17 Observation Payloads

17.4 The Evolution of Observation Payloads

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In less than 60 years, space-based observation payloads have evolved from simple 35-mm film movie cameras onboard converted World War II missiles providing imagery for just a few minutes to aggregations of widely different instruments covering much of the electromagnetic spectrum simultaneously from Earth orbit for more than 10 years. The very first space-based observation payload flew onboard a German V-2 rocket captured by the United States near the end of World War II. This rocket was launched from White Sands Missile Range on October 24, 1946 and produced the image shown in Fig. 17-28. Clyde Holliday from Johns Hopkins University/Applied Physics Laboratory, developer of this first space-based imager, wrote: “Results of these tests now are pointing to a time when cameras may be mounted on guided missiles for scouting enemy territory in war, mapping inaccessible regions of the earth in peacetime, and even photographing cloud formations, storm fronts, and overcast areas over an entire continent in a few hours…the entire land area of the globe might be mapped in this way.” [Holliday, 1950]

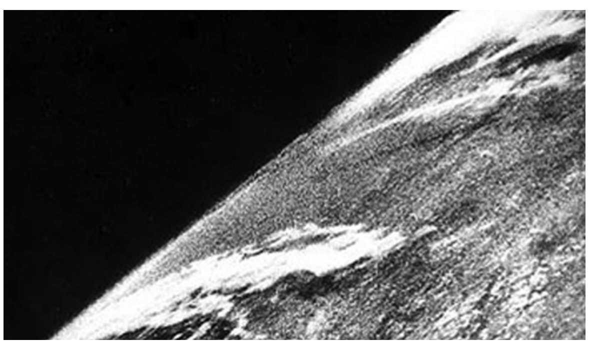

Fig. 17-28. The First Observational Payload to Collect Images from Space (>100 km alt.). Did so Using a V-2 Rocket Launched from White Sands Missile Range on October 24, 1946.

Early plans for Earth orbit missions were motivated by a desire for space-based observation payloads. The future RAND Corporation, then a division of Douglas Aircraft, completed the first serious design study for an operational space mission. The primary satellite application addressed by RAND was covert photographic reconnaissance of hostile territory. Launch approach was based on V-2 technology of liquid fuel rocket engines with multiple stages to send a satellite into orbit. The study considered practical design problems of guidance, communication, thrust control, structural material and fuel along with means to deal with the hostile space environment. Results from this pioneering report defined the basic architectural approach for US military space-based reconnaissance for the next 20 years.

Vanguard 2 was first satellite to collect Earth imagery. It was designed and built by the Naval Research laboratory and launched on February 17, 1959 for a 19 day mission that proved to be limited by radio transmitter function. The satellite was a magnesium sphere 50.8 cm (20 in) in diameter spin stabilized at 50 rpm. The sphere was internally gold-plated and externally covered with an aluminum deposit coated with silicon oxide. The observation payload was designed to measure cloud-cover distribution between the equator and 35 deg to 45 deg N latitude over the daylight portion of the orbit. Two photocells located at the focus of two optical telescopes aimed in diametrically opposite directions, measured intensity of sunlight reflected from cloud, land and sea. Satellite motion and rotation caused photocells to scan earth in successive “lines.” Measured reflection intensities were stored on tape. Ground stations interrogated the satellite by signaling its command receiver, which caused the entire tape to be played back in 60 sec. Communication capability was provided by a 1 W, 108.03 MHz telemetry transmitter and a 10 mW, 108 MHz tracking beacon. This experimental equipment functioned normally, but data was poor because of unsatisfactory satellite spin axis orientation.

TIROS 1 was the first successful Earth observation satellite (Fig. 17web-8). It was launched on April 1, 1960 into a 78 day mission. US government organizations involved in this mission included NASA, US Army Signal Research and Development Lab, US Weather Bureau and the US Naval Photographic Interpretation Center. The payload was designed to test experimental techniques for taking television footage of weather patterns from orbit. It consisted of two television cameras housed in a 120 kg (270 lbs) craft, along with two magnetic tape recorders to store data when satellite was out of communication range. TIROS 1 successfully demonstrated usefulness of satellites for surveying atmospheric conditions from space and led directly to the Nimbus program with first launch in 1964. The pioneering Nimbus program formed the basis for the current POES (TIROS-N) series of polar orbiting environmental satellites that is being replaced by the Joint Polar Satellite System (JPSS) as early as 2015.

