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The Inescapable Premise

Inventing Satellite Command and Control

No space program is feasible without an adequate ground environment.

—National Security Council Memorandum 1859, January, 1959

IN THE EARLY days of space operations, sending satellite telemetry over telephone lines—the most common means of transmitting data from the remote tracking stations to engineers in California—challenged engineers almost as much as launching the satellites themselves.[1] Telemetry in the 1950s and the 1960s, as it does now, contained important facts about systems status or for calculating a satellite's orbit, and engineers required the data for troubleshooting. The data, which were frequency modulated onto sine wave subcarriers, came down from satellites at high speeds, and the tracking stations recorded it all onto magnetic tape. After the satellite passed from view, the recorder operators rewound the tape and brought its speed down until the tape moved slowly enough to transmit on a low data-rate telephone line. The recorder operators in Alaska first made a voice phone call to the data center in Sunnyvale, California, and when the recorder operator there signaled "ready to record," the tracking station patched the tape playback in place of the telephone handset and then rolled the tape. Lockheed's satellite engineers often needed certain vital data on the tape, and transmitting with this method got the information to them faster than mailing the tape from Alaska would have.

Tracking station controllers called this system "Slow Poke" because the unattended tape usually played back at 1/32nd of the original recording speed, which thus required thirty-two minutes to deliver one minute's worth of telemetry. Most satellite supports at the Alaskan tracking stations on Kodiak

Island (station call sign KODI) or Annette Island (station call sign ANNE) lasted five minutes or longer and required more than two and a half hours to retransmit a single support's data. Fortunately, the trackers seldom re-sent a full set of data, so they did not object to tying up their only phone line to these isolated locations. Usually they sent only information that either the command center did not receive during the actual satellite support because of communications outages or that particularly interested the satellite engineers. Controllers at the tracking stations had contact with the outside world through only that one phone line and a 100-word-per-minute teletype machine. If during a transmission, the telephone operator in Sunnyvale needed to connect a northbound call and tapped the KODI or ANNE line to see whether it was in use, she might have only heard funny "beeps" and "boops" on the line. If she thought a line had actually failed, she might disconnect the call and log the line out to maintenance. Because KODI was then in the send-only mode, the station could not learn of the disconnection until the tape ran out hours later, wasting a lot of time. The tracking station controllers eventually let the phone operators know about the flaw in the procedure, and the phone operators learned about satellite data transmissions. Said one former operator at KODI, "Slow-Poke worked fine, but it sure was slow!"[2]

In those early days, everyone tried their best to make command and control work, inventing most things as they went along. As the former Lockheed program manager for the reconnaissance satellite puts it, "No one person can claim the responsibility for the design for something as complicated as [a satellite], the Agena [booster], or any large project like that. It's a group effort—there's management, there's specialists."[3] The system did not spring from one person's imagination—no "Eureka!" moment figures in its birth. Engineers borrowed from anywhere and everywhere, using teamwork to create the military's satellite command and control system.

By 1950 the larger air force organization had vested itself in existing technology, refusing to nurture an invention—space-based reconnaissance—that by its nature promised to contribute little to the organization and instead would challenge the status quo. The inventors of the military system of satellite command and control, therefore, distanced themselves from the mainstream air force research and development bureaucracy, Air Materiel Command, as well as the normal air force procurement system. The flying air force, uninterested in new technological systems for reconnaissance, did not contribute to the development of this new technology, which threatened obsolescence for piloted, airplane-based strategic reconnaissance.

In addition, the normal weapons procurement system simply could not bring a radical new weapon system online quickly enough for the American president, who wanted photoreconnaissance of the USSR in the dark days of the Cold War. Lockheed and the Central Intelligence Agency would take only nine months to get the covert *Corona* reconnaissance satellite program ready for launch, once given the go-ahead. Even today the air force has taken nearly twenty years to get the next-generation fighter aircraft ready for service, a time span President Dwight D. Eisenhower found impossible to accept in a national intelligence emergency like the ICBM race of the 1950s.[4]

Thus, a unique arrangement of free agents contributed to the development of a system of satellite command and control to support reconnaissance satellites. In the 1950s and 1960s the people who worked at the Western Development Division, the air force's center for space and missile research in El Segundo, California, did not invent systems development, but they raised it to a new level. They brought two major missile programs and a satellite reconnaissance program to fruition in just five years, using a developmental program they called "concurrency," and were spurred on to success by their self-determination.[5] These teams of scientists and engineers began their work in the 1950s by simply reading reports that others had written; they finished by creating a satellite command and control system to support the National Reconnaissance Program.

Independent Inventors Roamed Free

New and radical inventions occupied the minds of some airmen at the end of World War II. Gen. Hap Arnold stands chief among the air force visionaries. The Wright brothers taught Arnold to fly, and his distinguished career reached its culmination during World War II, when he was made a member of the Joint Chiefs of Staff while he was chief of staff of the Army Air Forces. Although he never served in an independent air force, General Arnold's vision and foresight created a powerful air and space force. His creative thinking gave people the opportunity to develop radical solutions to problems.

General Arnold fostered close relationships with various civilian academics, in particular Theodore von Kármán, one of the founders of NASA's Jet Propulsion Laboratory (JPL) at the California Institute of Technology in Pasadena. As the end of World War II approached, Arnold asked von Kármán and the U.S. Army Air Forces Scientific Advisory Group—a group of leading American scientists who advised Arnold—to develop a long-range vision for the postwar air force. Arnold speculated about "manless remote-controlled radar or television-assisted precision military rockets or multiple purpose seekers."[6] Von Kármán's science and technology forecast, *Toward New Horizons,* laid out his vision for the post–World War II air force. Summarizing his report in a December, 1945, letter to Arnold, von Kármán acknowledged that "scientific discoveries in aerodynamics, propulsion, electronics, and nuclear physics open new horizons for the use of air power. . . . The next ten years should be a period of systematic, vigorous development, devoted to the realization of the potentialities of scientific progress."[7] Von Kármán proposed a relationship between the air force, science, and industry that would provide young officers experience in science and industry and thus improve their capacity to make decisions later in their careers, much like Arnold's own personal experience. Von Kármán's report recommended the permanent establishment of a scientific advisory board and the creation of a major research and development command, both of which became reality in the newly independent service.[8] Once independent, the air force institutionalized the report's suggestions, thereby forging the scientific and technological orientation of the modern air force.

