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Genesis of Three-Axis Spacecraft Guidance, Control, and On-Orbit Stabilization

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John C. (Jack) Herther (http://www.peterson.af.mil/hqafspc/history/herther.htm) graduated from North Carolina State in 1953 with a B.S. in mechanical engineering. He graduated from Massachusetts Institute of Technology (MIT) in 1955 with a master's degree in aeronautical and electrical engineering. His thesis proposed a satellite guidance and stabilization system that he was later able to implement: over the years, hundreds of USAF, NASA, and other satellites would orbit successfully using the Herther three-axis active stabilization. He became an Air Force Space Pioneer and was inducted into the Space Hall of Fame in 2003. Aerospace historian Dwayne Day has called Jack Herther "one of the unsung pioneers of the early space age." In 1969, after 13 years at Itek on several generation satellite reconnaissance cameras [including the Large Format Camera (LFC), a high-altitude aerial mapping camera, which was operated from the NASA Space Shuttle Challenger Mission STS-4-G on 5–13 October 1984. It achieved a ground resolution of 14–25 m in Earth-orbital altitude of 180 nautical miles, continuing post-CORONA space mapping for the WGS84 Geoid, which became the basis for Transit and GPS satellite navigation systems (http://www.fas.org/spp/military/program/imint/at_950525.htm). Original development of the lens and prototype camera was done in Herther's Research and Development Directorate during his time at Itek (http://academic.emporia.edu/aberjame/geospat/space/space.htm)], Herther founded Iotron Corporation and served as its first president. The company developed the world's first fully automatic radar plotter for merchant ship collision avoidance. Transit satellite navigation was added, but due to ship speed inaccuracy, dead reckoning between fixes was not sufficiently precise to maintain Transit's accuracy. After obtaining a Loran receiver and testing it at sea, Herther used the repeatable accuracy of Loran to display traffic separation lanes designated by the International Maritime Organization (IMO) accurately on the radar PPI, by integrating Transit satellite and Loran C signals to provide a continuous 100-m ship position. Dead reckoning using conventional ship's through-the-water speed logs was totally inadequate when near land sailing in up to 5-knot currents that exist where the traffic lanes were mandated. Iotron's proprietary innovation was the first to use Transit satellite navigation's 100-m fixes every hour and a half to "calibrate" by using the better than the 18–90-m "continuous repeatability" of Loran C. This unpublished maritime navigation accuracy essentially equaled the 100-m accuracy of GPS for 20 years until GPS selective availability (SA) was removed in 2000. Iotron pioneered not only "hands-off" anti-collision self-plotting radar, which was installed on over 500 large ships, but also integrated Transit satellite/Loran C navigation, fitted on 34 super tankers. In 1983, Herther joined MITRE Corporation in Bedford, Massachusetts and was involved in communications and electronic systems engineering programs, including NAVWAR and GPS III, and on various classified Air Force, Army, Navy, and NSA contracts. At 75, he sails, water skis, and is still working and innovating full time.

Jim Coolbaugh (http://www.peterson.af.mil/hqafspc/history/coolbaugh.htm) is a 1947 graduate of the United States Military Academy, and a 1952 graduate of the University of Michigan, where he was awarded a master's degree in aeronautical engineering upon completion of the guided missiles course that the University was conducting for the Air Force. In the summer of 1952, Coolbaugh was assigned to the New Developments Office of the Wright Air Development Center. There he conducted studies to improve the performance of air-to-ground rockets in Korea, the use of drone aircraft for reconnaissance missions, and the feasibility of a tactical ballistic missile. These studies resulted in the development of guided air-to-ground rockets, drone reconnaissance aircraft, and the THOR intermediate-range ballistic missile. In December 1953, Coolbaugh was named the head of the Air Force's first satellite development program. The program was unfunded, but he was able to put together a fully operational development program that employed 225 Air Force personnel. This program became the satellite reconnaissance system that led to developments discussed in this paper. He became an Air Force Space Pioneer and was inducted into the Space Hall of Fame in 2002. He left the Air Force in 1960 and worked on research and development programs of the Itek Corporation, United Technology, and Raytheon. In 1969, with Jack Herther, Coolbaugh founded the Iotron Corporation, which developed an automatic self-plotting radar that revolutionized the use of radar at sea. From 1984 to 2000, he operated a classic car business that he founded.

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On 22 February 1995, President William J. Clinton signed an executive order declassifying imagery collected by CORONA, the program that put cameras aboard satellites for the first time in history. Long before the Soviets launched Sputnik, a small group of junior United States Air Force officers was working on the technology that eventually led to the invention of the three-axis active spacecraft stabilization technique that provided the "stable table" in space that was needed to take high-resolution photographs of the Soviet Union's military installations. The intelligence gleaned from these missions dispelled one of the nation's greatest fears, surprise enemy attack, at a critical moment in the history of the Cold War. It not only dispelled both the purported "bomber gap" and "missile gap," but also contributed to a revolution in cartography that led to World Geodetic System 1984 (WGS-84), a global reference frame for the earth. This aerial stereo photography, when it was declassified, was largely responsible for the WGS-84 coordinate system now underlying global positioning systems. The three-axis, on-orbit stabilization innovation was pioneered for CORONA and used on 300 National Reconnaissance Office imaging and signals intelligence satellite missions between 1960 and the mid-1980s. It was also used on 200 Agenas flown by NASA.

I. Introduction

THE Cold War shifted the art and science of military reconnaissance from terra firma into outer space. This article is the first historical documentation of a breakthrough engineering innovation, the three-axis spacecraft, which revolutionized military intelligence. The CORONA Project (CORONA is not an acronym; at the start, George Kucera of the CIA named the project after the CORONA typewriter for no reason), shrouded in national security obscurity with the Central Intelligence Agency (CIA) and United States Air Force (USAF) for more than 40 years, was crucial to the success of the U.S. photoreconnaissance program at the height of the Cold War. The three-axis inertial stabilization subsystem used on CORONA missions led to advances in high-resolution reconnaissance photography and cartography. [A high-priority use of the CORONA product was to identify and locate targets for the new intercontinental ballistic missile (ICBM) and submarine-launched ballistic missile (SLBM) forces. Geodesy was in a very primitive state at the time, and the relative location of points on different continents could be off by miles. Because there was no geodesy Ph. D. program in the U.S. yet, the Department of Defense (DoD) and the CIA helped set one up at up Ohio State University with European faculty. The graduates of this program revolutionized geodesy and were largely responsible for the WGS-84 coordinate system now underlying global positioning systems (GPS). For more information see http://www.fas.org/spp/military/program/imint/at_950525.htm.] It contributed to studying Earth's ecology, and ultimately laid the groundwork for human space flight.

What had once been considered a radical high-risk concept (active three-axis spacecraft stabilization) kept panoramic cameras stable, enabling them to scan the Earth and photograph it. This resulted in crisp, high-resolution images of Soviet military installations. This work was done when the need for high-resolution satellite photo imagery was critical. The quantity of pictures produced in the first spacecraft flight surpassed all those taken in previous flights of the CIA's U-2 spy aircraft. CORONA's first film recovery occurred only a few months after Gary Power's U-2 was shot down, and provided a more efficient and discreet method of photo reconnaissance.

President Dwight D. Eisenhower was determined that the United States would never again be the victim of a surprise attack, such as the one perpetrated on the U.S. fleet at Pearl Harbor by the Japanese. Former U.S. allies, the Soviets now had the hydrogen bomb, sophisticated bomber aircraft, and the intercontinental ballistic missile (ICBM). In a world where the subject of mutually assured destruction was familiar enough to all to be reduced to an acronym (MAD) and the prerogative of a first strike was nonnegotiable, the race for deterrence literally moved up into what had formerly been considered neutral territory: outer space. The surprise attack that led to the Korean War went on to confirm that national security depended on an accurate assessment of the adversary's military potential well in advance of any conflict. Reliable/accurate peacetime assessment of potential enemy capability was therefore an essential, and urgent, intelligence requirement strategy.

Eisenhower proposed an "open skies" policy to the Soviets in 1955, which would have enabled mutual overflight of territory to verify arms control agreements. The Soviet Union rejected this, because aircraft overflight could secure targeting information for possible future aerial attacks on Soviet territory. Mutual mistrust was endemic, so the rejection of open skies was no surprise. To secure the intelligence required meant using the Lockheed U-2 photoreconnaissance aircraft, which was risky. (The U-2's luck ran out when one of the aircraft, flown by Francis Gary Powers, was shot down over the USSR on May 1, 1960, creating an international political crisis.)

The Air Force had estimated as early as 1952 (correctly, as it turned out) that the Soviets would be able to detect and shoot down aircraft like the U-2 by 1960. Given the long lead time needed for developing state-of-the-art technology, this meant that a satellite reconnaissance capability would have had to have been in development well before then. [Air Force Colonel Richard Leghorn (a former member of Air Force General Ben Schriever's staff and founder of Itek, the corporation that developed the camera for the CORONA program) states that, in spite of known risks, "funding of WS-117L was woefully inadequate." It would take the Soviet launch of Sputnik on 4 October 1957 to shock the administration into providing more funds for a satellite program.] The Research and Development (RAND) Corporation, a research and development group that was initially founded as part of the Douglas Aircraft Corporation, had been investigating this concern since World War II.

RAND began its first project, a six-year study of the military use of satellites, in 1948, nine years before CORONA's inception. This study led the USAF to create the top-secret advanced reconnaissance satellite system (ARS), dubbed "Pied Piper," in 1954. RAND was to ensure that the military services would be equipped with superior weapons, mitigating chances of any enemy surprise attack.

II. RAND Incorporated as Proponent of Military Uses of Satellites

RAND eventually dropped its affiliation with Douglas and on 14 May 1948 became an independent corporation. Starting in mid-1951 and continuing until the fall of 1953, RAND prepared a case for developing a useful and economical reconnaissance satellite system for the USAF. RAND studied and documented the principles of almost all of the potential inertial guidance and stabilization and other vehicle and propulsion ideas that had evolved to date (mostly from the German V2 ballistic missile). Key contractors in the aircraft and electronics industries performed studies for RAND that enabled the design of a reconnaissance satellite. RAND published these in a two-volume report, Project FEEDBACK (R-262), on 3 March 1954. This report formed the basis for the Air Force's decision to establish a project to develop a satellite reconnaissance system at Wright Field in Ohio [this location is later referred to as the Wright Air Development Center (WADC)] in December 1953. All of the proper "official paperwork" for a program was created and approved, but, unfortunately, the project was not funded.

The RAND Project FEEDBACK program was predicated on the development of a three-axis spacecraft guidance and control system, which would be necessary for a reconnaissance satellite. The study recommended that the Air Force develop an electrooptical reconnaissance satellite that would operate at an altitude of 300 statute miles on an 83-deg retrograde orbit. A 300 statute mile orbit was recommended, because nothing was known about atmospheric density above 20 miles. It was believed that an altitude of 300 statute miles would guarantee a drag-free environment, which was necessary for the satellite to stay in orbit for a year, and RAND believed that a year's life on orbit was necessary to financially justify the program. This sun-synchronous orbit would provide continuous illumination of the satellite's tracks over the USSR for the projected one-year life of the satellite. To operate properly, the TV cameras installed in the satellite would have to be used in daylight conditions. Transmission of the images would take place when the satellites were overflying friendly territory.

Figure 1 shows how multiple orbit tracks at the North Pole would provide daily coverage, whereas the Earth circling the sun demonstrates why the 83-deg retrograde orbit was selected for high-latitude coverage of the USSR at constant illumination over the period of a year. At 300 statute miles and 83 deg inclination, the orbit plane precessed around the sun at approximately 1 deg per day, so that selected northern areas of the USSR would be visible every day during daylight hours. The visual reconnaissance imaging system recommended by RAND consisted of an image orthicon television camera looking through an f/24, 38-in focal-length optical system. From a distance of 300 miles, the two-pixel resolution on the ground was projected to be about 144 ft. A cross-track scanning mechanism was incorporated into the TV camera system, enabling it to cover a swath 375 miles wide.

III. Ascent Guidance and Control Concept

RAND's studies showed that both the plane and shape of the orbit would be dictated by the ascent guidance system. The guidance system would be inertial and wholly self-contained comprising a platform stabilized by three 1 deg/h gyroscopes (gyros). It would carry three integrating accelerometers, an electronic analogue computer, and associated conventional servo controls. An auxiliary power plant would provide power. Control over the vehicle during the propelled portion of the ascent would come from two gimbaled auxiliary thrust motors. The differential motion of these motors would supply the roll control.

RAND's proposed guidance platform assembly would occupy two cubic feet of space and weigh about 50 lb. Its computer would require an equal amount of space and weigh around 60 lb. The first stage servo system would weigh around 100 lb; the second-stage gyro would weigh about half that. The stabilized platform would serve as the reference from which measurements of vehicle attitude and motion could be made. Roll, pitch, and yaw would be discriminated on this basis. Three accelerometers, each at right angles to the others, would be used. The doubly integrating lateral accelerometer would detect the vehicle's lateral deviation from the programmed position. The yaw servos would continually drive this deviation toward zero, establishing the orbital plane with the required accuracy. This would reduce the guidance problem to one of properly vectoring the vehicle velocity in the established orbital plane at the desired altitude and elliptical eccentricity. A modified time-programmed control would be used to vector the velocity. A theoretical trajectory would be prepared to consider flight mechanics and control estimates of thrust motor performance, and aerodynamic and other forces. Pertinent control data would be recorded and fed into the guidance computer as a time program.

IV. Satellite On-Orbit Attitude Control Concepts

Three factors could affect the attitude of the satellite shown in Fig. 2: 1) the nature and magnitude of aerodynamic torques perturbing the vehicle from its desired attitude, 2) the errors of a sensing system determining the amount of deviation existing at any instant, and 3) the characteristics of the control system employed to restore attitude deviations to zero (attitude deviations have to be sensed before they can be corrected).

RAND considered a number of attitude control systems, but the three-axis option stood out because it offered specific advantages for Earth imaging. The decision was made to use a gyro-stabilized platform within the vehicle to provide a three-axis reference.

The pitch gyro would be continually torqued to yield a constant instantaneous vertical reference (and thus pitch rotation with respect to inertial space). Periodically flipping the gyro by an integral number of revolutions (corresponding to the number of times the vehicle circled the Earth) would be a method to compensate for the vehicle's torque biasing reaction. This posed a potential problem, however. If left to itself, such a platform would ultimately depart from the vertical because of gyro drift and incorrect gyro torque bias levels.

There was a way to solve this problem. An optical scanner system could be introduced, as illustrated in Fig. 3, to determine the vertical relative to the disk of the Earth by optically observing the horizon as the vehicle passed over the Earth. The scanner could be used to monitor the gyro system and provide periodic compensation for drift. The gyro system, in turn, could be used to overcome the frequency irregularities in the scanner signal that would inevitably result from clouds and mountains. Using the stabilizing platform with a horizon-scanning monitor would offer advantages over the separate use of either system.

Once the vertical was established and stabilized, it would then be possible to sense yaw by means of a device operating on the same principle as the gyrocompass. A roll rate gyro, suitably constrained, would be mounted on the stable platform. As the satellite moved around its orbit, this gyro's spin axis would tend to align itself with

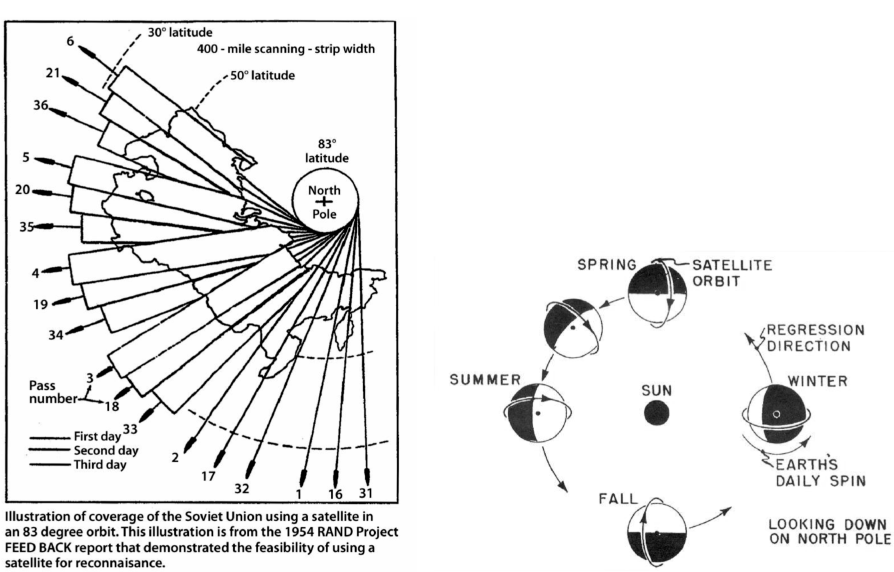

Illustration of coverage of the Soviet Union using a satellite in an 83 degree orbit. This illustration is from the 1954 RAND Project FEED BACK report that demonstrated the feasibility of using a satellite for reconnaisance.

Fig. 1 RAND's Project FEEDBACK sun-synchronous orbit parameters.

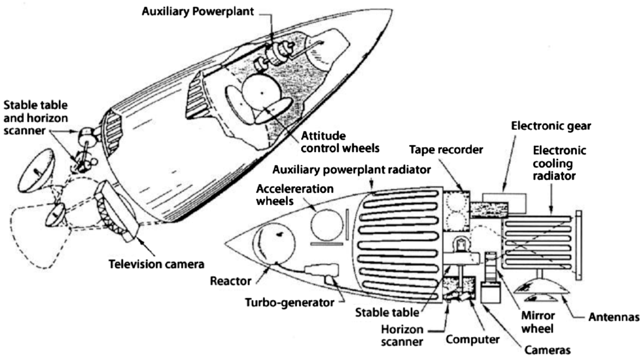

Fig. 2 RAND conceptual TV satellite.

