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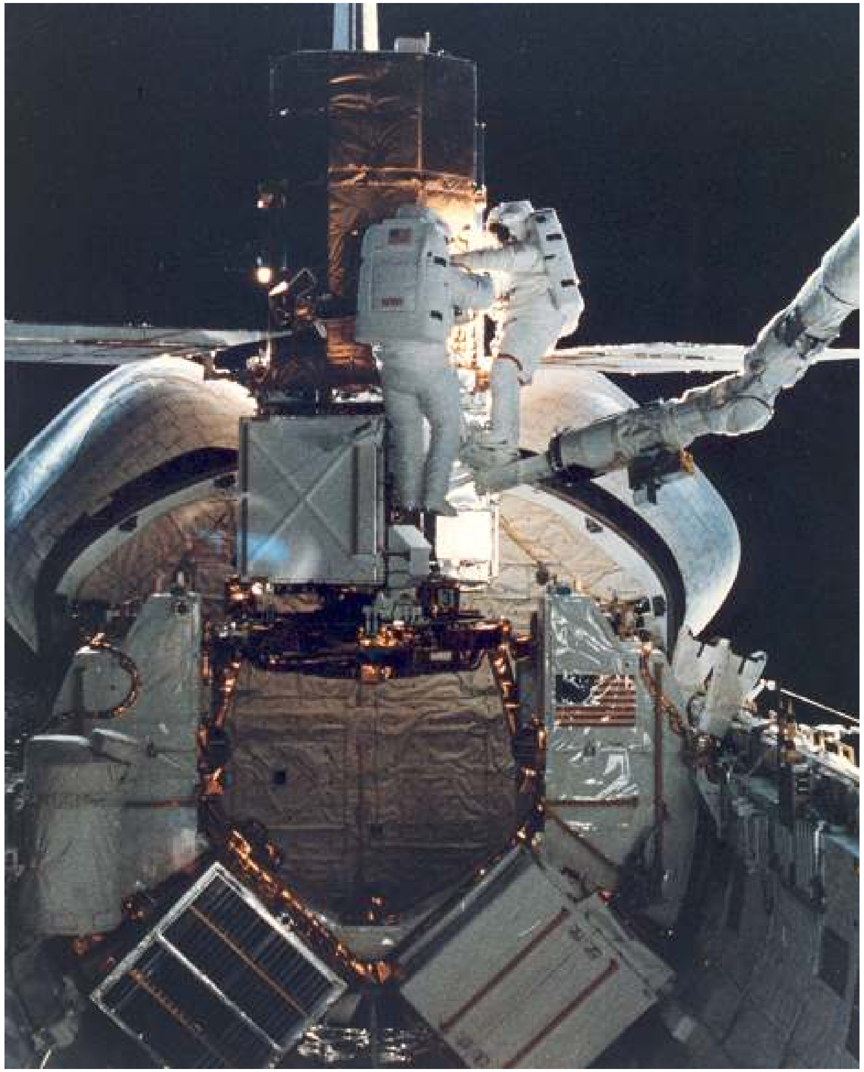

Mission Specialists George Nelson and James van Hoften repair the captured Solar Maximum Mission Satellite on 11 April 1984

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The *Tiros Space Information (TSI) - News Bulletin* is published to promote the scientific exploration and commercial application of space through the dissemination of current news and historical facts.
In doing so, Tiros Space Information continues the traditions of the Western Australian Branch of the Astronautical Society of Australia (1973-1975) and the Astronautical Society of Western Australia (ASWA) (1975-2006).
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Calling card...

Most of you readers know by know that when I am travelling the world, the News Bulletin looses its 'News' aspect and instead I publish some previously prepared articles. It is a means to give me some more quality time during my travels. And, indeed in this calendar year, Mrs. H and myself have travelled more than usual, so you get more large articles.

This time these are an article of mine that was earlier published in Sat Magazine of June 2014 and attracted some interesting comments from Intelsat.

The second article is something that I found on the internet and was written by Andrew J. LePage and that fits nicely in our treatment of cancelled projects.

Andrew is a physicist and freelance writer specializing in astronomy and the history of spaceflight. When not writing, he works as a Senior Project Scientist at Visidyne, Inc. located in the Boston, MA area where he specializes in the processing and analysis of remote sensing data. He can be reached via email at Drew@DrewExMachina.com or visit his website at www.DrewExMachina.com.

Jos Heyman

Servicing and refuelling spacecraft in orbit

By Jos Heyman

Introduction

Unlike our motor vehicles, which we take to the repair shops for maintenance and repairs or to petrol stations to refuel, spacecraft do not have that luxury. Instead they must be built to a standard that they do not break down during their anticipated operating life and must carry sufficient fuel for an operating life that sometimes lasts beyond 15 years.
It has been suggested that the availability of 'repair shops' and 'refuelling stations' for these orbital vehicles would extend their operating life and over the years there have been many proposals and physical attempts in this field..

In this article we will look at some historic examples of satellite in-orbit repairs, examples which are all of a different nature. We will also look at some proposals for future facilities like that.

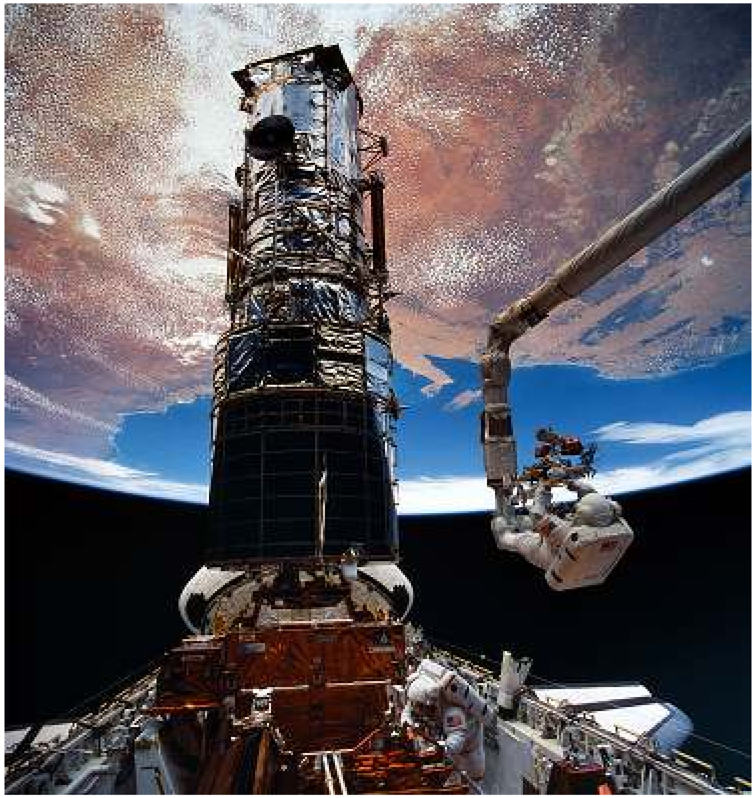
Historical perspective

In the past repair efforts have been made on several occasions. On 14 February 1980 the Solar Maximum Mission (SMM) had been launched with a Delta 3910 launch vehicle but in November of that year the satellite's attitude control system failed. The problem was subsequently repaired, in orbit, by the crew of the STS-41C mission in April 1984. On 10 April 1984 the satellite was captured by the Shuttle's RMS arm whilst on the next day
Nelson and Van Hoften made an EVA of 7 hours, 7 minutes during which they replaced the Modular Attitude Control System and the Coronograph main electronics box of the SMM satellite. On 12 April 1984 SMM was released again.