The U.S. Navy also had a small cadre of people who were willing to think in bold, new ways. In a simple, three-page report—including the cover page—the navy got the jump on the other services in the new medium of space. The navy's Bureau of Aeronautics (BuAer) issued report R-48 in November, 1945, "Investigation on the Possibility of Establishing a Space Ship in an Orbit above the Surface of the Earth," prepared by Lt. Cdr. Otis E. Lancaster and J. R. Moore. The mission for the ship would determine its orbit, but for reconnaissance of enemy positions, "all the necessary information could be obtained in a few trips over the target." Lancaster and Moore speculated that "television or automatic photography could supply the desired information, without personnel [on board]." They found especially interesting "a circular orbit, 22,300 miles above the surface of the earth, where the [space]ship would make one revolution per day. In this orbit, the ship may be kept over a designated point on the surface of the earth. Naturally, the higher the orbit above the surface of the earth, the more difficult it is to establish the orbit."[9]

Fortunately for the air force, Lancaster and Moore underestimated the technical requirements for their proposal. According to Robert Salter, a BuAer contractor at the time who reviewed the proposal, the navy wanted a single-stage-to-orbit vehicle, presumably to make worldwide ship-based launches possible. To achieve orbit using a single stage, however, required a thrust-to-mass ratio of around 95 percent, that is, 5 percent satellite and 95 percent booster, or "about the same mass ratio as an egg," given spacelift capability at the time.[10] (Even at the start of the twenty-first century, scientists and engineers have not been able to achieve such a lofty goal.)

Although brief, the Lancaster and Moore report did not ignore the need for satellite command and control, making it a significant first step. The Space-Missile Committee working under Lancaster and Moore assumed that an "experimental space missile" could be orbited at an altitude of about one thousand miles, suggesting that "one objective of constructing and launching such a missile" would be the "determination of the feasibility of radio tracking and control."[11] The Space-Missile Committee considered the program only an introduction to the more general problem of satellites and needed a further elaboration of the bureau's organization and objectives for definitive progress. They never got their answer, though, as the navy moved on to supercarriers and away from "experimental space missiles."

Some in the air force saw an obvious threat: If the navy developed a successful reconnaissance satellite, it would threaten the air force's monopoly on strategic reconnaissance.[12] The simple BuAer report directed only an examination into the possibility of a satellite, but Maj. Gen. Curtis E. LeMay, deputy chief of staff for research and development for the air force, found out about the research and responded on a far-reaching scale. LeMay directed Douglas Aircraft's Research and Development Group (later the RAND Corporation) to investigate the possible uses of satellites. Released in May, 1946, RAND's response, "Preliminary Design of an Experimental World-Circling Spaceship," offered a comprehensive look at what satellites could do for the military and suggested three missions: meteorology, communications, and reconnaissance. The report outlined four significant technologies for research and development: long-life electronics, video recording, attitude stabilization, and spacecraft design.[13] The flying air force, enamored with mammoth, long-range aircraft, largely ignored RAND's report when the navy competition disappeared.

Even at this very early stage, the 1946 report addressed the importance of tracking a satellite and calculating its orbital parameters, calling for a "series of telemetering stations [to] be established around the equator to obtain the data from the scientific apparatus contained in the vehicle."[14] The report recommended that the first satellites be placed in orbit around the equator, where they could be repeatedly observed from dedicated ground stations. A radar-equipped ground station could measure both range and angle, compute the rate of change of altitude, and send a corresponding pulse to the vehicle. A beacon in the vehicle, which acted as a transponder, could also convey information from the vehicle to the ground. Nevertheless, RAND acknowledged, current radar techniques involving radar ranging or Doppler shift measurements did not offer adequate accuracy.[15] Engineers and scientists understood the radar technology used in World War II, although they had yet to prove its utility for space vehicles.

The RAND scientists and engineers included in the report plans for a global network of tracking stations. For "orbital observation and telemetering," a satellite required some twenty to fifty stations installed or positioned in a belt around the equator, across the Pacific, Ecuador, Brazil, the Atlantic, French Congo, Kenya, the Indian Ocean, and Malaya. The tracking system had to link all these stations with each other or with a central station by rapid communications so that engineers could maintain continuous tracking and telemetering of the "satellite missile," particularly to guide its return to Earth, which would be essential if it had a pilot.[16] RAND's estimate of the required number of ground stations proved to be a little high, but their idea of a centralized command and control system proved prescient.

RAND admitted that its scientists and engineers still had much research ahead of them. They barely understood the infant technology of transmitting telemetry from guided missiles to ground stations, although American engineers made great strides during the 1940s using captured German V-2s and other test missiles. Scientists and engineers could learn a great deal about satellite command and control from these activities, so they launched a number of missiles for their benefit. Eventually engineers developed, tested, and exercised an entire communication system that would be required in an actual satellite operation.[17]

In the 1940s and 1950s the air force reconnaissance community was wedded to long-range bombers flying reconnaissance missions: "When you wanted to take pictures of something, you just got in your airplane, went out, and turned on your cameras and came back and processed the film."[18] Senior officials who endorsed the idea of satellites for military purposes rightly sensed that the air force—committed to the existing aerial reconnaissance technology—would not nurture a new, space-based reconnaissance technology.[19] The mainstream air force rejected space-based reconnaissance as technically crude and economically risky and continued to champion piloted reconnaissance aircraft. President Eisenhower, on the other hand, needed the alternative of space-based reconnaissance to provide evidence that the Soviets lagged far behind in missile development because reconnaissance aircraft like the RB-29, PB4Y-2, and later even the U-2 could not reach every site in the USSR to search for missiles and bombers.[20] Eisenhower's pressing needs and the air force's stubbornness proved an asset for the space community in the short term but a detriment for the air force in the long run.

