. al.*, "*Kosmos otkryvaet tayny zemli*", op. cit., pp.65-66, 97.
107. I. Marinin, "The Federal Space Programme of Russia for 2001-2005" (in Russian), *Novosti Kosmonavtiki*, 12/2000, p.2.
108. This section based on: "Future Polar Orbiting Meteorological Satellites Meteor-3M", "Meteor-3M N1 Capabilities and Russian Meteorological Satellites Development Perspectives", working papers prepared for the 30th meeting of the Coordination Group for Meteorological Satellites, Bangalore, India, 11-14 November 2002, on-line at the Eumetsat website at http://www.eumetsat.de/; the satellite section of the VNIIEM website at http://www.vniiem.ru/page/kosm.htm (satellite data only available on the Russian version of the website) ; Trifonov interview.
109. I. Lisov, "The Successes of Koronas-F and Prospects for Russian Scientific Space Projects" (in Russian), *Novosti Kosmonavtiki*, 6/2003, p.60. Earlier Koronas satellites used the AUOS bus of the Yuzhnoye design bureau.
110. V. Favorskiy and I. Meshcheryakov, *Voenno-kosmicheskie sily, kniga 1,* op. cit., p.217. This source claims the system was initially called "Energiya", but Trifonov denies this. He says the name Elektro was proposed by VNIIEM director N. Sheremetyveskiy and reflected VNIIEM's role in developing electrotechnical systems. "Elektro" was also the name of a series of expositions held regularly in the Soviet days to demonstrate products developed by the electrotechnical industry.
111. "History and Purpose of CGMS", on-line at http://www.wmo.ch/hinsman/cgmsp05.html.
112. Trifonov interview ; V. Favorskiy and I. Meshcheryakov, "*Voenno-kosmicheskie sily, kniga 2*", op. cit., p.188.
113. Ibid.
114. B. Konovalov, "Satellite Has Been Awaiting Launch for 9 Months" (in Russian), *Izvestiya*, 12 April 1994; Trifonov interview.
115. S. Stoma and Yu. Trifonov, "Geostationary Space System Electro (GOMS): Preconditions for Creation and Structure", *Space Bulletin*, 3/1995, p.3.
116. Satellite data collected from: O. Zhdanovich, "Launch of the Meteorological Satellite Elektro" (in Russian), *Novosti Kosmonavtiki,* 23/1994, pp.33-36; P.B. de Selding, "Elektro May Close Gap in Weather Prediction", *Space News,* 7-13 November 1994, p.4; N. Johnson, "*Europe and Asia in Space 1993-1994*", op. cit., pp.211-213; S. Stoma and Yu. Trifonov, "Geostationary Space System Electro (GOMS):

Preconditions for Creation and Structure", op. cit.; Yu. Trifonov, "S/c Electro Onboard Control Complex", *Space Bulletin,* 3/1995, pp.11-13; S. Garbuk and V. Gershenzon, "*Kosmicheskiye sistemy distantsionnogo zondirovaniya zemli"*, A and B Publishers, Moscow, 1997, pp.224-229; "Russian Geostationary Meteorological Satellite Elektro (GOMS)" (in Russian), Sputnik server at http://sputnik.infospace.ru/goms/rus_win/goms_1.htm.
117. V. Favorskiy and I. Meshcheryakov, "*Voenno-kosmicheskie sily, kniga 2",* op. cit., p.188.
118. "Russians Plan 1993 Launch of GOMS Weather/Telecom Satellite", *Aviation Week and Space Technology*, 1 June 1992, p.70.
119. "First Russian Geosynchronous Weather Satellite Set For Launch in 1992", *Aviation Week and Space Technology,* 16/23 December 1991, p.19.
120. K. Lantratov, "First Month of Elektro's Flight" (in Russian), *Novosti Kosmonavtiki*, 24/1994, pp.27-29.
121. K. Lantratov, "Elektro Continues its Work" (in Russian), *Novosti Kosmonavtiki,* 20/1995, pp.35-36; O. Miroshnik *et. al.*, "A Drama In Orbit With A Happy Ending", *Space Bulletin,* 3/1995, pp.7-10.
122. The other satellites operating as part of WMO's World Weather Watch system at the time of Elektro's launch were two US GOES satellites at 75°W and 135°W, a Japanese GMS at 140°E and a European Meteosat at 0°W.
123. "From the Omega Spacecraft to the Meteorological Systems", op. cit., p.8.
124. K. Lantratov, "Elektro continues its Work", op. cit.
125. Elektro picture archive on the Sputnik server at http://smisdata.iki.rssi.ru/goms-cgi/statgoms.pl?MonthMask=1998%2d08&lang=english.
126. "From the Omega Spacecraft to the Meteorological Systems", op. cit., p.8.
127. P. Clark, "Satellite Digest-316", *Spaceflight,* **41**, p.89, 1999.
128. Yu. Trifonov and A. Gorbunov, "Prospects For the Electro Space System Development", *Space Bulletin*, 3/1995, pp.14-15.
129. "Project GROT" (in Russian), on-line at the website of the Institute of Space Research at http://www.iki.rssi.ru/annual/2001/pr3.htm. The project is mentioned in the institute's annual reports for 1999, 2000 and 2001, but not in the 2002 report, indicating it is no longer being studied.
130. I. Marinin, "Federal Space Programme of Russia for 2001-2005" (in Russian), *Novosti Kosmonavtiki*, 12/2000, p.2; C. Lardier, "Le retour de la Russie", *Air et Cosmos*, 12 January 2001, p.36.
131. "Meteor-3M N1 Capabilities and Russian Meteorological Satellites Development Perspectives", op. cit.
132. Trifonov interview. Trifonov says the transfer to NPO Lavochkin took place some time in mid-2002; "Under the All-Seeing Celestial Eye: Problems of Space Meteorology", op. cit.; "Salon de Moscou MAKS 2003", *Air et Cosmos,* 29 August 2003, p.40.
133. Yu. Trifonov, "Small Spacecraft Unisat", *Russian Space Bulletin,* 3/1996, pp.2-4; G. Maksimov and L. Churkin, "Small Spacecraft Unisat: Configuration and Design Modifications", *Russian Space Bulletin*, 3/1996, pp.5-7.
134. "Small Spacecraft", *Russian Space Bulletin*, 4/1998, pp.16-18.
135. S. Saradzhyan, "Moscow Plans System To Track City's Weather", *Space News,* 14 June 1999, p.30; Yu. Zhuravin, "Moscow Wants To Know The Weather" (in Russian), *Novosti Kosmonavtiki,* 8/1999, p.27.
136. This section based on: "The Unified Multipurpose Space Platform UMKP-800 and Small Satellites Based On It" (in Russian), brochure distributed by VNIIEM at the MAKS 2001 aerospace show in Moscow; the satellite section of the VNIIEM website at http://www.vniiem.ru/page/kosm.htm (satellite data only available on the Russian version of the website); Trifonov interview.
137. V. Gubarev, "Academician Sheremetyevskiy: Funeral Speech for Russian Cosmonautics" (in Russian), *Tribuna*, 27 January 2000. On-line at http://www.nns.ru/interv/arch/2000/01/27/int925.html.
138. "Under the All-Seeing Celestial Eye: Problems of Space Meteorology", op. cit.
139. "Parliamentary Question to the [Prime Minister] of the Russian Federation M.M. Kasyanov on the State of the Russian Constellation of Meteorological Satellites" (in Russian), *Parlamentskaya Gazeta*, 3 March 2001.
140. Press release of the Russian government, 3 April 2003. On-line at http://www.government.ru/data/structdoc.html?he_id=102&do_id=893

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