Corona is the first known series of US intelligence collection satellites. The program was declassified in 1995. On March 16, 1955, USAF officially ordered development of advanced reconnaissance satellites to provide continuous surveillance of “preselected areas of the earth…to determine the status of a potential enemy’s

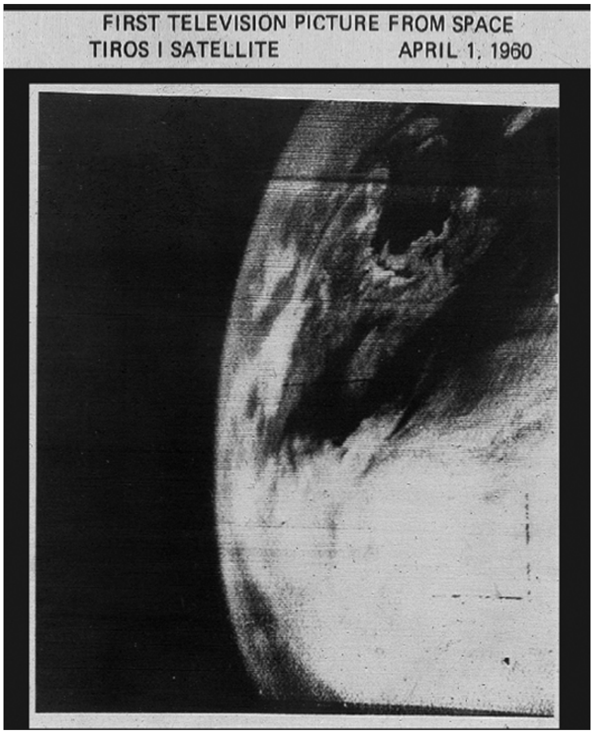

Fig. 17web-8. Early Imagery from TIROS 1, the First Successful Earth Observation Satellite.

war-making capability." The resulting program, Corona, was initially obscured as part of a space technology program called Discoverer. First test launches were in early 1959. The first launch with camera occurred in June 1959 as Discoverer 4, a 750 kg satellite. Corona satellites returned film canisters to Earth in capsules, called "buckets", which were recovered in mid-air by specially equipped aircraft during their parachute descent. Corona program development was accelerated following the U-2 crisis of 1960, in which a U-2 aircraft was shot down over the former Soviet Union. The pilot, Francis Gary Powers, was captured and imprisoned for more than a year. Unfortunately, early Discoverer missions failed to return usable film. Finally, on August 18, 1960, a bucket was successfully retrieved with Discoverer 14. Altogether, 144 Corona satellites were launched, of which 102 returned usable imagery. The last Corona launch was on May 25, 1972. The project was abandoned after a Soviet submarine was detected waiting below the mid-air retrieval zone.

As described in Figure 17web-9, Corona satellites used 9,600 m (31,500 ft) of special 70 mm film in a camera with a 0.6 m focal length lens. The early satellites orbited at 165 to 460 km in altitude from which cameras could produce images of Earth with 7.5 m resolution. Later systems improved resolution to 1.8 m and used a lower altitude pass.