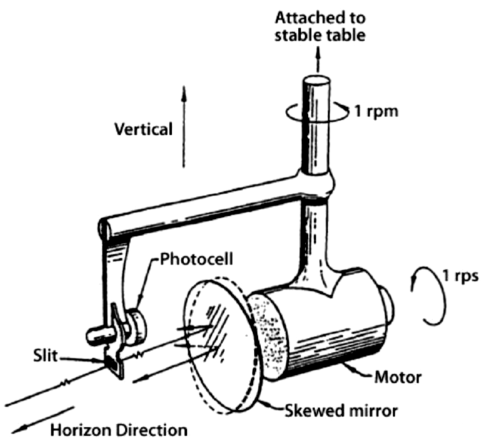

Fig. 3 RAND FEEDBACK Project proposed horizon scanner.

the orbital plane and provide a yaw error measurement by sensing orbital rate when the roll axis is out of the plane.

Of the feasible methods to control attitude, the one that appeared to require the least development was a scheme shown in Fig. 2, which depends on inertial reaction. There would be three flywheels in the satellite, the three axes of which would each be aligned with the three principal vehicle axes. To turn the vehicle through a certain angle, the appropriate flywheels would be rotated through a suitable angle with respect to the vehicle frame in inverse proportion to the relative moments of inertia of the vehicle to the flywheels. The actual control operation would begin when the sensing system received attitude deviation signals. These signals would then be introduced into a control computer (because all three wheels would generally have to be torqued for the desired control). If the deviations sensed were near zero, the torques on the flywheels would also be reduced to zero. The actual control equations involved the speed of vehicle response, the desired tolerable steady-state deviation, perturbation magnitudes, and the random noise arising from the sensing instruments. Detailed design studies indicated that the entire orbital attitude-sensing and control system could be built using components and techniques not requiring elaborate research and development.

V. RAND Recommends the Air Force Start a TV-Readout Program

Two RAND reports published in April 1953, R-217 ("Utility of a Satellite Vehicle for Reconnaissance") [1] and R-218 ("Inquiry into the Feasibility of Weather Reconnaissance from a Satellite Vehicle") [2], established the engineering feasibility and utility of a military satellite. These reports concluded that a "pioneer" reconnaissance mission (one that could generally locate and determine appropriate targets and weather) would be a suitable application, given the resolving power then available with a satellite television system. The RAND proposal specified an ascent control system for the first stage booster, using a gimbaled engine to provide pitch and yaw control and gas jets to control its rolling during the boost phase. These same jets stabilized the satellite while entering into orbit and during orbit, orienting the satellite when passive stabilization was to be used. Under these circumstances, the RAND engineers oriented the satellite so that its long axis was pointing toward the Earth; the Earth's gravity gradient would be a stabilizing force if disturbing torques were negligible. RAND concluded that a two-stage rocket weighing around 74,000 lb and carrying a 1000-lb payload could perform a general reconnaissance mission resolving objects with a dimension of around 200 ft. RAND engineers and scientists believed that the system would eventually be able to resolve objects with a dimension of only 40 ft. When the Air Force started planning the Atlas ICBM for potential use as a booster, RAND recommended they also start developing a reconnaissance satellite. The idea was to start developing critical components and devise a process to select a system contractor for the first satellite within a year.

VI. The USAF Satellite Program Gets Off the Ground

Captain James S. Coolbaugh, an aeronautical engineer (and one of the authors of this paper) had been serving in the New Developments Project Office of the Bombardment Missiles Division at WADC since 1952. (WADC was the Air Research and Development Command Headquarters at Wright Patterson Air Force Base, Dayton, Ohio.) Preliminary copies of Project Feedback had reached WADC around mid-December of 1953. Captain Coolbaugh was informed late that year that he was being named manager of the Air Force's first satellite program in the New Developments Project Office, and became the first Air Force officer assigned to space photoreconnaissance systems.

In January 1954, Captain Coolbaugh visited the RAND Corporation to discuss the proposed reconnaissance system with the authors of the Project Feedback report. The booster rocket was not considered a problem, because the Atlas ICBM was already in development. However, Coolbaugh's review of the RAND system pinpointed several problem areas:

1) The physical characteristics of the Earth's atmosphere for drag effect on orbital life, from its surface to the contemplated orbital altitude of 300 statute miles, needed better definition.

2) A guidance and stabilization system that would control the booster/satellite combination all the way from launch to operation on-orbit had to be developed.

3) A power source capable of providing the satellite's power for one year had to be developed.

4) A storage and readout system for commercial TV was already under development but would require modification for satellite application. At this point, monitoring commercial tape recorder developments would suffice. The satellite's TV reconnaissance system was not deemed critical because commercial pressure was already pushing TV development. Developing a lens was believed technically feasible.

5) The poor resolving power of this TV system at the orbital altitude of 300 statute miles (the height required for the long-life gravity gradient "dumbbell" stabilization system to work) limited resolution to 144 ft.

One other major problem (not technical) had no solution in sight. There was no funding for the reconnaissance satellite program, and chances were slim that any resources would be made available in the coming fiscal year. Yet, in spite of this apparently insurmountable obstacle, the program had been assigned a project number (1115) and a missile system development number (MX-2226), giving it all the trappings, if not the means, of official existence.

VII. Start of Horizon Sensor Development

In February 1954, an engineer working for the Communications and Navigation (C&N) Laboratory approached Captain Coolbaugh with a proposal to develop the horizon scanner that was part of the satellite stabilization system in RAND's Project Feedback report. RAND had received assistance in the area of satellite stabilization from Robert Roberson of the Autonetics Division of North American Aviation, which had provided design concepts for the horizon scanner. The C&N Laboratory at WADC knew of this work, and wished to pursue developing such a device with Autonetics.

Their representative showed Captain Coolbaugh a proposal to initiate a program to develop and test a horizon scanner from Autonetics without delay. The prospect was tantalizing, but Captain Coolbaugh had no option but to admit to the C&N Lab that his new satellite program had no development funds: nor were there any promised soon. He did state, however, that the new satellite program office could grant the authority to go ahead with the program were C&N willing to pay for it. Coolbaugh added that getting involved this way could position C&N favorably on a new program with the highest national priority rating. Besides, if they did not spend the present year's resources in a timely manner, C&N would stand to lose research and development (R&D) funds in the next fiscal year's budget. The C&N laboratory saw the wisdom in this argument, and decided to fund the research at Autonetics. A document containing the specifications for the development project was sent to the Air Force satellite program office for approval, and the new satellite development program was ready for liftoff. (Coolbaugh's talent and strategy for eliciting funds from laboratories is described in detail in his article [3])

Meanwhile, Major Robert Duffy of the Armament laboratory learned of the contract C&N had negotiated with Autonetics, and contacted Captain Coolbaugh about getting a similar contract for the research he was doing with the MIT Instrumentation Lab. Less than a week later he, too, had the approval of his laboratory to use its own funds for satellite research and development, and he was given a work statement similar to the Autonetics one. The satellite program, dubbed Weapons System 117L (WS-117L), had no budget: but it was keeping two contractors busy developing horizon-sensing hardware for an the advanced satellite reconnaissance system. Captain Coolbaugh became the Technical Director of WS-117L in May 1954 when Major Quentin "Q" Riepe was named program manager. Coolbaugh continued to build support for the program by enlisting the assistance of Air Force laboratories at WADC, the Rome Air Development Center (RADC), and the Air Force Cambridge Research Center (AFCRC). He did all this without dedicated government funding; the only money eventually allocated was earmarked for a competition to select a system contractor for the project in fiscal year 1956. In February 1956 the WS-117L program moved from WADC in Ohio to General Schriever's Western Development Division (WDD) in Inglewood, CA. [This location was renamed the Air Force Ballistic Missile Division (AFBMD) on 1 June 1957.]

VIII. Herther Embarks on WS-117L Mission

While on a visit to the MIT Instrumentation Laboratory in early 1955, Coolbaugh learned that three young Air Force reserve officers enrolled in the Air Force master's degree program there were doing theses on his laboratory's horizon scanner program. (The education of these students at MIT was sponsored by the Air Force for 21 months in exchange for a three-year tour of duty after they graduated.) Coolbaugh saw the potential for using these new Air Force engineers on his satellite program after they graduated that spring. He approached Dr. Charles Stark "Doc" Draper, professor of Aeronautics and Astronautics at MIT, to learn more about their backgrounds and individual capabilities. [Draper, called "the father of inertial navigation," ran the MIT Instrumentation Laboratory. It split off from MIT in 1973 and became The Charles Stark Draper Laboratory, Inc. (http://www.draper.com/corporate/profile/docslab.htm).]Draper agreed that it would be to the Air Force's advantage to put his graduate students to work on WS-117L.

Lt. John C. (Jack) Herther, whose M.S. was in aeronautical and electrical engineering (classical control systems), was assigned to Coolbaugh's program at WDD after he graduated from MIT. (One of his roommates, Lt. Malcolm R. Malcomson, was posted to the WADC Armament Laboratory; the other, Lt. William O. Covington, to the C&N Laboratory.)

Meanwhile, Captain William O. Troetschel, who had just finished an electrical engineering course at the USAF Institute of Technology, joined the WADC satellite program office. Troetschel provided the electronics expertise that the office needed, because he had been the chief engineer of a TV station before he was called up for the Korean War. The WS-117L satellite program office now consisted of Coolbaugh, Herther, Troetschel, and the director, Major "Q." Riepe. Whereas Riepe concentrated on program planning and funding, Coolbaugh directed technical operations, with primary responsibility for the booster and satellite vehicles, their propulsion, and the satellite's onboard power. Coolbaugh investigated various power sources and the various labs used their funds to contract with industry before and during the Agena design study competition: Coolbaugh held contracts to develop batteries, open- and closed-cycle chemical power plants and solar cells. He contracted for development of nuclear reactors and radioisotope power plants for satellites through the Atomic Energy Commission. He also shared responsibility for the reconnaissance payloads with Troetschel. Herther was responsible for the guidance, control, and three-axis stabilization subsystems. The dedicated men working on WS-117L were soon dubbed "the Space Cadets," then (as now) a less than flattering moniker. (Dick Leghorn later coined the nickname "Three-Axis Jack" for Herther; he still enjoys it.)

Herther had taken courses at MIT on radar and inertial guidance for aircraft and missiles on classified Air Force contracts, and had investigated on-orbit stabilization and guidance and on-orbit control of military satellites. He and his roommates had researched the RAND Project FEEDBACK Reports for background, and submitted complementary theses evaluating spacecraft guidance and on-orbit control system concepts for the WS-117L project. Their theses proposed placing a satellite in a 300-mile orbit using an inertially referenced, computer-controlled second-stage thruster fired at apogee. The satellite used passive on-orbit gravity stabilization. These proposed concepts would eventually become the foundation for the WS-117L ascent guidance and three-axis passive gravity gradient on-orbit stabilization of Lockheed's Agena spacecraft, implemented for the Satellite and Missile Observation System (SAMOS) and Missile Defense Alarm System (MIDAS) programs.

IX. Ascent Guidance and Control and Three-Axis On-Orbit Stabilization

Figure 4, from Herther's thesis, "A Transitional Control System" [4], was based on a three-gyro/single accelerometer inertial measurement unit (IMU) for a satellite stage ascent guidance transition control system. Inspired by RAND, the system assumed an Atlas first stage. The spacecraft ascent attitude control system used reaction wheels (or gas jets) for roll, pitch and yaw to enable correct control and reorientation while coasting, for accurately adding vernier velocity to achieve orbit, and to initiate Earth-pointing gravity gradient on-orbit stabilization. Roll jets were used during thrusting; the gimbaled engine controlled pitch and yaw.

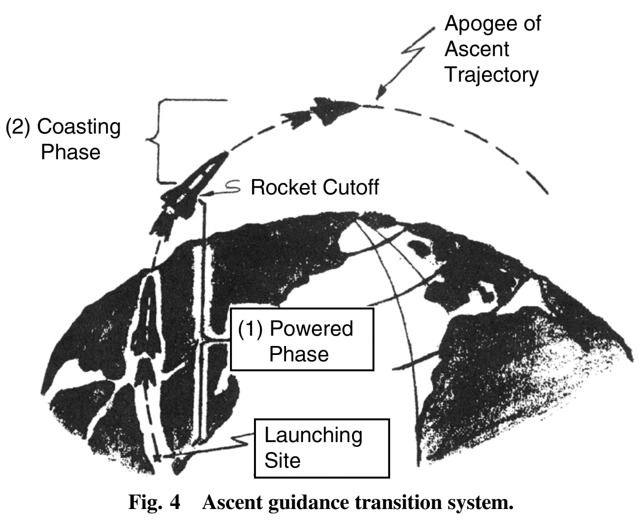

Fig. 4 Ascent guidance transition system.

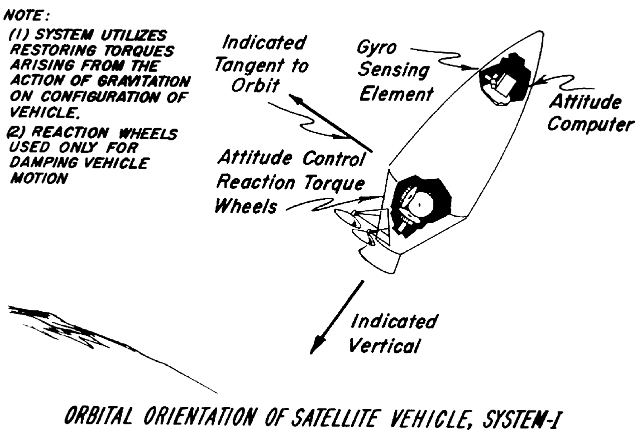

Fig. 5 Axis gravity gradient on-orbit control.

Figure 5, from an Orientation Control System study, shows the three-axis gravity gradient damping system vehicle configuration, which used solar recharged batteries to run rate gyros and flywheels [5]. Because there were practically no disturbing torques for drag-free, high-altitude, visual, and ferret reconnaissance and for the much higher altitude missile warning missions envisioned, this passive technique was used to stabilize the WS-117L Agena's SAMOS and MIDAS payloads.

After a six-month competitive system study, a Lockheed proposal was deemed the "most likely to be feasible." [The contenders were RCA (teamed with Bell Aircraft and North American Aviation), Lockheed (teamed with CBS Laboratories and Eastman Kodak), and Martin (teamed with IBM).] Its visual readout concept used film, which was to be processed and read out on-orbit for transmission to the U.S. ground stations so it could be forwarded for interpretation.

Advancing the project meant testing the Autonetics and MIT horizon sensors, so arrangements were made to do this with the General Mills balloon division. The objective was to demonstrate the horizon sensor's ability to establish a vertical line from the balloon to the Earth's surface, and to determine if it would be accurate enough for satellite use.

Figure 6 shows Herther's test of the MIT horizon sensor during preflight preparations in the General Mills balloon hangar in Minneapolis, Minnesota in mid-October 1955. Engineers are calibrating the infrared sensors used to determine accuracy and the optimum wavelength for sensing the limb of the Earth. (The scanner is located at the top of the tubular gondola.) The test system consisted of the balloon's command radio receiver, recorders, a downward-looking Air Force K-l mapping camera, controls, and a battery pack to power the equipment. The MIT Instrumentation Laboratory and Baird Atomic, the provider of the infrared sensors and test equipment, put this system together. The Autonetics system was also tested on a balloon flight a month later and yielded results similar to those of the MIT system.

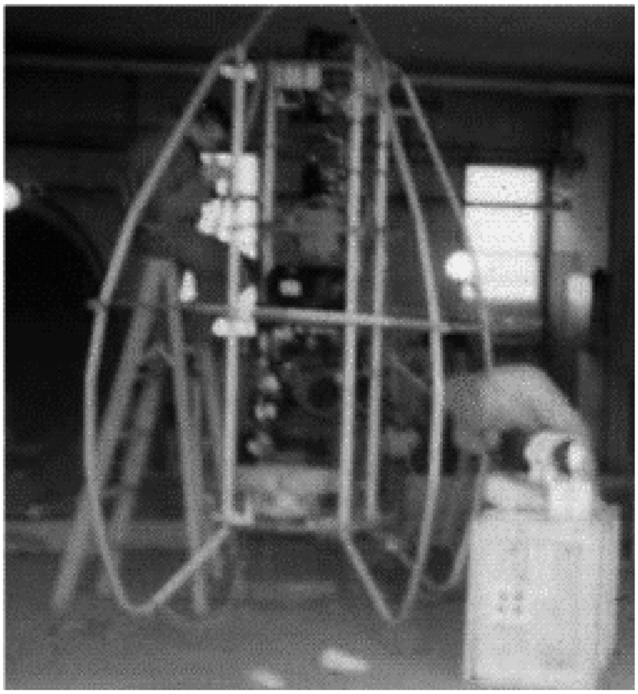

Fig. 6 Flight test of MIT instrumentation laboratory horizon sensor.

The two test flights at General Mills proved that a horizon-sensing system would satisfy the pitch and roll accuracy requirements of a precision ascent guidance system. This meant that establishing any circular or elliptical orbit would be possible, because the satellite stage could be accurately oriented horizontally. The guidance system gyros needed vertical corrections during the flight to orbit because their drift rates could increase significantly during the high-G boost portions of the flight. If not corrected, the gyros would not provide the accurate reference needed to accelerate the satellite stage into the correct orbit. Similar tests were conducted by North American Aviation.

X. Transfer from Wright–Patterson AFB to Western Development Division

Just before these tests the WS-117L program office received word that the satellite program was going to be transferred to General Bernard A. Schriever's organization at WDD in February 1956. Because the Atlas missile was going to be the satellite program's booster, the satellite program office also moved to WDD.

Figure 7 shows the program office and advisory support team shortly after the program's transfer from WADC to General Schriever's ballistic missile development group at the Western Development Division on 4 March 1956, in front of the Ramo-Wooldridge (now Aerospace Corp.) Building on Arbor Vitae, Inglewood, California. Standing, left to right: Capt. William O. Troetschel (Visual and Ferret Payloads, Communication and Tracking Subsystems), Edwin Kolb (WADC/AFRADC), First Lt. John C. Herther (Atlas Interface, Ascent Guidance and On-orbit Stabilization, Agena Airframe and Propulsion Subsystems), Lt. Col. William G. King (former WADC program director), Russell Johnson (AFRADC), James Suttie (AFRADC), Joseph Fallik (AFRADC), Capt. James S. Coolbaugh (Thor Booster), and Capt. Frank S. Jasen (Atlas Booster). Kneeling: Fritz Runge (Atlas Launch Facilities), Capt. Richard P. Perry (AFCRC), Capt. Robert C. Truax (USN WS-117L Program Director, Agena Chief Engineer), Robert Copeland (WADC), Lieutenant Colonel George P. Jones (AFCRC), and Lieutenant Colonel George Harlan (SAC liaison).

