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THE EVOLUTION OF THE SATELLITE TRACKING AND DATA ACQUISITION NETWORK (STADAN)

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BY

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

THE EVOLUTION OF THE SATELLITE TRACKING AND DATA ACQUISITION NETWORK (STADAN)

by

William R. Corliss

January 1967

Goddard Historical Note Number 3

GODDARD SPACE FLIGHT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Greenbelt, Maryland

THE EVOLUTION OF STADAN

PREFACE

Most of the popular interest in space technology focuses on satellites in orbit, probes to the Moon and the planets, and the impressive launch vehicles that send these spacecraft on their way. The vital role of satellite tracking and data acquisition, without which any space mission would be doomed to failure, has received little recognition and documentation in the literature. To partially redress this inequity and to relate the historical evolution of NASA's scientific satellite tracking facilities — so essential to the success of space science — this historical monograph has been prepared.

In this effort many people generously contributed their time for personal interviews, for reviews of the rough draft, and for the ferreting out of supporting information. Special thanks are due the following individuals: at NASA Headquarters, Frank Anderson, H. R. Brockett, Edmond Buckley, Norman Draper, Eugene Emme, Richard Heckel, Milton Rosen, Richard Stock, and Roland Theisen; at Goddard Space Flight Center, Harold Hoff, George Kronmiller, John Mengel, William Mitchell, and Clarence Schroeder; at Marshall Space Flight Center, David Akens; at the National Aeronautics and Space Council, Capt. Winifred Berg; at General Dynamics, James Crooks; at the Smithsonian Institution, Frederick Durant, III; at the Naval Research Laboratory, Roger Easton; at Electro-optical Systems, Henry Richter; and Ralph Burhans.

While every effort has been made to present the many facets surrounding this program as accurately as possible, the very effort has created awareness of the likelihood of error. Corrections and additions to this monograph are invited.

October 1, 1966 W. R. C.

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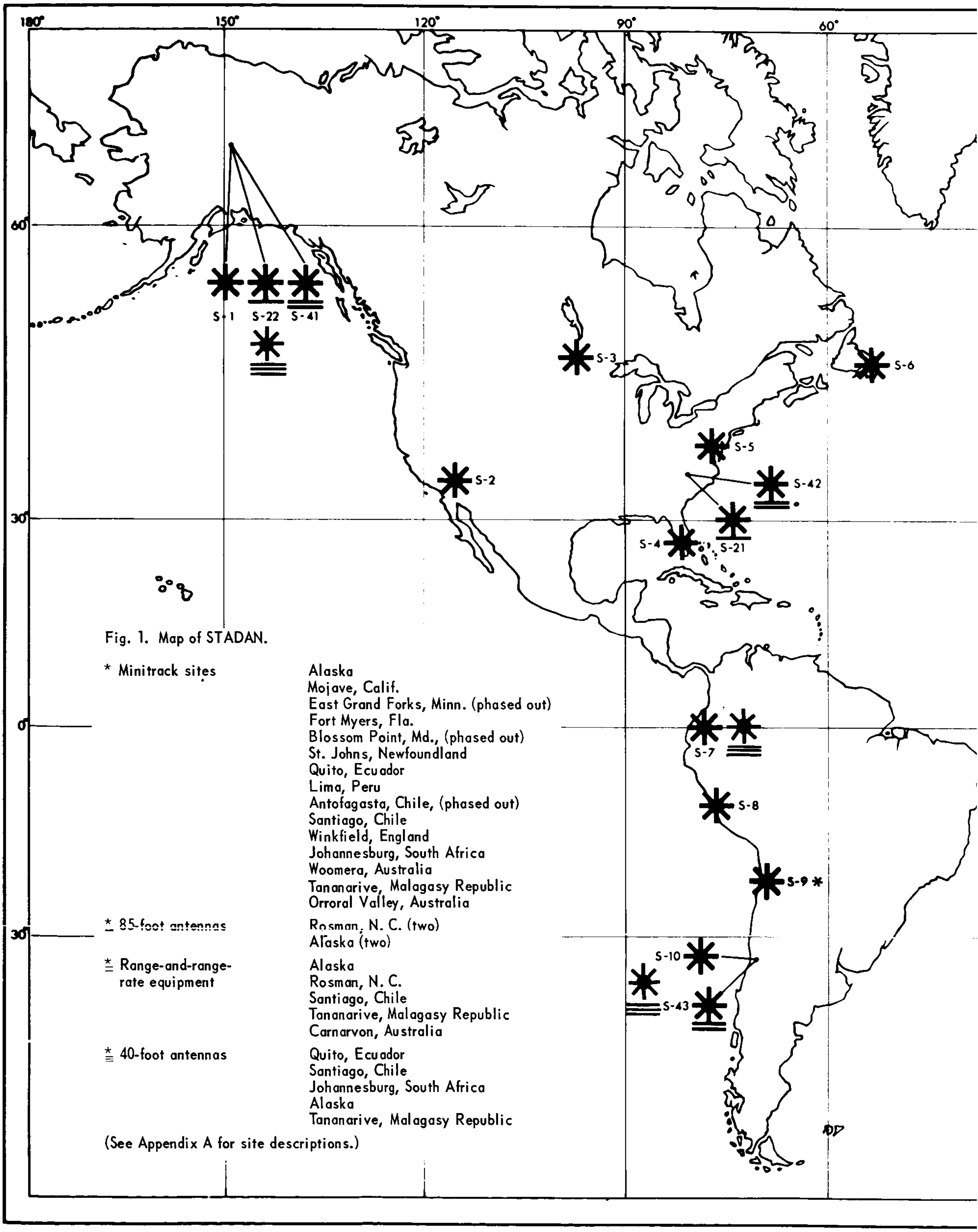
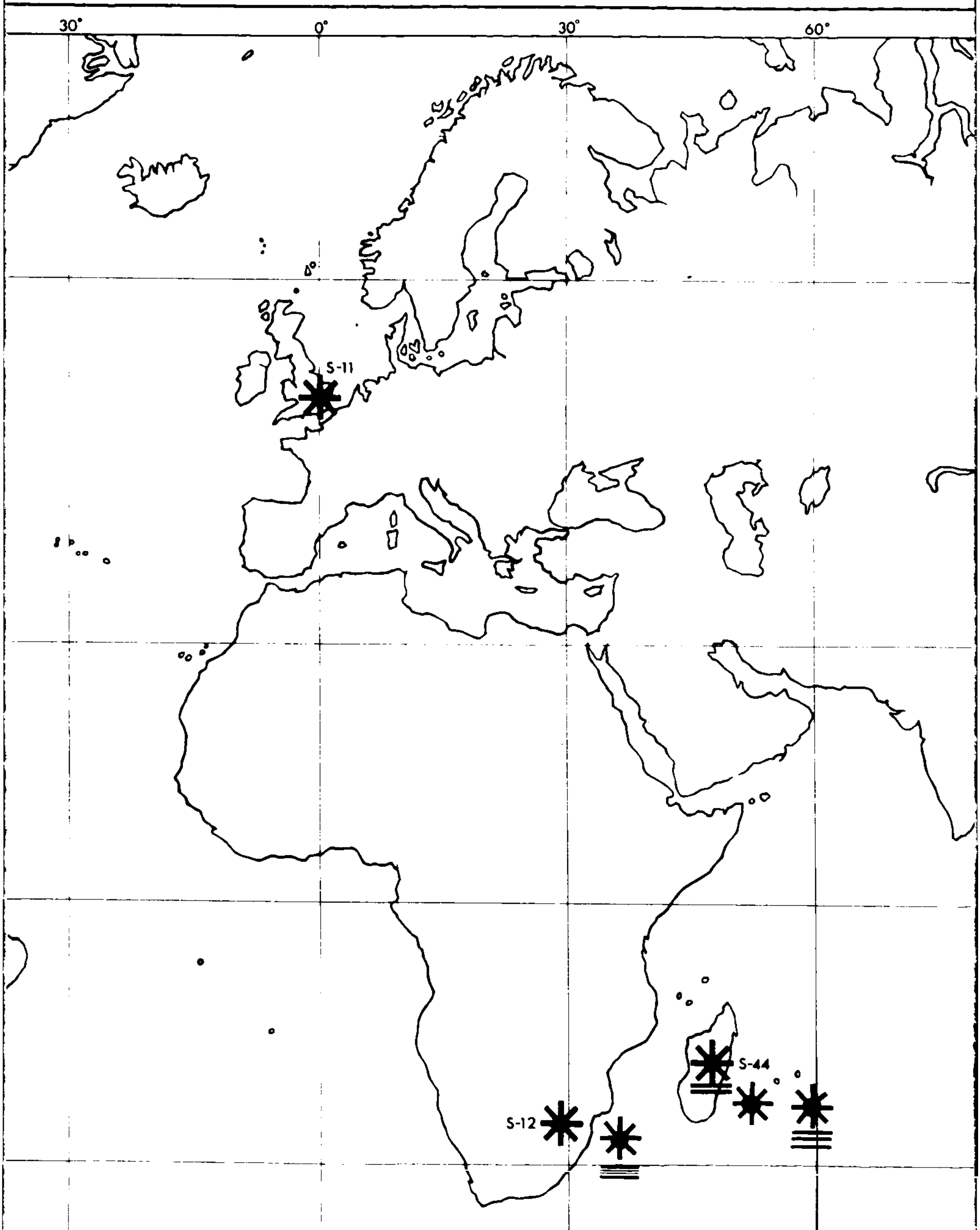


Fig. 1. Map of STADAN.

* Minitrack sites	Alaska Mojave, Calif. East Grand Forks, Minn. (phased out) Fort Myers, Fla. Blossom Point, Md., (phased out) St. Johns, Newfoundland Quito, Ecuador Lima, Peru Antofagasta, Chile, (phased out) Santiago, Chile Winkfield, England Johannesburg, South Africa Woomera, Australia Tananarive, Malagasy Republic Orroral Valley, Australia
* 85-foot antennas	Rosman, N. C. (two) Alaska (two)
* Range-and-range-rate equipment	Alaska Rosman, N. C. Santiago, Chile Tananarive, Malagasy Republic Carnarvon, Australia
* 40-foot antennas	Quito, Ecuador Santiago, Chile Johannesburg, South Africa Alaska Tananarive, Malagasy Republic

(See Appendix A for site descriptions.)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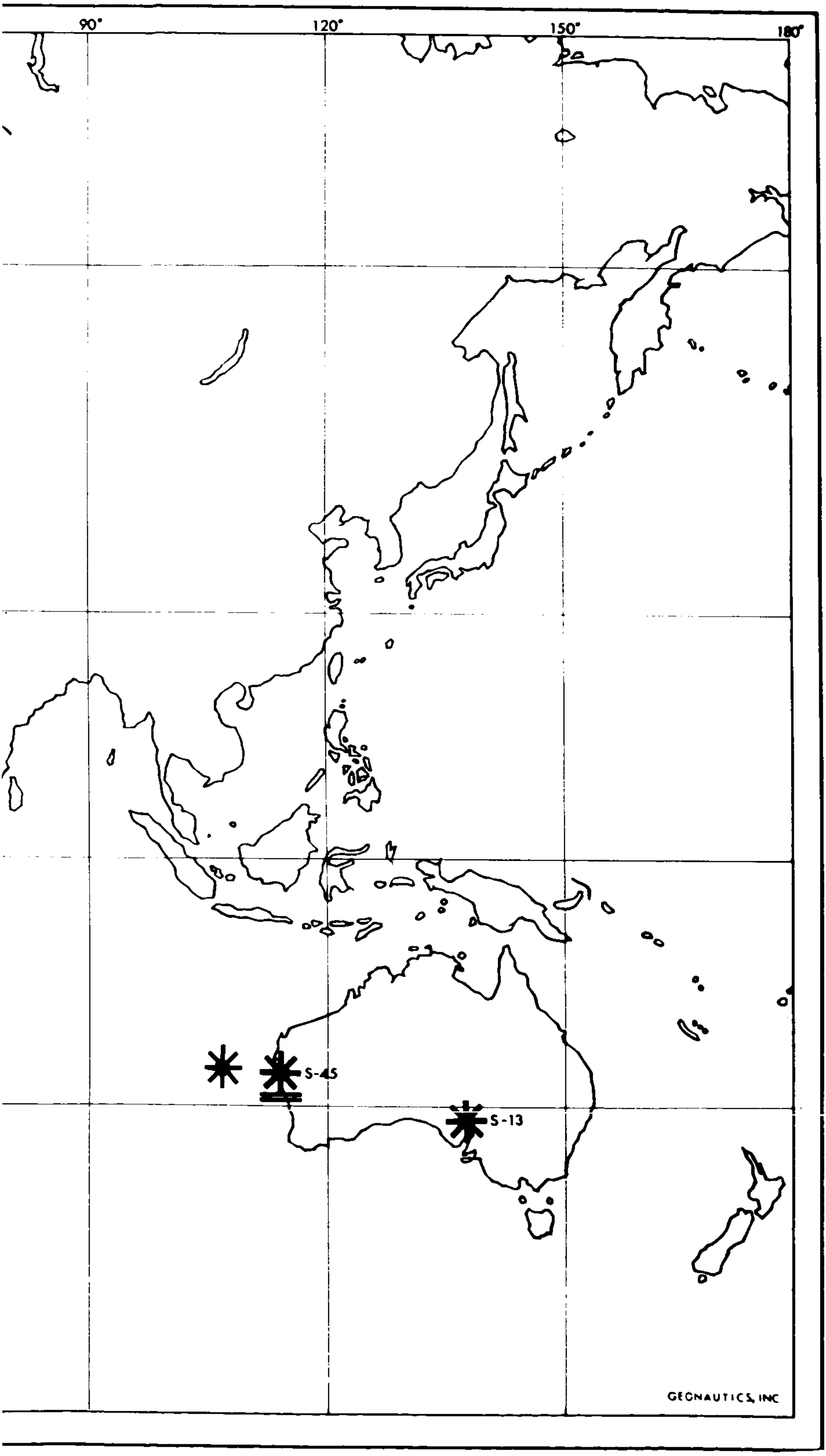
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GEONAUTICS, INC