The STS-41B flight of 3 February 1984 placed two satellites, Westar-6 and Palapa-4, in orbit but both had a failure of the PAM-D upper stage, leaving them stranded in a low orbit.
Whilst nether of the satellites was repaired 'in-orbit', they were both retrieved by the STS-51A space shuttle flight and taken back to Earth for repair, following which they were relaunched as Asiasat-1 and Palapa-6 respectively.

A slightly different approach was taken with the Syncom IV-3 communications satellite that had been placed in orbit by STS-51D on 12 April 1985. The satellite could not be placed into a geostationary orbit and it was repaired on 31 August/1 September 1985 by the crew of STS-51I.

The best known repair mission was that of the Hubble Space Telescope that had been placed in orbit by STS-31 on 24 April 1990. Once the astronomical observatory was operational it was discovered that the main telescope mirror provided fuzzy images due to a spherical aberration of the primary mirror. It was then learnt that the mirrors had never been tested. As a consequence, the Wide Field Camera could not be used whilst the Faint Object Camera could only produce inferior pictures.

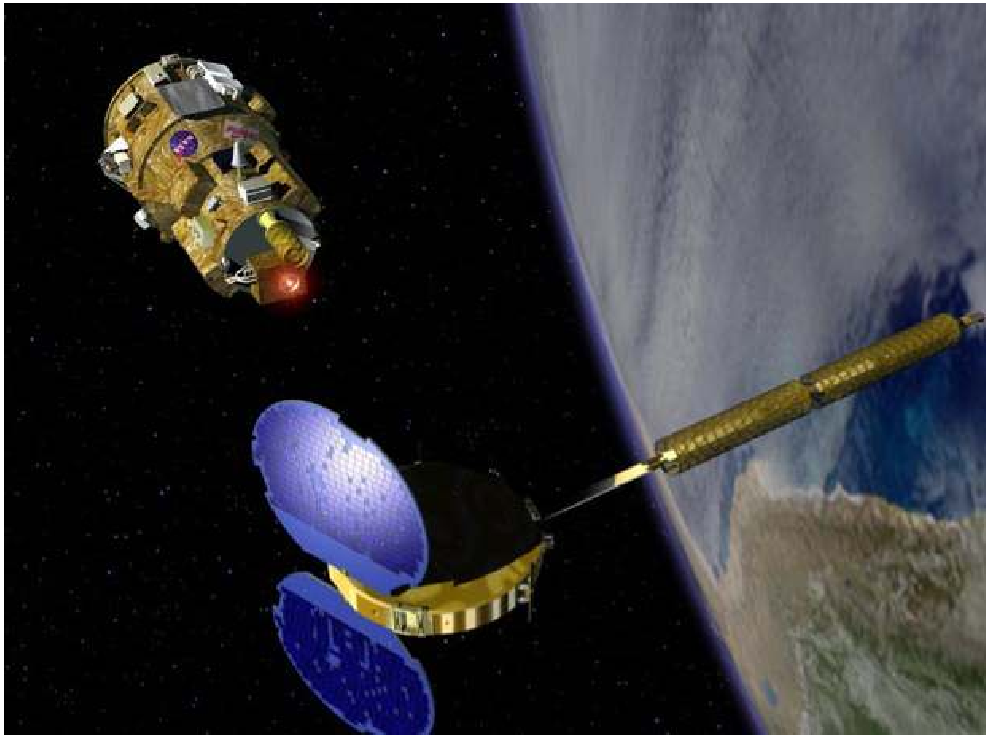


Astronauts Story Musgrave work on Hubble in Endeavour's payload bay

NASA then awarded a contract for the construction of the Corrective Optics Space Telescope Axial Replacement (COSTAR) that was installed during a service mission conducted by STS-61. After having been captured and placed in the payload bay of the Space Shuttle on 4 December 1993, the astronauts, during a series of five EVA's, not only installed COSTAR but also replaced other components. After having been in the payload bay for 145 hours, 1 minute, the spacecraft was released again.
Subsequent service mission to the telescope were conducted on 13 to 19 February 1997 (STS-82), 21 to 25 December 1999 (STS-103), 3 to 9 March 2002 (STS-109) and 13 to 19 May 2009 (STS-125). In all these missions systems and instruments were updated.

The common factor of the 'repair' mission described above was the use of the Space Shuttle and the involvement of astronauts during EVA's. With that vehicle no longer available for such missions, the subsequent attention started to focus on automated or robotic facilities

Amongst these was the Demonstration of Autonomous Rendez Vous (DART) satellite that was launched on 15 April 2005 by a Pegasus XL launch vehicle as part of a test program conducted by NASA in studies towards the Orbital Space Plane (OSP) programme for a 2nd generation Space Shuttle.



DART

The DART was built by Orbital Sciences and the 350 kg satellite was to demonstrate technologies to locate and maneuver near an orbiting satellite using an on-board computer. It was to approach the MULBLCOM satellite, launched on 18 May 1999, several times on 16 April 2005 with a distance of about 5 m. However, the fuel of the nitrogen thrusters ran out when the satellite was about 100 m of the target and the approaches were abandoned. In spite of this, the two satellites made physical contact, pushing MUBLCOM into a higher orbit. It is not believed that either satellite was damaged.

Proposals

There are various proposals for in-orbit repair and refueling spacecraft that are currently under development.

In 2011 Intelsat and Canada's MacDonald, Dettwiler and Associates Ltd. (MDA) entered into an agreement for MDA to service Intelsat in-orbit satellites using MDA's proposed Space Infrastructure Servicing (SIS) vehicle.