Thus began the U.S. Air Force Weapons System 117L Pied Piper program. Its purpose was to develop a strategic satellite system whose primary goal was to devise an orbital TV-readout reconnaissance payload platform. In March 1956, Lockheed won the design competition for the WS-117L and was named prime contractor for the Advanced Reconnaissance System Development Program. The core element of WS-117L was a new multipurpose spacecraft with a boost and maneuvering engine, which would act as the second stage of the launch vehicle as well as the carrier vehicle for the reconnaissance payloads. The Air Force proposal provided for a versatile satellite vehicle (later known as Agena) that would carry payloads for visual readout and ferret for signals reconnaissance, and infrared sensors for missile warning.

With Lockheed as system integrator, the work of the WS-117L program office expanded many times as the emphasis changed from research to the development phase. Navy Captain Robert C. Truax, a protégé of Dr. Robert H. Goddard (known as "the father of modern rocketry") headed the engineering efforts of the program. He entrusted the Air Force WDD subsystem project engineers with full responsibility and authority to produce the system and subsystem development work statements and technical development directives for Lockheed. Each project engineer planned and directed Lockheed

Fig. 7 Original Air Force WS-117L Reconnaissance Satellite Program office and advisors.

(and MIT's Guidance and Control) efforts in designing the Agena for WS-117L payloads according to their own specialty areas and responsibilities. Unlike the Atlas ballistic missile program at WDD, where Ramo-Wooldridge Corporation served as technical advisor, the Air Force engineering officers provided the overall technical direction for the program:

> …Lockheed's 1956 satellite proposal featured a pressure-fed Aerojet General Vanguard rocket engine in the second-stage booster-satellite. By 1957, however, Comdr. Robert C. Truax, USN (the WS 117L project deputy director), and Capt. James S. Coolbaugh, USAF, had convinced leaders of the firm to replace it with a turbo-pump-fed Model 8048 Bell rocket engine rated at 16,000-lb thrust, almost twice that of its pressure-fed alternate. Designed to propel the detachable bomb pod of the B-58 Hustler bomber, the Bell Hustler engine, as it was known, burned a noxious hypergolic combination of unsymmetrical dimethylhydrazine (UDMH) fuel and inhibited red fuming nitric acid (IRFNA) oxidizer. The Hustler engine had been recommended to Jim Coolbaugh in 1954 by Lt. Col. Edward Hall, the Head of the Power Plant Laboratory at WADC, and Bob Truax supported the effort to convince Lockheed to use this engine The engine was Government Furnished Equipment to Lockheed. Later models of the Bell engine were employed in the advanced Agena B that were capable of being reignited during ascent for a second burn. In contrast to single burn, where a satellite separates from the booster and coasts to apogee before its engine is fired, in dual burn, the satellite stage ignites right after separation and burns just long enough to provide a begin-coast speed sufficient for the long, shallow climb required for high efficiency. At apogee, halfway around the Earth, the satellite stage rocket is restarted to provide orbit injection. The greater begin-coast speed afforded by dual burn reduced the amount of propellants required in a satellite stage of a given gross weight, and these weight savings could be exchanged for increased payload [6].

XI. MIT Selected to Develop the Guidance and Control Subsystem

A contractor was needed to develop the guidance and control system. Lockheed was aware that it lacked the needed in-house expertise, but MIT's Instrumentation Laboratory and North American Aviation (NAA) Autonetics Division had it. Dr. Draper's reputation in inertial guidance and the availability of his associate director, Dr. Joe DeLisle [DeLisle is known as the father of the Navy's Submarine Inertial System (SINS)] as project engineer made MIT the stronger contender by far for this award. DeLisle's expertise and low-cost development approach (given the paltry WS-117L budget) offered the USAF a cost advantage. DeLisle's idea was essentially to scale down the performance and weight of the inertial measurement unit (IMU) from SINS, the system he had developed and recently turned over to Sperry for production. This would require only a small engineering staff. After vetting both choices, the Air Force awarded the sole-source contract for the spacecraft guidance and on-orbit control to MIT.

The MIT contract required building the first few systems and was run on a shoestring. It did not issue formal written reports, but relied instead on progress report letters. The only documentation for the project were MIT master's theses and briefing aids, and engineering drawings and manufacturing data. A few visual aids from the MIT Instrumentation Lab's October 1958 briefing included here provide examples of what was used for briefings at the time of final design review for Air Force and Lockheed approval for Agena integration. The charts, once classified information, show the fundamentals of the WS-117L ascent guidance and Orbital Attitude Control System (OACS).

XII. The Science Behind the Rocket

The WS-117L guidance equations show time-to-fire third stage (Atlas Stages Two included boost and sustainer plus Agena) and control equations for Agena's three-axis inertial active powered ascent-to-orbit control. The ascent guidance top-level physics-based equations were as shown in Fig. 8.

The IMU three-axis data were fed into an analog computer to command the gimbaled engine and roll gas jet controls (see the detailed hardware diagram, Fig. 9, the block diagram of the implementation of Herther and Malcomson's thesis, showing the Hustler engine cutoff command and steering signals). The digital MIT-designed Atlas ICBM guidance system computer required a memory capacity of only around 500 bits with 400 arithmetic

WS-117L GUIDANCE EQUATIONS

CONTROL

$$W_x = 0$$

$$W_y = S(K_1\bar{Q}_T - K_2\dot{\bar{V}}_g) \times \bar{V}_g \cdot \bar{j}$$

$$K_1 + K_2 = 1 \qquad \dot{\bar{V}}_g = -\bar{a}_T - Q\bar{V}_g$$

$$W_y = S(-\dot{\bar{V}}_g - K_1 Q\bar{V}_g) \times \bar{V}_g \cdot \bar{j} \quad \text{(Pitch)}$$

$$= S\{-V_{gx}[K_1(QV_{gz}) + \dot{V}_{gz}] + V_{gz}[K_1(QV_g)_x + \dot{V}_{gx}]\}$$

$$W_z = S(-\dot{\bar{V}}_g - K_1 Q\bar{V}_g) \times \bar{V}_g \cdot \bar{K} \quad \text{(Yaw)}$$

$$= S\{V_{gx}[K_1(QV_g)_y - \dot{V}_{gy}] - V_{gy}[K_1(QV_g)_x + V_{gx}]\}$$

TIME TO FIRE THIRD STAGE

$$t_3' = t_3 + a(t_B' - t_B) + b(t_S' - t_S) + C$$

$$t_3' = (t_3 - at_B - bt_S + C) + at_B' + bt_S'$$

PRIMED t's ARE ACTUAL TIMES OF ENGINE CUT-OFF.

UNPRIMED t's ARE PROGRAMMED TIMES OF ENGINE CUT-OFF.

Fig. 8 Agena ascent-to-orbit guidance equations.

operations per second. (An analog computer shown in Fig. 10 was adequate for Agena).

The gyrostabilizer was a gyroscope used in such a way that it not only sensed rates, but also supplied torques directly to the vehicle to be stabilized. The angular momentum equations were instrumented using two gyrostabilizers rotating wheels gimbaled in such a way that the spin axis of the wheel, which defined a characteristic angular momentum vector, could precess about an axis (the output axis) normal to the spin axis in response to angular rates about a third axis (the input axis) mutually perpendicular to both the spin and output axes. Damping of gimbal precession rates would be present as well as spring restraints about the output or precession axis.

The satellite OACS performed damping and stabilization equations, shown in Fig. 11. It began functioning when the satellite was injected into a desired orbit at a prescribed altitude. Figure 12 shows the overall ascent guidance and on-orbit gravity stabilization system. It had to settle with the axis of least inertia along the vertical and the axis of maximum inertia normal to the orbital plane, and hold this position during small torque disturbances.

An unequal moment-of-inertia configuration in the ratio of 10.6:10:1 is shown in Fig. 13. A fast settling time might not be compatible with a system that remained unperturbed in the presence of large disturbances. Because settling was brought about by the relatively small transient damping devices and there would generally be satellite position and rate errors when it was first injected into orbit, the satellite would not start out perfectly aligned to the vertical. A short settling time was a mission requirement. Small disturbances (for example, from micrometeorite impacts or internal mechanical reactions) could cause vehicle offsets, in which case a similar settling time would again be required for the gravitational-gradient torque to position the vehicle in the desired nose-down attitude within its desired specified error.

Early in the design of the SAMOS E1 and E2 visual reconnaissance payloads, Jim Plummer (In 1989, Plummer was named one of the ten original Air Force Space and Missile Pioneers. More history on him and other pioneers is at http://www.peterson.af.mil/hqafspc/history/plummer.htm), Lockheed's Payload Integration engineer, indicated that it would be essential for payloads to fit inside the truncated conical forward instrument section of a down-looking vehicle. Lockheed's SAMOS Subsystem contractor, Eastman Kodak, did not want their sensitive strip camera optics mounted near the rear downward-pointing engine because of the excessive vibration during thrusting on ascent into orbit. It was therefore necessary for the vehicle to be reoriented to a nose-down design, yet still be gravity stabilized. Previous orientation concepts for gravity gradient stabilization always had the heavier engine end pointing toward the Earth to ensure that the center of gravity created the maximum stabilizing restoring torque. RAND had the TV aft, as shown in the earlier MIT thesis configuration. Figure 14, representing the MIT/Lockheed coordinated design, shows that an alternate mass distribution configuration could be achieved by extending the helium spheres. Early designs had three flywheels, not two.

XIII. Evolution of the Agena, CORONA's Spacecraft

The Agena was an upper-stage booster satellite vehicle whose 5-ft-base diameter allowed it to be boosted by USAF ballistic missiles because they all had a 5-ft-diam at the interface. This was the diameter of the atomic warhead nosecone. Robert Powell's article quoted with the article's Figs. 15–18 describes the detailed functioning of the Agena Guidance and Control subsystems. All of the functions described were originally in the Agena A. They eventually integrated the AGENA into a single standardized package to reduce cost as the Agena evolved into its final high-production-volume version, the Agena D.

A. Guidance System Module

The Agena guidance and control system (Fig. 16) was designed to perform autopilot and flight-event programming functions in ascent and on-orbit flight modes. From the beginning, the basic Agena

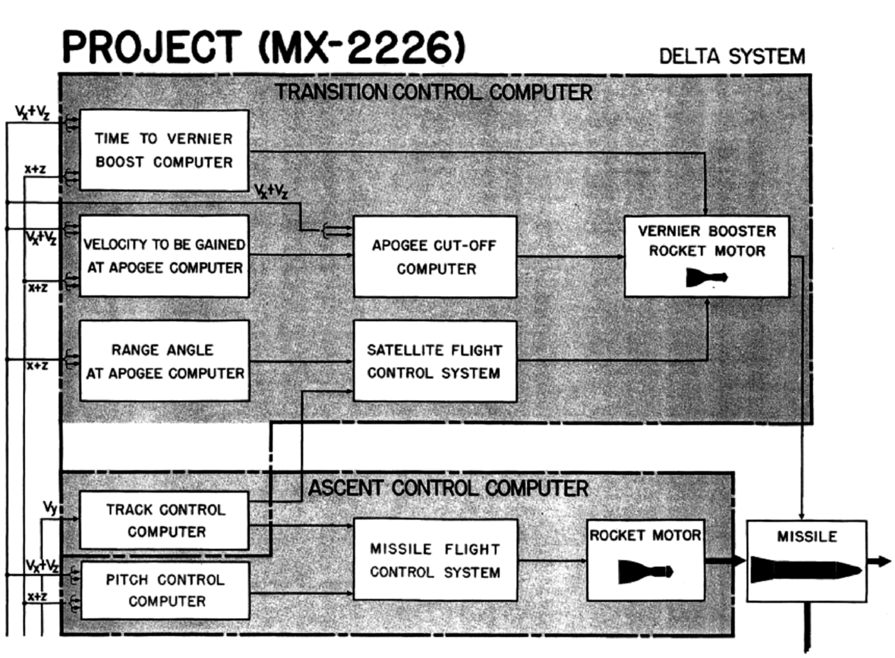

Fig. 9 Transition control computer block diagram.

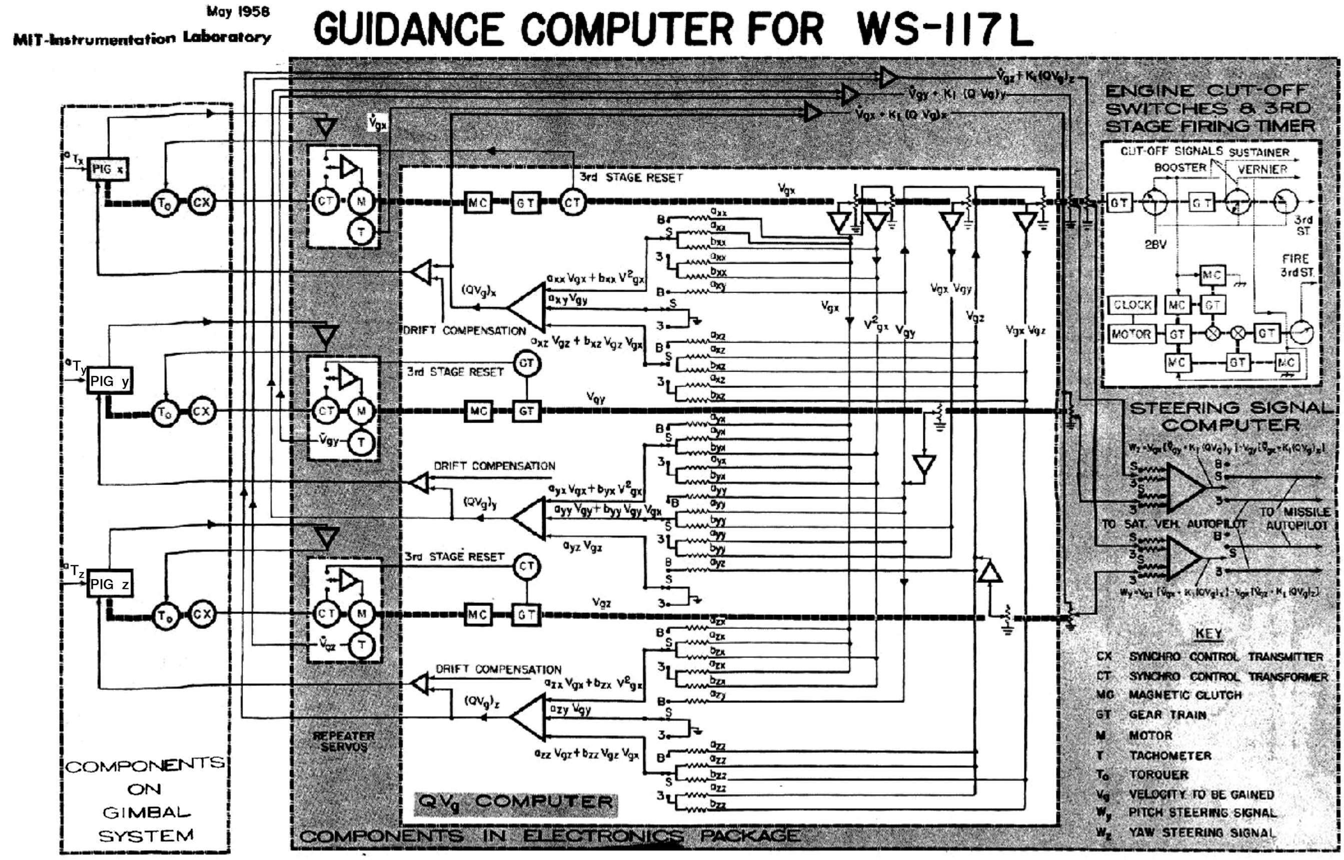

Fig. 10 Agena analog guidance computer.

WS-117L OACS EQUATIONS

$$H_{MY} = I_{WY} \frac{S_Y}{p + \frac{1}{T_Y}} W_Y \qquad M_X = -3W_O^2 (I_Y - I_Z) A_X$$

$$M_Y = -3W_O^2 (I_X - I_Z) A_N$$

$$H_{MZ} = -I_{WZ} \frac{S_X}{p + \frac{1}{T_Z}} \qquad M_Z = 0$$

Where
S_Y and S_X are sensitivities
T_Y and T_Z are the lag time constants of pitch and roll-yaw channels, respectively

I_{WY} and I_{WZ} are the moments of inertia of the pitch and yaw flywheels, respectively

Where
W_O is orbital rate
I_X, I_Y, I_Z are vehicle moments of inertia

A_X and A_N are angles between vehicle axes and reference axes

Fig. 11 Orbital Attitude Control System (OACS) equations.

subsystem was common to all mission applications. Its attitude-sensing elements consisted of a three-axis, body-mounted gyro reference system and a pair of horizon sensors, an integrating accelerometer to sense vehicle accelerations, a flight-control electronics system and sequence timer to perform logic and sequencing functions, a cold gas jet system for vehicle attitude control during coast periods and for roll control during engine burn, and hydraulic actuators to gimbal the main rocket engine nozzle during engine burn periods.

All of the sensing and logic elements for the Agena guidance system were packaged in a single guidance module that was installed in the forward equipment racks to facilitate handling, checkout, and alignment. Included in the module with the reference components were the flight-control electronics and J-boxes. The control components (gas jets, hydraulic actuators, and their associated parts) were electrically connected to the guidance module. This unitized guidance package (common to all Agena configurations) was in Agena D, the production model. The unitized packaging concept simplified procedures for the factory-to-launch sequence. The unit "plugged into" the Agena forward rack, complete with the horizon sensors. The gas jets and main engine gimbal actuators were separate.