THE EVOLUTION OF STADAN

CHAPTER I

INTRODUCTION

Most satellites are information gatherers. Some radio back to Earth measurements of the Earth's magnetic field; others transmit TV images of the cloud cover below. The success of such operations depends, first, upon a communication link from satellite to Earth and, second, upon some means of fixing the satellite's position when it makes its measurements. These two functions, data acquisition and tracking, are intrinsic to STADAN and form the basis for the acronym itself: STADAN = Space Tracking and Data Acquisition Network. NASA's STADAN performs two other major functions not blessed by the acronym: satellite command, wherein instructions are radioed to the satellite from the Earth; and terrestrial communication, in which satellite data gathered from all over the world are funnelled into a central data-processing center. By definition, STADAN stops where data processing begins. STADAN, therefore, is a worldwide complex of tracking equipment, data-receiving antennas, command antennas, all the electronic gear associated with these functions, and the terrestrial communication links that tie all facilities to the nerve center at Goddard Space Flight Center, Greenbelt, Maryland. (Figure 1) Under the overall direction of the Associate Administrator for Tracking and Data Acquisition, NASA Headquarters, Goddard has the operating responsibility for STADAN.

The records that arrive at Goddard carry not only data from the satellites' instruments and attitude sensors but also tracking information acquired by the ground station making the telemetry recording. It is of crucial importance that orbital position and satellite attitude be added to each record made by a satellite scientific instrument; because, if the scientist conducting the experiment does not know where the satellite is and which way his instrument is pointing, he cannot properly interpret his data. Worldwide STADAN is essential to the success of weather satellites, geodetic satellites, solar observatories, and the many other diverse instrument carriers orbited by NASA.

STADAN is not used for all spacecraft. NASA also operates the Deep Space Network (DSN) that tracks deep-space probes, such as the Mariners, and the Manned Space Flight Network (MSFN) that is used on the Gemini and Apollo programs. The boundaries or "interfaces" between the three NASA networks are not firm. STADAN is sometimes pressed into service on manned space flights; and sometimes the MSFN and DSN antennas follow the scientific and applications satellites that are STADAN's main reason for being.

Similar interfaces exist between STADAN, the farflung tracking networks maintained by the Department of Defense for military satellites, and the facilities of France, Italy, and ESRO (European Space Research Organization). There is constant interchange of information between all networks on scientific projects.[1]

One final point remains in connection with other satellite electronic tracking networks; particularly SPASUR, ESTRAC, and DIANE; most networks have adopted radio interferometry for satellite tracking, a technique pioneered, in the face of substantial opposition, by the U.S. Naval Research Laboratory (NRL) during the International Geophysical Year (IGY) on Project Vanguard. STADAN itself has evolved directly from the NRL Minitrack network as new stations and equipment have been added to the basic core of IGY Minitrack stations.

Another interface must be defined — the boundary between STADAN and the Smithsonian Astrophysical Observatory (SAO) network of satellite-tracking Baker-Nunn cameras. This network is financially supported by NASA, but it is not part of STADAN. The next chapter will discuss the fascinating confrontation between optical and electronic tracking prior to the IGY.

With the functions of STADAN established and its interfaces with other satellite networks summarized in Figure 2, what is the best way to organize an expedition into the past to dig out it's history? Unlike the vicissitude-ridden story of America's satellite effort[2], STADAN's history is a rather orderly, cause-and-effect tale that logically breaks down into four phases:

1. Pre-IGY tracking developments
2. The IGY phase; from proposals to satellites in orbit, 1955-58
3. Minitrack exploitation, 1958-1962
4. Minitrack evolves into STADAN, 1960-1966

Obviously the temporal boundaries between these phases are not hard and fast, nor did Minitrack metamorphize into STADAN one fine day. The phases overlap. A key feature of Minitrack and STADAN development has been the anticipation of satellite requirements — by several years in some instances — and the construction

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[1] For descriptions of SPASUR, ESTRAC, DIANE, and the other acronym-bearing satellite networks that exist, see William R. Corliss, Satellite Science and Technology (NASA SP-133). Washington: NASA, 1967.

[2] R. Cargill Hall, "Early U.S. Satellite Proposals," Technology and Culture, Vol. IV (Fall 1963), 410.

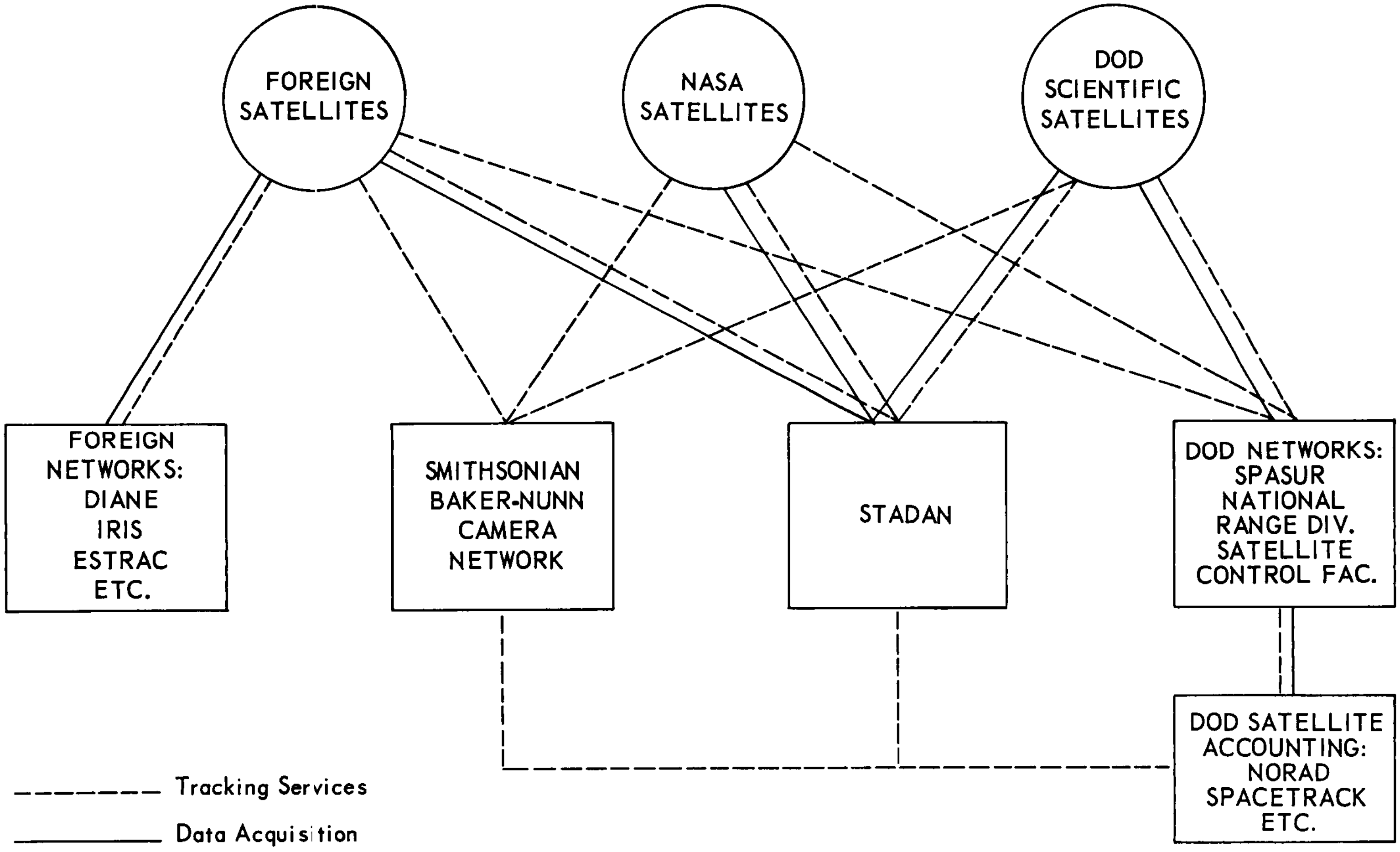

Figure 2. Summary of STADAN Interfaces

of equipment and deployment of stations to handle new satellites from the day they are launched. Just as obviously, STADAN cannot be static today. Tomorrow will bring new tracking techniques and new satellite programs will call for new stations in far-off places. At the moment, however, STADAN has reached a temporary plateau of development which is adequate for the present state of America's scientific and application satellite programs. Thus we have a propitious period of relative quiet in which to look back and see how STADAN became what it is today.

CHAPTER II

PRE-IGY TRACKING DEVELOPMENTS

STADAN has four functions: tracking, data acquisition, command, and communication; each of which has a historical trail leading back many decades, even into the Nineteenth Century. Data acquisition via a radio link goes back at least to 1925, when the Russian scientist Pyotr A. Moltchanoff received telemetry signals from instruments he had installed on a balloon launched in Siberia. The function of remote command, where unmanned machines are controlled by radio signals, goes back to the 1920s, when many tinkerers built remote-control boats and aircraft. The concept of a network of geographically dispersed information-acquiring stations linked to a central processing facility by communication lines undoubtedly goes back millenia to the times when military outposts sent runners and chariots back to headquarters. Weather stations and astronomical observatories have had centralized data-collecting facilities for centuries. Fascinating as the histories of such activities may be, it is the tracking function that leads us directly to the early Minitrack network, the core of NASA's STADAN. Even more specifically, radio interferometer tracking has done the most to shape the present STADAN network, although optical tracking and, to a lesser extent, Doppler tracking, have all contributed.

Antiquity of Optical Tracking

Tracking means measuring the position of a moving object. Today astronomers track the stars with telescopes driven by clock-controlled motors, Before such refinements, Tycho Brahe, in the 16th century, Ptolemy, in the 2nd, and their predecessors in earlier centuries had manually followed the stars and planets with astrolabes and other sighting devices. The point is that optical tracking is a venerable, well-proven part of our technical repertoire. When faced with the problem of tracking an artificial celestial object, it was logical to think first of optical techniques. This is precisely what happened with the artificial satellite.

As a matter of fact, the first allusion to the optical tracking of man-made satellites came the fictional route, in 1870, when Edward Everett Hale published his precocious tale "The Brick Moon" in the Atlantic Monthly. Hale envisaged flinging a large, inert mass into orbit along the Greenwich meridian with a large, water-powered flywheel. The satellite would be visible to mariners through their sextants, making the computation of their ship's longitude easier. In truth, of course, Hale was suggesting terrestrial navigation via optical observations of a man-made satellite in a known orbit rather than the reverse problem of tracking

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[3] The story is also available in a collection of Hale's works, The Brick Moon & Other Stories, Boston: Little, Brown, 1899. Hale also wrote the better-known "The Man Without a Country."

a known satellite of unknown position from ground stations whose locations are precisely known. The idea of visually following a satellite made visible by sunlight was a key concept, however.

Optical tracking of the V-2 and early U.S. missiles at White Sands during the late 1940's and early 1950's seemed to confirm the value of optics in this embryonic space work. Most intriguing, though, is the blank spot that existed in the plans of the early satellite thinkers during the same period. Although V-2's, Vikings, and other rockets were being regularly tracked, no one seems to have been concerned about tracking the satellites which were constantly in the backs of the minds of these missile pioneers. No one seemed to have thought much about how to confirm that a satellite was actually in orbit or how to measure the orbital elements once the satellite was discovered. This myopia probably had its roots in the fact that the satellite pioneers were missile and rocket men, not astronomers. Their thoughts gravitated to the brute-force construction of a successful launch vehicle instead of the delicate problem of finding and tracking the few pounds of payload it carried.