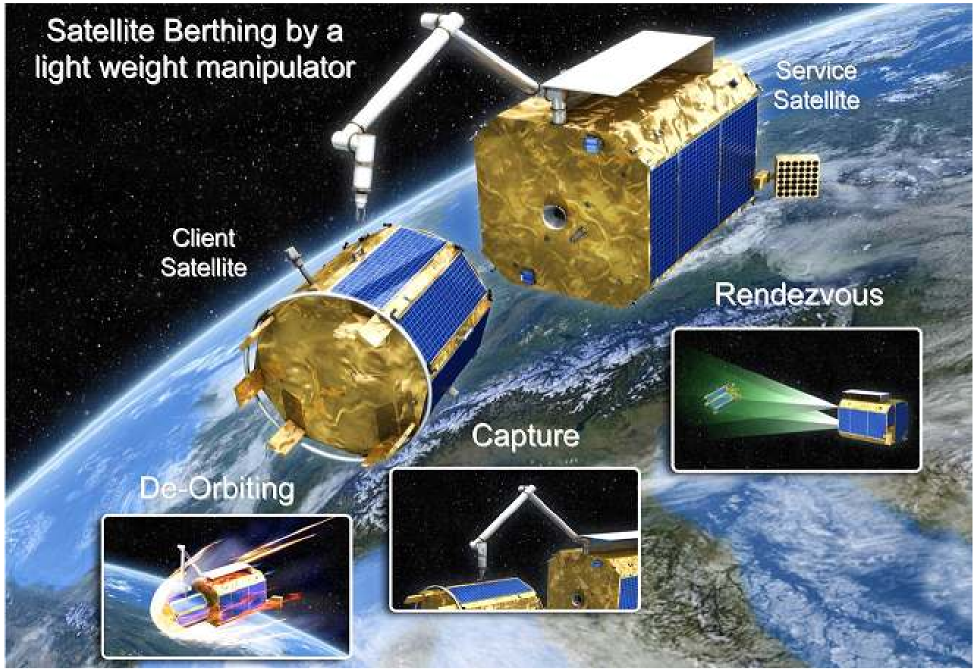
SIS was to service satellites in need of additional fuel, re-positioning or other maintenance whilst utilizing a sophisticated robotics and docking system. It was to carry a robotic arm that would not only be used in refuelling, but could also be used to perform maintenance and repair tasks.
The first launch was expected to take place in 2015 but development was cancelled in January 2012 as there was a lack of interest from Intelsat, other commercial firms and the US Government.

SIS

The Deutsche Orbitale Servicing Mission (DEOS) is a proposal by the German space agency DLR for a two satellite system to demonstrate the performance of in-orbit maintenance tasks, in particular refuelling, that will extend the service life of satellites.

The test will consist of two satellites, a 'client' and a 'servicer'. The satellites will be built by Astrium and will be launched in 2018. At launch the two stacked spacecraft will be placed into a near polar orbit of about 400 to 600 km altitude. Following further separation, the satellites will undertake a number of experiments with increasing complexity. These will include capturing a tumbling non-cooperative client satellite with a servicer spacecraft as well as to de-orbit the coupled configuration in a pre-defined corridor at end of mission.

Recently an engineering team at the Massachusetts Institute of Technology (MIT) advanced the idea that future lunar mission could be fuelled through a propellant depot somewhere in orbit between the Earth and the Moon. It was argued that this would reduce the amount of fuel to be carried during the spacecraft launch, allowing heavier payloads.
Rather than focussing on sending 'tankers' into space to refill orbiting depots, this study advanced the idea that the unused 'contingency' fuel carried by lunar spacecraft in case of emergency situations, be deposited at the fuel depots before the lunar spacecraft returns to Earth. This fuel can be collected by a next mission as its contingency fuel and, if not used, brought back to the depot. Alternatively, quantities of contingency fuel can be stockpiled in the depot over a period of time and used, at a future date, by a large cargo mission to the Moon as its primary fuel source.



DEOS

Whilst the current experiments with the Robonaut on the International Space Station are clearly related to the operation of the ISS, the experience with this robotic device, permanently located at ISS, may have long term influence of the discipline of satellite repairs in orbit. In such a scenario, a 'descendant' of the current Robonaut would fly to an ailing satellite and provide an in-orbit repair.

In a similar way, the current efforts by NASA in developing robotic refuelling techniques through the demonstrations of the Robotic Refuelling Mission (RRM) on the International Space Station in January 2013 and the follow-on ground-based Remote Robotic Oxidizer Transfer Test (RROxiTT) may, eventually see wider applications.
The RRM demonstrations were made with Dextre, the twin-armed Canadian robotic handyman, using four unique RRM tools and an RRM module containing satellite piece parts and refuelling components.

Whilst the RRM tests used ethanol as a substitute for the more volatile satellite fuels, RROxiTT will test the transfer as oxidizers, in particular nitrogen tetroxide (N_2O_4 or NOX), to test how robots can transfer such oxidizers at flight-like pressures and flow rates, through the propellant valve and into the mock tank of a satellite that was not designed to be serviced in space.

Calling the effort "satellite life extension," the ViviSat project is claimed, once established, to be able to provide in-orbit satellite life extension and protection services. These will range from significantly extending a satellite's mission length, engagement into new markets, and will also drive asset value as well as protect franchises. US Space and ATK Space Systems created ViviSat to provide satellite mission length extensions with flexible, scalable, capital-efficient, and low risk services. U.S. Space will be the operating entity, while ATK Space Systems will build the ViviSat as well as the launch and ground segments. ViviSat uses a Mission Extension Vehicle (MEV) that will safely connect to an orbiting satellite. This maneuver will provide supplemental attitude and propulsive capabilities without client satellite operational disruption—quite a plus. The MEV uses a space-ready docking system and a suite of integrated proximity sensors to securely rendezvous with the host satellite. The US Space company's tagline seems to be highly appropriate, should this project fall into place: "Revitalizing Your Space Assets."

Is it worth it?

The establishment of in-orbit spacecraft servicing and refuelling facilities is ultimately dependent on the cost – or rather the savings that can be made. And here lies the biggest problem: is it worth the effort?

In this context it is appropriate to consider that the repair services provided with the Space Shuttle, were not primary missions (with the exception of the Hubble related mission). Whilst there was obviously a cost involved, it did not involve the cost of a special launch. The exception to this was the STS-61 Hubble servicing mission. In that case, it was, however, a choice between the extra costs of an STS launch and the abandoning of the Hubble Space Telescope.

As far as future scenarios are concerned and in very broad terms, the choice seems to be between a dedicated servicing mission for a single spacecraft in trouble and an orbital 'repair shop', the latter fitted with the necessary spare parts for an operating life of, say, 10 years. The obvious cost in both scenarios is the launch vehicle to place the repair facility in orbit. In the case of the orbital 'repair shop' there is the additional cost of re-stocking the repair facility with additional spare parts.
The equation the case of a single spacecraft servicing missions is simple and will follow the same considerations as the STS-61/Hubble mission referred to above. But in case of the permanently orbiting repair shop, one should consider the range of spares to be carried. This is relatively simple in the case of communications satellites that carry fairly standard transponders and other components, but it would be less clear for other satellites. Furthermore there is the cost associated with getting the two spacecraft to rendez-vous in space at possibly totally different orbits.
Furthermore one should consider the frequency of satellite breakdowns during the operational life time of an orbital repair shop.
Finally, and that is perhaps the most overriding argument against an orbital repair shop, is the obsolescence of parts – technology developed ten years ago is totally out of date by now.

In the case of in-orbit refuelling, the biggest problem to be considered here is that sending fuel up into orbit is at a cost, whether it is with the original spacecraft or at a subsequent refuelling mission. In this context the MIT proposal discussed above is interesting in that it makes use of spare fuel that is already in orbit.

But all these cost-benefit arguments should not stop scientists and engineers from developing and experimenting with in-orbit repair and refuelling techniques.
The knowledge gained from these effort will be essential in case lunar bases are established or, for instances, new sources of energy floating around in space, can be harnessed.