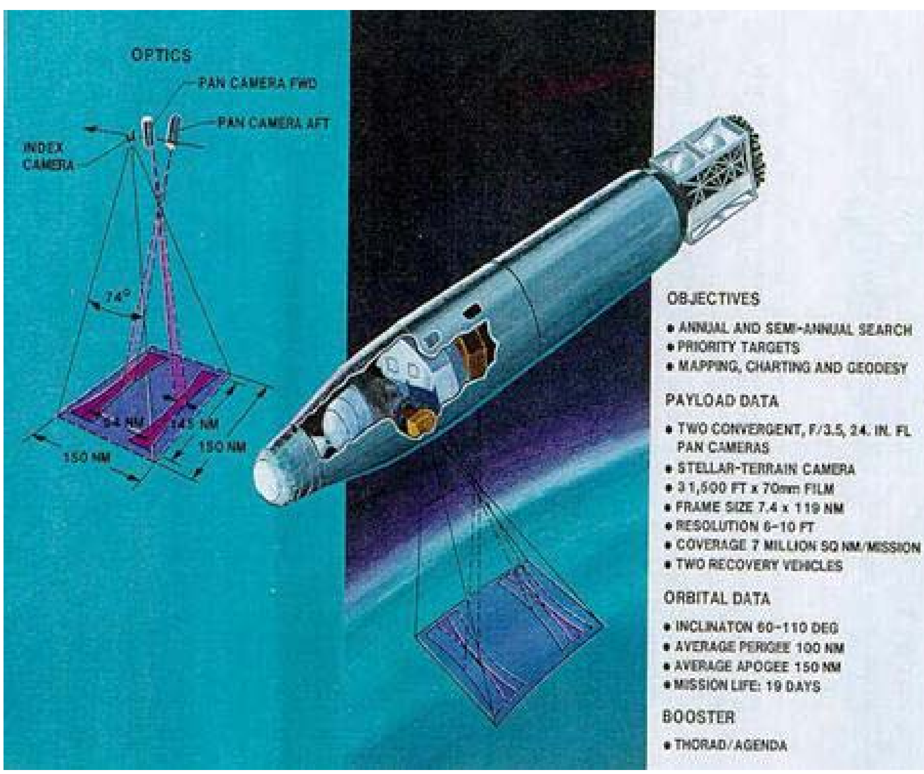

Fig. 17web-9. Description of the Corona Payload, the First Known Space-based Observational Payload for Intelligence Collection.

Many important engineering lessons learned from the early Corona flights were implemented in later flights and in other observational payload programs, resulting in improved reliability and performance. Initial missions suffered from many technical problems including mysterious fogging and bright streaks seen on returned film of some missions, only to disappear on the next mission. A collaborative team of scientists and engineers from the project and from academia, (including distinguished physicists Luis Alvarez, Malvin Ruderman, and Sidney Drell) determined that electrostatic discharges (called corona discharge, ironically), caused by rubber components of the camera, were exposing the photographic film. Recommended corrective actions included better grounding of spacecraft components and outgassing and testing of parts before launch.

The first geosynchronous Earth orbit (GEO) satellites with observation payloads were multifunctional satellites that combined Earth observation experiments for meteorology with other experiments to test advanced satellite technology, communication payloads and space physics measurement systems. The first satellite of this type, Applications Technology Satellite 1 (ATS-1) was launched on December 7, 1966. The weather imager onboard ATS-1 provided useful data through 1970. ATS-1 continued to function as a communication satellite until 1985. Continuous and, to this date, uninterrupted observations of the United States from GEO began shortly thereafter in 1974 with the launch of Synchronous Meteorological Satellite 1 (SMS-1), the first operational meteorological satellite in GEO [Davis, 2007].

Over time, observational payloads have become increasingly complex as continuing improvements in instrument spectral coverage, spatial resolution, radiometric sensitivity and performance characterization are designed and built into new instruments. In addition, payload complexity for some recent satellite programs has increased by adding more instruments to the payload in an attempt to reduce overall cost by spreading launch and mission operations costs across a larger user base and to enable simultaneous measurement of a wider range of geophysical data. These changes have occurred within context of increased bureaucratic oversight of all spaceflight development programs, following the space shuttle accidents in 1986 and 2003 and other well publicized space mission failures with calls for improved system reliability that resulted in more reviews and crosschecks from program management and system engineering [Rogers, 1986]. These complications have created difficult management and technical challenges that have been blamed for significant increases in cost and development schedules for space-based observational payloads relative to programs in the 1960s and 1970s, especially [Minsky, 1990] and [Johnson, 2008]. For example, the payloads onboard the sun-synchronous NASA Terra and Aqua satellites, key platforms in the NASA-led international Earth Observing System (EOS), have five and six Earth observation instruments respectively that collect data across a wide swath of the electromagnetic spectrum from microwave to ultraviolet wavelengths. Key instruments onboard Terra and Aqua include: MODerate resolution Imaging Spectroradiometer (MODIS), a 36 spectral band visible-infrared imager that effectively replaced the 5-band visible-infrared imager Advanced Very High Resolution Radiometer (AVHRR) in development and operation since 1970s and the Atmospheric InfraRed Sounder (AIRS), a 2378-band imaging spectrometer plus 4-band multispectral imager that effectively replaced the 20-band High-resolution Infrared Radiation Sounder (HIRS) also dating from the 1970s. MODIS and AIRS have transformed Earth observation and led directly to breakthrough improvements in Earth system understanding, weather forecasting and climate monitoring that will be implemented in NOAA's emerging operational remote sensing system, Joint Polar Satellite System and in the DoD's corresponding system called Defense Weather Satellite System (DWSS). Nevertheless, the Terra and Aqua satellites with these very capable new instruments and others, though highly successful in operation since 1999 and 2002 up through publication of this book in early 2011, required more than 10 years of development, versus about a 2 year development period for the very successful ATS-1 described above and the equally successful TIROS-N, which pioneered AVHRR and HIRS in 1978.