The first serious U.S. satellite study confirms this statement through omission — the omission of any mention of satellite tracking at all. The study referred to is the landmark report: Preliminary Design of an Experimental World-Circling Spaceship, written by the Rand Corporation, then a part of Douglas Aircraft Co., and published on May 2, 1946, as Douglas Report SM-11827. The only STADAN function mentioned in the report was that of data acquisition; a set of equatorial telemetry-receiving stations was proposed. Naturally the report was written mainly by rocket and aircraft engineers who had never really had the problem of locating a small object lost in the immensity of space. The significance of this blindspot became obvious nine years later when various satellite proposals were being evaluated for the U.S. IGY effort.

The first clear statement of the tracking problem came, as we should expect, from an astronomer. In an article, "The Heavens Open," in Colliers, in 1952, Dr. Fred L. Whipple of Harvard said:

> Predicting the position and motion of the space station itself will be one of the most difficult problems ever encountered in celestial mechanics, or the science of predicting the positions of astronomical objects.

Whipple went on to become the major proponent of optical satellite tracking during the IGY days and was one of the few recognized scientists who helped "sell" the IGY satellite idea to the rather reluctant political and scientific communities.

Radio Tracking is of Recent Vintage

To recapitulate developments in electronic tracking and bring its history up to the confrontation with optical tracking in the middle 1950s, there is no need to reach back to the ancient civilizations. Hertz did not discover radio waves until 1888, and Marconi's experiments did not begin until the 1890s. Radio tracking of moving, astronomical signal sources began when a Bell Laboratories engineer, Karl Janksy, discovered and followed celestial radio noise sources across the sky with directional antennas in 1932.[4] Grote Reber followed up Janksy's work, building the first paraboloidal radiotelescope in his backyard in 1937. Reber was preceded by developments in radar, which employs artificial "illumination" of the target. Sir Robert Watson-Watt was tracking aircraft in Great Britain with primitive radar as early as 1935. Radio echoes had been noted decades earlier.

By the time Grote Reber had finished making his backyard radio dish, there were four electronic tracking schemes in being that had some potential for tracking satellites:

- Radar, which required no signal source on the satellite.
- Dish tracking, a lá Reber, which necessitated a satellite-borne transmitter.
- Triangulation using radio-direction finders, which also required a signal source on the satellite.
- Doppler analysis of the radio signals received from a moving source. This technique was recognized in 1937, but its value in tracking was not appreciated.

Still a fifth technique was potentially available — that of radio interferometry. The basic idea here was the use of two receiving points, as shown in Figure 3, and the comparison of the phases of the signals received separately by each. Physicists have long used optical interferometers in experiments, such as Albert Michelson's first attempt to detect the motion of the postulated ether past the Earth in 1881. The first use of radio guidance (not tracking) seems to have been by German engineers at Peenemünde.[5] Here, VHF transmitters laid down a lobed

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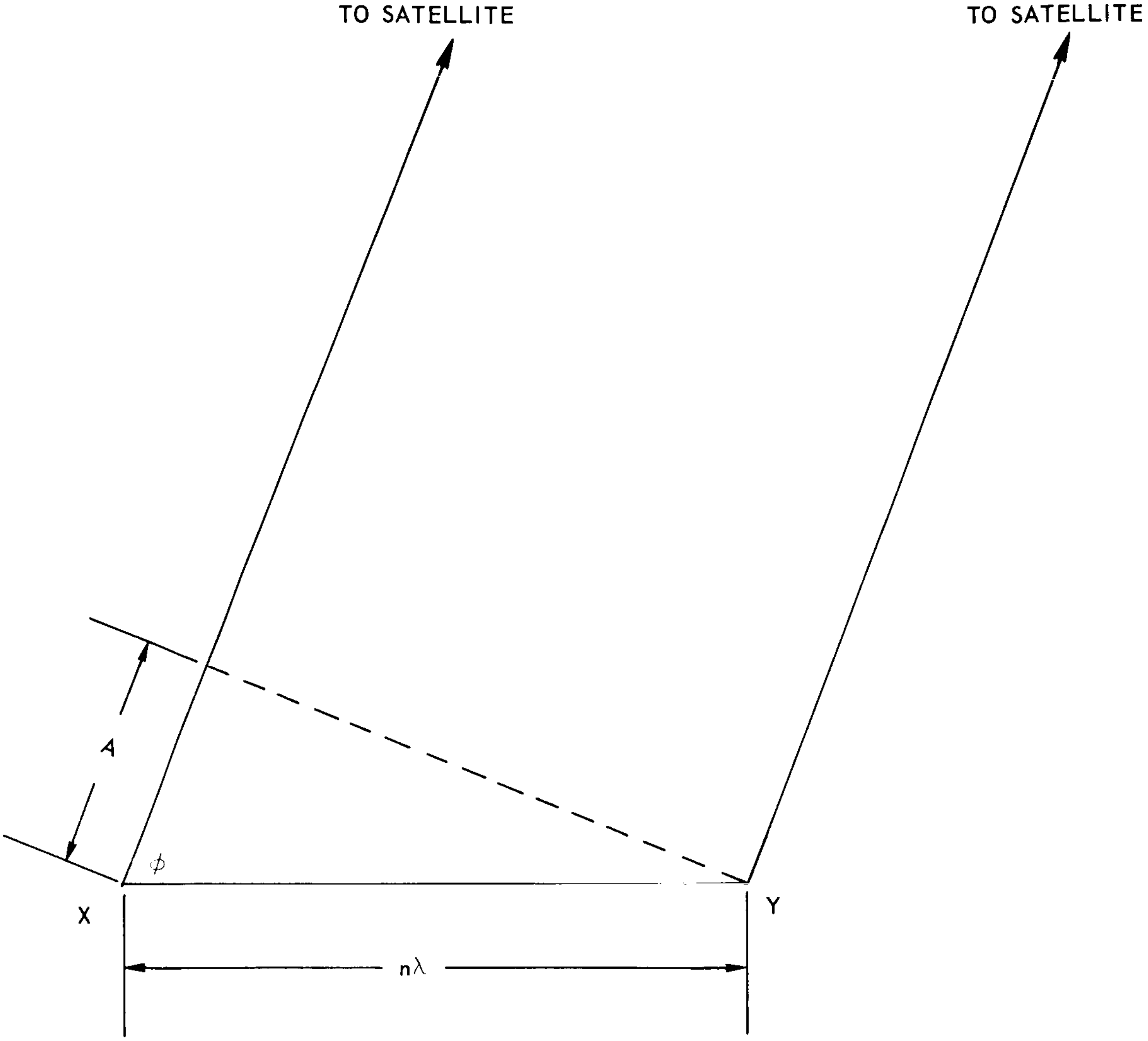
[4] Before this time radio direction finding was used by ships and aircraft as a navigation aid. During World War I, the American engineer Edwin H. Armstrong developed a radio-detection system that picked up and tracked the ignition noise of approaching aircraft.

[5] Personal communication from James W. Crooks, Jr., July 28, 1966.



$n\lambda$ = BASELINE IN WAVE LENGTHS
A = TOTAL PHASE DIFFERENCE IN WAVE LENGTHS
ϕ = ANGLE FROM BASELINE TO SATELLITE IN PLANE DEFINED BY ANTENNA X, ANTENNA Y, AND SATELLITE ANTENNA

BASIC INTERFEROMETER EQUATION: $\mathrm{COS}\ \phi = A/n\lambda$

Figure 3. The interferometer principle. The quantity A is measured electronically by phase comparison; then, the interferometer equation is used to find ϕ.

antenna pattern to improve azimuth guidance during a few V-2 flight tests in the early 1940s. The technique, however was not employed during operational use of the weapons; it bears only a superficial resemblance to later satellite-tracking interferometers.

In radio interferometry, we get on the main track leading directly to Vanguard, Minitrack, and ultimately STADAN. Of course, no one knew this in 1940, or even 15 years later. Our hindsight, however, permits concentration on this tracking scheme in preference to the other electronic and optical techniques. It is a matter of conjecture whether radio interferometry would actually have been chosen for tracking the Vanguard satellite had all available tracking possibilities been systematically evaluated and compared when the Vanguard program began in 1955. Like many technical ideas that see hardware form, the path to success was not clearly logical; rather, the decision was a complex function of personalities, timing, past experience, and nontechnical considerations.

The Crucial Viking Work

In the U.S. missile effort the path to Minitrack and STADAN becomes wide and straight. Radio interferometry has the advantage of yielding very accurate tracking angles when the target cooperates by emitting a radio signal. The angular precision of interferometry led to the development of the Azusa tracking system as part of the Army Air Corps MX-774 Project, forerunner of the Atlas ICBM program, at the Vultee Field Division of Consolidated Vultee Aircraft Corporation in Downey, California.[6] Two of the basic patents (2,972,047 and 3,025,520) in the field of interferometer tracking are shared by James Crooks, Jr., Robert C. Weaver, and Robert V. Werner, all members of the Azusa design team. By the spring of 1948, the Azusa team had built an interferometer operating at 148.58 Mc.[7] In a strange circle of history, the U.S. Naval Research Laboratory (NRL) was working on underwater sound interferometers at the time Convair was developing Azusa. Since the two groups were in close contact, there was considerable interchange of ideas.[8] The circle was completed in the early 1950s when the Navy picked up the Azusa interferometer work for its Viking project at White Sands, New Mexico. The Navy wanted to explore the possibility

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[6] Personal communication from James W. Crooks, Jr., July 28, 1966. The first formal report uncovered bears the title "A Precision Missile Tracking System," by James W. Crooks, Jr., Consolidated Vultee Aircraft Corp. (Convair) Report DEVF 4038, December 1946. Army Contract W33038-AC-14168.

[7] Robert C. Weaver, "Phase Comparison Angle Tracking System," Convair Report ZN-6002-017, March 2, 1948.

[8] Interview with Milton Rosen, May 18, 1966.

of converting the Viking or some derivative of it into a guided missile and it needed an accurate guidance system. In an early report from this program[9], NRL's J. Carl Seddon explained how the Viking would determine its position: "The Missile will detect its position relative to the hyperbolic guidance path by phase comparison of modulation waveforms derived from signals received from two pairs of stations." In this scheme, the missile would guide itself using onboard electronics and navigational signals received from the ground. This seems a far cry from Minitrack and satellite tracking, but phase comparison, the essence of Minitrack, is there. Within a year, NRL reports from the Viking program were diagramming ground-based, tracking interferometers, which relieved the Viking of the burden of signal-processing equipment by computing the missile's position from the ground.[10] Two precursors of Minitrack are evident in the interferometer arrangement shown in Figure 4. First, only a tiny radio beacon needs to be carried on the Viking itself. This was to be an important feature of the Vanguard "Minitrack," in which the prefix "Mini" applies to the minimum-weight satellite transmitter. The second precursor is the "L" arrangement of the interferometer antennas which persisted in some early designs of Minitrack, although the final deployed version extended the bars of the "L" to make a cross.

Pressures for a Satellite Program

While NRL was flying and tracking Vikings at White Sands, pressure for a national satellite program was building up. Scientific instruments carried on captured V-2s, Aerobees, and Vikings and whetted the appetite of the scientific community for a long-lived instrument platform above the atmosphere, where space phenomena could be measured directly over long periods of time. In 1952, V-2 experimenters such as James A. Van Allen pushed for a strong upper atmosphere rocket program. In 1954, the Ad Hoc Committee on Space Flight of the American Rocket Society (ARS) proposed to the National Science Foundation that the United States sponsor the construction of a small satellite to be launched by military rockets during the IGY.[11] In the fall of 1954, the U.S. Committee for the IGY formed a small study group, with Fred Whipple as chairman, to study the idea of a U.S. IGY satellite. Whipple's group reported on a "Long-Playing Rocket," or LPR, that would orbit a 5-kg white sphere that could be tracked optically from the Earth. Whipple's zeal and salesmanship undoubtedly did much to sell the satellite idea to the U.S. government. His astonomer's predilection for optical tracking, however, was evident.

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[9] Milton W. Rosen, and J. Carl Seddon, "Rocket Research Report No. VI" Conversion of Viking into a Guided Missile." NRL Report No. 3829, April 1, 1951. (In NASA Historical Archives.) Both authors are now with NASA.

[10] John T. Mengel, and K. M. Uglow, Rocket Research Report No. XI, "A Phase-Comparison Guidance System for Viking," NRL Report 3982, May 5, 1952. John T. Mengel is now Assistant Director of the Office of Tracking & Data Systems, Goddard Space Flight Center, NASA.

[11] This ARS Committee was chaired by Milton Rosen, from the Naval Research Laboratory, who later helped put the Vanguard proposal together. For further details of the ARS recommendation see Rosen, "On the Utility of an Unmanned Earth Satellite," Jet Prop. XXV (Feb. 1955), 71.