Comment

The above article was published in Sat Magazine of June 2014 and drew the following comment by Bryan Benedict, Principal Program Manager, Business Development of Intelsat, posted on http://www.intelsatgeneral.com/blog/article-servicing-and-refueling-satellites-bit-misleading:

Article on Servicing and Refueling Satellites Is a Bit Misleading (June 12, 2014)

An article titled "Servicing + Refueling Satellites in Orbit" in the June issue of SatMagazine contained a lot of good information on the topic, but also presented a couple of points which I feel are a bit misleading.

First of all, regarding what the author called the "most overriding argument against an orbital repair shop," he stated that "satellite technology developed ten years ago is now totally out of date and unusable." Well, as a matter of fact, commercial GEO operators are bringing in hundreds of millions of dollars in revenue annually by providing communications using satellites that have been in orbit more than 10 years – they certainly seem very "usable" to me and to the rest of us here at Intelsat.

Suppose we gave our customers a choice: they could continue to receive several years of additional service from a life-extended heritage spacecraft at their current price, or they could make a long-term commitment to purchase services from a new satellite at a higher price. Might they not choose to stay where they are a little longer?

Orbital slots are valuable real estate, yet satellites continue to be operated in these slots well past their design lifetimes of around 15 years or so. If the older technology were unusable, a business plan for continued operation would be difficult to justify. Commercial operators instead would have replaced the spacecraft. These older spacecraft are not only quite usable, but they are even operated in inclined orbits after the propellant remaining is insufficient for continuation of north/south station keeping.

Another justification for in-orbit servicing is that it might be needed for a brand new satellite. For example, an improperly launched satellite might benefit from a tow to GEO orbit or a refill of the on-board propellants to replace what was used to get to the GEO arc. A new satellite with a stuck solar array or antenna – as Intelsat's New Dawn satellite experienced in 2011 -- could also benefit from an assisted deployment. Insurance companies certainly would appreciate that service offering.

A company with a satellite inadvertently running out of fuel in GEO or suffering system failure might pay handsomely for a service that could tow their defunct spacecraft into graveyard orbit.

In fact, the liability associated with NOT REMOVING the “orbital debris” could be substantial and would be an incentive to properly dispose of the dead spacecraft.

The second misleading point about the article regards Intelsat’s contract with MDA to provide refueling services. Intelsat contracted with MDA for the delivery of 1000kg of propellant to our heritage spacecraft fleet of over 50 satellites. The author writes that “this project was canceled in January of 2012 as there was a lack of interest from Intelsat.” That is completely incorrect. Intelsat continues to be the most vocal advocate of in-orbit servicing among commercial operators. Intelsat did NOT cancel the project with MDA. Rather, MDA made the decision to invest its resources elsewhere only after other commercial operators AND the U.S. government didn’t step up to take advantage of these service offerings. At the time of MDA’s decision, both NASA Goddard and DARPA TTO were also pursuing robotic servicing programs for GEO satellites. Certainly both the commercial world and the U.S. government are very interested in developing this technology.

The author’s closing comment that the redeeming value of developing robotic servicing is that “knowledge gained from these efforts will be essential in case lunar bases are established.” Hmmm -- I think we will not have to wait that long.

I replied to this on 19 June 2014:

I would like to thank Mr. Benedict for his valuable comments regarding my article in SatMagazine, especially as he speaks directly from experience. As an external observer, I find these comments extremely valuable, as they offer a rare insight into the industry itself. Unfortunately, I must have been misinformed concerning the MDA contract and I apologize for that oversight.

However, I still maintain that, in general terms, instruments carried on satellites launched some 10 years ago are obsolete. Look at the development of computers over the past 10 years-everyone realizes that a computer built in 2004 is out of date by 2014 and, if it breaks down, the effort to repair that computer is simply not worth the expense. I firmly believe the same is the case for other instruments, whatever they may be. The technical world does not stand still.

This does not necessarily mean such instruments cannot be used-if they continue to perform well, it would be financially irresponsible not to continue their use. And I would expect that where in-orbit repair and/or refueling would be considered, each specific instance would have to subject to a detailed cost/benefit analysis to be undertaken by the customer (i.e. the satellite owner). In a similar way, an in-orbit repair and/or refueling project, such as the MDA proposal, would be subject to a detailed financial cost/benefit analysis.

Understandably, such cost/benefit studies, whether conducted by the potential customer and/or the repair/refuel service provider, are not made available to the public. However, to me, as an external and experienced observer, it seems that the cost/benefit analysis for the MDA proposal was-at this point in time-not a favorable one. This may (hopefully) change in the future."

(BTW: Intelsat did not bother to place my comments on the above mentioned website)

Cancelled Projects: RAMOS: The Russian-American Observation Satellites

By Andrew LePage

I find it hard to believe, but ten years ago today I was finishing preparations for my last of what seemed to have been countless business trips I had made while I was involved in the RAMOS (Russian-American Observation Satellites) program. After devoting about half of my professional career up to that point in time involved to one degree or another as a member of the US science team on this joint Russian-American space project, RAMOS was quickly winding down after it had been unilaterally cancelled by its American partner despite over a decade of work by a dedicated team of American and Russian engineers and scientists with the expenditure of $120 million.

What is almost as difficult to believe is that even after all this time, a history of this groundbreaking international cooperative project has yet to be written. And except for the program’s participants and a relatively small handful of scholars involved in studying esoteric aspects of international cooperation, RAMOS seems to have been largely forgotten today. There has even been at least one instance that has come to our team’s attention recently of a group hoping to start a new cooperative project with the Russians being genuinely surprised to learn that a joint program like RAMOS even existed!

I feel that I am hardly in a position at this point to present a detailed programmatic history of RAMOS with all of its diplomatic, political and bureaucratic twists and turns. Despite this, I feel it is time to attempt to begin to provide an overview of the RAMOS program, its objectives, the science it was to produce as well as the results from cooperative experiments performed with our Russian partners in support of RAMOS at least from the perspective of one scientist involved in the program.

The Origins of RAMOS

Since the first flights of the experimental American MIDAS (Missile Defense Alarm System) early warning satellite series starting in 1960, it was recognized that one of the major issues limiting the ability of early warning satellites to detect the launch of a threatening missile was the high false alarm rates resulting from the spatial structure in the natural background presented by the Earth. Signals from highly structured, cloudy scenes and solar glints off of clouds or bodies of water, for example, have to be filtered out to reveal any signal produced even from the relatively bright, hot plume of an ascending rocket. Over the last half a century, a range of solutions have been developed to overcome these issues to varying degrees even as operational early warning satellites like the American DSP (Defense Support Program) satellite series and the Russian Oko series came on line starting in the early 1970s. While work has continued on gathering more information on natural backgrounds over a range of wavelengths using data from instrumented aircraft and satellites as well as developing better methods to increase the sensitivity of early warning systems, there have been a number of documented instances where a false alarm almost led to nuclear Armageddon.