B. Attitude-Sensing Function

The basic attitude sensor was the three-gyro inertial reference package (IRP) built by Minneapolis–Honeywell. It contained two hermetic integrating gyro (HIG) units to sense pitch and yaw, and one miniature integrating gyro (MIG) unit to sense roll and acting as a gyrocompass for yaw angle. The pitch and roll gyros were torqued by signals obtained from two Barnes Model IIA infrared horizon sensors. For Agena's first burn, the yaw reference was established by the booster attitude at burnout. For long coast periods (15 min or more), the technique of gyro compassing was employed to establish

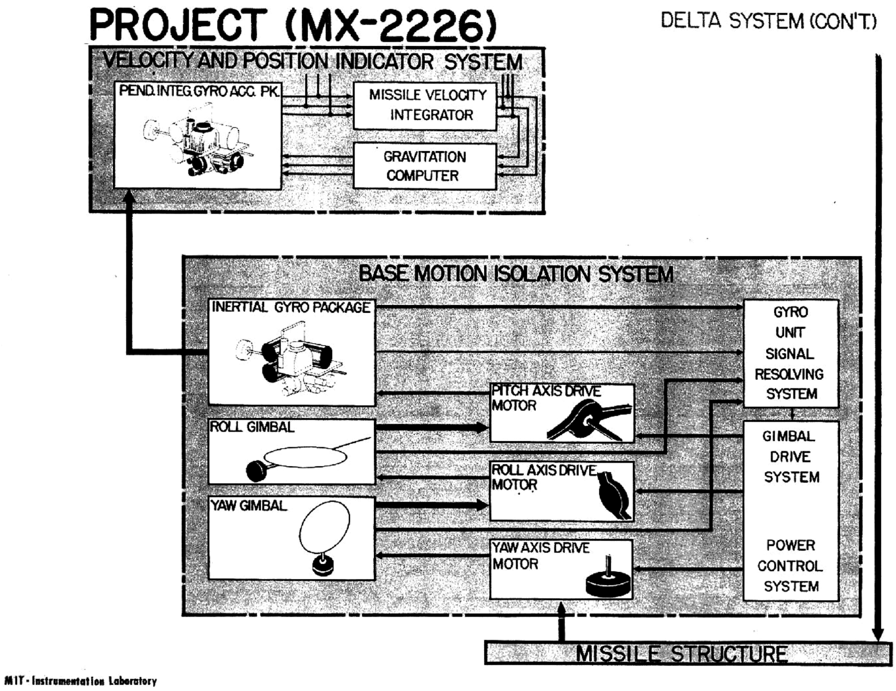

Fig. 12 Overall ascent guidance and gravity stabilization diagram.

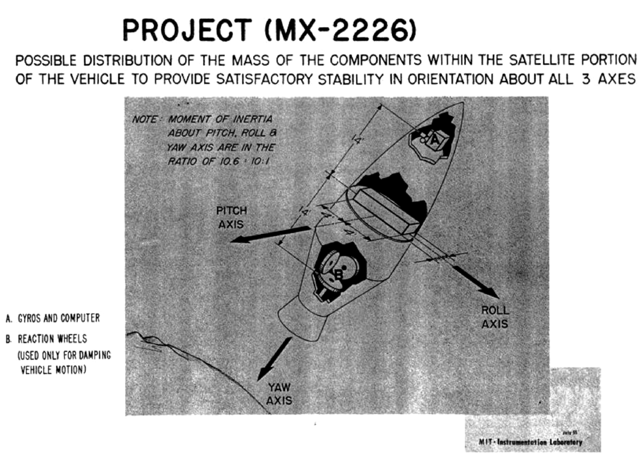

Fig. 13 Gravity gradient three-axis stabilization with three flywheel damping.

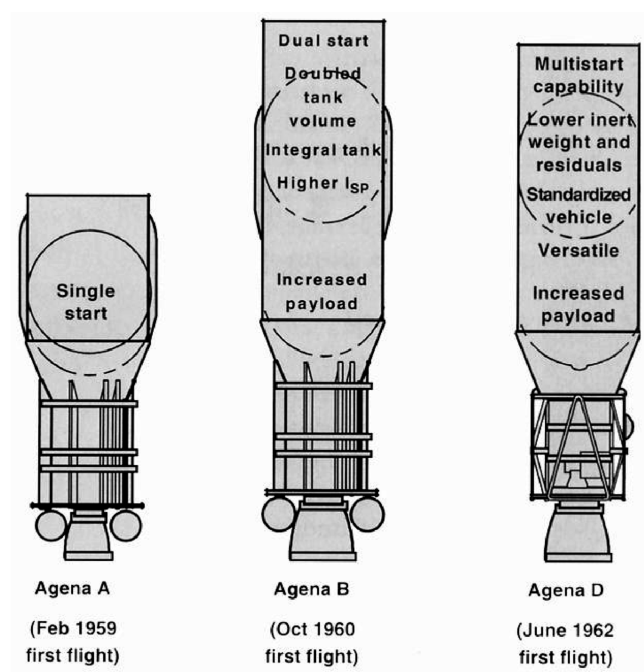

Fig. 15 Agena configurations [7].

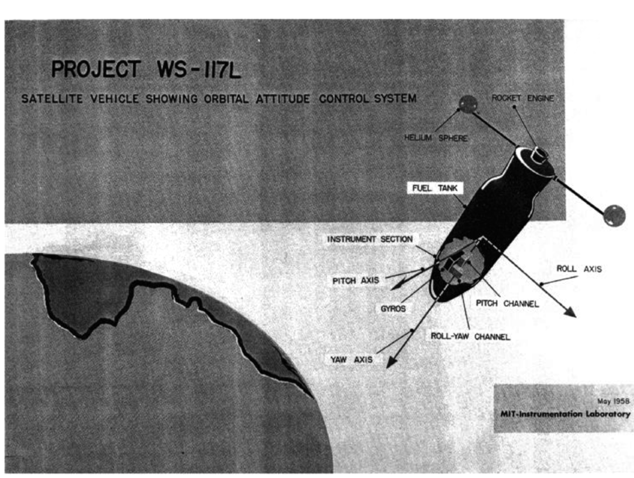

Fig. 14 Nose-down SAMOS/MIDAS Agena OACS.

the yaw reference. Control moment gyrocompassing (CMG) oriented the vehicle to an orbit plane yaw reference by detecting a component of the programmed pitch rate through the roll horizon sensor. The geocentric pitch rate (typically 4 deg / min for a low-altitude orbit) was programmed as a constant torque to the pitch gyro. If there was a yaw error, this pitch component would be sensed differentially when compared with the roll components of the two horizon sensor heads. The differential would be seen as a function of yaw error. The roll output was separated into a constant yaw-induced angular error and a normal roll oscillation by integrating the output over time. The roll-error component caused by yaw was fed as a torquing signal to the yaw gyro, the output of which then corrected the vehicle's yaw orientation.

The booster's radio guidance system sent commands to the Agena to either start the primary timer (for Atlas flights) or to reset it (for

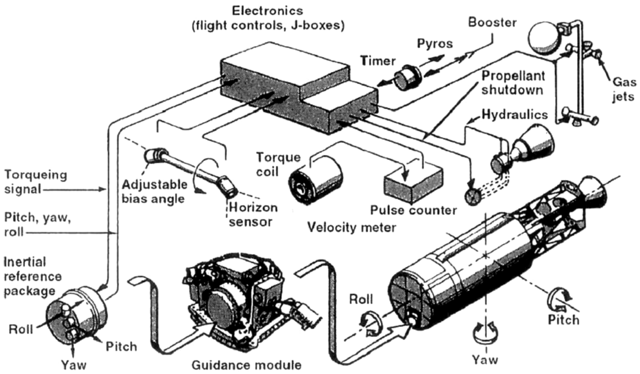

Fig. 16 Overall functional diagram of Agena guidance control [7].

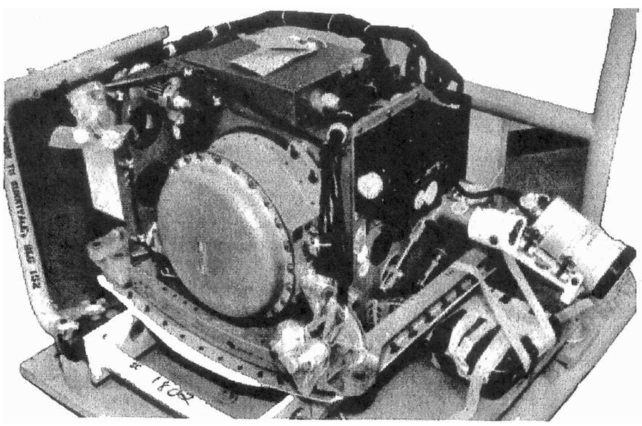

Fig. 17 Agena guidance and control IMU module [7].

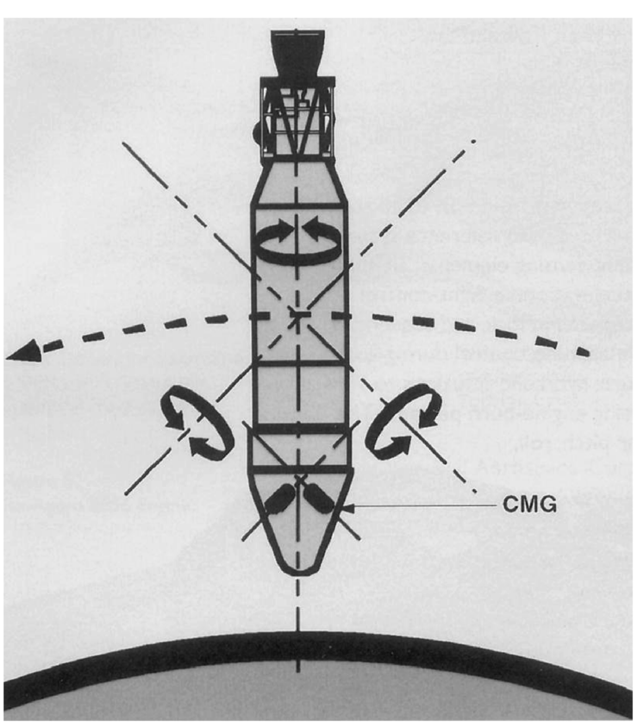

Fig. 18 Gravity gradient stabilization.

Thor flights). The timer was a resettable electromechanical device that had a running time of 6000 s and was capable of programming 24 events. It was used during ascent to provide separation signals, engine start commands, change in pitch rates, and other events required by the Agena or the mission profile.

C. Velocity-Sensing Function

A single-axis velocity meter built by Bell Aerospace Corporation was used to measure the velocity changes imparted by the Agena propulsion system and to shut the engine down when it reached the proper speed. The velocity meter consisted of a pendulous torque coil that detected acceleration on the longitudinal axis that would cause the coil to move off-center. The coil was returned to center by a series of electrical pulses proportional to the acceleration. These digital pulses were summed in a binary counter to determine the integral of acceleration, or velocity. The digital pulses from the accelerometer were used to count down from the preset binary number representing the desired velocity increment. Two such binary numbers were preset in the velocity meter. These numbers represented the predetermined velocity increments required for first and second burns, if required. When the prescribed speed was attained, the counter registered zero coincidence and a signal was given to close the propellant shutdown valves.

D. Gravity Gradient Stabilization

When placed in a nose-down position on orbit, the Agena was essentially gravity gradient stabilized by virtue of its moment-of-inertia distribution (Fig. 18). However, some form of damping was required to nullify oscillations that could build up to appreciable amplitudes as a result of the local gravity-field restoring torques. An active damping system employed control moment gyros (CMG) that damped out vehicle oscillations before they reached sizable amplitudes.

Stabilization evolved from SAMOS to Corona/Agena. Because SAMOS was originally designed for long-life missions at an atmospheric drag-free altitude of 300 miles or higher, plans called for the SAMOS Pioneer Agena to employ gravity gradient stabilization. That is, the vertically oriented Agena moved in orbit with its fixed, nose-mounted Eastman Kodak strip camera pointed toward the Earth, thus aligning the long axis of the satellite's mass distribution radial to the Earth. The gravity gradient stabilization scheme eliminated the expendable weight required for gas jets in Corona (and has been used since in other satellites). With the gravity approach to stabilization, only electrical power (which could be supplied by solar cells) was required for momentum wheel damping with rate-sensing gyros.

The three-axis attitude control system designed to meet the horizon sensor-referenced vertical pointing and stability requirements for a long-life SAMOS reconnaissance mission at an altitude of 300 miles proved readily adaptable to a short-life, higher resolution CORONA reconnaissance mission. The horizon sensors' original purpose was to ensure accurate ascent into orbit. Corona used an active on-orbit control stabilization technique. The Agena operated in a horizontal position with respect to the Earth at about 100 miles altitude, with the ascent guidance IRP consisting of the three ascent guidance gyros, two horizon sensors, and proportional (later pulse) micro-jets using cold gas (a nitrogen-freon mixture) which provided attitude control for the Agena and its oscillating panoramic ltek camera. Two hermetic integrating gyro units sensed pitch and roll, and one miniature rate gyro unit determined yaw error by sensing orbital rotation rate. The pitch and roll gyro errors were corrected from the horizon sensors. The gas jets were activated by signals from the IRP. The early attitude control system sensed vertical attitude to approximately one-tenth (0.1) degree accuracy and provided a yaw pointing accuracy on the order of 1 deg, adequate for SAMOS and CORONA cameras [as shown evolving in Table 1 (author's note)]. The corresponding rate gyro sensing threshold was approximately 17 μrad/ sec, quite adequate for blur control sensing. Later Earth-viewing payloads with narrow view angles and longer

Table 1 Characteristics [7]

System	No. of gyros	Gyro weight	Power	Rate threshold	Attitude accuracy altitude, n miles			Flight experience
					300	500	2000	
Mod I	4	16 lb	7 W	0.75 deg /h	7 deg	2.5 deg	3 deg	11 flights
Mod II	2	22 lb	10 W	0.01 deg /h	5 deg	0.5 deg	1 deg	To fly late 1964

focal lengths required better stabilization and pointing to achieve improvements in resolution on the order of inches.

The number of pulses (at a specific thrust level) fired by a gas jet or set of gas jets was proportional to the magnitude of the disturbing torque, and sufficient to cancel the momentum without overcorrecting or undercorrecting. For the early proportional control gas jets, the thrust level varied in proportion to the magnitude of the disturbing torques. Subsequent Agena attitude control systems were improved with sun and star trackers to meet more stringent demands.

XIV. Discoverer-Thor/Agena: Selecting a Launch Site

The Agena needed to be boosted into a near-polar orbit in a southerly, slightly easterly direction from a West Coast launch site. This pointing was necessary for Agena to achieve an 83-deg retrograde orbit that would cover the Soviet Union's high-latitude areas. This created range safety issues: an off-course launch might turn the Thor/Agena into a short-range ballistic missile aimed in the direction of Los Angeles. The decision to assume this risk was relayed all the way up to the Secretary of the Air Force. Herther briefed AF Secretary Donald Quarles on the orbital mechanics underlying the calculation, and showed that launching in this direction was operationally absolutely necessary to obtain high-latitude illumination over a one-year mission life.

Quarles approved the risky decision based on Herther's explanation of the physics involved. Meanwhile, Truax and Coolbaugh, as part of their monthly B-25 proficiency flying, pinpointed the ideal spot for the polar launches, on the south side of the Army's Camp Cooke on Point Arguello, around 55 miles from Santa Barbara, California. The Camp Cooke site had Navy radar tracking facilities, and the Air Force was authorized to build a launch base for satellites there. Figure 19 shows one of CORONA's 144 Thor/Agena launches. The site is now known as Vandenberg Air Force Base. [The alternate launch site selected (near Santa Cruz) eventually became Lockheed's Santa Cruz Test Facility, where the Agena vehicle was "hot" fired as part of its prelaunch validation. Truax and Coolbaugh were actively involved in locating this site as well. See Coolbaugh [3] for more detail.]

XV. Hi-AC Genesis

CORONA's Itek-proposed high-resolution camera needed to be three-axis stabilized to accommodate image-motion compensation and still remain stable throughout long exposure times. It would be necessary to use slow, high-resolution film to take high-quality photographs in orbit.

Fig. 19 Thor-Agena launch from Vandenberg (Lockheed Horizons).

The Boston University Physical Research Laboratories (BUPRL) had had experience throughout the 1950s in designing and building special mission aerial reconnaissance cameras for the Air Force. Headed by Dr. Duncan McDonald, it had pioneered the use of very long-focal-length side-looking airborne cameras for high-resolution aerial photography early in the Cold War. Merton Davies and Amrom Katz of RAND had encouraged BU's photographic subsystem manager, Walter Levison, to adapt the concept of the panoramic camera to long-focal-length lenses for high-altitude photography in connection with Balloon Reconnaissance Project 461L. This unique camera design had existed since the 19th century and had been used mainly for large group photographs. Air Force Colonel Richard W. Philbrick, working at the BUPRL in 1949, had already synchronized film with a rotating cross-track scanning lens as a panoramic camera in such a way as to provide horizon-to-horizon coverage. He had once used this camera to photograph the entire length of Manhattan, a shot which made the cover of LIFE Magazine. It therefore seemed possible to maintain the high static lens/film resolution in orbit in the presence of cross-scan torques. But actually achieving high-resolution images was problematic, largely because of the need to minimize blur.

At a meeting at Boston University in early 1957, Davies and Katz met Walter Levison of the BUPRL. He described for them the wide-angle, high-resolution camera he was working on for use in balloons. His plan was to use 70-mm film held by a curved platen with a 12-in radius using an f/3.5, 12-in focal-length lens that covered an angle of around 120 deg. (The mechanics of this process is described in detail in Smith's 1972 LIFE article [8].) Several weeks later, at another professional meeting, Davies and Katz learned of a different design by the Fairchild Camera and Instrument Corporation (Fairchild). The Fairchild camera rotated in one piece and a slit served as a focal plane shutter to create the exposure while scanning during the lens cross-track rotation.

Levison had another idea. He thought it would be possible to take a wide-angle picture on-axis with a diffraction-limited lens with high optical resolution by panoramically scanning across the flight path using a narrow-angle lens with a field flattener. This would not require film synchronization. Only the rear nodal point scanning lens and the slit through which the camera snapped the picture would move, rocking back and forth like a pendulum around an axis. Katz dubbed Levison's high-acuity camera the "Hi-AC" (The Hi-AC camera is spelled more than one way in the literature. In quotations or figures in this paper it is also referred to as *HI-AC* or *HY-AC*. The Smithsonian spells it *Hi-AC*: See also http://www.si.edu/archives/ihd/videocatalog/9536.htm), because his design was the first camera to achieve 100 lines per millimeter resolution during the 1957 high-altitude balloon tests. (The resolution of WWII photography had been only 10 to 15 lines per millimeter.)