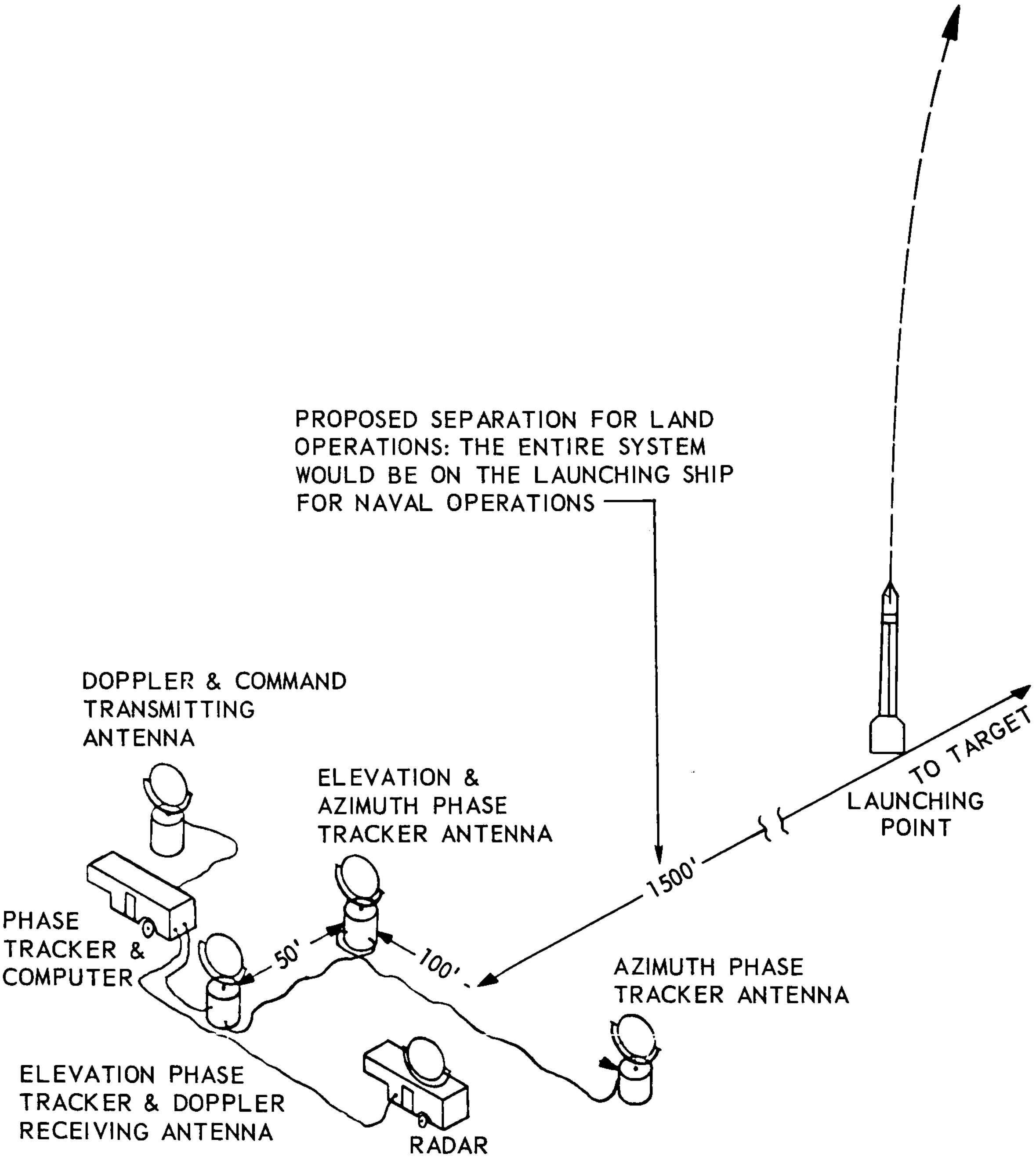

Figure 4. Viking White Sands radio interferometer proposed in NRL Report 3982, dated May 5, 1952. The L-shape antenna layout and Doppler features were part of the original Vanguard Proposal in 1955.

Whipple was also closely associated with "Project Orbiter," which was aimed at establishing the engineering feasibility of an Earth satellite. Project Orbiter pooled the talents of the Office of Naval Research,[12] the Army Ballistic Missile Agency (von Braun's group), the Jet Propulsion Laboratory (JPL) of the California Institute of Technology, and several industrial concerns. Commander George Hoover of the Office of Naval Research headed the Orbiter program. The plan of Orbiter was simple and straightforward: take one of von Braun's military rocket boosters, perhaps a modification of the Redstone, add solid-rocket upper stages built and proved by JPL, and propel a small satellite into orbit.[13] The concept was feasible and would represent a technical first for the United States. Tracking would be accomplished optically, but at this time this seemed secondary to getting something into orbit.[14]

NRL was also interested in the idea of an Earth satellite and conducted a study independent of Orbiter during 1954 and early 1955.[15] The NRL feasibility study concluded that an Aerobee solid rocket, plus a small solid third stage, on top of a Viking first stage could put a small payload into orbit. Satellite tracking was not considered in this propulsion study.

By the summer of 1955, the stage was set for concrete action on a U.S. satellite program. The ingredients forcing such a decision were:

- The coming IGY and the manifest desirability of a small scientific satellite.
- The existence of a rocket technology capable of launching a small satellite.
- The cold-war pressure to produce a spectacular technical accomplishment.

Consequently, on July 29, 1955, President Eisenhower announced that the United States would launch "small, unmanned earth-circling satellites as a part of the U.S. participation in the IGY." The Department of Defense was to be the launching agency.

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[12] The Naval Research Laboratory, which was to make the Vanguard proposal in 1955, was administratively attached to the Office of Naval Research, but was a much older organization with a long history of recognized scientific and engineering excellence. NRL remained rather aloof during the Orbiter study.

[13] Von Braun frequently proposed such a combination of rockets for satellite launching. See: "A Minimum Satellite Vehicle," Redstone Arsenal Report, dated 15 September 1954.

[14] It is interesting to note that at the time of Orbiter JPL engineers such as Henry Richter, Eberhardt Rechtin, William Sampson, and others were working on phase-locked electronic tracking systems, the forerunners of the Microlock Doppler-interferometer system.

[15] John P. Hagen, "The Viking and the Vanguard," Technology and Culture, IV (Fall 1963), 435. See p. 437.

By the time of the President's announcement, three major satellite proposals were on hand: the Orbiter proposal, using optical tracking; an NRL proposal, using an electronic tracking scheme derived from its White Sands work; and a proposal based on the highly classified and very high priority Atlas program. To select the most appropriate program, a Committee on Special Capabilities, chaired by Homer J. Stewart, was convened by the Department of Defense. The arguments were hot and heavy; each proposal team was emotionally involved in its ideas. The Committee's final decision was far from unanimous, but the NRL proposal was recommended for several reasons:

- NRL emphasized the scientific aspects of the program.
- The proposed launch vehicle did not entail the use of military rockets, a fact that made the program more palatable from the standpoint of international relations and the IGY program. Furthermore, no U.S. military rocket program would be compromised.
- NRL had proposed a good tracking scheme that showed up some deficiencies in the Orbiter proposal.

Since electronic tracking was an important, though perhaps not deciding, factor in the decision to adopt the NRL proposal, we should review briefly those few months in the spring of 1955 at NRL that led up to the successful proposal and the beginning of Vanguard.

Genesis of the NRL Vanguard Proposal

With so many years of experience with V-2s and Vikings at White Sands behind them, the NRL Rocket Development Branch, under Milton Rosen, could hardly be indifferent to all the talk of artificial scientific satellites making the rounds in early 1955. Rosen, as mentioned earlier, was Chairman of the ARS committee that made satellite recommendations to the National Science Foundation. Furthermore NRL had refined the White Sands tracking interferometers described earlier. In early April 1955, Milton Rosen, John Mengel, and Roger Easton assembled informally at NRL and generated a document entitled, "Proposal for Minimum Trackable Satellite (Minitrack)." No date and no authors are listed on this key report; but, according to Rosen, it preceded only by a few days a more formal report with the title, "A Scientific Satellite Program," dated April 13, 1955, and written by the NRL Rocket Development Branch. Appendix B of this document was labeled, "The Minitrack System" and was nearly identical to its predecessor of a few days. The name "Minitrack," now appearing for the first time on paper, was coined by John Mengel. The radio interferometer concept advanced in these two reports differed only in the wavelength used from an

X-band (1000-Mc) interferometer developed by NRL for submarine-based tracking of Viking test vehicles in pre-Polaris research. (Figure 5) The antenna geometry and supporting electronics were essentially identical.

The formal NRL proposal set before the Stewart Committee bears the date July 5, 1955. In content, it differed by little from the earlier informal documents.[16]

Why did NRL emphasize Minitrack in its proposal? Optical tracking was the way to go, according to many experts. Fred Whipple, who had made many significant camera observations of meteorites entering the Earth's atmosphere, had proved that a small payload of a few kilograms could be seen with terrestrial optical instruments. Rosen, at NRL, had doubts; and he asked Richard Tousey at NRL to check through the calculations in the spring of 1955. Tousey confirmed the visibility computations, but believed that there would only be a "million-in-one chance" of finding the satellite with optical equipment, given the uncertainties of a rocket launch, variable weather conditions, and the fact that the satellite would be visible only at dusk and dawn. This factor — satellite acquisition — was the practical fact of life that made electronic tracking desirable. What good was the precision of optical equipment if it could not find the satellite in the first place?

Tousey had found a weak spot in the Orbiter proposal, and Rosen pushed for the inclusion of electronic tracking in the NRL satellite proposal. John Mengel and Roger Easton showed, in the NRL reports mentioned above, that electronic interferometer tracking using a tiny satellite-borne transmitter was quite feasible, based upon White Sands experience.[17]

The NRL tracking scheme met with disdain and disbelief in optical quarters. Von Braun, however, was apparently taken aback by this hole in the Orbiter argument. He stated his willingness to include a Minitrack beacon on Orbiter.[18] Nevertheless Minitrack emerged as a definite plus sign in favor of the NRL proposal.

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[16] The full reference for the NRL proposal is: "A Scientific Satellite Program," NRL Memo 487, July 5, 1955, with addendum letters S-7140-26255, Aug. 23, 1955, and C-711-14355, Sept. 3, 1955. A full history of Project Vanguard is now being prepared for NASA by Mrs. Constance M. Green.

[17] We would expect NRL to adopt the system of electronic tracking most familiar to them, but radar and Doppler tracking were also examined. Radar was also plagued by the acquisition problem — you had to know where to look. Doppler tracking, as we shall see in the next chapter, was actually implicit in the first Minitrack proposal. NRL also looked at artificial satellite illumination using searchlight; but, again, one had to know where to point the searchlights. In a modern version of this pinpointing idea, lasers bounce light off satellites in known orbits to improve the precision of the orbital elements.

[18] Milton Rosen interview, May 18, 1966.

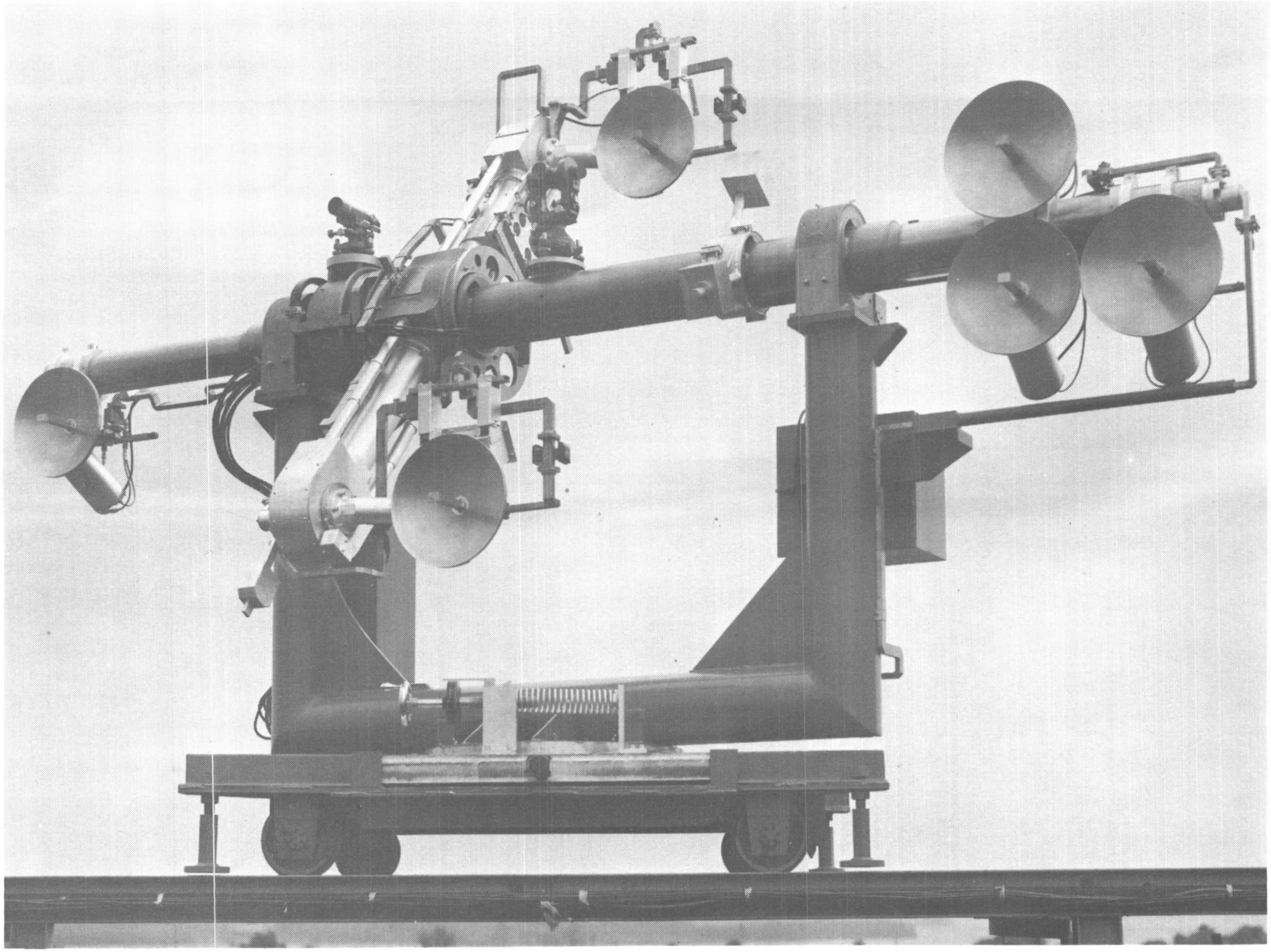

Figure 5. Photograph of the X-band interferometer that was constructed by NRL for possible use on submarines for tracking Vikings. The baseline is 12 ft and the L-shaped antenna pattern has been retained. Picture taken in early 1955. (Courtesy of Naval Research Laboratory)

Project Vanguard began at NRL on Sept. 9, 1955, when the Secretary of the Navy was authorized by the Department of Defense to proceed with the NRL proposal. Electronic tracking was firmly established in the NRL Minitrack concept.