Inside the air force, a small but vocal minority of space enthusiasts argued that the notion of spacecraft and satellites had technical practicality. Espousing the cause of continuing satellite studies at considerable risk to their careers, leaders such as Maj. Gen. Donald L. Putt, air force deputy chief of staff for research and development; Gen. Hoyt S. Vandenberg, later air force chief of staff; and then Col. Bernard A. Schriever, military liaison to the Scientific Advisory Board, kept official interest in satellites and space programs alive. As Gen. Thomas Morgan later recalled, word came down from the highest levels in the air force that officers should not talk about such missions because space was a "nonuseful type of endeavor for the military to get into."[21] Yet, in forbidding officials even to speak the word "space," the air force merely acknowledged the radical character of the new invention.[22]

In the late 1940s, RAND scientists and engineers continued to develop a basis for making satellite control systems a reality. Building on the 1946 report, RAND submitted twelve detailed, supplemental studies that aimed at convincing the air force of the usefulness of the orbiting spacecraft. Finally, in January, 1948, the vice chief of staff of the air force, General Vandenberg, authorized the air force's Engineering Division to fund further RAND studies of satellite operations. Vandenberg also issued a policy statement that staked the air force's claim for space operations: "The USAF, as the Service dealing primarily with air weapons—especially strategic—has logical responsibility for the satellite."[23] Although the air force did not have a formally approved space program at the time, some service leaders had an interest in the possibilities of space and never retracted General Vandenberg's statement. Building a satellite for any reason, let alone strategic reconnaissance, endured an extended infancy in those postwar years.

In the early 1950s, organizations besides RAND investigated the usefulness of satellites. The first unclassified publication on satellites came from the British Interplanetary Society (BIS) in 1951. Little more than a pamphlet, *The Artificial Satellite* speculated on the possibilities for an unpiloted satellite and even offered plans for an Earth-orbiting space station. Whereas RAND envisioned military applications for satellites, the British Interplanetary Society's ideas of satellite applications emphasized scientific research: "The extension of radio-telemetering into free space will permit studies of radiations, corpuscular and electromagnetic, emanating from outer space."[24] The society recognized the need for telemetry, tracking, and control of space vehicles and commented favorably on "the multiple-channel telemetering systems used in the American high-altitude rocket programme."[25] BIS's pamphlet was not nearly as remarkable as what RAND produced in 1951.

RAND's 1951 report, "The Utility of a Satellite Vehicle for Reconnaissance," became the first, detailed technical report in the evolution of satellite command and control. RAND took a major step by stating the technical and engineering possibilities for a reconnaissance satellite employing television techniques for data readout to ground stations. RAND found its earlier satellite advice largely ignored, but its scientists and engineers did not give up, preparing another report for the air force on "The Utility of a Satellite Vehicle for Reconnaissance." RAND personnel advocated television because they recognized that satellites must transmit large amounts of imagery data, and television seemed the easiest medium. In addition, in the early 1950s the reentry and recovery capabilities needed to return an object from outer space through atmospheric heating did not exist. Very heavy copper heat sinks constituted the only available heat-reducing system. Weight put a tremendous strain on the launch and recovery capabilities of the time, so engineers tried to keep the satellite as small as possible.[26]

In building their technical case, RAND devoted most of its April, 1951, report to the type of orbit a reconnaissance satellite needed—for example, its speed, altitude, shape, and so forth.[27] Analysts suggested that the best orbit for reconnaissance of the USSR would be an 83-degree retrograde orbit at an altitude of 300 miles. At that altitude the orbit precesses one degree a day, giving the satellite repeated daily visits in the same sunlight over a certain point. It also gives the vehicle a longer line-of-sight communication time with ground stations.[28]

RAND also pointed out the need to convey the data recorded by the satellite back to the ground. Assuming that satellites could use television signals to broadcast the data to stations "sited either in friendly territories or on ships," transmissions still had to take place on a line-of-sight path because of the required radio frequencies, which were in the AM/FM range (530 KHz to 108 MHz). The maximum slant range (the line-of-sight distance) from a satellite in a 350-mile orbit to the ground would be about 1,400 miles, too far for effective data transmission using either AM or FM unless multiple channels could be modulated onto a single carrier wave (that is, joined together onto a single broadcast signal from the satellite to the ground). Further, this slant range required five stations off the Eurasian landmass, but such an orbit would still miss about 15 percent of the USSR because of the relatively low altitude. The possibility of eliminating unobserved areas increased when employing the technique RAND called "delayed broadcasting." The RAND team nevertheless underestimated the transmitting device technology as so bulky and complex that delayed broadcasting did not "appear to warrant any further investigation."[29] Significantly, the report illuminated most of the problems of using a satellite for reconnaissance and raised important issues in the area of command and control.

RAND's Robert Salter used personal connections at RCA to conduct research at NBC studios in Hollywood and determined early parameters of satellite command and control. On "the basis of a couple of martinis," Salter succeeded in simulating satellite photography. A year later, when Salter began working for eventual satellite contractor Lockheed, he took a few highly accurate pictures of Earth and put them on easels. Salter built degradations into the photos that he assumed matched those from space. Using image orthicons, which were vacuum tubes used in some television cameras, he scanned the pictures in a simulated satellite path and then transmitted them to Mount Wilson, near Los Angeles. Rebroadcasting the pictures back through the atmosphere, Salter recorded them using a kinescope, an early motion picture camera. A group of photo interpreters looked at the pictures to determine what they could see.[30]

RAND devoted considerable attention to the ground tracking stations. A station with an appropriately sized receiving antenna can theoretically track a satellite in a 350-mile orbit for about 3,000 miles, from horizon to horizon. A satellite would traverse that distance in approximately eleven minutes at an average angular tracking rate of 15 degrees per minute, requiring the antenna tracking system to be carefully tied in with the satellite's system. Engineers assumed the diameters of both the satellite's and the ground station's antennas to be one foot and sixteen feet, respectively, and that the ground station's antenna would be reasonably small enough to permit construction.