XVI. Briefings, Choices, and Decisions

Several months earlier, in May 1957, the Air Force WS-117L project office had briefed Secretary of the Air Force Donald Quarles and his staff on their activities. This meeting had been considered important enough for Dr. Draper of MIT to accompany Jack Herther (who was making the guidance and control presentation) to back him up, particularly on the matter of passive gravity stabilization for SAMOS. The MIT Instrumentation Lab brought a prop to the briefing for illustrative purposes. [It had become obvious during Coolbaugh's experiences in attempts to obtain funds (or in his experience reviewing industry proposals) that good props are very effective, important, and influential tools for understanding new physical principles and for convincing an audience of the proof of a principle or the value of a project.] A model of a dumbbell on a rotating arm illustrated the principle that, when the center of gravity and the center of mass do not coincide, a restoring torque is created which is similar to a satellite's vertical restoring torque. The dumbbell was mounted slightly offset on jeweled pivots and, when rotated horizontally on an arm, it tended to line up radially and oscillate, explaining the need for a rate damping system. Herther used an example (the moon) as physical proof that the gravity gradient principle works, because the moon's face always points toward the Earth. It was thought the active flywheel damping concept used in the Agena would settle quickly (compared to the moon): within a few orbits, at worst, if no other significant disturbing torques were present.

The overall WS-117L program, including Herther's theories on guidance and control, was briefed in May 1957 to President Eisenhower's Science Advisory Committee (which included Dr. James Killian, president of MIT, and Dr. Edwin "Din" Land, president of Polaroid). This briefing of the status of the WS-117L visual payload was probably the reason for Air Force Secretary Quarles' go-slow decision, and the shift to accept RAND's recommendation to use available ICBM warhead technology for a film recovery system rather than the TV data readout data link, the limiting technology of the current WS-117L program.

Although the Air Force was not participating in the International Geophysical Year (IGY, whose mission was "to observe geophysical phenomena and to secure data from all parts of the world"; NAS IGY Program Report, cited on http://www.nas.edu/history/igy/), General Schreiver sent Herther to brief the Naval Research Laboratory (NRL) in May in the spirit of inter-Service cooperation. The NRL was conducting the U.S. Navy spin-stabilized Vanguard satellite project in conjunction with IGY activities. Herther gave the NRL personnel and contractors a briefing similar to the one he had delivered to the Secretary of the Air Force, and he learned in turn about the NRL's progress with the Vanguard IGY satellite.

On 14 August 1957 Herther, again representing General Schriever, presented a technical briefing on WS-117L in Washington, D.C. to the DoD's Ad Hoc Committee on Basic Problems in Aeronautics. In late August he gave another technical progress briefing to the NRL on the MIT/Lockheed project . Herther was not then aware of the NRL's plans for a satellite-based navigation system (i.e., the Transit program), and had no idea that their intention was to use gravity gradient technology to stabilize these future satellites. [The NRL later invented the two-axis gravity gradient stabilized Transit navigation satellite which, unlike the MIT active design (which used gyros and flywheels) was completely passive, damped by using a "lossy" hinge as its antennas unfolded when deployed in orbit. Keeping Transit's broadcast antennas pointing downward did not require a particular yaw alignment in the velocity vector direction. The MIT three-axis Agena passive gravity gradient restoring design had a particular unsymmetrical inertia ratio, which would also settle out the yaw attitude, aligning the roll axis to the velocity vector in the orbital plane. The WS-117L Earth observation payloads all required a yaw alignment of the velocity vector to the orbital plane at the required yaw accuracy as determined by each payload's sensors to relate to the Earth's geography.]

Meanwhile, during the summer of 1957, Lockheed's development of Project WS-117L was only inching forward, mainly because Secretary Quarles' go-slow order had halted progress [9]. By the end of the summer, the TV visual reconnaissance readout WS-117L was still underfunded. RAND had questioned the technical feasibility of providing the necessary national intelligence soon enough because of the lack of state of the art bandwidth needed to transmit the TV data. RAND instead proposed a recoverable film approach, and went on to suggest the SpinScan spin-stabilized camera design which the CIA was actually in the process of putting on contract. Because Herther was unaware of this at the time, the future of the WS-117L three-axis Agena project seemed bleak to him. As a result, in August, Herther, had already obtained approval from the Air Force to reenter the Ph D. graduate program at MIT in the fall semester, and planned to do so.

Earlier, in the spring of 1957, Jim Coolbaugh was transferred to the Thor missile program. He was assigned responsibility for the airframe and the rocket propulsion system. When the Thor was selected to be the Agena's booster, he was responsible for the modifications made to the missile to adapt it for that mission. Later, he was the AFBMD technical representative to Vandenberg AFB for the installation of the launch pads for Thor/Agena and for monitoring the Thor's performance during the satellite launches.

XVII. Itek Becomes Part of the Picture

Around this time, Herther met with Richard Leghorn (Leghorn had been Chief of Intelligence and Reconnaissance Systems Development at the Pentagon, and has been called a "true visionary in the field of airborne and space reconnaissance developments"; his achievements included origination of the open skies concept. He was a consultant to the USAF Scientific Advisory Board, and Special Assistant to the President for Disarmament Affairs; http://www.nro.gov/corona/pioneers.html), a specialist with a long history in aerial reconnaissance who, along with Dr. Macdonald, had attended many of his WS-117L briefings. He learned that Leghorn was forming a company, Itek, dedicated to information technology and space reconnaissance. Other principals of the company were Dr. Arthur Tyler (also an Eastman Kodak officer) and Dr. Duncan Macdonald of BUPRL.‡ (BUPRL was being closed; Leghorn's new company, Itek, would take it over, absorbing its employees and projects, including Walt Levison's Hi-AC I high-resolution balloon camera.) Leghorn and his colleagues believed there were weaknesses (a short focal length and no image-motion compensation) in the original RAND Katz–Davies (SpinScan) camera proposal and were convinced that a better solution could be found for high-resolution satellite reconnaissance photography‡.

Herther was unaware that Leghorn and Macdonald were familiar with RAND's film satellite concept, and that they had already discussed it with the CIA. The RAND concept, the earliest (and a more simple) spin-stabilized film return system, incorporated the recoverable SpinScan camera pod and was to be launched by a Thor/Able rocket. Leghorn and Macdonald were aware that Project WS-117L was not funded and that Herther planned to return to MIT for a doctorate.

In a surprise move, just as Herther's orders to return to MIT were about to be implemented in late August 1957, General Osmond Ritland refused to release him from his assignment on WS-117L in order to assign him to work on a "high-priority national program." The logic of this escaped Herther, given that the WS-117L project had been stalled and, since its inception, had received only $3 million out of the $100 million funding it had requested.

In yet another twist, these very funding problems again affected Herther's immediate future with the Air Force. Headquarters personnel were implementing a DoD-wide reduction in force and, despite General Ritland's original orders that he remain with the WS-117L program, Herther received a telegram direct from the Air Force personnel office in early October offering an early release (5 December 1957) from his three-year tour of duty contract.

On 27 September 1957, Richard Leghorn and his partners incorporated Itek. The Soviet Union launched Sputnik just a week later. Leghorn, who had been trying to raise venture capital for Itek, received seed money from financier Laurance Rockefeller, and Itek opened for business on October 10. (In a review of Jonathan Lewis's "Spy Capitalism," http://www.cia.gov/csi/studies/vol47no1/article08.html, CIA historian David Robarge made the point that, besides the start-up challenges facing any new company, Itek had to find investors who were willing to fund a company without knowing exactly what the company was doing .) Later that fall, Leghorn negotiated a subcontract for Itek with Ramo-Wooldridge Corporation to develop and manufacture equipment to process and catalogue the images produced by the WS-117L readout reconnaissance satellite.

‡From Don E. Welzenbach's (retired CIA historian) draft (unpublished, untitled) biography of Richard S. Leghorn.

CIA historian Don Welzenbach's description of Leghorn's meeting with Doc Draper about Herther provides context for the events of that time[‡]:

> . . .Although the infusion of money from the small CIA/SEI contract (on stealth overflight technology) gave Itek some breathing room, Leghorn had to find more substantial work and money for his firm. Inasmuch as he was working as a contractor for the CIA, Leghorn was aware not only of the GUSTO project to develop an ultra-high-speed reconnaissance aircraft, (the CIA's A-12, a later-larger version known as the Air Force SR 71) he also knew more about the Pied Piper/WS-117L and the project the Air Force wanted to split off for launching a film-based photo satellite. Upon his return from California in early October, Leghorn told Duncan about the Katz-Davies (RAND) SpinScan proposal and pointed out its weakness, a short focal length and absence of image-motion compensation. Figure 20 shows the trajectory from launch to the photo operation orientation of the Spinscan over the Soviet Union mid-latitude and also internal vehicle camera pod details. Both Leghorn and Macdonald were convinced there was a place for Itek in developing a better reconnaissance camera system.
>
> Later that month, Leghorn visited with MIT's famed professor of aeronautics, Charles Stark Draper, to discuss a briefing given by one of his Air Force graduate students, Lieutenant John "Jack" Herther, who was responsible for the WS-117L Lockheed Agena Ascent Guidance and Control and On-orbit Stabilization and also had the development contract with the Instrumentation Laboratory. At the time, Herther was investigating and evaluating various methods for stabilizing spacecraft. His current approach was to control all three axes—pitch, roll and yaw for ascent guidance—and in order to achieve what Herther referred to as a "stable table" on orbit, he proposed using essentially the ascent inertial guidance system referenced with horizon sensors to keep the spacecraft in a stable relationship with the Earth. If this could be achieved, spin stabilization would become a thing of the past. This was possible because the DISCOVERER program's recoverable mission was short and gravity gradient stabilization wasn't needed, as it wasn't for a long duration for visual reconnaissance TV/ readout or other mission operation.
>
> A light went on in Leghorn's head: if a spacecraft did not have to be spin stabilized, then a different type of camera could be employed, one that would always be pointed at the Earth and allow IMC (image motion compensation). Such a camera could have a longer focal length and image-motion compensation, permitting slower-higher resolution films, which would produce much better images. As soon as Leghorn returned to Itek headquarters he told Macdonald about Herther's efforts. Both men agreed the stable-table idea was a development of great importance for controlling spacecraft. They decided immediately to offer Jack Herther a job at Itek and he became the first Itek employee. Macdonald had just the camera for such a space platform; it was one the Boston University Physical Research Laboratory (BUPRL) had designed several years earlier for a second Air Force balloon reconnaissance program called WS 461L (Genetrix). Boston University Physical Research Laboratory (BUPRL) employee Walt Levison, who had worked with Leghorn, Macdonald, and Katz photographing the 1946 Bikini nuclear tests, designed that camera in 1956. Levison had adapted a 19th century panoramic camera design, originally used to make photographs of large groups of people at graduations and reunions, so it could be pointed at Earth. Its 12-inch lens pivoted in an arc and focused an image on a curved surface of 70-millimeter-wide, very fine grain high contrast Kodak Microfile film.
>
> This camera produced such a remarkably sharp image that Amrom Katz dubbed it the "HI-AC I" camera because of its high acuity. Figure 21 shows camera photograph in Smithsonian. BUPRL manufactured 40 of these units during 1957, three of which were launched by huge balloons and allowed to drift across the Soviet Union, from east to west. (Not one of them was recovered. The remaining units were adapted for use in aircraft.)

Leghorn later met with Harold C. Casey, BU's President, who was

> . . .now intent on divesting the university of the formerly Air Force-funded enterprise. . . (H)e arranged to acquire for Itek the entire

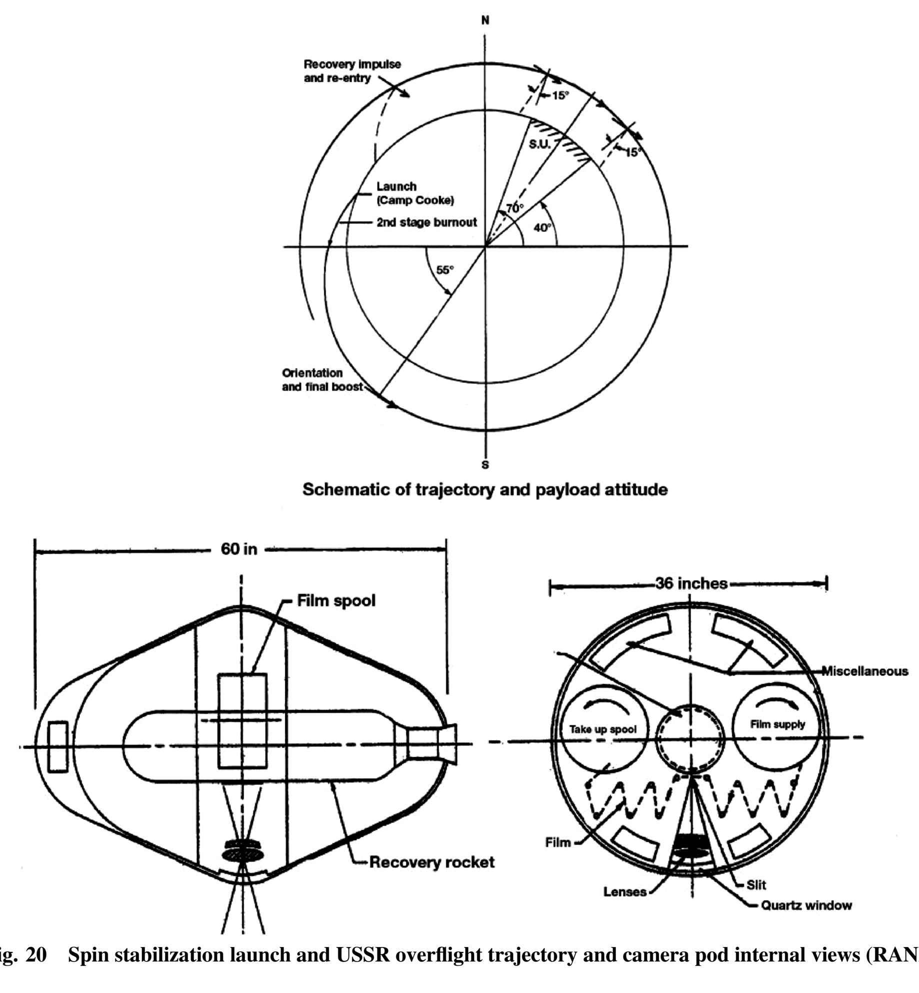

Fig. 20 Spin stabilization launch and USSR overflight trajectory and camera pod internal views (RAND).

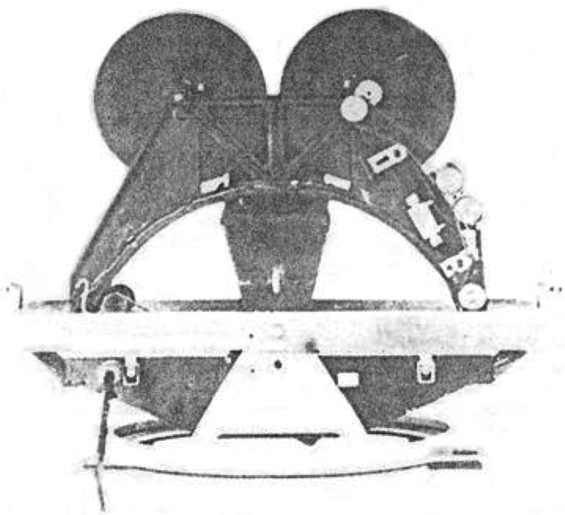

Fig. 21 Hi-AC I balloon panoramic camera.

106-member staff of the BU Physical Research Laboratories and all its ongoing contracts, along with their physical equipment, camera designs, and research reports, effective January 1, 1958. Itek, at its core, was BUPRL resurrected to operate for profit.

On October 28, the WS-117L project office made a two-day presentation to the Reconnaissance Panel of the USAF Scientific Advisory Board. (This was the same day the Board of Consultants, chaired by Dr. James R. Killian, Jr., Eisenhower's recently appointed Science Advisor, made its presentation to the President.) Other members of the group included Edwin Din Land of Polaroid, Duncan Macdonald and James Baker of BUPRL, Amron Katz and Merton Davies of RAND, and a dozen people from Air Force Headquarters.

Herther gave the group a detailed briefing about progress on the ascent guidance and gravity gradient stabilization for both the SAMOS and MIDAS programs. He also briefed the group on the guidance and control system of the new Discoverer-Thor/Agena biomedical experiment test program that was then being planned. He was disappointed that the short mission and low altitudes planned for the biomedical recoverable vehicles would not test the MIT gravity gradient concept. He advised that the ascent guidance inertial system's accuracy was assumed to be adequate to provide a sufficiently stable reference for the short missions of the various experiments contemplated. The system also needed the ability to maintain the proper attitude accuracy for the capsule to splash down in a recovery area at sea.

XVIII. From the Air Force to Itek

After he was discharged from the Air Force in December, Herther went to see Richard Leghorn in Boston. They spoke about a verbal offer to join Itek that Macdonald had extended after Herther's October 28 briefing of the USAF Scientific Advisory Board. Herther was surprised to find that Leghorn's description of the job offer did not include work on the satellite photo ground data handling system contracted to Itek. Instead, Leghorn spoke about wanting to develop an on-orbit "stable table" for a high-resolution camera.

Herther was thrilled at the prospect of continuing in the reconnaissance satellite vehicle field, so he joined Itek, its first technical employee. Immediately upon reporting for work on 16 December 1958, he started designing a three-axis stabilized camera concept. Only then did he learn of the existence of the CIA's secret RAND SpinScan panoramic camera/recovery vehicle contract. (The integral camera-vehicle concept was an inertially spin-stabilized camera: a spinning football-shaped pod. Both the film and the camera were to be recovered at sea, similar to the WS-461L "Genetrix" balloon configuration. The program was a Lockheed/Fairchild/General Electric contract run by Jim Plummer's "Skunk Works.")