History, always retrospective, often makes things look too easy. Actually, because of Orbiter's momentum, the NRL proposal team believed that they stood little chance of winning the U.S. satellite program. According to John Mengel, the surprise announcement came as the NRL tracking team was checking out the second and last X-band interferometer. The interferometer was quickly put in moth balls and work began on Minitrack, with its ten-times-longer wavelength and correspondingly larger baseline.

CHAPTER III

MINITRACK THROUGH THE IGY

When the Naval Research Laboratory was assigned the U.S. satellite program by the Secretary of the Navy on Sept. 9, 1955, one would expect that Minitrack would also become the "official" satellite tracking system. It is true that the Minitrack idea was turned into hardware and deployed in the first worldwide electronic tracking net during the IGY; but this chapter must also deal with proliferations of the Minitrack concept as well as those competing tracking schemes that were spawned during the pre-Vanguard days and refused to die.

Perhaps it was just as well that Minitrack did not have a clear field; though it annoyed NRL personnel, the competition was stimulating.

This competition came primarily from two sources:

- The Orbiter program that lived on close to the surface at ABMA, ONR, and JPL. By now, the Orbiter proponents had adopted the JPL Microlock electronic tracking concept to counter Minitrack. It was this "shadow" Army satellite program, of course, that ultimately launched the first U.S. satellite, Explorer I.
- The SAO optical network, which was funded by the National Science Foundation as complementary to Minitrack. Deep in their hearts proponents of optics and electronics each knew their system was better and would be the "prime" tracking system.

Two offshoots of Minitrack also deserve a few words: Minitrack II (or Mark II Minitrack), an amateur tracking program; and Active Minitrack, a military space surveillance system. First, though, let us see how the NRL proposal ideas of April 1955 were turned into an operational network.

Development and Deployment of Minitrack

The Minitrack network that became operational in October 1957 was substantially different from that proposed to the Stewart Committee in the summer of 1955. Here is what NRL originally proposed:

> The complete Minitrack System will consist of two complete phase comparison stations, the second identical to the one just described but located at a distance of 20 miles on an E-W line to permit determination of satellite altitude to an accuracy of 0.5 miles, and satellite velocity to an

> accuracy of better than 100 feet per second. Both of these stations will include a second ground station to permit the determination of the satellite position in a direction normal to its direction of travel, giving a complete 3 axis fix on the satellite as well as its velocity.[19]

In addition to angle-tracking interferometry of White Sands vintage, the quotation implies distance (altitude) measurement through triangulation from a pair of stations and Doppler velocity measurements. Note that only a single pair of stations was anticipated, not a worldwide network.

Before the end of 1955, ideas changed drastically. First, it was realized that a single pair of stations would provide very limited geographical coverage, rendering data acquisition difficult and the accumulation of orbital data very slow. Four pairs of stations across the southern U.S. were next proposed. The idea of an "electronic fence" was implicit in this suggestion i.e., the creation of a long chain of overlapping antenna patterns that the satellite must intersect frequently. The trouble was that the orbital inclination of the Vanguard satellite would keep it away from the southern U.S. too much of the time. The next logical step was the construction of a long north-south fence that the satellite would pass through on almost every orbit. But the Vanguard program could not financially support a long chain of paired stations; besides, further thought soon showed that complete orbital data could be computed from angular (interferometric) tracking alone. These changes in thinking manifested themselves in a report describing a chain of nine single Minitrack stations strewn along the 75th meridian.[20] To the regret of some engineers, ranging and velocity-measuring capabilities were dropped.[21]

The technical desirability of Minitrack stations on foreign soil was one thing; more formidable were site negotiation, site preparation, and logistics. The situation was particularly acute in South American countries that were sensitive about U.S. bases and where transportation and communication facilities were primitive. Unfortunately Minitrack stations required radio-quiet spots which are usually not coexistent with the also-desired communication links and supply facilities.[22]

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[19] "A Scientific Satellite Program," NRL Memo 487, July 5, 1955.

[20] Project Vanguard Report to Assistant Secretary of Defense (Research and Development), NRL Memo 548, Dec. 12, 1955. The suggested station locations were Washington, Jacksonville, Havana, Barbuda, Canal Zone, Quito, Huancayo, Tocopilla, and Santiago. (See Appendix A.)

[21] Rather ironically, ranging and Doppler capabilities are now being added to STADAN as the Goddard Range and Range Rate equipment is deployed. The logically neat sequence of (1) requirement definition, (2) plan definition, and (3) equipment development was impossible at a time when engineers knew little about satellites and tracking.

[22] "Preliminary Specifications and Considerations — Minitrack Site Facilities," NRL document dated Feb. 27, 1956. No author or number. (In NASA Vanguard files.)

Captain Winifred Berg, the Navy Senior Project Officer assigned to Vanguard, had the task of getting Minitrack stations into the South American countries. He was aided by two already-existing organizations: (1) The Inter-American Geodetic Survey (IAGS), in which the U.S. Army Map Service was very active, and (2) the International IGY committees that existed in most countries. As 1956 began, Berg and others realized that time was already growing short. The IGY was to end in less than two years, Vanguard was barely started, and the long slow process of site selection, negotiation, construction, and station checkout was not even begun. Prodding the State Department produced little added speed. In early March, Captain Berg informed the Department of State that he was leaving on March 23 with a Site Selection Team to negotiate Minitrack sites in South America.[23]

Between March 23 and late April, Berg's team, which included NRL and Army personnel, toured South America, locating sites and drawing up the requisite agreements with the countries concerned. The Army Map Service saw to it that the Site Selection Team saw the right people in the political and scientific spheres. With the convivial feeling engendered by the IGY, with all its scientific and non-military features, and the good offices of the Army, the task was accomplished in only five weeks. Back in Washington, Berg informed the State Department that all countries concerned had agreed to a joint July 1, 1956, release of the news of the IGY tracking sites. Although the State Department missed the July 1 target date by several weeks, the formalities were completed and Minitrack entered the deployment phase.

The Site Selection Team had picked six South American locations: Havana, Panama, Quito, Lima, Antofagasta, and Santiago; but who would undertake the imposing task of setting up stations outside the United States proper? The U.S. Army, by virtue of its IAGS experience, was the logical choice; in September 1956, the Army Chief of Engineers initiated construction at the six sites at the request of NRL.[24] More specifically, the task fell to the specially created Project Vanguard Task Force of the Army Map Service. It should be mentioned here that the South American sites, though near large cities, were generally some distance from modern facilities and the associated radio noise. The isolation and primitive conditions caused logistics and morale problems in the early days.

The Minitrack sites in the continental U.S. were established with greater ease. The Navy set up and operated the Blossom Point and San Diego stations;

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[23] Captain Winifred Berg, personal interview, May 12, 1966.

[24] Ultimately the Panama site was abandoned (See Appendix A for details). The Army also handled construction at the Ft. Stewart site. See: Smitherman, W. D., "Army Participation in Project Vanguard," IRE Trans., MIL-4 (June 1960), 323.

the latter being at the Brown Naval Auxiliary Air Station, near Chula Vista, California, and operated by the Naval Electronics Laboratory. The stations downrange from Cape Canaveral were set up in cooperation with Great Britain and operated by the U.S. Navy and Air Force. After deliberation over tracking requirements, logistics, and support facilities, Antigua and Grand Turk were finally chosen for down-range stations instead of the initially planned Barbuda and Mayaguana. More details about the sites and the factors influencing their choice or rejection can be found in Appendix A.

The Blossom Point station, just 40 miles south of Washington, went into operation in July 1956, and was soon employed as a training headquarters for Minitrack operators and as a test facility for Minitrack equipment. During the IGY and after, many foreign nationals took the Minitrack course at Blossom Point. In fact, the willingness of NRL and NASA to employ and train foreign nationals at the Minitrack and STADAN stations greatly eased the task of placing U.S. facilities on foreign soil. Minitrack stations have "earned their keep" many times over as non-political, no-strings-attached representatives of the United States.[25]

The full Minitrack network of ten stations was placed in operation during October 1957, with the eleventh, at Woomera, Australia, added a month later. It should already be evident that the Minitrack network was not a static thing. Stations were added and subtracted as the space program required. Bigger satellites with more transmitter power made stations such as Antofagasta redundant. Political harassment in Cuba made it apparent as early as September 1957 the Havana station would probably have to be moved.[26]

Simultaneously with the Minitrack station construction, NRL engineers were proving out electronic equipment that would track and communicate with the satellite. Frequency selection was an early item on the agenda. The original NRL proposal had postulated 100 Mc as the interferometer frequency. At this frequency, the subminiature circuits needed for the tiny satellite transmitter would be reasonably efficient; the interferometer baseline of 100 wavelengths would be a practical 1093 ft.; and the width of the fence projected up toward passing satellites would be adequate. A frequency of 108 Mc was finally agreed upon by the countries concerned, on a local basis, but only for the duration of the IGY. Local interference proved a problem at 108 Mc; and Minitrack switched to the 136-to-137 Mc range in 1960 when the International Telecommunications

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[25] Arnold, Frutkin, International Cooperation in Space, Prentice-Hall, Inc. Englewood Cliffs, New Jersey, 1965.

[26] NRL Memo 4130-417: JTM: lds, Sept. 23, 1957. (In NASA Vanguard files.) See Appendix A for details and chronology of station changes.

Union (ITU) set aside this band for space research. For years, however, 108-Mc satellites were on the air (especially Vanguard I), and conversion was not completed until three years later.

The Minitrack interferometer antenna layout, which had begun as a simple "L" at White Sands (Figure 4) became a cross, actually two crosses, because two separate interferometers with different baselines were needed to resolve an ambiguity in satellite direction inherent in a single interferometer. These two interferometers were termed "fine" and "coarse." The classical Minitrack antenna layout is shown in Figure 6. It has changed little since first installed during 1956 and 1957.