RAND's engineers preferred using a receiver in the satellite that would respond to a continuous wave signal from a ground beacon to direct the satellite antenna toward the ground station. Before the satellite appeared over the horizon, the ground station would begin transmitting its electronic "greeting." This "handshake" required the orbit to be established precisely enough to enable the ground station operators to predict the azimuth angle—the direction at which to point the antenna when the satellite "rises" above the horizon—to within one or two degrees. Once the two had made their radio connection, the ground station's receiving antenna could follow the satellite by means of a tracking receiver locked onto the television signal. RAND speculated that to make it all work, a beacon of about 1,000 watts of power would yield a broad enough beam to illuminate the satellite when it rose above the horizon.

Because of a ground station's size and the fact that it did not move much (whereas satellites moved a lot), considerations of circuit complexity and power consumption did not significantly affect the ground station design, which could take any of several forms. The ground station's sixteen-foot receiving antenna could have a single feed connected through a power receiver to two receivers for system redundancy. The search phase consisted of aiming the axis of the dish in the direction of the satellite's scheduled appearance and then oscillating the dish through its axis so that the axis of the scan would describe an arc centered on the direction of the satellite's orbit. When the satellite appeared, its tracking antenna would first contact the ground station's beacon, thus aligning the satellite's transmitting antenna with the ground station.[31] RAND believed that only a single ground station would be necessary, suggesting that its location be somewhere in Alaska, perhaps Fairbanks or Point Barrow, and believing that weather, communications, and transportation would all be sufficient even that far north.[32]

With the tracking problem seemingly solved, RAND turned its attention to the assimilation of the TV pictures after they arrived on the ground. The equipment required at any forward receiving station would not be complex and in fact would be similar to television broadcasting gear then in use. Any ordinary television receiver would probably suffice for monitoring for satisfactory picture quality. For recording, a station would need a second television receiver. Camera optics would reduce the image to the appropriate film size; RAND thought 35-mm film might be adequate, but if they lost a significant amount of detail, they could employ 70-mm film. Schedulers furnished each ground station with a plan for operations that was based on the satellite's orbit. A time coding scheme would be included with each frame that would indicate not only when the satellite took the picture but also when it arrived at the ground station. The central evaluation station—presumably the one at Hanscom AFB, Massachusetts, which already housed the air force's photograph interpreters, or later, the National Photographic Interpretation Center (NPIC) in Washington, D.C.—would receive the composite films from the forward stations and assemble the orbit into an integrated whole. The entire presentation system would be simple, rapid, reliable, state of the art, and practical, using well-known, photo evaluation techniques.[33] Anyone who was within the range of the remote tracking station could also easily intercept the signals. The report ended with a discussion of how the enemy might track the reconnaissance satellite, either actively with radar or passively with cameras similar to the air force's own Baker-Nunn camera, which was used for ground-to-space observations (an entirely different type of satellite tracking).

In sum, the scientists and engineers of the Scientific Advisory Group and RAND Corporation roamed widely to find solutions to the problems they encountered. Von Kármán's report to Gen. Hap Arnold presented a vision for the air force in space. Arnold's successors, although stymied by a conservative organization, turned the vision into reality by seeking out independent research organizations. RAND's reports on the utility of an artificial satellite became the first detailed technical reports in the evolution of satellite command and control. However, unlike aerial reconnaissance, the air force did not have an exclusive interest in satellite command and control.

Invention of Satellite Command and Control outside the U.S. Air Force

During the 1950s, the United States had several organizations besides RAND researching the usefulness of a satellite and the technology of satellite command and control. These organizations all had to overcome the same problems and questions that RAND faced in its research; among the most important of these was "What do you *do* with a satellite once you've got it in space?" Without exception, everyone came to the same conclusion: Gather data. The Minitrack and Microlock satellite tracking networks—which scientists and engineers developed in the 1950s for the Naval Research Laboratory and the Army Ballistic Missile Agency and which were both innovative but essentially conservative inventions—proved the viability of satellite command and control, while simultaneously improving and expanding existing telemetry systems.

After World War II Johns Hopkins University's Applied Physics Laboratory (APL) broke new ground in telemetry systems. Working for the navy on the Bumblebee series of guided missiles, APL made enormous strides in the late 1940s, establishing many of the standards for radio telemetry and introducing subcarriers on radio frequencies to enhance data transmission capabilities. By the time telemetry matured, engineers and scientists had continuously enhanced and increased the flexibility of ground station equipment. Recording techniques, especially, progressed from making a phonograph record to recording on magnetic tape.[34] Scientists and engineers outside APL borrowed their methods and used them for their own satellite programs.

S. Fred Singer, a young Princeton physicist whose doctoral committee had included nuclear physicist J. Robert Oppenheimer, offered his Minimum Orbital Unmanned Satellite of the Earth (MOUSE) to the American Rocket Society in April, 1955. In his discussion of the technical problems associated with the launch, control, and instrumentation of MOUSE, Singer made sure everyone understood the ramifications of telemetering, including—for the first time in a satellite proposal—channels and frequency modulation. He suggested a polar orbit for MOUSE as the most economical by storing data on board the satellite and then releasing it over either the North or South Pole. Because polar orbiting satellites passed over the poles and therefore over polar-based tracking stations on every orbit, this plan called for a minimum number of ground stations. Singer's strategy would thus obviate the need for the large number of tracking stations required to support an equatorial orbit, which other proposals advocated. Singer drew the same orbital conclusions RAND had drawn, but an international treaty made Antarctica off-limits for anything but purely scientific research, so for RAND's proposed reconnaissance satellite the South Pole sat too far away, both physically and politically. Singer understood that his proposed test satellite could not perform the types of missions—like reconnaissance—that required a high degree of orbital precision. He noted that engineers could accept deficiencies in optical visibility and the accuracy of the orbit for a satellite with geophysical or astrophysical research applications. Such a scientific satellite required only extremely simple propulsion, guidance, and control in comparison to satellites meant to fulfill more ambitious functions like space-based strategic reconnaissance.[35] Singer's proposal, the first significant proposal for a scientific satellite discussed in nongovernmental circles, caught on with the scientific community, but not with the U.S. government.