Herther realized that flying the Agena horizontally was necessary for drag reduction (see the configuration in Fig. 22, which is similar to a discarded one for SAMOS in an MIT thesis). (This differed from the vertical nose-down three-axis vehicle orientation employed for SAMOS or Midas.) This orientation would inherently have smaller aerodynamic torques because the altitude would be much lower than that contemplated for the long-life (one-year mission), high-altitude WS-117L payload flights (100 nautical miles vs 300 statute miles). This was unlike WS-117L's practically passive payloads, and the reason the active concept (shown in Fig. 22) was rejected. The active approach for CORONA was dictated by the large torques of the Itek Hi-AC II oscillating panoramic scanning camera, which required an active control system with pitch and roll feedback signals from the added horizon sensor.

Because of his two previous years of AF work on Agena spacecraft stabilization, Herther was able to design an active three-axis horizon-updated inertial-based concept, and he sketched out a spacecraft inboard profile. He also worked on resolution prediction calculations based on minimum gyro sensing rates.

XIX. Three-Axis Design Details Evolve

On a layout drawing, the cross-track oscillating panoramic camera was configured into an Agena that would fly horizontally. Herther assumed that the Agena incorporated the Discoverer three-axis gyro stabilization system developed by the MIT Instrumentation Laboratory. This system could easily be horizon-referenced by

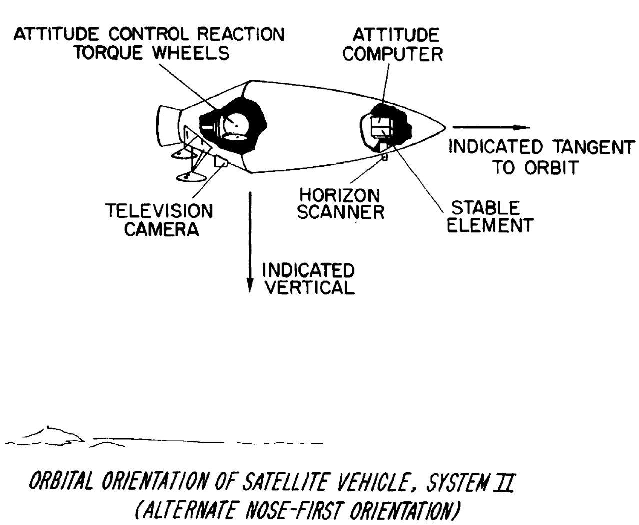

Fig. 22 CORONA active three-axis stabilization (MIT thesis).

adding a sensor to ensure gyro drift cancellation. The concept would contain the IMU, which would control the gas jets that were already a part of the Agena's ascent guidance system. Providing a continuous active gas jet control without an excessive weight penalty for the gas was possible because the mission was short (only a few days, not a year, which had been the goal for SAMOS and MIDAS). This approach provided three-axis Earth-viewing stabilization based on the horizon sensor's updating of the ascent inertial control system of the vehicle.

Leghorn and McDonald were both enthusiastic about the design and immediately called Bissell at the CIA to tell him about it. Herther remembers that Leghorn called Gen. Schreiver a few days before Christmas to inform him of the new concept of simply modifying the Agena ascent guidance system by adding horizon sensing and using it for active on-orbit stabilization. (Cargill Hall states that "(t)he interim reconnaissance satellite system that Quarles compared with the WS-117L readout was the same plan that had been described in November by Davies and Katz, and already endorsed by Colonel Fritz Oder and Generall Bernard Schriever. It consisted of a Thor IRBM liquid-propellant launch vehicle with an Aerobee 75 solid-propellant second stage developed for the Vanguard IGY satellite launcher. Mounted atop the Aerobee was a football-shaped third stage satellite that contained the camera and film, and a small solid propellant recovery rocket" [11].)

> Concurrently with the Horner recommendation (Air Force Asst. Secretary Richard E. Horner was of the opinion that a Thor-boosted reconnaissance vehicle could be operational sooner than the Atlas-boosted option, which was affected by a shortage of funds; see "The Corona Story," pp. 16–17), RAND circulated the first written discussion of its proposal for an interim reconnaissance system based on a combination of the Thor booster with the Aerobee-derived upper stage used in the Vanguard program. Advance copies were distributed on 15 November 1957, the day of the Horner memorandum. In addition to using Thor as booster, RAND urged a technique of spin stabilization for a third stage, camera-carrying element of the system. (The concept had been invented by Davies and Katz, two of several RAND scientists who contributed to the study.) RAND also suggested abandoning the WS-117L readout concept for the interim system, urging a mode of payload deboost and water landing to permit recovery of the entire third stage.
>
> That approach, undoubtedly influenced by the Teller Report (the Teller Report recommended a unified, closely integrated national space program under Air Force leadership, but ultimately failed to convince government officials to adopt a unified program under either military or civilian direction; see http://www.gl.iit.edu/wadc/History/BeyondHorizon/BH2.pdf), the Horner memorandum, and the RAND study, appeared as a BMD [Air Force Ballistic Missiles Division (AFBMD)]–Lockheed plan for the acceleration of the entire WS-117L program. Discussions between Lockheed and BMD officials preceded the dispatch of an informal Lockheed proposal on 26 November. It was considered in some detail immediately thereafter, particularly in the course of a 5 December meeting at BMD. (Mert Davies-The CIA history remarks that the CORONA program was pursued through oral briefings only during a crucial period: i.e., that there are no official records in CIA's Project CORONA files bearing dates between 5 December 1957, and 21 March 1958.) Lockheed urged the adaptation of the WS-117L upper stage to the Thor missile as the first step in program acceleration. Taking issue with Teller Report and RAND conclusions that the Aerobee upper stage promised earlier availability than the WS-117L upper stage, Lockheed proposed a "more realistic" system embodying elements of the RAND-proposed camera technique, the Horner vehicle concept, and Teller committee suggestions for schedule acceleration.
>
> On 23 December 1957 (although there is no known record of the factors on which this decision was based, Leghorn's call to Bissell about the "possibility" of Itek's concept of achieving three-axis on-orbit stabilization for much better resolution with a simple Agena change was significant among numerous other factors that must have influenced the decision to settle on the Agena vs the Vanguard second-stage Able), General Schriever asked Lockheed to prepare a formal proposal along such lines, and on 6 January 1958, Lockheed completed and forwarded a development plan. Central to the system concept proposed by Lockheed was a booster configuration consisting of the Thor missile as a first stage and an upper stage, powered by the Bell XRM-81 rocket engine (originally designed for the "powered pod" missile of the B-58 Hustler bomber, hence the name Thor-Hustler). Much later, the upper stage acquired the more lasting name "Agena."
>
> One aspect of the Lockheed proposal was particularly applicable to a clandestine satellite reconnaissance program, an approach revived at BMD early in December. General Schriever's November correspondence with Lockheed had included some mention of the highly sensitive U-2 program and Lockheed's success in pushing that reconnaissance aircraft system to early completion. Lockheed had also called attention to its relatively recent experience in the development of a covert reconnaissance vehicle. Using these inputs, General Ritland was a principal in early December discussions between Schriever and a group of important policy figures in Washington: Richard Bissell of the Central Intelligence Agency, Drs. Land and Killian, and General Goodpaster from the White House. That group quietly considered the political and technical aspects of the satellite reconnaissance problem, discussed aircraft reconnaissance capabilities, as well as advanced satellite options, and finally concluded that the best course for the nation was to sponsor a covert program employing the Thor-WS-117L vehicle [9].

Lockheed prepared a development plan to this effect in early 1958 after General Schriever's specific request of 23 December to use the WS-117L vehicle with the Rand SpinScan recoverable camera pod.

XX. Herther's "Mother of All Briefings" and Unanticipated Long Term Ramifications

Cargill Hall, the National Reconnaissance Office (NRO) historian, has given an account of the decision-making process behind the ultimate choice of Itek's proposal [11]:

> Leghorn and Macdonald were aware of the impending Air Force-CIA satellite reconnaissance project and its use of the Fairchild panoramic camera. With the experience of the flight-tested HI-AC camera behind them, they possessed an impressive alternate. If scaled-up from a 12 to a 24-in. focal-length lens, and using high-resolution 70-mm film, calculations showed that this nodal point scanning, 70 deg panoramic camera would provide a resolution on the Earth's surface of 20 ft that translated into a significant interpretation improvement over the 60-ft resolution offered by the Fairchild spin-stabilized camera. Moreover, with sufficiently low blur rates, faster optics, and projected Eastman Kodak film improvements, a scaled-up HI-AC type camera might achieve a resolution at the Earth's surface approaching that of balloon-borne cameras. The Itek camera proposal, which arrived at C1A headquarters in mid-February 1958, prompted Bissell and Ritland to consider funding a backup to the Fairchild camera. But were other camera systems available that might be preferred in the space reconnaissance role?
>
> To answer that question, on 11 March 1958, CORONA leaders conducted an evaluation of alternate cameras at the old executive office building in Washington, D.C. Beside Bissell and Ritland, the assessment panel consisted of the President's science advisor James Killian and two of his key PSAC advisors, Edwin Land and Harvard chemist George Kistiakowsky. The remaining panel members included Herb York, ARPA's chief scientist, and the Air Force WS-117L managers Colonel Fritz Oder and his deputy, Navy Captain Bob Truax, who had just moved to Washington for an ARPA assignment that would in fact cover his new role as a technical advisor to Richard Bissell on Project CORONA.
>
> Four companies had been canvassed and each offered an alternate camera at this review: General Electric, Fairchild, Eastman Kodak, and Itek. The presenters for each of the firms arrived separately and waited in different anterooms, and each of the teams briefed the assembled advisors alone. General Electric had hired Richard Raymond from RAND and that firm offered a variation of the Fairchild spinner. Fairchild, in turn, offered a refined version of the original camera that could, it was hoped, secure a resolution at the Earth's surface somewhat better than the 60 ft claimed for the original. Eastman Kodak, which held the contract for the pioneer and advanced strip cameras of the WS-117L readout system, likewise recommended a version modified for panoramic coverage with spin stabilization. Finally, the physicist and Itek cofounder Duncan Macdonald and John C. (Jack) Herther offered a reciprocating 70-deg scan panoramic

camera with an f/5 Tessar-type 24-in focal-length lens, otherwise similar to the high performance HI-AC balloon camera.

Itek's proposed vertical looking camera scanned at right angles to the line of flight, which demanded a satellite horizontally stabilized on all three axes. That introduced technical complexity and accounted for the presence of Jack Herther. Richard Leghorn had hired him as Itek's first technical employee just before the BUPRL acquisition. A 1955 MIT graduate, his thesis had focused on a gyro-stabilized ascent guidance system for the WS-117L (then Project 1115) orbiting stage, after which he had been posted as a reserve officer to the nascent program office to the Air Research and Development command's Detachment 1 at Wright Patterson AFB, Peterson AFB. Now Herther explained for the Project CORONA evaluation team how the Lockheed ascent guidance system could be modified to stabilize the Agena horizontally on all three axes in space for a short duration, low-altitude reconnaissance mission. This orbital attitude control system, Herther affirmed, would produce the pointing accuracy and low roll and pitch blur needed for the Itek camera to deliver a resolution at the Earth's surface of at least 20 ft.

Duncan Macdonald had worked previously with Arthur Lundahl, chief of the CIA's photo-interpretation unit, on matters of high-altitude Air Force balloon and U-2 aerial photography. He knew that a camera's effective resolution at the Earth's surface allowed photo interpreters to positively identify objects three to five times larger than the resolution achieved. Based on photo-interpretation needs, the performance experience with HI-AC flight test program, and a stable low blur rate platform in space, Macdonald predicted that eventually it should be possible to achieve balloon quality photographs from satellite altitudes. After all of the presentations, the CORONA evaluation team conferred and selected Itek. The long-shot newcomer would be supplier of the alternate backup camera.

On 24–26 March 1958, Bissell and Ritland closeted themselves with all of the primary CORONA contractor representatives at the Flamingo Motel in San Mateo, California. Bissell informed attendees that a backup camera would be procured from Itek. Lockheed announced that James W. Plummer, formerly in charge of the WS-117L Eastman Kodak payloads, would serve as the CORONA manager responsible for the technical integration of the project. Project participants agreed that General Electric would provide the recovery system and that effort would consist of ten CORONA vehicles, with three more if needed, launched from Vandenberg AFB on the California coast. Component fabrication, assembly, testing, and a first launch, participants agreed in a burst of optimism, could be accomplished before the end of 1958.

Back in Washington, D.C., on 9 April 1958, Bissell finished for the President's approval the CORONA Project Proposal. It called for the concurrent procurement of both the Fairchild and Itek cameras, though at this point the Itek system appeared a clear favorite because of its better initial resolution and promise of even greater resolution for photo-resolution growth potential. Two days later, perhaps at the urging of Din Land, General Ritland and Bissell decided against procuring the Fairchild camera with its spin stabilization, and in favor of the Itek HI-AC-type camera that required a stable platform in space. The revised proposal outlined a project that would consist of 12 launchings, become operational in June 1959, and conclude a year later in June 1960 when the WS-117L (later SAMOS) readout system was scheduled to become operational. Fairchild would remain in the project, at least temporarily, fabricating the Itek-designed cameras.

The revised CORONA Project Proposal also identified ARPA as exercising overall technical supervision, with the Air Force, through Air Force Ballistic Missile Division, acting as its agent. The CIA would remain responsible for CORONA's security system and for procuring the reconnaissance equipment With the concurrence of ARPA director Roy Johnson and other project participants, Bissell and the Deputy Director of Central Intelligence, General Charles P. Cabell, presented this proposal to President Eisenhower on 16 April 1958. After asking some questions, the President verbally approved it. On April 25, Bissell issued a two-page Statement of Work to guide the prime contractor, Lockheed's Missile and Space Division. Among other objectives, it called for photographs with a resolution at the Earth's surface of 25 ft or better with a location accuracy objective of plus or minus one mile, maximum possible ground coverage, and recovery of latent image film "by means of ballistic reentry and land or sea recovery." After identifying the primary subcontractors and items that the government would furnish, the statement turned to the question of managing the organizational amalgam. Overall technical direction, it advised the firm, "would be the joint responsibility of several agencies of the Government. In the interest of effective management, however, such direction will be provided primarily by and through the Air Force Ballistic Missile Division acting as the agent for all interested components. . ." (U.S. Central Intelligence Agency, 1958).

> At the end of April 1958, CORONA participants thought that they had embarked on a short term, high-risk strategic reconnaissance venture that would augment the U-2 as an overhead technical collection system until WS-117L satellites became operational in 1961. That CORONA would succeed beyond anyone's expectations, that it would eclipse the WS-117L program entirely, that it would continue in operation over 12 years and set the pattern for American reconnaissance satellite projects to follow, and that managing it would prompt creation of a National Reconnaissance Office, they could not know and would not have believed. On the recommendation of science advisors, on the approval of the President, on the word of businessmen and government officials pledged in the clasping of hands, and on a broadly drawn statement of work, Project CORONA was underway. The space-based "intelligence revolution" had begun.

After Itek was awarded the camera contract, Levison and Herther traveled to the Lockheed "Skunk Works" to meet with representatives from Lockheed, GE, the recovery contractor, and Fairchild. The CIA set an ambitious schedule for a June 1959 first launch. Upon returning to Boston, Herther, whose role was system integration engineer, working directly on the interface definition with Lockheed and GE, had to learn more about camera development details. The Agena's active stabilization would only work if the camera design did not cause the spacecraft's attitude disturbances to blur the excellent inherent static lens film resolution of the Hi-AC camera. Herther realized that the inertial reactions of the camera's scanning lens assembly and the film supply spools would impose torque impulses on the spacecraft. So the first thing he did was order a $50,000 Pace Analog Computer on the CIA's "black" (secret) budget. Figure 23 shows Herther on the right with slide rule. He then hired two engineers and a technician to set up a very elaborate analogue simulation of the Agena vehicle attitude control system and the Itek camera's reaction to it for continuous scanning and starting operation tests with full and empty film spool conditions. This was essential to verify that the calculations were within the extremely tight tolerances to avoid image smear during exposure. The CORONA Keyhole KH-1 camera had a lens and scanning arm with capping shutter that oscillated back and forth inside the spacecraft. Running the simulation revealed that the first CORONA design created more angular movement of the spacecraft than the active gas stabilization system could cope with without creating excessive blur in the pictures. Fairchild was directed to alter the design to cut down the inertia of the reciprocating scan arm.

Itek was responsible for developing the dynamic resolution simulator, which was used to test the cameras for acceptance and qualification, for meeting full photo-qualification specification after

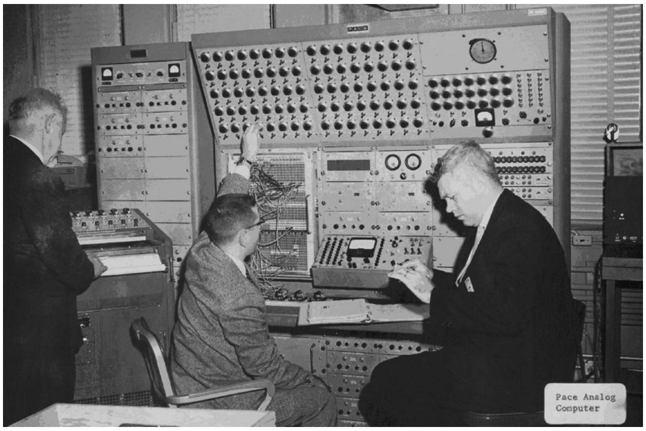

Fig. 23 Analog computer for camera reaction satellite dynamic analysis [12].

environmental tests, and for prelaunch photo-quality verification. Herther managed the supporting program to develop and produce dynamic photo simulation test equipment to test photography, including the image compensation mechanization. A vehicle torque disturbance measurement feature was also built into the photo resolution test equipment, which allowed the camera under test to be supported on air bearings on the roll axis. Actual camera operating tests were run to ensure that the KH-1 transient disturbing torques from the oscillating scan would not exceed allowable roll blur rates at the 25-ft resolution level. Throughout development, the blur rate along track (IMC error) was reduced mainly through better-compensated image motion (velocity to height, or V/h) because of increased accuracy of commanded V/h vs time as well as internal camera mechanization. The blur factor was reduced from around 25% initially to less than 1%. (Full 100% IMC error was used in Appendix C comparison calculations for RAND's "NO IMC" SpinScan camera.) Reduced camera reactions on the vehicle were achieved by further minimizing the oscillating lens inertia and eventually, in later models, by constantly rotating the heavier lens and oscillating only a much smaller inertia scan arm containing the capping shutter. The final improved model KH-4 configuration also had back-to-back cameras for the stereo configuration. This essentially balanced the momentum of the already reduced scanning inertia of the oscillating lens assemblies as well as both counter-rotating film supply spools (also on the roll axis) to significantly minimize any reactions on the Agena. These camera improvements, as well as much better Agena attitude control, contributed to minimizing overall blur.