Recent increases in program development cost and schedule have not been confined to NASA alone. The USAF Space-Based InfraRed System High (SBIRS-High) program is a satellite constellation to be deployed in GEO and HEO to provide space surveillance for missile warning, missile defense and other areas. Currently, the estimated program cost has increased by about 400% beyond the original estimate and delivery of the first GEO satellite is more than 5 years behind its original schedule. Much of the blame for these delays lies with inadequate planning and budgeting early in the program and with complexity of onboard processing software in the observational payload.

These increases in system acquisition cost with associated delays in system delivery have increased demand for lower cost payloads and faster delivery times that can be expected to impact near term future observational payload system designs. However, this cycle of demand for improved system reliability in the turbulence after a major system failure followed by equally passionate requirements for reduced system cost after significant cost growth followed by renewed demand for improved system reliability has been ongoing in the US national space enterprise for decades. A relatively recent change to the operating environment of space systems is the increasing threat to space assets, as evidenced by the Chinese ASAT demonstration in 2007 and by growing realization that the relentless increase in space debris especially in low Earth orbit threatens viability of current and future space systems [Reichhardt, 2008]. The perception that space is no longer a safe sanctuary necessitates more survivable architectures that can be built for lower cost and at lower risk with capability to be upgraded routinely over time—much like the early observational payload systems of the 1960s and 1970s, which regularly built new technology into continuing mission systems every few years.

Is it possible to break the cycle of oscillating between lower cost, faster delivery (faster-better-cheaper) developments and much higher cost, extended delivery schedule, but perceived high system reliability developments? Can systems be built with high enough reliability at low cost? The answer to both questions is a compelling and resounding YES! The recipe for doing so is well known and has already been demonstrated in development of the Iridium constellation, as described in SME-SMAD. This recipe requires less expensive access to space, to realize any significant net savings with respect to current system developments.

Key elements in the recipe are to: simplify payloads and create economies of scale with common observational payload modules and distributed architectures that require a larger number of relatively simple satellites.

Simplify payloads. An obvious way to simplify payloads is to fly individual spacecraft and payloads with a single focused mission. That is, develop systems more like SEASTAR with a single observational payload (SeaWiFS ocean color imager, in this case) versus platforms like Aqua with a multipart payload comprising many different instruments that includes complex multi-mission instruments like MODIS and AIRS. The European weather satellite agency, EUMETSAT, has already decided that its next generation GEO system, Meteosat Third Generation (MTG) will use an architecture that separates its two main instruments onto separate spacecraft, each with a focused mission. This so-called disaggregation of missions and associated payloads is being discussed within the US DOD, too [Taverney, 2011].

A related approach is to deploy constellations like the NASA A-train (Figure 17web-10), which involve different satellites possibly from different nations, each with its own distinct mission. The A-train flies in close formation so that this collection of satellites is able to collect a wide range of data of the same Earth scenes nearly simultaneously. Satellites can be added to the A-train when available or removed from the constellation, following obsolescence or system failure. A-train like constellations are well suited for international partnerships in which individual nations or collaborations provide specific satellites that join the train in coordination with other partners—thereby avoiding export control issues and simplifying financing of multi-sensor international missions. Today's A-train includes a variety of satellites ranging from the multi-mission Aqua and Aura satellites from NASA to the single instrument payload satellites CloudSat (Cloud Penetrating Radar) from NASA and POLDER (polarimeter) from CNES.