Scientists and engineers often publicly discussed how best to build the needed tools for communicating with satellites. At the February, 1957, Astronautics Symposium in San Diego, cosponsored by the Air Force Office of Scientific Research and the Convair division of General Dynamics, prime contractor for the Atlas ICBM, experts from Lockheed, RAND, and the Jet Propulsion Laboratory gave papers on satellite tracking. The conference attendees concluded overall that no additional major breakthroughs would be required for an adequate communications system for space travel. Using systematic exploitation of the techniques and devices already known, electronics engineers could achieve a level of communications system performance that would satisfy space travel requirements for years to come.[36]

Max Fishman, a researcher at Lockheed, suggested at the conference that the size of the transmitters and receivers on the satellites themselves might be the biggest problem in satellite command and control because early designs placed a premium on "legroom." Increasing the bandwidth of the communication link (that is, the amount of data that could move across communications signals) with a satellite dictated greater transmitter power, increased receiver sensitivity, or increased antenna size. The simplest solution called for increased antenna size on the ground and a decreased number of operating frequencies, which Fishman achieved with a fixed base, steerable antenna system.[37] Fishman's ideas eventually found their way into the air force's tracking stations.

After years of engaging in little more than intellectual discussions, governmental officials found their indifference to satellites fading in the glare of the International Geophysical Year (IGY). First discussed by the scientific community as early as 1954, this international project of a concentrated, coordinated exploration of Earth's cosmic environment was planned to run from July, 1957, to December, 1958. Publicly, the United States denied that a race with the Soviet Union to orbit a satellite for the IGY forced its decision to go ahead with a satellite program. Privately, the United States staked its technological reputation on a research and development project called Vanguard. Vanguard would develop a grapefruit-sized, scientific satellite that utilized a radio tracking plan called Minitrack, which the Naval Research Laboratory would run.

On March 26, 1955, the National Security Council ruled that the American scientific satellite program should not use ICBMs or IRBMs. The army's proposal depended on the new Jupiter IRBM then under development, but the Vanguard engineers planned an entirely new rocket for their satellite. Then in August, 1955, the Stewart committee, the scientific review panel that was charged with selecting the American entry for the IGY, formally selected Vanguard as the scientific satellite program. According to Homer J. Stewart, chair of the panel, Vanguard's Minitrack network had a direct bearing on the decision to accept Vanguard over the army's Project Orbiter, which planned a visual instead of an electronic tracking network. Vanguard's brand-new missile, perceived as untainted by either the air force's or army's long-range missile development programs, also helped sway the Stewart committee.[38]

Vanguard's electronic tracking system used radio interferometry. Essentially, two ground receiving stations tracked the signals broadcast by a satellite; by comparing the phases of the signals, each of them separately received, scientists could accurately calculate the angles to the spacecraft and therefore calculate its orbit. In a sense, radio antennas work much like our ears in that they are able to locate the source of a sound by determining the phase differences in the sound waves, which arrive at each antenna at slightly different times.[39] Vanguard originally included an optical tracking plan, but this method, although accurate, had limitations. By using the best equipment, trackers could observe an object in orbit with the sun only at five degrees below the horizon, that is, just before sunrise or just after sunset; even then, visual tracking required clear and relatively cloudless weather.

Vanguard's tracking system became the nation's first dedicated satellite control system. In the early 1950s, Vanguard engineers under Milt Rosen at White Sands, New Mexico, built and field-tested a tracking system for their Viking missile tests. John T. Mengel and his associates came up with a 13-ounce transmitter for the Vanguard satellites, far smaller than those carried aboard their Viking rockets but employing the same system. Mengel gave the tracking system the name Minitrack. Minitrack consisted of a quartz-crystal-controlled and fully transistorized oscillator aboard the spacecraft. Its 10-milliwatt output operated on a fixed frequency and had a predicted lifetime of ten to fourteen days.[40] In addition to the tracking function, Minitrack included antennas and receivers to read the data transmitted by the satellites—in other words, ground telemetry stations.[41]

Vanguard faced political limitations on its tracking network that made it useless for reconnaissance satellites. Because they planned to launch Vanguard from Cape Canaveral, the satellites had to go into an orbit limited to 35 degrees above or below the equator. An orbit with such an inclination could prove useful for not only tracking reasons but also political ones. Vanguard satellites would not track so far north that it would invade the "space" above the USSR, but they could still help set a precedent for freedom of navigation in orbit above Earth, a major American concern before the first satellite launch.[42] Therefore, to track the satellite, the Vanguard team planned to establish a "picket line" of Minitrack stations along the roughly equatorial orbital path, eventually placing stations on the islands of Grand Bahama, Antigua, and Grand Turk, as well as in South Africa, Australia, and South

America. These stations, including one in the United States, would be leased with the help of the navy and the Department of State. These seven stations had a 90-percent chance of tracking every pass of the planned 300-mile orbit.