Imagery is mainly degraded by uncompensated image motion arising from two sources: the speed of the satellite in the orbital plane and the cross-track lateral motion of the ground caused by earth rotation. The early CORONA panoramic cameras were compensated only for image motion along track by translating the lens axially during its panoramic rotation. This method works well when the image-motion direction is lined up with the compensation direction to within about 1 deg. Because the Agena's three-axis stabilization maintained this yaw accuracy and later was able to improve both the yaw angle and yaw rate accuracy, the compensation for the changing lateral component of earth movement with latitude was also compensated by a rotational change of about 2 deg about the vertical. This correction became necessary and was implemented for later models of the camera to produce imagery of ever increasing quality.

Itek planned from the outset to design and manufacture a proprietary next-generation Hi-AC camera with a faster lens that would use even higher resolution, slower film, and reduce the angular impulse of the nodal point scanning oscillation of the vehicle that had been causing roll rate blur during exposure.

An official CIA handout (Table 2) distributed in 1996 shows that in 1960 CORONA had achieved only 40-ft resolution. The original Itek proposal for evolution to 6-ft resolution was eventually achieved by the KH-4 camera in flights made between 1967 and 1972. Evolutionary changes involving lens, film, camera IMC and other camera mechanical improvements as well as Agena stabilization steadiness accounted for improved resolution. It was mandatory that the camera platform be extremely stable in pitch and roll during instantaneous exposure to preserve resolution. It was also needed in yaw for map-making stability both during the panoramic scan and from frame to frame over a photographic pass. Horizon and index camera photographs, as well as scan rate monitoring fiducial marks and other instrumentation, were included to improve cartography. The KH-4 Model was almost completely momentum-balanced by counter-rotation, causing minimum reactions on the Agena stabilization and providing maximum resolution due to the blur being practically eliminated. Operationally, the two film capsules were recovered up to 19 days apart. Figure 24 shows the KH-4 CORONA/Agena and Fig. 25 details the film recovery sequence.

By mid-1959, after serving as Itek's test director through the second successful CORONA operational flights, Herther turned his attention, as system engineer, to the short-lived Air Force SAMOS E-5 [SAMOS E-5 had a dual mission: to triple Corona's resolution in stereo and serve as the entry to the Air Force Man in Space Soonest

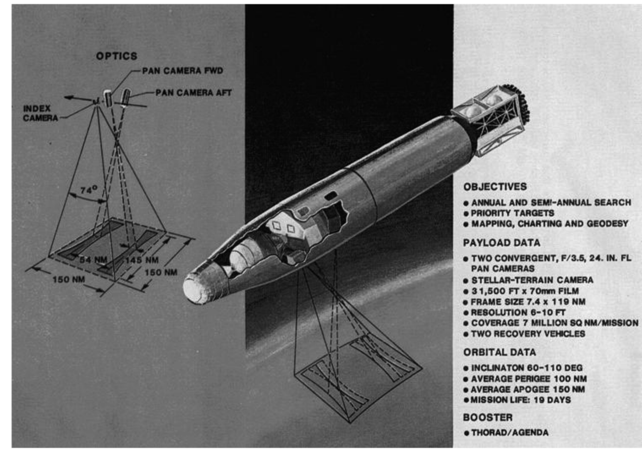

Fig. 24 Thor-Agena launch with CORONA twin stereo camera on-orbit [9].

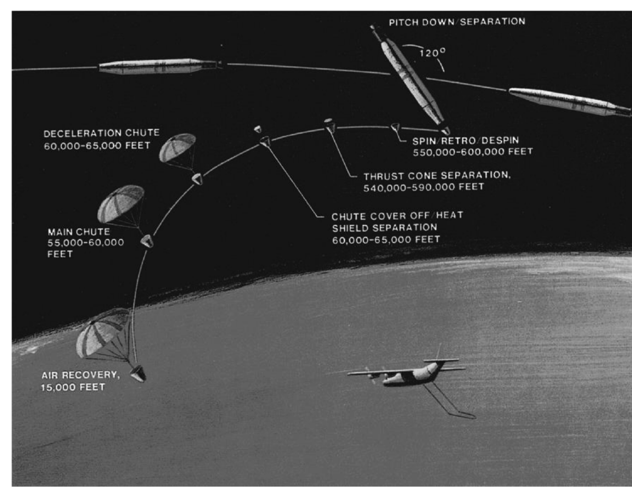

Fig. 25 CORONA capsule reentry and parachute air snatch recovery sequence; three-axis stabilized panoramic camera evolution.

(MISS) program. The E-5 design was to recover the entire camera with its 500 lb of film. To alternatively accommodate a man in the same recovery vehicle, the camera was designed to operate in a pressurized capsule identical to the NASA's Mercury in size, shape, weight and even forward recovery capsule center of gravity (requiring moving the 300 lb lens scanning assembly forward after photography). Three Atlas/Agena flights failed to be recovered and by then, the NASA Mercury program had succeeded and E-5 was cancelled. The NRO continued the reconnaissance mission as Lanyard. (Four articles referenced here by Dwayne Day in *Spaceflight* magazine detail these events [12].)] that evolved into the NRO's simplified E-5 or Lanyard (KH-6) satellite program, which achieved two-foot best resolution, as shown in Table 2. The OPTICS diagram on the left side of Fig. 26 shows the index camera ground coverage encompassing the high-resolution panoramic stereo camera pairs required for cartography.

XXI. Thirteen—CORONA's Lucky Number

The first 12 CORONA flight tests failed; the 13th was a success; however, each CORONA failure gave scientists and engineers new insight into space operations. The information from them not only improved camera operations, but also led to significant space launch and recovery techniques for both CORONA and the early manned space programs.

The CORONA program's initial failures were successive, but nonrepetitive. (The Federation of American Scientists' Space Discovery Project gives a concise account of the reasons for the

Table 2 Ground resolution improvement for ITEK three-axis stabilized cameras[a]

System	Dates operational	Cameras	Focal length	Image format	Best ground resolution	Successful missions	Capsules recovered	Total film footage
CORONA								
KH-1	Aug. 1960	1	24 in	2.18 × 29.8 in	40 ft	1	1	3,548
KH-2	Dec. 1960–July 1961	1	24 in	2.18 × 29.8 in	30 ft	3	3	17,949
KH-3	Aug.–Dec. 1961	1	24 in	2.18 × 29.8 in	25 ft	5	5	24,676
KH-4	Feb. 1962–Dec. 1963	2	24 in	2.18 × 29.8 in	25 ft	20	20	239,299
KH-4A	Aug. 1963–Oct. 1969	2	24 in	2.18 × 29.8 in	9 ft	49	92	1,293,025
KH-4B	Sept. 1967–May 1972	2	24 in	2.18 × 29.8 in	6 ft	16	32	505,970
ARGON								
KH-5	May 1962–July 1964	1	3 in	4.5 × 4.5 in	460 ft	7	7	22,503
LANYARD								
KH-6	July–Aug. 1963	1	66 in	4.5 × 25 in	2 ft	1	1	2,251

Declassified imaging satellite systems

[a]An online catalog and browse images are available online at the U.S Geological Survey-National Mapping Information-EROS Data Center GLIS: http://edc.usgs.gov/products/satellite/declass1.html as referenced on page 207 of the chapter "Declassified Intelligence Satellite Photographs Available from the US Geological Survey" by Donna K. Scholz in McDonald (1997) [7].

various Discoverer/CORONA flight failures: http://www.fas.org/spp/military/program/imint/kh-1.htm.) Herther's approach to stabilization, considered risky at first, was not part of the problem.

Fortunately, each major failure occurred only once. One major early problem was the brittle nature of the acetate-based film. Conditions duplicated in vacuum chamber tests confirmed that the film had dried out in space and broken. Eastman Kodak devised a new, lighter polyester film coated with an emulsion (the new film was Mylar®) that, in addition to not drying out, was much thinner and so yielded twice as many pictures per pound of film.

Discoverer/CORONA XIII, carrying only an American flag, was a success (see Fig. 27). Although the capsule was not snatched in midair, it was recovered at sea and returned to the mainland. Discoverer/CORONA XIV, with a camera and 20 lb of film aboard, was a complete success. It took the first photograph from space of the Mys Shmidta Airfield in the Soviet Arctic on 18 August 1960 (see Fig. 28). The CORONA capsule traveled 17 times around Earth that day in a north-south polar orbit. During the first couple of orbits the capsule was off balance, but by the third orbit it had stabilized and was taking pictures over the Soviet Far East. With each orbit, the capsule moved westward and by the last orbit it was taking pictures over Eastern Europe. Itek's camera had performed successfully, and all 20 lb of film had been used during the voyage.

The moment of truth arrived. The capsule's rockets successfully fired for reentry. After releasing its parachute, the capsule floated down toward Earth and was snatched in midair by a specially equipped Air Force C-119 cargo plane. Kodak developed the film and the results were rushed to the CIA's photo interpretation center for analysis.

Art Lundahl, director of the National Photographic Interpretation Center (NPIC), gathered his staff for a briefing about the wondrous accomplishment of Discoverer XIV. Many would learn about the CORONA program for the first time at this meeting. A curtain was opened over a map of the Soviet Union, and the audience broke out into a cheer as NPIC staffers realized that something special had occurred. During the days of the U-2 program, they had become accustomed to such briefings: when the curtain opened in the days of the U-2, they would generally see a single line representing a U-2 flight path. This time, the map was covered with lines. The mood turned joyous as Lundahl explained the true purpose behind Discoverer XIV and CORONA. Itek's camera had taken pictures covering more than 1.6 million square miles, more area than all the previous U-2 missions combined. By the time Lundahl's team finished examining the photographs, 64 new Soviet airfields and 26 new surface-to-air missile (SAM) sites had been found.

The Cold War would never be the same. The U-2 had pierced the Iron Curtain; CORONA tore it to shreds. Now the USSR's ICBM sites could finally be located, and America would at last have the intelligence it needed. It was a grand accomplishment. President Eisenhower, the man who had initiated this revolution in intelligence collection, was soon pushing Itek to develop an even better camera system. Not long after the mission, he sat through his own private showing of Itek's photography. Din Land, who was at the meeting, told Eisenhower that Itek could do even better. The quality of CORONA's pictures improved significantly from these first photos to a resolution of approximately 6 ft by 1967.

> ...Calculated risks can have big payoffs. When Bissell bet on Itek, the company was less than a year old. Three-axis stabilization, the concept at the heart of Itek's spy satellite proposal, was nothing more than an untested idea. Yet the CIA's Dick Bissell selected Itek, and the rest is history... Itek delivered its cameras, and America was safer. Nothing could be clearer. Except, perhaps, a photograph of the Soviet Union taken by an Itek camera [10].

In 1995, after 40 years of secrecy (see Appendix D), it became possible to reveal the true technical story behind CORONA. When word was finally out, both Jack Herther and Jim Coolbaugh received the Air Force Space and Missile Pioneers Award and were inducted into the Hall of Fame at the U. S. Air Force Space Command Headquarters in Colorado Springs, Colorado: Coolbaugh in 2002 and Herther in 2003 (awards and pioneer biographies are found at http:/www.peterson.af.mil/hqafspc/history/pioneers.htm).

Spin stabilization had been state-of-the-art for spacecraft attitude control in the 1950s. Sputnik used this technique, as did the first 10 satellites preceding the first three-axis Agena design. Herther's technique for a "stable table" system was innovative and, at the time,

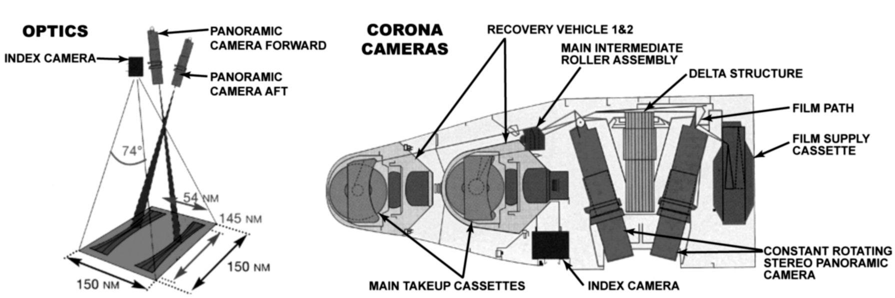

Fig. 26 CORONA KH-4 twin recovery capsule stereo panoramic camera configuration.

Fig. 27 President Eisenhower displaying flag recovered from space.

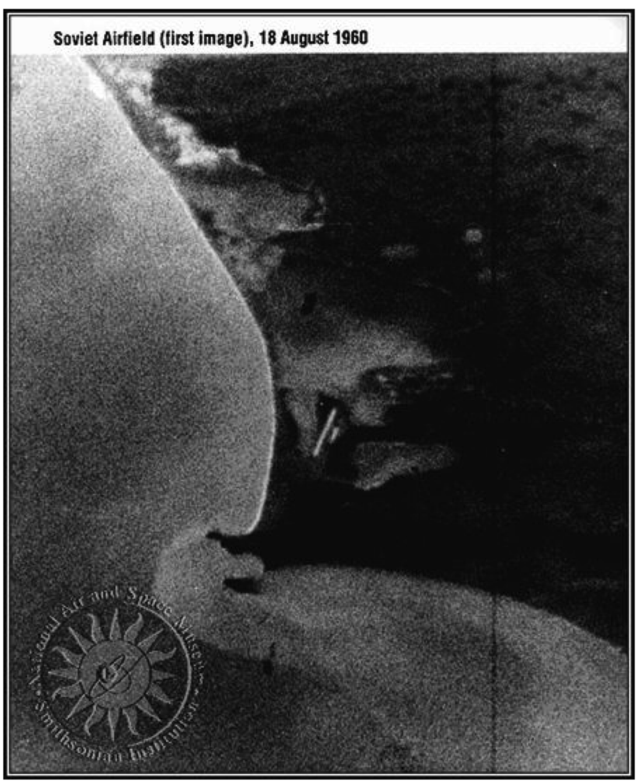

Fig. 28 First satellite photo (19 August 1960) Mys Shmidta Airfield, USSR: resolution 40 ft.

perceived as risky and experimental. As it turned out, the modification was essential to meet national intelligence needs in a timely manner.

Since then, hundreds of satellites have used three-axis active type stabilization, including the world record of 500 Agenas orbited from 1959 to 1987 [13]. [The bandwidth limitation had been recognized from the outset, but the readout program was continued through initial flight tests. The SAMOS E-1 and E-2 film readout programs were cancelled after both payloads failed in two flights in 1961. The NRO surreptitiously transferred the technology to NASA in 1961 (this fact was only recently declassified) and five of the three-axis stabilized SAMOS Lunar Orbiters were successfully flown between August 1966 and 1967. The first three completed the original task of obtaining the detailed photographs needed to select Apollo landing sites. The remaining two photo-mapped virtually the entire moon, allowing detailed examination of its surface features. Far from an abject failure, SAMOS secretly helped make possible lunar exploration, and it became the nation's first near-real-time film imaging system in space.] Agenas were so successful that they became the standard in 1961 on other government programs. Virtually every satellite since has been controlled using variations of the optically updated three-axis stabilization concept. When the CORONA program ended in 1972 after a dozen years and 145 flights, close to a million photographs had been taken, on 400 miles of film.

CORONA's impact on American foreign policy began when its photographic output made it possible to sign nuclear test ban treaties knowing that there was a means to verify whether or not they were being respected.

Albert "Bud" Wheelon, head of the ClA's Directorate of Science and Technology from 1962 until 1966, once stated that "CORONA did as much to win the Cold War as the Enigma code did to win World War II."[§]

The veil of secrecy that still drapes much Cold War history slipped briefly in 1967, when President Lyndon Johnson revealed one of America's worst-kept secrets to a Nashville audience: the country had a reconnaissance satellite program. Satellites routinely surveyed the Soviet Union, assuring American analysts that Soviet military assets were finite, known and at rest. This confidence allowed the two superpowers to survive the balance of terror without scaring each other into a war that neither dared to initiate. Estimating that the United States had by then spent $35 or $40 billion on space activities (the CORONA program cost $850 million in 1967 dollars, which would come to around 10 times that amount now) [14], Johnson said, "if nothing else had come of it except the knowledge we have gained from space photography, it would be worth 10 times what the whole program has cost" [14].

XXII. Conclusions

CORONA resolution, as Fig. 29 shows, had improved significantly from the original 25-ft specification to approximately 4–6 feet. The slanted line inside the clear area is a single line of people making a right turn to visit Lenin's tomb.

Herther's work in three-axis engineering research was considered routine when it was being done, and its long-range importance could not be foreseen. Only with hindsight and the declassification of national security records does it becomes evident that his role amounted to more than the average Air Force assignment.

Hundreds of USAF, NASA, and other satellites have orbited successfully using this three-axis active stabilization technology over the years since CORONA's launch. Three-axis satellite stabilization, which allowed CORONA's Itek cameras to capture 400 miles of high-resolution photos, played a crucial role in geopolitical stability and maintaining a balance of power during the Cold War because arms control treaties could now be verified. Another high-priority use of the CORONA product was to identify and locate targets for the new ICBM and SLBM forces. With geodesy in its infancy, before verification through CORONA photography, the relative location of points on different continents could be highly inaccurate, off by miles, not feet.

The present state of the art of GPS owes its beginnings to CORONA, and its legacy has been a gift, not only to our national security, but to the world at large. Today anyone with access to a personal computer can visit the globe as if traveling through space on a CORONA spacecraft.

Appendix A: CORONA/Agena Achievements

1) First three-axis active payload on an inertial/horizon sensor gas jet controlled CORONA spacecraft

2) First sea recovery of a reentry vehicle from space

3) First midair recovery of a reentry vehicle returning from space

4) First multiple reentry vehicles returned from space. Later missions had two reentries separated by up to 19 days.