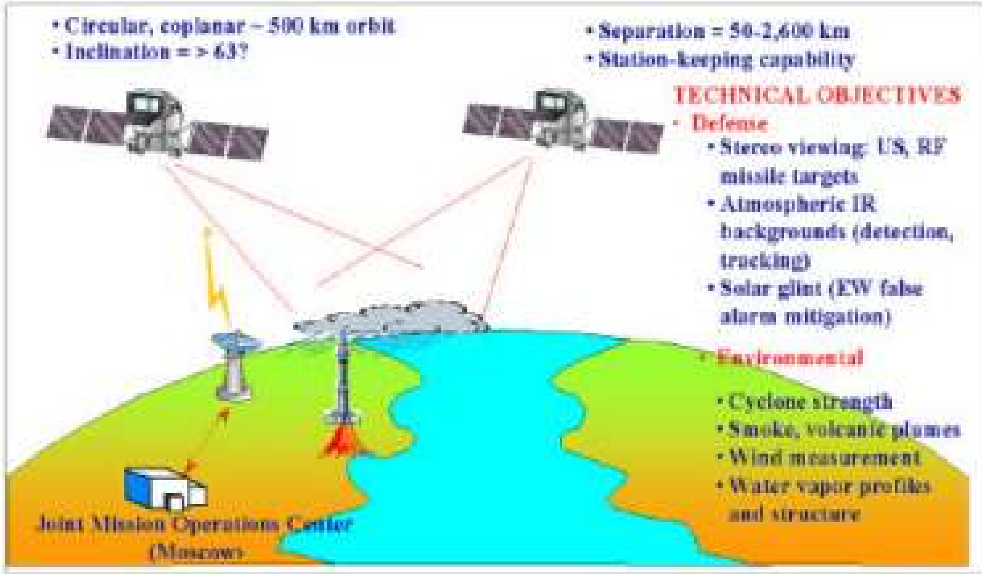
After the dissolution of the USSR in 1991, there were concerns in the US not only about the disposition of the Soviet's nuclear weapons deployed amongst the newly independent Republics, but also about the state of their quickly deteriorating early warning capabilities. After a series of preliminary discussions, in 1992 what would become the joint Russian-American RAMOS program was born with the stated purpose of providing vital data for the development of instruments and data processing techniques for the next generation of American and Russian early warning satellites as well as providing a means of fostering cooperation between the military establishments of the former Cold War adversaries.

The US Department of Defense Ballistic Missile Defense Organization (BMDO, renamed the Missile Defense Agency or MDA in 2002) was given responsibility for administering America's RAMOS effort with Utah State University's Space Dynamics Laboratory (SDL) in Logan, Utah selected as the prime contractor. Subcontractors included the Aerospace Corporation of El Segundo, California and Visidyne, Inc. headquartered in Burlington, Massachusetts (the company I worked for from 1985 to 1987 and continue to work for since returning in 1992). The former Chief Scientist of the Air Force Geophysics Laboratory and, by then, the President of Visidyne, Dr. A.T. Stair, Jr., was the Chief Scientist of the American science team of which I was a member. The Russian team was led by the legendary Academician Anatoly Ivanovich Savin who was the General Director of TsNPO Kometa (who was responsible for developing the Soviet's Oko early warning satellites) and included the participation of other Russian organizations such as Astrophysica, the Vavilov State Optical Institute (also known by the Russian acronym, GOI) and others.

RAMOS Science Objectives & Experiments

While the political objective of the RAMOS program was to engage Russia in a cooperative defense-related space program, the primary technical objective was to conduct joint research and development on new approaches to improve space-based early warning capabilities especially enhancing the ability to detect dim targets and reduce false alarms. Secondary technical objectives included performing observations of a more environmental nature in an attempt to broaden the appeal of the program beyond defense interests. To meet these objectives, seven generic experiment categories were formulated by the Russian and American teams during the course of the 1990s. These proposed experiments and how RAMOS would meet their objectives were reviewed as part of a Conceptual Design Review (CoDR) in January 1998 and were subjected to additional reviews including a Joint Independent Science Review in May 2000.

RAMOS_system



The major RAMOS system components

- Moving Object Experiment (MOE): The objective of this experiment was to demonstrate the ability to observe a post-boost warm body (i.e. a warm "target" after its booster had burned out) against the hard Earth background and accurately reconstruct its trajectory in three dimensions. Dedicated rocket targets would be launched from instrumented ranges in the US and Russia with the objectives met through post-flight processing of the collected data.

- Multi-Spectral & Stereo Backgrounds (MSB): In this experiment, the goal was to acquire spatial and temporal radiance image databases of Earth backgrounds taken simultaneously in multiple wavelength bands. Of primary importance was the direct comparison of images acquired in the 5.4 to 7.2 µm water vapor band and the 4.23 to 4.43 µm CO_2 band. These data would then be used for constructing future models as well as simulating the performance of the next generation of space-based sensors.

- Background Effects of Solar Scatter (BES): The objective here was to characterize polarized solar scattering from water and ice clouds as well as investigate the multi-spectral properties of solar glints. These polarization observations would be performed primarily in the SWIR (shortwave infrared) and visible wavelengths.

- Short Duration Events (SDE): Here we would perform stereo observations of short duration events at high frame rates using a range of wavelengths to demonstrate the ability of accurately locating them under a range of conditions. Short duration events would included ignition spikes from rockets as well as their subsequent burns, artillery engagements and explosions of various kinds.

- Fast Changing Events (FCE): For this experiment, the goal was to demonstrate that fast changing events could be detected, observed and characterized from low Earth orbit. Primarily an environmental investigation, this included observing large fires, characterizing the extent and volume of volcanic plumes and estimating the strength of tropical cyclones.

- Wind Velocity Distribution (WND): The objective of this environmental experiment was to use visible band stereo data to demonstrate the ability to determine the three-dimensional wind velocity on a worldwide basis using remote sensing data.

- Water Vapor Profiles (WVP): Here the objective was to characterize the three-dimensional distribution of water vapor concentration in the lower ten kilometers of the atmosphere using SWIR and MLWIR (mid-long wave infrared) spectrometers.

RAMOS Spacecraft & Instruments

In order to meet the jointly agreed science objectives, a pair of co-orbiting satellites would be used to make the required stereo observations with a nominal 100-meter pixel footprint and with sufficiently accurate pointing information to create three dimensional reconstructions of an observed scene to an altitude accuracy of on the order of 100 meters. Originally it was envisioned that the RAMOS constellation would consist of one American and one Russian satellite with each side responsible for the instrumentation of their own satellites. But in July 2000, BMDO decided to change the architecture of the constellation to a pair of Russian-built satellites with each carrying a suite of Russian- and American-built instruments.

This change greatly complicated technical and security issues resulting from the need to comply with highly restrictive American ITAR regulations(International Traffic in Arms Regulations) in addition to usual need to protect the proprietary technology and intellectual property of the companies involved. This severely restricted the flow of technical information to the Russians and what kinds of hardware could be flown on Russian satellites launched on Russian rockets. When each country was responsible for their own satellites with joint discussions limited to more abstract technical objectives and coordinating joint operations, such issues were much less of a concern.