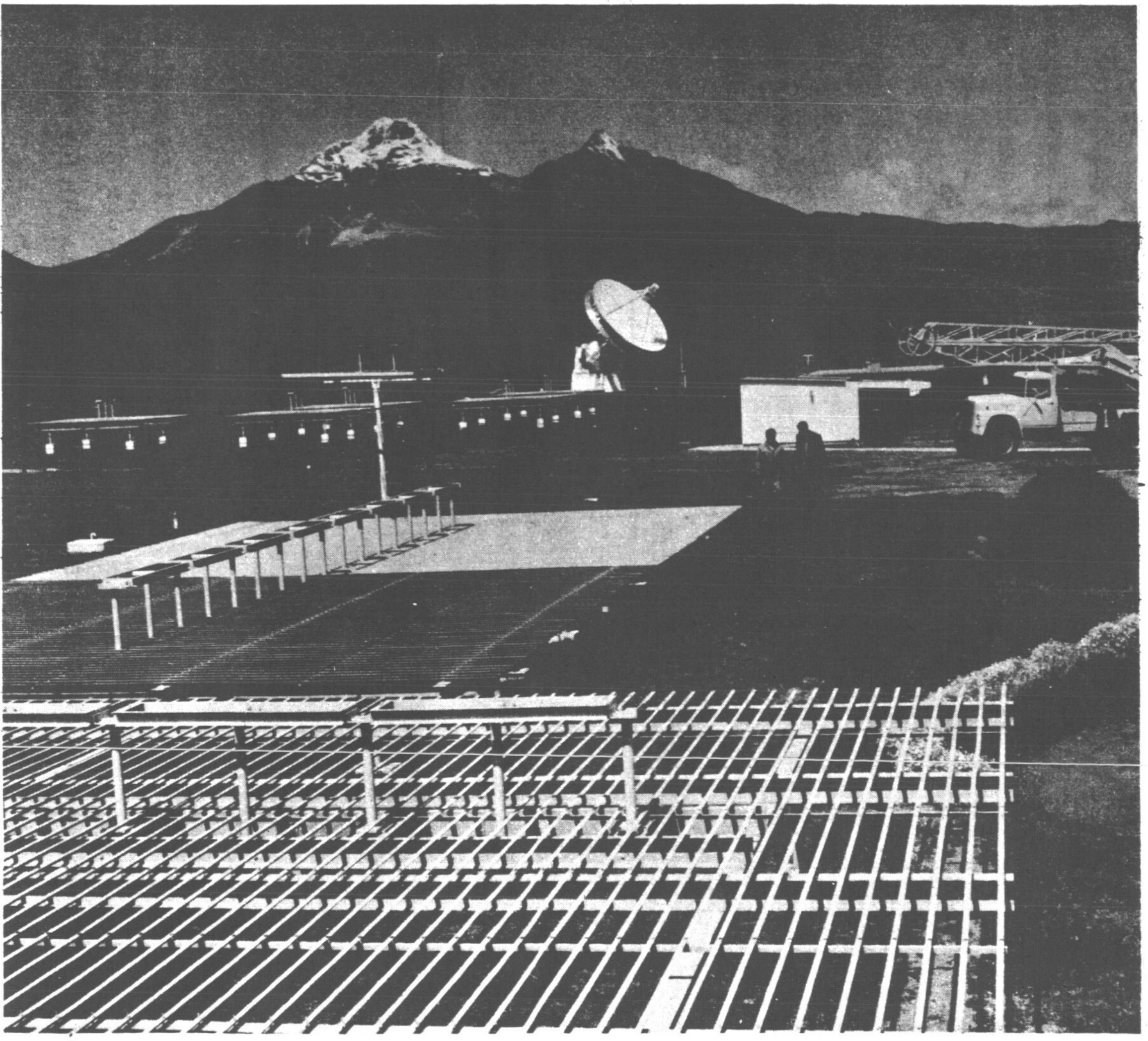

Figure 6. Minitrack antenna field in the foreground; 40-ft paraboloid antenna in the background.

In contracting for Minitrack antenna construction, NRL first asked the D. S. Kennedy Company and the Technical Appliance Company to build test hardware versions. In one of those strange turnabouts in government contracting, the D. S. Kennedy Company came up with the best antenna, but the Technical Appliance Company received the construction contract on a price basis, ultimately turning out their competitor's antenna for deployment at the Minitrack sites.

Another aspect of Minitrack contracting had consequences that persist in today's STADAN operation. The Bendix Corporation, at Towson, Md., won the contract to build the electronic gear that amplified and analyzed the signals picked up by the Technical Appliance Company antennas. As their equipment was dispersed to the field sites, NRL asked Bendix to send their men along to the South American sites to familiarize the Army and local personnel with the equipment. Bendix has subsequently won all open competitions for Minitrack electronic equipment and now holds contracts for STADAN "M&O" (Maintenance and Operation). It became hard to find a STADAN station without also finding a Bendix engineer.

In addition to the tracking function, each Minitrack station had to pick up and record the satellite's telemetry transmission. The fixed, narrow, wedge-shaped interferometer antenna pattern was unsuited to this task. NRL had to design some sort of antenna that would follow the satellite from horizon to horizon. A Blossom Point experiment was carried out in 1956 with Yagi antennas fixed on a framework resembling a playground swing. The test emphasized the need for following the satellite with a directional antenna. A "seesaw" or "rockinghorse" antenna evolved. (Figure 7) This consisted of half a Minitrack antenna pivoted on a horizontal axle. As the satellite passed overhead the antennas were manually tilted from one extreme to the other, just like a seesaw. The primitive "seesaw" later gave way to a succession of more refined data-acquisition antennas that will be described later.

It is one thing to have an operating interferometer station and quite another to turn the received satellite signal into data that can be digested by a computer and rendered as precision orbital elements. First, the centers of the Minitrack antenna arrays had to be accurately located on a consistent, interconnected system of geodetic coordinates. This was easy within the U.S., and, thanks to the Army Map Service work in South America, it was eventually done for all stations within the Western Hemisphere. A special Vanguard Datum reference system came into being. The Woomera site in Australia was another matter, no one knew the distances between continents with real precision. One of the important accomplishments of satellites, of course, has been the tying together of previously isolated continental geodetic grids with the help of satellite geodesy; thus, Woomera and other isolated stations were tied into a unified reference system.

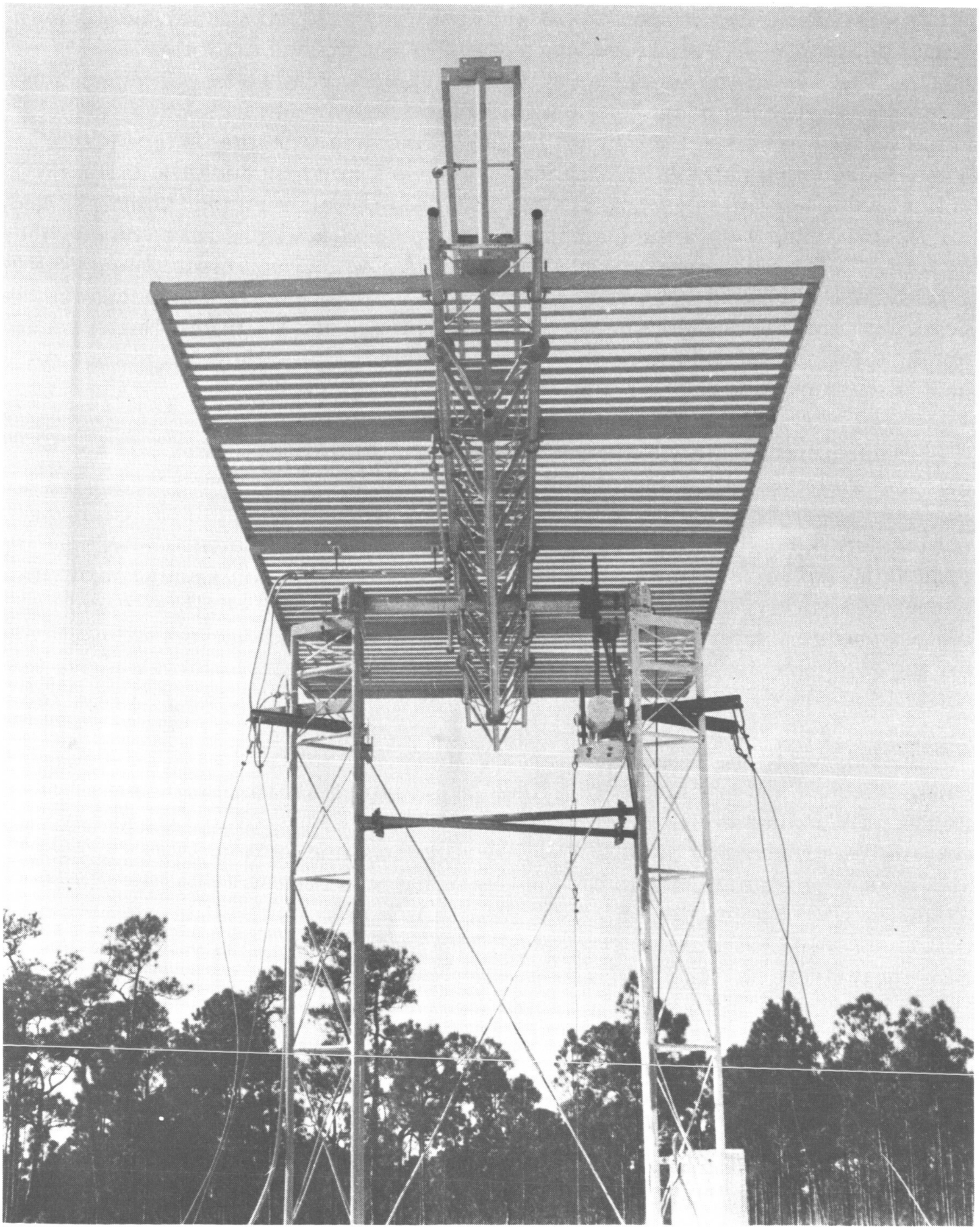

Figure 7. Photograph of the "rockinghorse" data-acquisition antenna deployed around the Minitrack network during the IGY. The antenna portion—the part that "teeters"—is just a section of the regular interferometer antenna. (Courtesy of W. Mitchell, GSFC)

A second Minitrack operational problem was calibration in terms of known signal sources. At first, it was suggested that one of the SAO Baker-Nunn cameras be located at the center of each Minitrack array so that airplane-borne radio signal sources could be tracked electronically by Minitrack and, at the same time, against the known background of fixed stars by the Baker-Nunns. There were emotional and operational problems that prevented this fusion of optical and electronic networks. Although it was proclaimed that Minitrack and the Baker-Nunns were complementary, their proponents were yet to be convinced in 1957. There were practical reasons. Neither optical nor electronic satellite tracking had yet proved itself, and it would be unwise to make the success of one dependent upon the success of the other. Furthermore, the Baker-Nunns needed much better seeing conditions than those available at the Minitrack sites, which had not been chosen with "seeing" criteria in mind.

Consequently the Baker-Nunn cameras went to their own sites and small astrographic calibration cameras were emplaced at the Minitrack stations.[27] High-flying aircraft, helicopters, and both free and tethered balloons carrying optical and radio signal sources calibrated the Minitrack interferometers.[28] By comparing light flashes and star backgrounds from the camera plates with simultaneously received radio signals, the signals from real satellites could be more accurately interpreted. This calibration technique, however, did not account for the much greater refraction of radio waves in the ionosphere well above the calibrating source.

In addition to their geodetic ties, the Minitrack stations had to have coordinated "clocks" and communication lines back to the NRL Vanguard Control Center in Washington. Basic time referents came from standard frequency transmitters, such as station WWV. A Precision Time Standard Rack at each station was capable of an accuracy of one millisecond per day after calibration against WWV. The matter of communication was more difficult in remote, undeveloped areas. Again the Army experience and facilities in South America came to the rescue. The Map Service's Project Vanguard Task Force set up the rather impressive system of data links diagrammed in Figure 8. Data converged on the NRL Vanguard Control Center and was transmitted from there to the

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[27] An interesting technical aside: The Army had suggested in 1957 that the Minitrack sites be electronically calibrated through the use of radio signals bounced off the Moon, whose position, of course, was known as well as the stars. This technique was not employed for calibrations, although radio echoes from the Moon were obtained by the Army.

[28] John H. Barbert, et al, "Minitrack Calibration System," Photo. Sci. Eng., VII (Mar.-April 1963), 78.

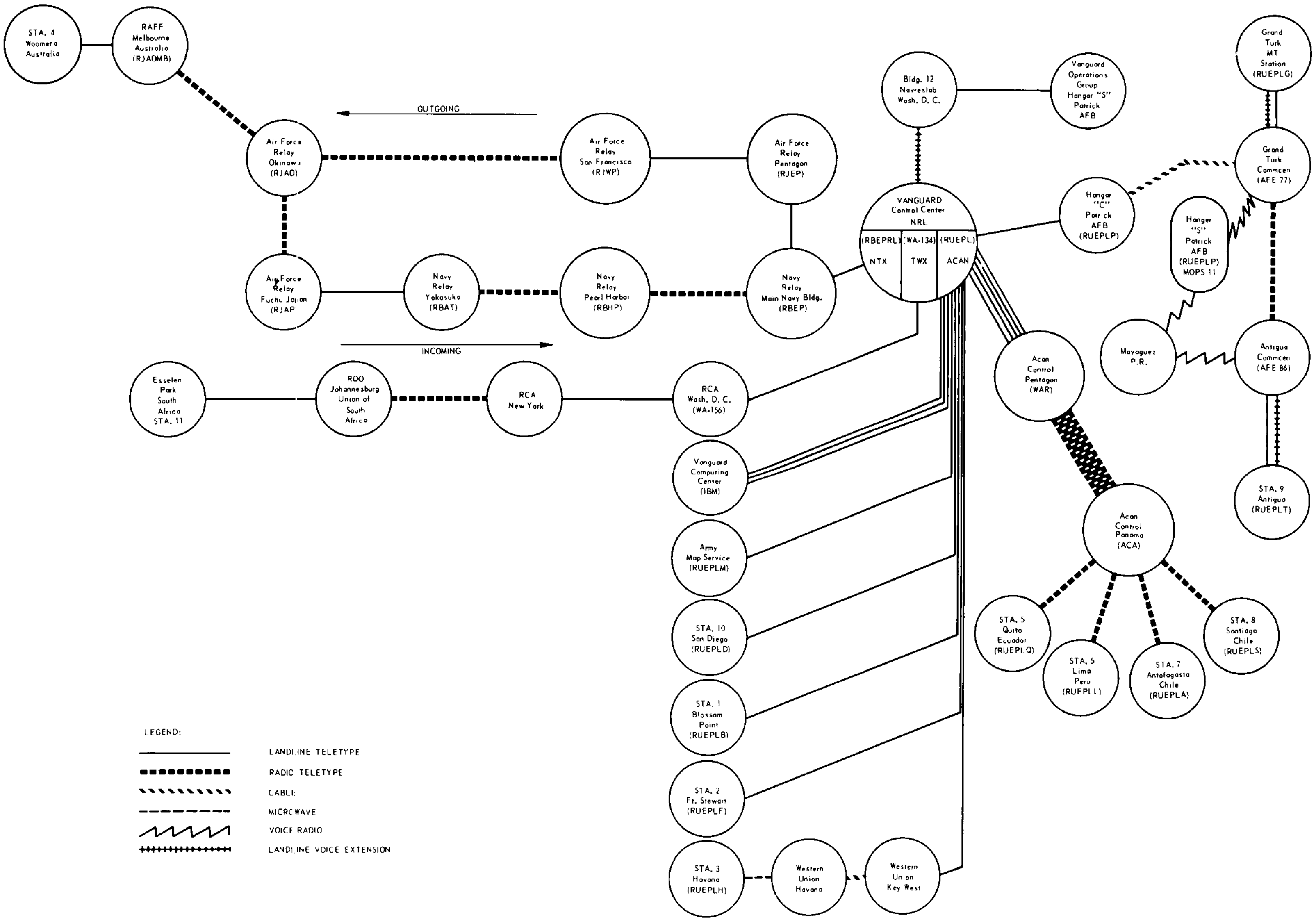

Figure 8. The Vanguard communication network, showing the great variety of communication links employed.