[§]1995 CORONA Celebration speech; paraphrased from Albert Wheelon, Space Policy, Nov. 1995.

Fig. 29 Moscow photographed by a CORONA satellite at 100 miles altitude on 28 May 1970.

5) First CORONA photo taken from space, best resolution 40 ft
6) First CORONA photos at best resolution of 6 ft
7) First LANYARD photo at best resolution of 2 ft
8) First stereo-optical photos from space
9) First use of a satellite to gather intelligence
10) First reconnaissance satellite program to fly 100 missions
11) First Atlas/Agena SAMOS E-2 payload (300 statute mile) passive three-axis gravity gradient controlled spacecraft
12) First Atlas/Agena MIDAS payload (2000 n mile) passive three-axis gravity gradient controlled spacecraft
13) First stereo photo reconnaissance satellite. CORONA was used for mapping the earth's surface from 1968 until 1998. It resulted in the World Geodetic System 1984 (WGS 84) Geoid, used as the grid for the Transit satellite and later the GPS navigation systems [15].

Appendix B: 50 Years of Space Stabilization Highlights [16]

Appendix C: Proposal Resolution Analysis Comparison

The Itek proposal and briefing used a "physics-based" system level tradeoff comparison for determining the photographic performance comparison of camera-spacecraft configurations. It related ground-resolved distance to the flight altitude, the camera's optics, film resolution at various contrasts, and the overall image-blurring factor during the exposure time at the desired lowest illumination level.

At the outset, Leghorn expressed this stabilization need as an analogy for a "stable table" similar to Itek's prior balloon-borne high-resolution camera, the Hi-AC I.

A very stable (low angular rate) Earth-pointing velocity vector aligned camera, which can accommodate image-motion compensation (IMC), significantly increases resolution by minimizing blur. The optical system's focal length and aperture determines the film and exposure time to be used at the available illumination level. At northern latitudes, because shadows aid in measuring heights of USSR missiles, coverage at very low light levels from low sun angles of 2 deg is desired.

The satellite must be steady in its angular motion in pitch and roll rate during exposure, particularly considering vehicle roll rate reactions from the panoramic scanning camera, which is oscillating angularly and causing counter-rotation in roll if momentum is not balanced. The film used may either be "fast with low resolution" or "slow with high resolution," i.e., Itek-proposed Microfile "copy film" with its red sensitivity increased to make it a suitable aerial emulsion. (This film is a very slow high-resolution emulsion and provides a wide range of scene contrasts.) The SpinScan concept took the opposite approach by using very fast film, which was considered an overall simplification, because when this film was combined with inertial stabilization, it did not require image-motion compensation. At extremely short exposure times, blur is negligible at large resolved distances. SpinScan's very fast low-resolution grainy film, with a shutter speed of 1/4000 s, effectively eliminated motion blur, but its ground resolution was much larger than Itek's Hi-AC II.

The 1958 Itek proposal for estimating MIL STD 150 ground resolution for the purpose of comparing Hi-AC II camera with SpinScan was expressed in the following photo-interpreter's empirical equation:

$$d = h/F[1/R_{\text{optics}} + 1/R_{\text{film}} + 0.6F\omega t]$$

where d is the ground-resolved distance, ft (line and space); h is altitude, n miles; F is focal length, in; R_{optics} is resolution of optics (at $F = 5$, Hyac II diffraction limited 340 in lines/mm on 70 mm film and SpinScan $\sim$170 lines/mm on 5 in film); $1/R_{\text{film}}$ lines/mm, selected from Table C1; ω is the equivalent angular velocity of blur [Hyac II KH-1 $= 10$ mr/s…to….KH-4 $= 0.5$ mr/s, SpinScan (NO IMC) $= 40$ mr/s]; and t is exposure time, s, which is based on film speed and processing level, filter factor, optics T number, and sun angle varying with North latitude (Hi-AC II $= 1/200$ to $1/100$ s and SpinScan $= 1/4000$). Use consistent units.

Table C2 shows the actual "best ground resolution" results that were achieved during CORONA according to CIA photo-interpreters.

Table C1 shows the evolution of Eastman Kodak aerial films MIL STD 150 three-bar resolution vs contrast for various relative exposure times.

The equation using these parameters illustrates how these factors interact in the CORONA camera candidate comparison. The results are calculated for the narrow-angle diffraction-limited Hi-AC II camera lens. The camera Itek proposed was a three-axis stabilized Hi-AC II 24-in focal-length/f-5 lens using 70 mm film with image-motion compensation. SpinScan used a lower resolution and much wider angle over the field 12-in/f-5 lens with 5-in film without IMC. Potential growth was projected for the Itek-proposed Hi-AC panoramic design, based on presumed improvement in the Agena stabilization, improved internal camera IMC, and fewer reaction torques from scanning, resulting in lower blur rates. Minimizing blur allows much higher resolution film accommodated by "faster film processing" and permitting even shorter exposure times, which further improves resolution by reducing smear.

Table C2 shows the resulting calculated performance figures for the satellite cameras at $\sim$100 n mile altitude.

As Table C2 shows, the ground resolution comparison of the predicted resolution of the SpinScan concept vs Itek's active three-axis satellite control which provides a "stable table" for the Hi-AC II camera indicates a factor of at least three (and eventually 10) times better resolution.

Appendix D: Letters of Recommendation to Air Force to Qualify Herther for Pioneer Award

Richard S. Leghorn
143 Bayberry Way
Osterville, MA 02655

Table B1 Dates and events

Month/Day/Year	Event
07/01/1954	Air Research and Development Command establishes the Western Development Division (WDD), in Inglewood, CA, under command of Brig. Gen. Bernard A. Schriever. He is formally given full authority over the Atlas ICBM project.
09/08/1954	The Air Force approves the WDD's selection of the Ramo-Wooldridge Corp. to perform systems engineering and technical direction functions for Project Atlas.
01/06/1955	USAF awards a contract to the Convair Division of General Dynamics Corp., for development and fabrication of the Atlas airframe and control system, the integration and assembly of the various subsystems with the airframe and control system, and for checkout and testing.
02/15/1956	Responsibility for the Advanced Reconnaissance (Satellite) System WS-117L (later, Satellite and Missile Observation System, or SAMOS) is officially transferred to WDD.
10/29/1956	Lockheed awarded the prime contract for the development of the Military Satellite System and its associated Hustler (later redesignated Agena) upper stage vehicle.
10/04/1957	Soviet Union stuns the world with the launch of Sputnik I, world's first man-made satellite, aboard one of their new SS-6 ICBMs (spin stabilization).
11/03/1957	Launch of Sputnik II, satellite bearing the world's first living creature into space (the space dog Laika).
01/31/1958	The Army's Explorer 1, the first U.S. satellite successfully sent into space launched at Cape Canaveral (spin stabilization).
05/15/1958	Sputnik III Geophysics Laboratory (spin stabilization).
12/18/1958	Project Score, a communications repeater satellite, launched by an Atlas booster into Earth orbit. On 19 Dec., it broadcast a Christmas message from President Eisenhower to Earth, the first time a human voice was relayed from space.
02/28/1959	In a test, USAF successfully launches the Discoverer 1, the world's first polar-orbiting satellite, from Vandenberg. It is part of the secret CORONA program (first orbit of development test flight active three-axis on-orbit stabilization for CORONA).
04/13/1959	Air Force Thor/Agena A boosts the Discoverer 2 satellite into orbit, the first satellite to be stabilized in orbit in all three axes, to be maneuvered on command from Earth, to separate a reentry vehicle on command, and to send its reentry vehicle back to Earth (first Air Force public recognition of active three-axis on-orbit stabilization).
09/17/1959	Transit 1A Prototype launched (failed to orbit).
04/13/1960	Transit 1B first U.S. navigation satellite in space (gravity stabilization).
05/24/1960	MIDAS 2 the first early warning satellite in orbit (DSP-Defense Support Program). (First MIDAS passive three-axis on-orbit gravity gradient stabilization.)
08/11/1960	Discoverer 13 satellite, launched 10 Aug., ejects a capsule that is recovered in the Pacific Ocean, first successful recovery of a man-made object from an orbiting satellite. (First active three-axis on-orbit stabilization-sea recovered.)
09/17/1960	Transit 1A first U.S. navigation satellite prototype operating in space.
08/18/1960	Discoverer 14/CORONA satellite takes first image of Soviet territory from space. (First active three-axis on-orbit "photo-quality" camera stabilization.)
08/19/1960	Crew of a modified C-119J uses two trailing wire hooks to snag a descending Discoverer 14 capsule over the Pacific. It is the first aerial recovery of an object returned from orbit. (First active three-axis on-orbit stabilization "adequately accurate" for aerial trapeze recovery.)
08/19/1960	Sputnik deorbits and recovers dogs Belka and Strelka (unstabilized on-orbit stabilization).
01/31/1961	Launch of SAMOS 2-E-1 real time readout reconnaissance Satellite (first SAMOS passive three-axis on-orbit stabilization).
04/12/1961	USSR stages world's first successful manned spaceflight. Cosmonaut Yuri Gagarin, piloting Vostok 1, becomes not only history's first spaceman but also the first person to orbit the Earth. (Unstabilized on-orbit, tumbled until deorbit, then manually aligned for deorbit thrusting.)
05/05/1961	Navy Cmdr. Alan B. Shepherd, Jr. becomes first Project Mercury astronaut to cross the space frontier. His flight in Freedom 7 lasts 15 min, 28 s, reaches altitude of 116.5 miles, and ends 303.8 miles downrange. (Horizon/sun/moon display for three-axis hand controlled stabilization.)
07/12/1961	First Atlas D/Agena B booster lifts MIDAS 3 satellite, heaviest U.S. spacecraft to date, into a record 1850-mile-high orbit. (First passive three-axis gravity on-orbit stabilization.)
09/06/1961	Secretary McNamara establishes the National Reconnaissance Program, formally creating classified National Reconnaissance Office.
12/22/1961	SAMOS E5 orbited by an Atlas/Agena B, designed to yield three times better resolution than CORONA with six times the film load. Designed to recover both the film and camera in a "NASA Mercury equivalent" capsule as part of the AF "MIS" (Man in Space) program.
	Telemetry indicates successful camera operation, but recovery fails. Second launch 11/22/61 does not orbit and on third try (3/7/62) recovery fails again, and program is cancelled because NASA's Mercury has been successful. (First successful orbit of active three-axis on-orbit stabilization was improved over CORONA for higher resolution in spite of higher camera reaction torques. This required momentum balancing of the film spools and MV balance of the lens IMC motion, which proved successful in the NRO follow-on Lanyard.)
02/20/1962	NASA Friendship 7 first U.S. man in space (John Glenn) (passive three-axis on-orbit stabilization).
06/14/1963	First Soviet man in orbit to achieve controlled rendezvous with Vostok 6.
16/16/1963	Transit 5A3 operational prototypes (first passive two-axis on-orbit stabilization).
07/01/1963	CIA KH-6 achieves "best resolution" of 2 ft from space, then 4–6 ft for rest of flight (first active three-axis on-orbit with "much improved camera quality" stabilization).
09/28/1963	Transit 5BN-1 navigation satellite (upside-down gravity gradient two-axis stabilization).
12/05/1963	Transit 5BN-2 first operational navigation satellite (first successful navigation satellite employing gravity gradient two-axis stabilization).

HQ Air Force Space Command
150 Vandenberg Street
Peterson AFB 80914-4290

Rick Sturdevant, Deputy Director
History Office
23 April 2002

Dear Dr. Sturdevant:

I understand the name of Jack Herther has been placed in nomination for an USAF Space Pioneer Award, a nomination I would like to second.

Jack Herther was responsible for conceiving and developing the gyro-stabilized satellite control system using horizon-scanning sensors. This system was flight-tested as part of the Air Force 117L program. It was first used operationally in the Corona Program where it stabilized Lockheed's Agena satellite so effectively that the

Table C1 Film resolution

Kodak number	Type	Relative exposure	High contrast (1000:1)	Medium contrast (6:1)	Low contrast (2:1)
3401	Plus X	1	120	100	65
3400	Pan X	4	170	150	100
3404	Hi Res	33	840	550	280

Table C2 Itek's three-axis proposal vs SpinScan

	SpinScan	Itek three-axis Hi-AC II
Focal length/f-number	12 in/f-5, no IMC	24 in/f-5, with IMC
Ground resolution-d	60 ft	20 ft, growth to 6 ft

resolution of the resulting photography was virtually the same as that from earlier high-altitude balloon flights over the USSR. Combined with Itek's HI-AC photographic system it resulted in essentially a ten-fold improvement over aerial photographic technology of the day.

As I recall he conceived the method of using horizon detectors with other stabilizing components while a student at MIT, and managed its flight testing while on Air Force active duty at Wright Field, and later as a member of MIT's Draper Laboratories.

I became familiar with the issues as an Air Force Colonel heading up reconnaissance development planning for General B.A. Shriever at Air Force Headquarters. In 1957, as the President and CEO of ltek Corporation, a newly organized start-up funded by the Rockefeller family, I recognized the significance of his work for space systems in general and photographic satellites in particular. I was fortunate to be able to employ him to work on the Corona Program. Itek's photo satellite design incorporating Herther's stabilization was competed successfully against such major players as Kodak, GE and Fairchild Camera and Instruments. The award was based on the potential of Itek's HI-AC photo reconnaissance system stabilized for satellite reconnaissance by Herther's design. After the Corona program his approach became the standard for stabilizing many other space endeavors.

Because the Corona program and its results were highly classified for 35 years, Herther's contributions have gone largely unrecognized. It would be very fitting indeed if he were to be recognized as a Space Pioneer of the Air Force. As historians have recorded, after Sputnik astounded the world. President Eisenhower authorized the vital Corona program, managed by the CIA in collaboration with the Air Force, building on the partnership so successful in managing the U-2 program. The U-2 program over the USSR was cancelled when Gary Powers was shot down May 1, 1960.

Beginning August 18th of that year, the dramatic and vital success of Corona photography over-flights was in no small part due to Herther's efforts. Corona's historic impact on US Security during the crucial years of the Cold War has long been recognized.

Unfortunately Jack Herther's essential contribution has not. It is impossible for me to overstate my strong recommendation that he be designated a USAF Space Pioneer. If you should want more detail on his contribution I find he is again working at the Mitre Corporation, If there is anything further I can do to bring recognition, at least by historians, to the tremendous contributions of "3- Axis Jack," I will be more than delighted.

Best Regards, Richard S. Leghorn

Fritz Oder, Program Manager WS-117L, coauthor of the official Secret CORONA history wrote the following letter of endorsement to Dr. Rick Sturdevant, dated 11 January 2003:

Dr. Rick Sturdevant
HQ AFSPC/HO
150 Vandenberg Street, Suite 1105
Peterson AFB, CO 80914-4290

Dear Rick:

I am writing in support of Jack Herther's nomination to be an Air Force Space and Missile Pioneer. He, as an Air Force officer, planned and directed Lockheed's effort in building a three-axis stabilized Agena in the SAMOS (WS-117L) program. When CORONA was being started he provided overwhelming rationale for that satellite also to be three-axis stabilized. Rand had proposed a spin-stabilized concept, which was dropped in favor of the three-axis approach. This guidance decision, in which Herther played a key role, was, in retrospect, fundamental to the classified satellite reconnaissance programs, which followed CORONA. I seriously doubt that we would have the success that we have had if the roll-stabilized approach had been mandated for CORONA. In other words Jack Herther's actions have made a very important contribution to the Air Force space program, as we know it today.

Warmest personal regards,

Frederic C F Oder
Colonel, USAF (Ret)

Acknowledgments

Author dedicates this paper to Elaine, his wife of more than 50 years, who has been instrumental to his motivation and success. Without her patience and understanding, he would not have had the opportunity to risk a career of pioneering. He appreciates her support and her patient endurance of his preoccupation and obsession with accurately documenting history in this paper.

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This work honors the memory of the visionary leadership of several individuals from different institutions:

The MIT Instrumentation Laboratory (now Draper Laboratories)

Charles Stark Draper, the "father of inertial guidance," whose personal influence on Herther's graduate work at the MIT Instrumentation Laboratory (now Draper Laboratories) proved crucial in his development of Agena's Guidance and Control subsystem for the three-axis stabilized Agena booster satellite. Doc taught his students to have a "can do" attitude and once remarked that "in some cases solving a problem is much easier than defining it."

Joseph E. DeLisle developed the Submarine Inertial System (SINS) at the MIT Instrumentation Laboratory for accurately launching Polaris IRBMs, which used Transit Navigation satellite position updates. DeLisle was responsible for guiding the MIT laboratory effort under an Air Force contract for the design and development of the Agena Guidance and Control system, which Lockheed would integrate into the Air Force WS-117L universal payload Agena spacecraft.

The Itek Corporation

Walter Levison was the Boston University Physical Research Laboratories inventor of the Hi-AC balloon reconnaissance camera concept and managed the development of the Itek Corporation's scaled-up CORONA, E-5 and LANYARD panoramic camera systems.

Duncan Macdonald, director of the Boston University Physical Research lab, and a cofounder of Itek, was a recognized "Pioneer in Aerial Reconnaissance" and a key CORONA pioneer.

The RAND Corporation

Amrom Katz used his photographic background and his strong, technically savvy, apolitical personality to "say it like it is" within high government circles. Katz made what was probably the most critical contribution to satellite reconnaissance by causing development of the delayed satellite TV/readout reconnaissance system and by convincing government officials to use Intercontinental Ballistic Missile (ICBM) warhead technology to return exposed film canisters from space. Bringing the film back from the satellite provided much higher resolution and coverage of target areas, which permitted both area search and continuous surveillance of targets of interest.

Merton Davies convinced Air Force leaders that early development of a film recovery system was essential to meet the national intelligence objectives. He advocated a program that employed spin stabilization of the satellite as the quickest way to have the "simplest panoramic camera/film recovery system."

The United States Air Force

William O. Troetschel, a third member of the original Air Force satellite engineering team at Wright Patterson AFB, was responsible for tracking, communications and ground control for the Agena and its Ferret electronic intelligence (ELINT) payload.

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