The system introduced the concept of control from a central location. Bendix Corporation built the ground station equipment, including the radio-frequency receivers, power supplies, operating consoles, phase measuring equipment, analog and digital recorders, and quartz-crystal oscillator clocks. Melpar, Inc., built the AN/DPN-48 radar beacons for tracking. Observers at the tracking sites sent information by teletype to the Vanguard Computing Center in downtown Washington, D.C., where technicians fed the figures into an IBM-709 "electronic calculator," leased to the government at $900,000 for six weeks (including a backup capability at IBM's headquarters in upstate New York).[43] As the stations collected observations along various points of the orbit and controllers transmitted them back to Washington by teletype, technicians fed the data into the computer that calculated Vanguard's orbit. The software included corrections for atmospheric drag and the wobble of the orbit due to Earth's bulge. It could give a minute-by-minute position 150 times faster than Vanguard actually flew.[44] The program centered its communications network in Anacostia, in Washington, D.C., from which teletype connections stretched to Cape Canaveral and all of the tracking stations, as well as to the Vanguard Computing Center. From one central location, then, scientists were able to follow and control the whole progress of Vanguard's tracking and data acquisition. Thus Vanguard became the prototype for future satellite systems.[45]

Just before going operational in late 1957, the system faced its first test. All the Minitrack equipment operated on the IGY frequency of 108 MHz, which later became the edge of the civilian FM radio band. In October, 1957, the Soviets' Sputnik satellites operated at 20 MHz and 40 MHz, the same as American ham radio frequencies. Minitrack engineers scrambled to get as many stations as possible retuned for this de facto operational test and to send new oscillators and instructions out to all of the ground stations. Most of the stations never got accurate data on Sputnik, but the stations at Lima, Peru, and San Diego, California, picked up useful tracking data on both *Sputnik 1* and *Sputnik 2,* which launched a month later. The IGY committees had chosen 108 MHz because it would give a more accurate indication of direction for tracking purposes, but the Sputnik frequencies nevertheless yielded information about the ionosphere and its effects on radio frequencies.[46] Sputnik demonstrated that the nascent American tracking system worked, although it had little flexibility.

Vanguard's Minitrack became the nation's first ground-based, space tracking network, but engineers had designed it for only one satellite program and operated it at only one frequency at a time—both major shortcomings. Minitrack operated full-time as a worldwide satellite network, but only in a limited fashion. Minitrack had 35 full-time tracking and data acquisition facilities in operation, and another 15 that were shared or part-time facilities, but the entire network supported a single satellite at a single frequency. In addition, virtually no capability existed for polar orbits, and Minitrack could support only about half of those orbits with inclinations greater than 51 degrees, thus making it virtually worthless for a satellite reconnaissance system reconnoitering the USSR. The only satellite programs fully supportable included those at 35-degree inclinations and transmitting at 108 MHz, like the Vanguard satellite itself. The meager data acquisition capabilities included only low-bandwidth capabilities and also required the use of magnetic tape to record and send data by mail to the central office. Teletype transmitted only the most rudimentary data in real time. Eventually, Minitrack's shortcomings became so pronounced that NASA and the DoD proposed the creation of a national tracking program on the "inescapable premise that no space program is feasible without an adequate ground environment," at a total cost of $41 million for FY 1959.[47] When Vanguard finally orbited successfully, Minitrack served it exceptionally well, but its shortcomings limited its usefulness for an American system of satellite command and control that could support reconnaissance satellites.

Other important developments in satellite command and control occurred on the West Coast. Engineers at JPL generated a number of technical innovations that proved significant in their contributions to the programs that would follow. The receiver in JPL's Microlock—a phase-locked loop tracking system capable of picking up minute signals at great distances (e.g., under ideal conditions, a 1-milliwatt signal 6,000 miles away)—was as an impressive innovation. As adapted in 1955 for the army's Project Orbiter studies (which eventually became Explorer, the first American satellite to achieve orbit), Microlock separated out five telemetry channels. Explorer also included a tape-playback system that made it possible to store and then transmit data when in view of a ground station, which Explorer would not be for most of its orbit. In 1958, *Explorer 3* even contained a miniature tape recorder that moved at the slow speed of 0.005 inches per second, using less than three inches of tape per orbit. This recorder is the archetype of the satellite-based, store-and-forward systems in use today. When a satellite neared a tracking station, a ground signal turned on the satellite's playback head and its high-powered transmitter. In less than five seconds, the satellite sent all its data on the tape, erased it, and reset.[48] Many of Jet Propulsion Laboratory's innovations found their way into satellite programs over the years.

For the scientists and engineers at the Jet Propulsion Laboratory, the problems of tracking Explorer called attention to the need for a worldwide tracking system. On a dry lake one hundred miles from Pasadena, a huge revolving dish 85 feet in diameter rose out of the Mojave Desert at Goldstone, California. In those days, because only minimal ambient radio "noise" reached out that far from Los Angeles and because of the dry desert weather, Goldstone proved ideally suited to set up the Deep Space Network, soon to provide support for all aspects of American civilian spaceflight and to become a vital part of JPL's activities. The Jet Propulsion Laboratory engineers received approval for foreign stations in Australia, Spain, and South Africa.[49]

The American Mercury space program also required a worldwide tracking network to support its astronauts. Of all of those efforts, NASA had the most difficulty in establishing a new tracking network from scratch. When flight surgeons decided they needed to have constant contact with the astronauts, Mercury program engineers realized they had to create a worldwide tracking and communications network with gaps of no more than ten minutes. They knew that the technically immature Minitrack network already in place had too many gaps in its coverage to meet the flight surgeons' criterion and thus was inadequate. In February, 1959, the Space Task Group at NASA Langley put together an ad hoc team that built a telemetry, tracking, and control network within two years.[50] NASA, therefore, built its second worldwide tracking network to serve the needs of its piloted, low-declination space program. The Mercury network stretched from the Mission Control Center at Cape Canaveral to eighteen communications relay stations on three continents, seven islands, seven foreign countries, and two ships. It used 177,000 miles of hard-wired communications lines, most of which were leased; 102,000 miles of teletype; 60,000 miles of telephone lines; and more than 15,000 miles of high-speed data circuits, all cross-linked and connected to NASA's Goddard Center in Maryland, where two IBM 7090 computers calculated orbits in real time.[51] NASA estimated the total cost for the system in 1959 at $41 million.