In this final form, RAMOS consisted of a pair of co-orbiting spacecraft based on the Russian “Yacht” universal space platform with an estimated mass of 1,200 kilograms each. The satellites were to be launched six months apart into a high-inclination, 500-kilometer orbit from the Plesetsk Cosmodrome on separate Rokot launch vehicles. The satellites would control their orbits using onboard propulsion systems to maintain a nominal separation of 500 kilometers that could be varied from 50 to 2,600 kilometers to meet the objectives of different experiments over a range of viewing geometries. The spacecraft would have been controlled from a joint operations center located in Moscow. The minimum mission length was two years with the goal that the spacecraft could continue to function for at least five years to provide a large archive of stereo data under a wide range of conditions for future study.

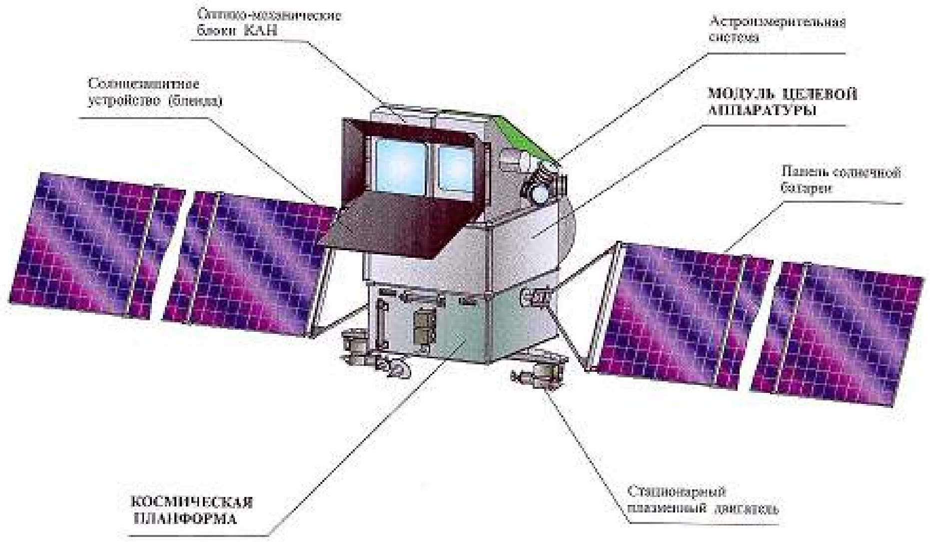


Diagram of the RAMOS satellite based on the Russian Yacht universal space platform.

The pair of RAMOS satellites would carry nearly identical payloads of sensors primarily grouped behind two slaved pointing mirrors that moved in concert to keep the field-of-view (FOV) of the various instruments co-aligned. These pointing mirrors would allow the instruments using them to point anywhere inside a 30.5° field-of-regard (FOR) to track the region of interest and provide flexible simultaneous measurements during the course of an observation session. The whole satellite could be rotated to move this FOR over 4π steradians so that any point could be observed outside of a solar exclusion zone. The pointing system would have also been equipped with sunshades to allow observations to be made at very high scattering angles.

- Infrared Radiometer & Infrared Spectrometer (IRR & IRS): Behind the first pointing mirror was the primary instrument of the payload: a two-channel IR imaging radiometer, the IRR, designed and to be built by SDL. It consisted of a pair of co-aligned 128 by 128-pixel detector arrays cooled to 77° K to improve sensitivity. The arrays would have had about a 140 µrad pixel footprint yielding a total field of view (FOV) of about 1.0°. The two arrays would allow a pair of simultaneous images to be acquired in the SWIR and MLWIR over a wavelength range from 1.5 to 7.5 µm. The IRR packages on each RAMOS satellite were of slightly different designs. The IRR on one satellite was also designed to operate in a mode to act as a SWIR imaging polarimeter. The IRR of the other satellite also included an imaging spectrometer, the IRS, with its own pair of dedicated 128 by 128-pixel detector arrays that together covered the 2.3 to 7.5 µm spectral range using diffraction gratings. The 1° entrance slit of the IRS was offset 1° from the center of the IRR FOV. With the IRS staring in a fixed direction, the motion of the satellite would build up hyperspectral image working in a push-broom mode.

- Visible Camera (VC): Behind the second mirror was a set of three Russian-built cameras. The first was a visible high-speed camera, the VC, with a 3.1° FOV operating at frame rates as high as 100 Hz. It was designed to provide visible band images of the observed scene and was capable of recording quickly changing scenes or events. The VC had a 512 by 512-pixel array with four different filters that together covered wavelengths in the 400 to 960 nm range .

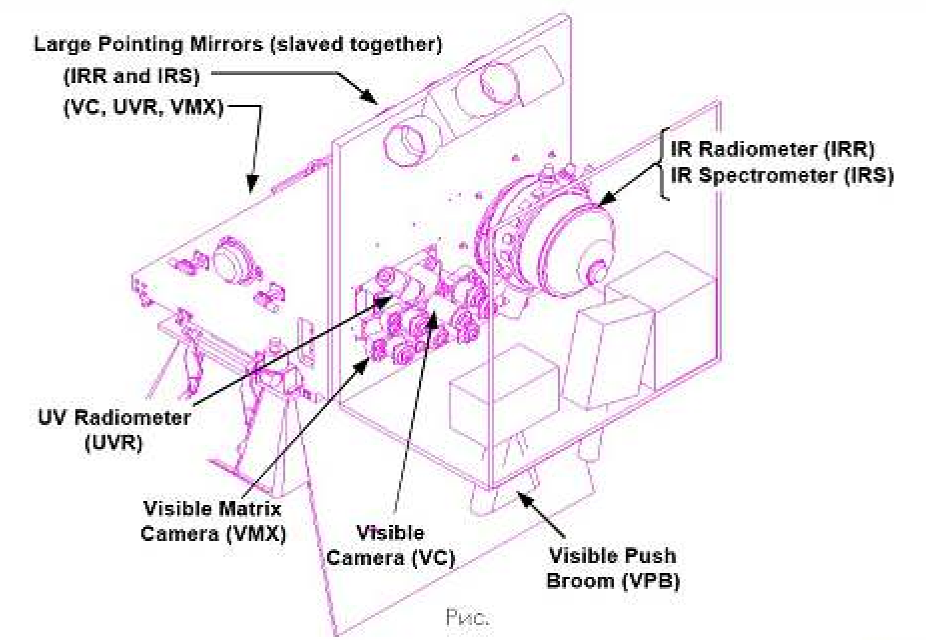


Diagram showing the configuration of the RAMOS instrument suite.

- Visible Matrix Camera (VMX): The second Russian instrument was a wide-field visible matrix camera system, the VMX, that used five cameras with overlapping fields to provide a total FOV of 3.5° by 30°. The VMX would be fitted with RGB filters as well as others of environmental interest that together would cover wavelengths from 460 to 960 nm. The VMX could acquire continuous image swaths to provide a regional context of what was being observed by the other instruments with narrower FOVs.

- Ultraviolet Radiometer (UVR): The final Russian instrument was a multi-filtered, two-channel ultraviolet imaging radiometer, the UVR. One channel of the UVR used a 290 by 384-pixel array and would cover wavelengths ranging from 200 to 300 nm with a 1.44° by 1.92° FOV. The second channel employed a 576 by 576-pixel array that would cover from 300 to 400 nm with a 1.47° FOV.