Vanguard Computing Center in downtown Washington. IBM provided an IBM 704 computer, operating personnel, and analysis for orbit calculation.[29]

By October 1, 1957, Minitrack was complete except for the checkout of some teletype links and the calibration of some stations.[30] Three days later, Sputnik I began crossing the Minitrack fence every 96 minutes; but it was transmitting at 20 and 40 Mc instead of the 108-Mc Minitrack frequency. Minitrack operators knew Sputnik I was passing overhead but could not track it with 108-Mc interferometers. Actually the Russians had launched a satellite, as they had said they would, and were using frequencies recommended at an international planning meeting the year before.[31] In their preoccupation with Vanguard and Minitrack, American engineers had paid little attention to Russian pronouncements.

Sputnik I was transmitting in the amateur radio bands and getting a lot of good publicity as hams all over the world picked up the signals. Army radio engineers and many amateurs spent the night of October 4 building and modifying equipment for Doppler tracking. Crude orbital data were available within a day. At NRL, the Minitrack team, alerted by radio announcements of the Sputnik launching, burned the midnight oil cutting 40-Mc dipoles and planning network modifications.[32] 40-Mc crosses were quickly installed at Blossom Point, San Diego, and Lima; and later, at Santiago and Woomera. In several days, good tracking data was being received. Sputnik I and Sputnik II, in fact, gave Minitrack good shakedown runs.

When the Explorers and Vanguards came along a few months later, Minitrack was completely successful, fulfilling all expectations, and surprising many who

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[29] IBM letter to NRL, dated April 23, 1956. IBM also supported the SAO in preparing satellite ephemerides from raw tracking data. In 1956, mathematical techniques and computer programs did not exist for handling raw tracking data. IBM donated considerable time and talent in helping astronomers and mathematicians to overcome this problem, which turned out to be quite different from the usual astronomer's job of computing star and planet positions.

[30] John T. Mengel and Paul Herget, "Tracking Satellites by Radio," Sci. Amer., CXC VIII, (Jan. 1958), 23. Mengel's coauthor on this paper, Paul Herget, was one of the astronomers who helped get the orbit-computation problem under control.

[31] CSAGI Resolutions at Barcelona — Sept. 9-14, 1955 (Working Group on Satellite Launching, Tracking and Computation), Recommendation C. "Establishment in all countries of radio observation stations for frequencies of 20 mc/sec and 40 mc/sec."

[32] The night of Sputnik I will never be forgotten by any of the government and civilian engineers and scientists who rushed back to the lab to try and track that 184-lb sphere. The long-distance telephone calls and sense of comradeship in a common goal was perpetuated by scrolls (still hanging in some offices) dedicated to "The Royal Order of Sputnik Chasers."

had never had anything good to say about radio interferometry. The Minitrack interferometers are still the basic core of STADAN.

Minitrack II

Minitrack II was a simplified version of the interferometer deployed at the prime Minitrack sites. Only four antennas were needed (two sufficed in the simplest design), but with the consequent loss of the ability to resolve the angle ambiguity mentioned earlier. A Minitrack II station could fix the time a satellite crossed its meridian with high precision by analysis of the nulls in the interference pattern. This information, as later proved by observations from the Sohio Minitrack II station, was sufficient to yield accurate orbital elements with only a single station.[33]

Minitrack II, also called "Jiffytrack" and "Poor Man's Minitrack," was the brainchild of Roger Easton at NRL. Easton even suggested that Minitrack II be installed at the prime Minitrack sites, but this was vetoed in favor of the larger, more sophisticated ambiguity-resolving interferometer. Still, Minitrack II was simple and "cheap" to build — something around $1,000. Perhaps amateurs could build it and thus supplement observations from the prime Minitrack stations.[34] In cooperation with the American Radio Relay League, NRL started Project Moonbeam, the electronic cousin to the SAO amateur optical tracking activity, Project Moonwatch.

A thousand dollars plus was quite a sum for most radio amateurs and only a few stations were actually built.[35] The major Minitrack II station was built by amateurs associated with the Standard Oil Company of Ohio (Sohio). Sohio supplied some equipment, limited funding, and personnel to help reduce the data acquired.[36] The first version of the Sohio station went "on the air" at Burhan's home in Chagrin Falls, Ohio, on January 31, 1958, just in time for Explorer I. A larger installation was next built at the Sohio Research Center, in Warrensville Heights, Ohio, a suburb of Cleveland. (Figure 9) The second Sohio station remained in operation for about five years. Some notable firsts recorded were: First station in the world to pick up Explorer IV; orbit confirmation for Explorer VII, Echo I, and Courier I; and the Doppler monitoring of the Vostok III-Vostok IV separation.

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[33] Letter from Ralph W. Burhans, May 21, 1966. Burhans was the Project Leader of the Sohio Station.

[34] Roger L. Easton, "Radio Tracking of the Earth Satellite," QST, XL (July 1956), 38.

[35] See QST, Feb. 1958, p. 60, for a station list.

[36] Ralph W. Burhans, "Sohio Project Moonbeam," Sky and Telescope, XXV (March 1963), 1.

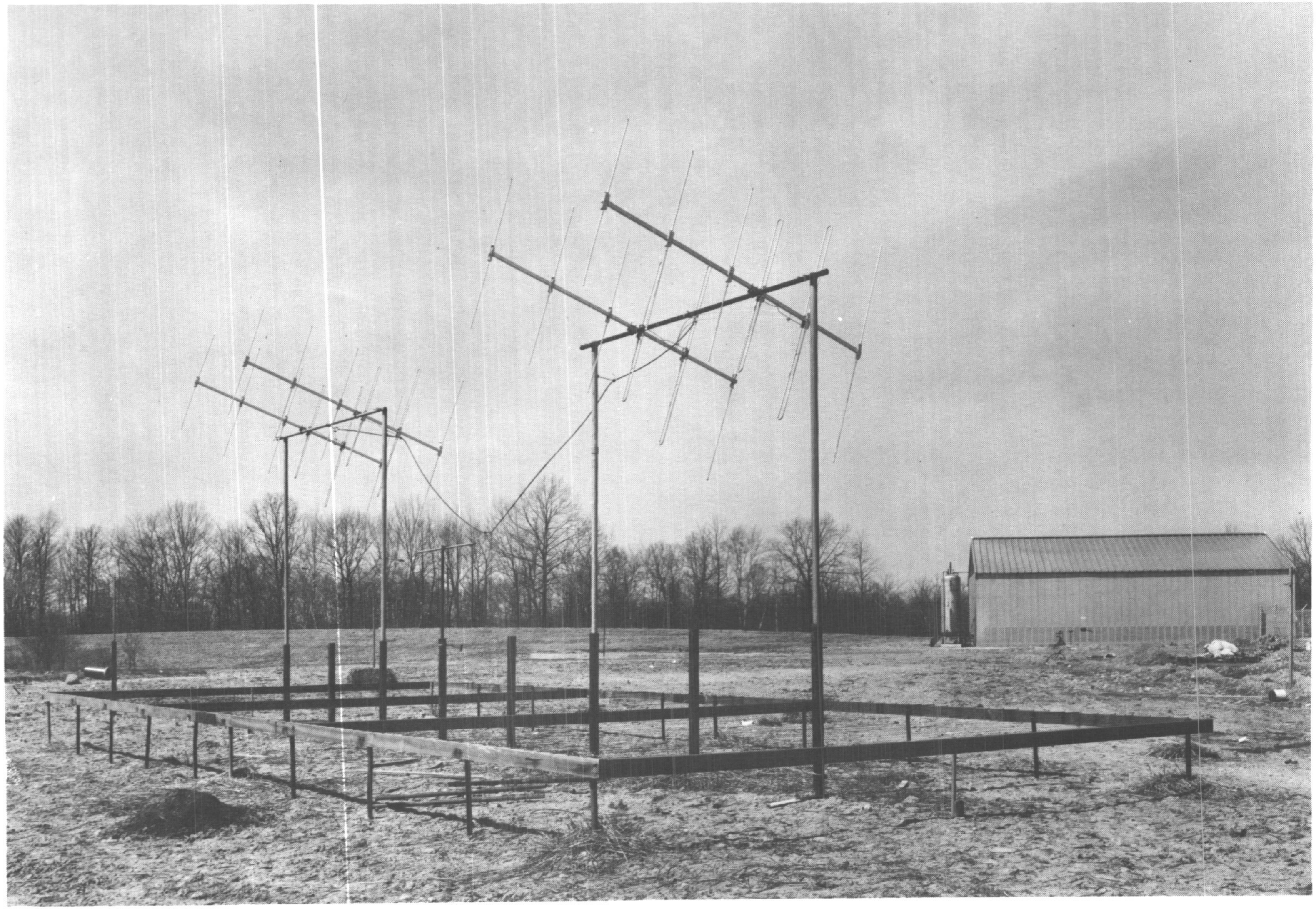

Figure 9. Photograph of the Sohio Minitrack II antenna. (Courtesy of R. W. Burhans)

NRL also built and installed Minitrack II equipment at Blossom Point (operational Jan. 23, 1957) and at Cape Canaveral for tracking operations with Vanguard TV-0.[37]

Active Minitrack

Sputnik I caused a major tremor in military circles. Did the Russians have other satellites already in orbit that did not advertise their presence via a tracking beacon? The specter of undetected nuclear bombs in orbit started a crash project aimed at detecting and tracking "dark" or "uncooperative" satellites. Obviously the target had to be illuminated with radio waves; several proposals were submitted that required long chains of radar-type installations. In contrast to these billion-dollar programs, NRL, notably Roger Easton, suggested in May 1958 using Minitrack-type interferometers in an East-West chain across the U.S. Several powerful transmitters along the chain would project a wedge-shaped "fence," so that a satellite crossing it would announce its presence by reflecting radio waves into the interferometers waiting below. Easton's computations showed that it would be easy to detect an object with an effective reflection area one meter square at 3000 miles altitude. Furthermore the whole job could be done for about $3.5 million. The NRL price was three orders of magnitude less than other proposals. The Secretary of Defense bought the NRL concept. In a Horatio Alger story of military electronic tracking, Active Minitrack stations were quickly installed between Ft. Stewart, Georgia, and Brown Field, California, meeting all dollar, schedule, and performance goals. Active Minitrack is now called SPASUR (for Space Surveillance System) and generates ephemerides for each of the several pieces of space debris that cross its fence each minute.

The impact of Active Minitrack on "passive" Minitrack was slight. The Ft. Stewart station was turned over to SPASUR and replaced by the Ft. Myers (Florida) station that received the equipment withdrawn from Havana in 1959.

Microlock

Even after Vanguard became the "official" U.S. satellite program, Army engineers and scientists continued to agitate for an Army satellite effort based on ABMA/JPL (Army Ballistic Missile Agency/Jet Propulsion Laboratory) technology. Participants in Project Orbiter were particularly bitter over the Stewart Committee selection. Realizing the weakness of the original Orbiter proposal in the tracking area, the JPL Microlock phase-comparison tracking system was added to the Army arsenal.

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[37] See NRL Report 4880, Dec. 3, 1956. (In NASA Vanguard files.)