For the fifth launch of a Mercury spacecraft on board an Atlas booster (MA-5), the tracking network performed flawlessly. Unfortunately for Enos, the chimpanzee sitting inside, the same was not true for the incorrectly wired systems inside the spacecraft, which shocked him repeatedly even though he did his tasks correctly. The tracking network's first challenge in real time came near the end of Enos's first orbit, when the trackers noticed that the spacecraft's clock ticked eighteen seconds fast, and they sent a command to reset it. The stations in the Canary Islands and Western Australia detected other problems, but the Woomera, Central Australia, station could not confirm them. In late 1961, NASA approved the tracking network for human flight and prepared MA-6, John Glenn's *Friendship* 7.[52] This tracking network formed the nucleus of NASA's tracking network for piloted spaceflight all the way to the moon flight.

The Minitrack and Microlock tracking networks—and their offspring used in Mercury—improved upon and expanded the existing systems; engineers did not invent radically new systems. The later Air Force Satellite Control Facility began its evolution as part of a radical new system of satellite reconnaissance but became essentially a conservative system as well. Ideas about satellite command and control developed similarly inside and outside the air force, but engineers built the networks differently because the space programs had different missions. In effect, therefore, the United States had two tracking networks: one civilian and in the open; one military and in the background.

Invention of Satellite Command and Control in the USSR

Unlike the United States and because of the nature of the totalitarian state, the Soviet Union did not have the artificial distinctions of civil and military space programs. The USSR's space program served state purposes, whether scientific, military, or propagandistic. Interestingly, though, little differentiates the Soviet and American space programs with regard to their general purpose and direction. Both included elements of scientific exploration, technology development, national image building, practical uses, and military support applications. For example, between 1957 and 1981, the U.S. Defense Department conducted about 57 percent of the nation's space flights, including 44 percent for military-only reasons; by 1981, the Soviets had conducted about 66 percent of their successful space flights for "strictly military purposes." Budgetary comparisons are harder to make, but it might be safe to assume that they equate roughly as percentages of gross domestic product, perhaps weighted more to the USSR.[53]

Regardless of the purpose, the Soviet space program had to have a tracking network just like that of the United States to verify space "firsts" and to maintain command and control over satellites. In this regard the Soviet tracking network did not differ from the two U.S. tracking networks. As in the United States, the Soviets developed their tracking network from the systems that were originally designed to evaluate the success of missile test flights.

Historians have already written much about the advanced state of rocketry in the Soviet Union in the years before and after World War II. Even in Imperial Russia, Konstantin Tsiolkovski had speculated about multistage rockets and space stations. Sergei Korolev and his compatriots also tried to create the Soviet space program they wanted within the system they were using, much as has been suggested about Wernher von Braun during and after World War II.[54]

While von Braun and others worked hard on artificial satellites in the United States, Korolev and others did the same in the USSR. The Technical

Documents Liaison Office at Wright-Patterson AFB in Dayton, Ohio (the center of the U.S. Air Force's weapon system program development offices, including reconnaissance satellites until 1956), obtained and translated a copy of a Soviet technical report nominally written by A. Shternfel'd [*sic*], called simply *Artificial Satellites* and classified as top secret. The report covered a variety of subjects on the application and operation of satellites. In these highly technical chapters, Shternfel'd speculated that "three or four ground stations" would be sufficient for the continuous maintenance of communications "with a space radiosonde-satellite flying around the moon." As American engineers and scientists already knew, "[s]ince the operator controlling the space rocket-sonde would be on the earth, telemetering and telecontrolling would have to be provided with a device to compensate [for] the earth's rotation."[55] In fact, the Soviets accomplished much more than just researching and writing about the command and control of artificial satellites.

Contrary to popular opinion, in creating their system of satellite command and control, Soviet space engineers used advanced science and technology. In 1953, in an address to the World Peace Council in Vienna, the president of the USSR Academy of Sciences noted that "Science has reached a state when it is feasible to send a stratoplane to the moon [and] to create an artificial satellite of the earth."[56] Soviet scientist G. I. Pokrovskii speculated that although a satellite the size of a billiard ball would be of sufficient size to be observed from Earth, a "satellite several decimeters in diameter" could be more useful.[57] Soviet scientists and engineers published papers and gave talks in an effort to share knowledge, "provided, of course, this [research] will be directed to the good of mankind, for the progress of science," but also in an effort to show the world that the Soviets' science and engineering capability matched "that of most great countries."[58] Thus, even before the international propaganda success of *Sputnik 1*'s 1957 launch, Soviet scientists and engineers had begun planning for a tracking network, just as their American counterparts had.

The unique Soviet political structure also affected the organization of the Command-Measurement Complex (KIK), which has served every single piloted, interplanetary, scientific, and military space mission from 1957 to the present time. A government decision in January, 1956, following "fierce interministerial wrangling," placed the responsibility for developing a satellite command and control network onto the shoulders of the military.[59] Engineers, scientists, and military officers expended a major effort in creating a ground infrastructure to track and make contact with *Sputnik 1*. After fierce competition between the Academy of Sciences and the Ministry of Defense for the contract to build the telemetry, tracking, and command network, the defense ministry took on the job of satellite command and control. Overseen by Deputy Director Yuriy Mozzhorin, KIK initially comprised seven major stations spread across the USSR—at Tyura-Tam, Makat, Sary-Shagan, Yeniseysk, Iskhup, Yeilzovo, and Klyuchi—euphemistically called "scientific measurement installations" in order to justify the high ranks and salaries of the commanders and personnel, as well as to provide a cover story for the military's involvement.[60]

Scientists and engineers in the USSR positioned their satellite tracking stations in a way that kept their locations secret; at the same time, however, they provided an acceptable environment for communications, power, and living arrangements. At each site the military established new units with their own seal, banner, and guard. They placed the stations in the arid desert or steppe on both sides of the flight trajectories from the Baikonur launch site in Kazakhstan. The stations became independent units with their own supplies, technical support, and financial resources, employing five or six officers and thirty to eighty conscripts. Officers' families lived with them but had no schools or other support facilities. Life at the tracking stations, as in the American systems, grew monotonous when the personnel were not supporting a launch. At first newcomers would feel elated because of the apparent freedom and independence of the isolated sites. Then they would become bored and often volunteered for transfers to anywhere else.[61] In one case, a lieutenant colonel who was appointed commander of one such outpost committed suicide rather than accept his assignment.[62] Although their satellite tracking sites existed in the same sorts of isolated environments, American commanders mostly dealt with alcohol abuse as their main problem.