- Visible Push-Broom (VPB): The final instrument was a visible-band push-broom imager, the VPB, designed and to be built by Visidyne. Unlike the other instruments that used the pair of pointing mirrors, the VPB was mounted on the spacecraft bus with a fixed 30° wide FOV aligned at the bottom edge of the FOR of the instruments using the pointing mirrors. With a cross-track pixel footprint of 64 μrad, it would use the orbital motion of the spacecraft to create its images in a push broom mode. It was designed to make measurements of polarization and cloud top altitude independently of the stereo observations (but with much less accuracy) by comparing the radiances in two selected wavelengths. This instrument also provided a wide FOV context image of the area being observed by the other instruments to complement the Russian VMX images.

RAMOS Near Term Experiments

As the design and architecture of the RAMOS constellation and its ground segment were being developed, it was decided early in the program that a series of field science campaigns would be performed to gather data on various types of cloudy scenes. The goal of these near term experiments was to develop the mechanisms needed to plan experiments, coordinate operations as well as share data and analysis results between the American and Russian teams during joint data collections. In the process, these near term experiments would acquire data needed to refine the program's science objectives and validate performance requirements for the instruments to be carried by the RAMOS satellites. I was one of the key members of the American science team responsible for the processing and analysis of the data collected from these joint experiments including the development of the algorithms required to create three-dimensional, multispectral scene reconstructions using stereo data.

The first near term experiment campaign took place in 1995. This campaign involved the Russian Resurs-O1 satellite and the USAF/NASA ARES (Airborne Remote Earth Sensing) aircraft. The Resurs-O1 remote sensing satellite, whose design was based on the successful Russian Meteor meteorological satellite series, was equipped with a range of remote sensing instruments and was roughly analogous to the American Landsat satellites. The WB-57F ARES was a modified RB-57F strategic reconnaissance aircraft (which itself was a modified B-57 Canberra tactical bomber) designed to carry up to 1,900 kilograms of remote sensing instruments at high altitudes. For our measurement campaign, ARES carried an imaging spectrometer capable of gathering data simultaneously in 75 spectral channels from 1.9 to 6.1 μm as well as a video camera with a 6.8° FOV to provide visible-band context images.

The first opportunity to make observations as part of this effort occurred on July 27, 1995 in the vicinity of Lamont, Oklahoma which, in addition to being known for its afternoon thunderstorms, was also the site of the highly instrumented Southern Great Plains ARM (Atmospheric Radiation Measurement) site run by the US Department of Energy which could provide vital environmental support data. Near-simultaneous observations were successfully acquired using the MSU-E push-broom visible imager and from the red-near infrared channel of the MSU-SK conical scanner of the Resurs-O1 as well as the infrared spectral imager and video camera of the ARES aircraft. While the experiment was successful in that we had started to develop the means of working together with our Russian colleagues, no clouds were visible at the time of our observations.

The second joint observation opportunity during the 1995 campaign took place on October 5, 1995 this time in the vicinity of Mt. Whitney in California's Sierra Nevada range. The Russian Resurs-01 satellite successfully acquired long wave infrared (LWIR) data using its MSU-SK conical scanner and visible data using its MSU-E push-broom imager. Likewise, the American ARES aircraft successfully acquired infrared spectral imaging and visible video data from three passes over Mt. Whitney – one pass looking at nadir and a pair of subsequent side-looking passes. But once again, while the objectives relating to cooperation with our Russian partners were met, there were no clouds present in the area as had been hoped. Nonetheless, I was able to use a sequence of video images acquired by ARES to create a three-dimensional reconstruction of Mt. Whitney as a demonstration of our early stereo algorithms then under development.

The second near term experiment campaign took place in December of 1996 this time using Russian and American satellites. Once again, the Russian Resurs-O1 satellite was employed working together with BMDO's MSX (Midcourse Space Experiment) satellite. Because these two satellites were in near-polar, Sun-synchronous orbits with differing orientations, joint observations were only possible at high northern or southern latitudes where their orbits crossed. As luck would have it, both satellites nearly simultaneously passed over the vicinity of Mt. Erebus on Ross Island in Antarctica on December 23, 1996. While Resurs-O1 and MSX successfully carried out their observations, once again Mother Nature conspired against us and no clouds were visible in the area during the time of our experiment. Undeterred by the lack of clouds, I was able to combine data from the MSU-E push-broom imager of Resurs-O1 and the UVISI imager of MSX to create a three-dimensional reconstruction of Mt. Erebus as a further demonstration of our a stereo reconstruction algorithms.

In support of the conjunctive experiment with MSX, Resurs-O1 had also acquired LWIR data using its MSU-SK conical scanner in the area of Mt. Erebus on December 22, 1996 as a rehearsal of the following day's joint observations and again on January 14, 1997 this time with plenty of clouds present. Unfortunately since neither MSX nor any other participating American spacecraft were in the area during these passes, stereo reconstructions of the clouds in these scenes was not possible. Likewise the BMDO-sponsored MSTI-3 (Miniature Sensor Technology Integration-3) satellite acquired an additional 444 images of the region at SWIR and MWIR wavelengths on March 2, 1997 as part of the campaign.

The next phase of the near term experiments shifted from aircraft and satellite-based conjunctive experiments to a field measurement campaign designed to gather data in support of refining the RAMOS instrument requirements. For this phase, the FISTA (Flying Infrared Signatures Technology Aircraft) was employed to gather polarization measurements in the infrared in an effort to validate the models members of our science team were developing to predict the polarization properties of light reflected from water and ice clouds.

The FISTA aircraft (which was actually the second used in this long-running program) was a USAF NKC-135E aerial refueling tanker that had been modified in 1995 to act also as an instrument platform to gather data in support of various Defense Department research programs. For the 1997 campaign, FISTA was equipped with several instruments that had been modified to obtain polarization measurements at various infrared wavelengths. First was a trio of Michelson interferometers supplied by AFRL (Air Force Research Laboratory) to gather data in the 1.5 to 7.0 µm range of the infrared including the water absorption bands that were of the greatest interest to RAMOS. SAIRS (Schottky Array Infrared Sensor), also supplied by AFRL, was an infrared imager modified to obtain polarization images at wavelengths of 2.33 to 2.65 µm. Next was MAVIS (Multispectral Airborne Video Imaging System) built by Visidyne to obtain visible light context images and modified to provide polarization measurements for us. The last instrument was PEELS (Portable Eyesafe Environmental Lidar System), also built by Visidyne, to obtain information on the altitude of the clouds being observed by the other instruments as well as help determine whether they were composed of water or ice.

The first group of three flights took place in July of 1997 with another three flights taking place the following September. All together, about 16 hours of useful polarization data were gathered of cloud fields over various locations of the western US including observations of solar glints on clouds. These data largely agreed with our model results and allowed us to refine them further to provide better predictions of what would be observed from real clouds. Also noted was the wide variability of the scattering environment even in apparently featureless decks of clouds.