Yet another approach that can simplify individual payload elements is to fly fractionated spacecraft, in which individual spacecraft functions, such as power and communication, are separated into individual modules that free fly in very tight formation. Individual modules in these fractionated architectures can be swapped out for newer or working modules. The DARPA F6 (Future, Fast, Flexible, Fractionated, Free-Flying) spacecraft program is the best known fractionated spacecraft program.

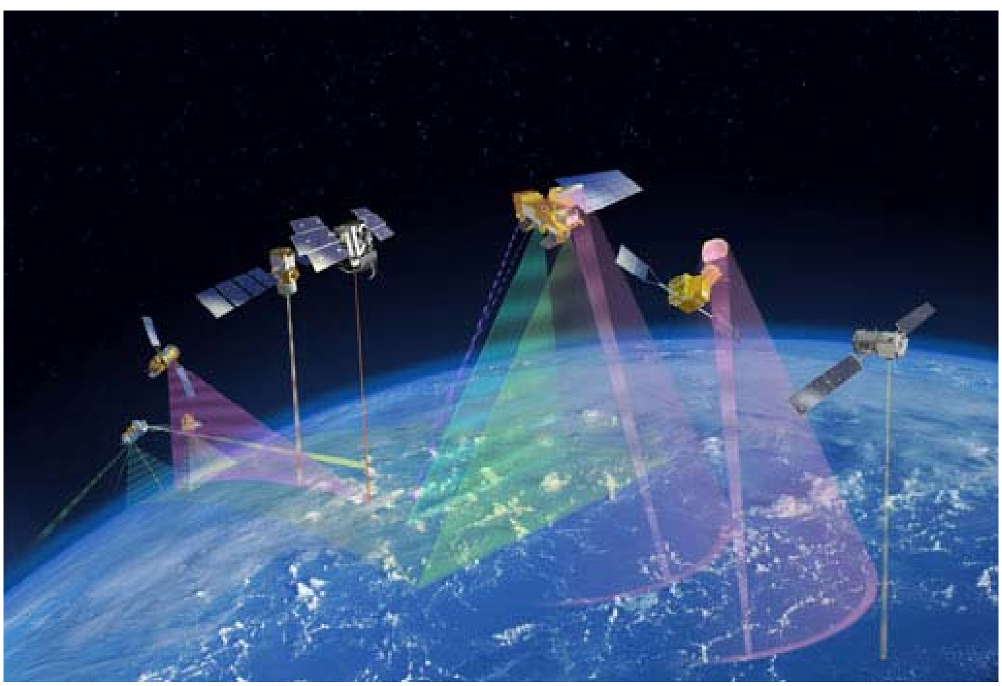

Fig. 17web-10. NASA's A-train of Environmental Monitoring Satellites. (Photo courtesy of NASA Goddard)

Create economies of scale and bring the industrial revolution to the global space enterprise by building relatively large constellations of nearly identical payloads and satellites at low recurring cost in focused continuing builds rather intermittent builds. This approach for simultaneously reducing system production cost and improving system reliability requires a sustainable, production culture based on infrastructure and processes that are optimized for and driven by highly predictable and efficient delivery of effective products with successful implementation of lessons learned from recent system builds. This approach could involve modular, interchangeable payload elements for similar, but distinctly different missions to enable cost-effective performance upgrades and incorporation of new designs and parts with flight qualification occurring in flights preceding actual operational implementation. For observation payloads, common modules for a broad range of similar payloads could be employed, including common telescopes, onboard processors, other payload electronics and thermal control subsystems. For example, continuing improvements in space-qualified FPGAs enable standard spaceflight electronics boards that can be adapted with software to different missions. In many cases, commercial electronics can be modified and qualified for use in space. Likewise, standard modules such as a telescope or a processor using standard "plug and play" mechanical, electrical and data interfaces can be combined with more specialized modules like detector array modules and mechanical refrigerators to create families of systems. Open, industry wide standards for electronic and data interfaces, especially standards derived to the greatest degree possible from established commercial standards, can reduce cost and improve performance by encouraging multiple suppliers to enter the market, thereby creating competition in price and performance and by creating a common design language and understanding that can increase specification efficiency. In some cases, especially with newer higher performance technology that enables vitally needed new capability, it may be appropriate to sacrifice system lifetime in favor of faster development times and more frequent technology refresh. Products should be designed to avoid assembly errors by making sure they can be put together in one way only. Furthermore, these systems should be built with assured components—that is, subsystems tested extensively before system integration—so that relatively little system level testing is required.