Soviet engineers, scientists, and military officers created a ground infrastructure capable of centralized satellite command and control. Each station relayed all the tracking and telemetry data to the Coordination-Computation Center, established in Moscow in early 1957, under the command of Pavel A. Agadzhanov.[63] In addition to its responsibility for the missile-tracking network, the ministry of defense was accountable for the tracking, telemetry, and command network for all Soviet satellites. Despite rumors to the contrary about women doing all the calculations by hand, computer facilities in the USSR could easily determine the initial trajectory of a space launch with a high degree of accuracy. Like their competitors in the United States, the Soviets did data processing for orbital calculations as early as 1961 using an advanced digital computer capable of 20,000 operations per second, with another computer probably capable of around 50,000 operations a second. These computer capabilities easily rivaled those of their counterparts in the American space program of the 1960s.[64]

The size of the USSR presented unique problems for the developers of command and control. The Soviet Union stretched two and a half times the width of the United States, but only nine of every twenty-four hours of a satellite's orbit passed over the Eurasian, ground-based tracking network. When tracking requirements became more stringent for the piloted space program—as they did in the Americans' Mercury program—the Soviets added six new ground-based tracking stations. The lack of a global tracking network capable of continuous observation and communication with satellites became the chief limitation on Soviet capabilities for satellite command and control and necessitated another solution.[65] The Soviets filled in the gaps in their tracking coverage primarily with tracking stations on ships, by positioning them at strategic points around the world (similar to the one NASA later used to fill in holes in its coverage, though on a much wider scale). Perhaps reluctant to negotiate or unable to achieve agreements for placing tracking stations in foreign countries as NASA and the American military had, the Soviet Union relied on fully equipped, self-contained, floating tracking stations, which first set sail during the ICBM tests of the late 1950s as part of Pacific Ocean Hydrographic Expedition Number 4.[66] As in the U.S. programs, the satellite command and control ships developed out of the missile-testing program. By the mid-1960s, the tracking ships, including *Kosmonaut Yuri Gagarin* and *Akademik Sergei Korolev,* each displaced at least 17,850 tons, and each had a crew of 121 plus a science team of 118. American ships like the USNS *Hoyt S. Vandenberg* and USNS *Henry H. Arnold* exhibited similar displacements. *Gagarin* reportedly made frequent port calls to Havana.[67]

As in the United States, Soviet engineers sometimes had to improvise in the development of a satellite command and control system. In 1959, when Korolev first began developing interplanetary spacecraft to fly to Mars and Venus, he proposed a dedicated site to build a deep space tracking station, comparable in capability to NASA's deep space tracking network. Because they had a deadline of just eight months, Korolev came up with the ingenious idea of mounting the dishes using leftover parts from the Soviet navy. Construction workers dug a huge crater out of the rocky ground, poured in a foundation, took the revolving gun turret of a former seafaring battleship consigned to the junkyard, and placed it on the foundation. Then workers placed the open framework of a railroad bridge over the turret. The solid hull of a scrapped submarine, to which they fixed the antennas, covered the bridge itself. Eventually the station, located at Yevtaporia on the Black Sea, consisted of three complexes separated by several kilometers: one designed to send commands, and the other two to receive telemetry. Each complex had eight antennas, each one with a diameter of 16 meters and a surface area of 1,000 square meters and a total maximum range of 300 million kilometers. The facility became fully operational on December 30, 1960.[68]

Thus, the Soviet Union created a single satellite command and control network rivaling the two American tracking networks, creating perhaps an economically more efficient network that was able to serve both the civilian scientists and the defense needs of the military, one just as limited by the constraints of politics and society as its American counterparts. Soviet scientists and engineers created their satellite command and control network according to the sociopolitical needs of their highly controlling national system.

Summary

Although separate from the mainstream, the air force did not invent satellite command and control on its own; a variety of scientists and engineers, free from the constraints of large industrial or governmental organizations, developed solutions to the issues that engineers and scientists encountered when working on the problem of satellite command and control. The air force, for example, received assistance from a group of scientific advisors who represented the best minds in the nation and from the RAND Corporation to answer the questions the air force could not resolve alone. Gen. Hap Arnold gave Theodore von Kármán wide latitude for his report, *Toward New Horizons.* Later, Douglas Aircraft's RAND group produced a series of reports on the utility of a "world-circling spaceship," which eventually became the first technical reports in the history of satellite command and control. In addition, General Schriever had unprecedented autonomy in developing the ICBM and the reconnaissance satellite. He did not give details about his programs through normal air force channels but instead reported with the highest national priority directly to the secretary of the air force and the president of the United States.

The inventors of satellite command and control in the United States—scientists and engineers at RAND Corporation, the Naval Research Laboratory (Vanguard's Minitrack), and the Jet Propulsion Laboratory (Explorer's Microlock)—distanced themselves from their larger organizations. Large organizations that are vested in existing technology rarely nurture inventions that by their nature contribute little to the organization and even challenge the status quo, so the air force went outside—to the Scientific Advisory Group and the RAND Corporation—and found answers to questions it could not answer by itself. These scientists and engineers roamed widely and developed solutions to the problems they encountered, according to their own unique situations. RAND's series of reports on the uses for satellites became the first technical reports in the history of satellite command and control and specifically endorsed the idea of satellites for strategic reconnaissance, which fell within the air force's purview.

Ideas about satellite command and control developed similarly inside and outside the air force, but scientists and engineers in the United States built their networks differently because their satellite programs had the very different mission goals of science and military reconnaissance. During the next developmental phase, engineers transformed the invention proposed by the RAND reports into a system of satellite command and control that could support a space-based, satellite reconnaissance system.