Building on our experience from our 1997 campaign with FISTA, we altered the mix of polarization instrumentation for a follow up campaign in 1998. Among the new instruments was HIP (Hyperspectral Imaging Polarimeter) built by SDL to gather infrared polarization data in the 2.5 to 3.5 µm spectral range. In addition, we also added the Aquameter Water Band Radiometer. The Aquameter was a scanning radiometer built by our Russian partners at the Vavilov State Optical Institute in St. Petersburg, Russsia that simultaneously gathered data in forward- and back-looking directions in four infrared bands from 4.6 to 7.2 µm . The purpose of this instrument was to gather pseudo-stereo imaging data in or near various water absorption bands to characterize the structure of clouds at pixel footprints of a few to a few tens of meters (depending on the altitude of the observed clouds relative to the FISTA aircraft) in order to help the science team refine the choice of filter bands to be used on the RAMOS IR imaging radiometer.

A total of six flights were made in late September to early October 1998 over various locations in the southwestern US as well as off the Pacific Coast of California. The first three flights were dedicated primarily to obtaining polarization measurements in a continuation of our 1997 measurement campaign. The final three flights emphasized measurements using the Russian-built Aquameter. These six flights gathered a huge volume of data including around a dozen hours of Aquameter data that helped us further refine our models and the design requirements for the RAMOS instruments. One of the unexpected discoveries from our flights was the observation of tropospheric waves in the cloudless atmosphere in some of the Aquameter water-band images. While waves with scales on the order of ten kilometers had been observed by us and others in association with mountainous terrain and were orographic in origin, we had also recorded much smaller scale clear air waves with wavelengths on the order of a few hundred meters which had apparently never been observed before.

A final FISTA measurement campaign in support of RAMOS was flown in December 1999. These flights used essentially the same mix of instruments flown in 1998 with some modifications made to improve instrument performance. While three of these flights had the Aquameter operating in a nadir-viewing mode as had been done during the 1998 campaign, for the remaining three flights, the center of the Aquameter's scan pattern was canted forward to provide imaging data at higher nadir angles in support of RAMOS science objectives. Once again, all six flights were successful in gathering huge amounts of additional polarization and IR radiance data including over 18 hours of useful Aquameter data. With these data in hand, the near term experiments of the RAMOS program were ended.

The End

I will have to leave a full and accurate accounting of the political and bureaucratic machinations that led to the eventual cancellation of RAMOS for a later time. However, from my perspective as a member of the US science team, I knew that the program was suffering from a series of problems unique to this endeavor. In addition to what was felt to be a pattern of chronic underfunding and the constant threat of cancellation (which was hardly unique to this particular space project), there was the simple fact that BMDO (and later, MDA) was institutionally ill-suited to carry out this kind of research and development project. Unlike the earliest days of BMDO and especially its predecessor, SDIO (the Strategic Defense Initiative Organization which ran America's "Star Wars" program in the 1980s), by the late-1990s BMDO had largely gotten out of the business of performing pure R&D and had been transformed into an agency concerned with the acquisition of systems from contractors. The "square peg" of a cooperative international R&D program like RAMOS just did not fit conveniently into the "round hole" of an acquisition-oriented government bureaucracy.

These problems were further exacerbated by stark differences between how American and Russian space programs were run – a problem that caused me many sleepless nights when I was responsible for the effort of negotiating hardware requirements with Russian engineers especially after the architecture of the RAMOS constellation was changed in 2000 to a pair of Russian-built satellites. In an American program, the science objectives are set, system performance requirements are then formulated to meet those objectives and finally hardware specifications are derived to meet those performance requirements with the engineers building to those specifications.

The Russians practiced a different philosophy that in some ways turned this process on its head. With a broad understanding of the ultimate scientific goals of a program, Russian engineers would design and build the best hardware that they can with the technology and resources they have available leaving the scientists to do the best they can with what the engineers actually built. While it was a relatively straightforward process to get agreement with Russian engineers on requirements that could be readily met, it became increasingly difficult to get agreement on the more difficult requirements needed to meet the agreed science objectives. Fold in the limitations and extra layers of bureaucracy required to conform with highly restrictive American ITAR regulations and just the process of setting system requirements literally dragged on for years longer than it normally should have.

While there were a host of diplomatic, political and bureaucratic issues that plagued forward progress of the program in the upper echelons of the American and Russian governments, there were also a series of missteps that strained the relationship of trust that had developed between the Russian and American teams over the years. One of the more serious ones was in 2001 with the unexpected insertion of a new player into the program, a team of talented engineers and managers from Ball Aerospace in Boulder, Colorado, to provide an additional layer of oversight of the program for BMDO. While BMDO was footing the bill for the entire program and felt it required an independent set of eyes to look out for its interests, the Russians were wary of the introduction of these "strangers" into the program and the additional layer of oversight further slowed progress.

Despite the problems and delays along with escalating costs and a slipping launch date, the RAMOS program was making progress. The PDR (Preliminary Design Review) for the American instrument payload was successfully completed in May 2002 followed by the joint PDR with our Russian partners for the space and ground segments in June 2003. As we were pushing forward towards CDR (Critical Design Review) and launch by about 2009, we got word about the cancellation of the RAMOS program in the worse possible way.

On the morning February 6, 2004 while we were conducting a joint meeting with our Russian partners at SDL in Logan, Utah, we got word via a press release that Secretary of Defense Donald Rumsfeld had withdrawn funding for the RAMOS program in his FY2005 defense budget and that MDA was unilaterally cancelling the program without consultation with our Russian partners after a dozen years of effort and the expenditure of $120 million. The reason for the cancellation given in the press release was that MDA had concerns about the future of the RAMOS program. The basis of these concerns included the program delays and the lack of a government-to-government agreement that explicitly covered the latest incarnation of the RAMOS constellation – issues, it could be argued, that were largely of MDA's own making. The press release went on to state that it was felt that the estimated $550 million needed to complete the program could be better spent on other cooperative missile defense projects with Russia.

In July 2004, MDA issued a notice for the immediate termination of the RAMOS contract and rescinded funds already obligated for the balance of FY2004. Despite the best efforts of supporters of the RAMOS program in Congress to reinstate funding for FY2005 as well as the valiant attempts by the managers at the various American contractors to reinstate the already obligated FY2004 funds and stretch them out in order to keep the teams together for as long as possible, RAMOS officially ceased to be on September 15, 2004. While attempts were made to revive RAMOS or some other replacement project in the following years, there was simply insufficient support in the Administration or Congress to do so. And despite the claim of the Bush Administration that the savings from the cancellation of RAMOS would be used to fund new cooperative missile defense projects with Russia, none ever materialized.

Since the cancellation of RAMOS, the American engineering and science teams have dispersed to work on other projects and, in most cases, for other employers. In addition, a large number of its most experienced team members including many of those responsible for creating the program to begin with, have long since retired. Work on some of the RAMOS-related experiments continued in various forms including, most recently, the proposed Visidyne/SDL CyMISS (Cyclone Intensity Measurements from the ISS) project to measure the strength of tropical cyclones using remote sensing data – a revival of the science originally developed as part of the Fast Changing Events experiment of the RAMOS program. While it is too late to revive RAMOS, only time will tell if there will ever be another cooperative defense program between the US and Russia like it.

Disclaimer

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