This technical approach of bringing affordable, industrial scale manufacturing to the space payload and satellite business proved to be an engineering success with the Iridium system development in the 1990s. As described in more detail in Sec. 10.6.2, Iridium is a satellite communication constellation of 66 active satellites with spares in six planes of ~780 km (485 mi) high orbits at an inclination of 86.4 degrees. The satellites and payloads were built by Motorola in partnership with Lockheed Martin, Raytheon, ComDev and BAE. Iridium is the first and still the only truly global communication system. This world's largest satellite constellation provides voice and data services to the entire planet simultaneously and has operated with high reliability for more than 10 years, making use of system level redundancy built into a relatively large network of satellites rather than into a few individual satellites. Iridium pioneered mass production of satellites and satellite payloads with relatively simple but effective payloads by bringing in manufacturing experts from outside the space industry. The resulting technology processes and infrastructure enabled mass production of satellites in weeks rather than months or years at a cost of $5M per satellite (1998 dollars) versus the much higher cost in the mid-1990s of $100–200M per satellite for a standard GEO communication satellite procurement [de Weck, 2003].

The Iridium constellation has proven to be remarkably reliable and resilient, despite the failure of the original global cell phone business model, early launch failures, on-orbit failures (e.g., Iridium 28 in 2008) [Sladen, 2008], and the destruction in 2009 of one of the Iridium satellites resulting from its collision with the Russian Kosmos 2251 satellite [Space, 2009]. The current constellation is expected to remain fully functional through at least 2017. Starting in 2015, the original satellites will be replaced by the next generation Iridium NEXT system to be supplied by Thales Alenia Space to Iridium Communications Inc.

It is interesting to consider how mass production of payloads and satellites could be applied to observational payload systems. Today's operational environmental monitoring system consists of six satellites in GEO and four in SSO. Next generation GEO imagers like GOES ABI are expected to provide coverage of the full disk within view of a satellite every 5 min. A similar global coverage rate could be provided by a constellation of ~20 satellites in SSO. Cost modeling shows the much reduced recurring cost of the ~20 satellite constellation enables this system to be built for a lower overall cost than the current smaller production system in multiple orbits. This system development approach could open up possibilities for both international cooperation and competition with different organizations (nations, companies, consortia) vying to provide individual payloads and satellites in the constellation. Revenue stream for data purchased by all subscribing nations could go to system providers or to their customers.

As new observational payloads are developed with ever increasing data collection rates, the driving technology for these systems is expected to shift from focal plane technology for visible-infrared systems toward onboard and ground processing to handle the vast amounts of data generated by ever more capable systems. Future systems based on distributed architectures that are refreshed routinely may be able to keep pace with availability of improved technology better than today's systems which are refreshed on decade time scales.

Space-based observation systems are most valuable when they're effective, ubiquitous, affordable, reliable, flexible and rapidly replaceable. Readers should not confuse low system cost with low performance. The original Iridium system proved that it is possible to achieve both low cost and unprecedented performance. Unfortunately, the failure of the original Iridium business model prevented this production approach from being sustained in near term upgrades and in the building of similar expected systems. Any future observation system must meet its operational or research performance requirements. For instance, regardless of satellite constellation, space imagers must meet operational performance requirements for parameters such as spatial resolution, spectral coverage, area coverage rate, sensitivity and geolocation. Likewise, systems in any architecture must meet system level hardness, reliability and operational lifetime needed to fulfill customer mission needs. System-level trade studies early in program development need to be broadened to consider alternative system architectures that might be built at lower overall cost using highly engineered and reliable systems designed for affordable, efficient manufacturing and operationally effective performance and built using well understood and continuously improving processes. These early studies would trade satellite design life, technology improvement schedule, constellation refresh rate, survivability and cost within context of firm system performance parameters.