Technically, the Microlock system consisted of (1) a phase-locked receiver, with implicit Doppler-tracking capabilities, (2) interferometer receivers, and (3) auxiliaries, such as acquisition-control, recording, and timing equipment. The phase-lock and Doppler features were not part of Minitrack; but the Microlock interferometer receivers — usually just three or four separate antennas along the baseline — were similar in function to the Minitrack antenna arrays. Mobility was another important characteristic of Microlock units. Most field units were trailer-based.

The phase-lock feature of Microlock, in which the receiver automatically "locks on" to the signal phase, like radar "locks on" to a target, had been under study at JPL since the early 1950's.[38] A satellite-tracking-feasibility study was completed for the Army in September 1955 — too late for the first Orbiter proposal. The Army Ordnance Corps (supporting von Braun) ordered hardware development of Microlock. A prototype was completed in early 1956, with tests at Earthquake Valley, Calif., in May 1956. On September 20, 1956, the Grand Turk Microlock station downrange from Cape Canaveral tracked a Jupiter-C carrying a dummy fourth stage along a trajectory 3000 miles long and 700 miles high. The Army believes that it could have put a satellite into orbit on that shot.

The primary Microlock station was the one at Earthquake Valley. Eventually, this station was moved to Goldstone Lake (site of a present DSN station). The mobility of Microlock made the station list a fluid one. At one time or another there were additional stations at Ibadan, Nigeria; Cape Canaveral; Singapore; China Lake, Calif.; Aberdeen, Md.; and several other locations. Some of these stations deployed the interferometer antennas; others relied solely on Doppler measurements. The Sputniks and Vanguard troubles gave Project Orbiter another chance; and, on November 8, 1957, the Secretary of Defense announced that the Army would also participate in the nation's satellite program. Explorers I, II, and IV resulted from this decision. They were tracked by Microlock as well as Minitrack stations. For these satellites three Microlock stations were employed in a network called "Spheredop."[39]

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[38] Robert C. Tausworthe, "Theory and Practical Design of Phase-Locked Receivers," Vol. 1, NASA CR-70395, JPL TR-32-819, Feb. 15, 1966. The key JPL personnel on Microlock were Henry Richter, Eberhardt Rechtin, William Sampson, Walter Victor, and D. Jaffee.

[39] The stations were Earthquake Valley; China Lake (Naval Ordnance Test Station); and an amateur station run by the San Gabriel Valley Radio Club. Other amateur Microlock stations were at Cedar Rapids and White Sands. The Sohio Minitrack II station actually adopted the phase-lock and Doppler features of Microlock. See Henry L. Richter, William F. Sampson, and R. Stevens, "Microlock: A Minimum Weight Radio Instrumentation System for a Satellite," Jet Prop. (Aug., 1958), 28, 232.

When NASA was formed on October 1, 1958, it dismantled the Microlock stations. Microlock ideas, however, still survive in the space program. JPL phaselock techniques are central to the tracking of deep-space probes from the DSN. In another interesting parallel between Minitrack and Microlock, history finds that an Active Microlock was also proposed for the tracking of dark satellites. Dr. Debeye, at the Army Ballistic Research Laboratory, Aberdeen, Md., was the moving force behind this approach. Though it lost to Active Minitrack, the Active Microlock idea became the military Doploc missile-tracking system.

The SAO Baker-Nunn Camera Network

The Smithsonian Astrophysical Observatory's Baker-Nunn satellite-tracking camera network is not officially considered part of STADAN; but, because of Minitrack's early confrontation with optical tracking in the pre-Vanguard days and the present complementary relationship of the two systems, a very brief recounting of the evolution of the SAO network seems proper here.[40]

Fred L. Whipple had suggested the use of three equatorial optical tracking stations as part of Project Orbiter in June of 1955. Prior to the fateful Stewart Committee decision against Orbiter in late summer 1955, the National Science Foundation budget had already set aside $10 million for ten satellites and five optical tracking stations placed along the equator — a fact attesting to Whipple's influence and reasoning before the Long Playing Rocket Committee of the U.S. National Committee for the IGY. When Orbiter fell before Vanguard, Whipple realized that optical tracking of the much smaller Vanguard satellite would require a camera with an extremely large aperture. In addition, he appreciated the satellite-acquisition problem and pushed "Project Moonwatch," a worldwide amateur effort that would find the satellite and provide rough times of transit over the local meridians. From these data, the big, new cameras could acquire the satellite and generate precision tracking data. In late 1955, the National Academy of Science and National Science Foundation, acting for the U.S. National Committee for the IGY, assigned optical tracking responsibility to the SAO. Money started flowing January 1, 1956.

The critical piece of hardware in the SAO program was, of course, the big camera. Whipple asked James G. Baker, a consultant to Perkin-Elmer of Norwalk, Conn., to design it. By February 1956, Whipple and Baker, joined by J.

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[40] For abundant detail, see Nelson E. Hayes, "The Smithsonian's Satellite-Tracking Program: Its History and Organization," Part 1, Smithsonian Report for 1961, Rpt. 4482, p. 275. Part 2. Annual Report of the Smithsonian Institute, 1963, p. 331.

Allen Hynek, who had left Ohio State University to become associate director of the SAO tracking program, had laid out plans for the new tracking camera. They asked Joseph Nunn of Pasadena, Calif., to do the mechanical design work. By fall of 1956, the Baker-Nunn camera design had progressed to the point where hardware contracts were let. Perkin-Elmer built the optical system, while Boller & Chivens, South Pasadena, Calif., built the camera proper. The first camera was tested October 2 and 3, 1957, at South Pasadena. It was decided at that time to dismantle the camera for minor alterations and adjustments. A few hours later, Sputnik I went into orbit. Sputnik I accelerated the Baker-Nunn, just as it did all other U.S. satellite work. The first Baker-Nunn station became operational at Organ Pass, New Mexico, in November 1957, just a few weeks later.

The SAO Moonwatch program paralleled the Minitrack Moonbeam amateur effort. One might have expected there to be more amateur radio enthusiasts than astronomy enthusiasts. The Moonwatch Program, however, was well publicized and, under the direction of Leon Campbell, Jr., was sold all across the U.S. by SAO representatives. Through the astronomical fraternity, many international Moonwatch stations were set up. By October 1957, there were 80 registered Moonwatch teams in the U.S. and 84 in foreign countries. The night of October 4 caught Moonwatch by surprise just as it had the Minitrack group. Only two people were at the SAO Cambridge facility when the news of Sputnik I came through. Others hurried back to help as they heard the news. By the dawn of October 5, over 100 Moonwatch teams were looking for Sputnik I as it was lit by the morning sun for the Moonwatchers still in darkness on the Earth below. Unfortunately the attempts at camera acquisition of Sputnik I was as futile as the attempts at reception of its signals by radio hams. The Baker-Nunn cameras were not completed and the Minitrack frequency was wrong.

Although no more will be said about the SAO optical network in this monograph, its twelve worldwide stations are an important adjunct to STADAN, particularly where precision tracking data is wanted for geodetic purposes.

CHAPTER IV

FOUR YEARS OF STABILITY, 1958-1962

The last prime IGY Minitrack station went operational at Woomera during October 1957. Outside of some minor shuffling and addition of sites and the rebuilding of temporary installations, no major changes were made to Minitrack until the big 85-ft paraboloidal antenna was installed at the new Fairbanks site in May 1962. This chapter covers the four years of relative stability following the first Explorer and Vanguard satellites. During this period, the Minitrack network easily tracked the few, relatively simple scientific satellites that passed overhead. It was a time of intense planning, research, and development as the Nation planned space programs that would soon saturate Minitrack's capabilities. It was also a period of organizational flux as the government searched for the best way to prosecute a space effort that would surpass that of the U.S.S.R.

NASA Is Organized

The official U.S. IGY satellite program — Vanguard — was buried deeply within the country's military organization. The Army's successful Explorer satellites further split a satellite effort that Russian accomplishments quickly proved was far too weak in total. The National Aeronautics and Space Administration was created on October 1, 1958 to remedy these deficiencies by concentrating all peaceful space programs into a single organization.[41] Of this major realignment and upgrading of the national space program, only the fate of the tracking, data-acquisition, and other STADAN functions interest us here. Under Vanguard, tracking responsibility had been assigned to the NRL Radio Tracking Branch, under John T. Mengel. (Figure 10) When NASA was formed, the Vanguard group was transferred bodily to NASA.[42] The NRL Vanguard team became the nucleus of the Beltsville Center, which in May 1959 was renamed the Goddard Space Flight Center. In the tracking area, Mengel remained in charge of the Goddard work with the title of Assistant Director, Tracking and Data Systems, reporting to the Office of the Director of Goddard. The man, the title, and the position of the tracking and data-acquisition functions remain the same at Goddard in 1966.

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[41] Executive Order 10783 established NASA. A subsequent, separate agreement between NASA and DOD transferred the Minitrack network. See Robert Rosholt: An Administrative History of NASA, 1958-1963, NASA SP-4101 (1966), p. 45.

[42] The cohesiveness and permanence of the Vanguard Minitrack group over a period exceeding ten years is remarkable. In the transfer to NASA, only a few of the original Minitrack team, notably Roger Easton, remained behind at NRL.

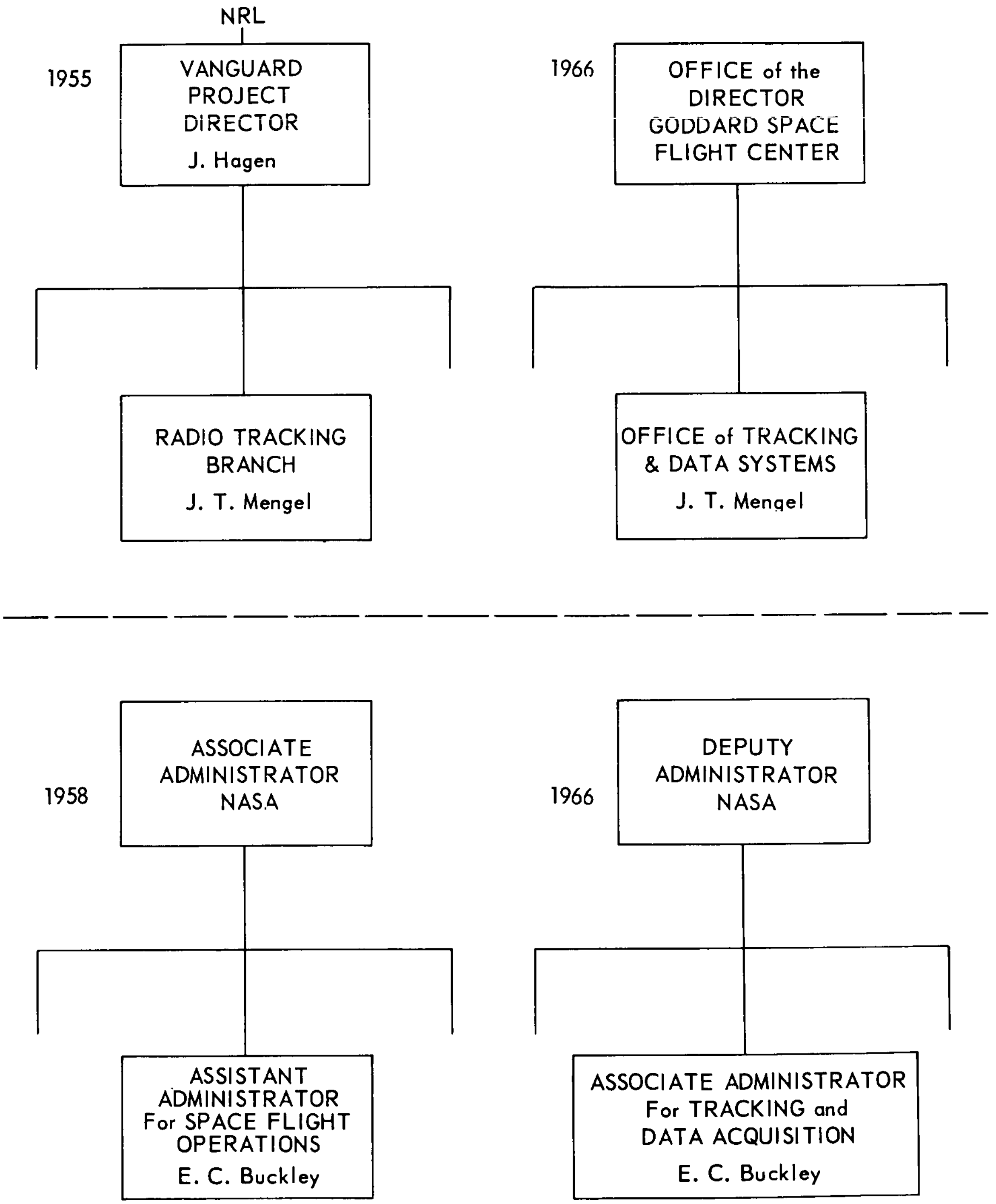

Figure 10. At the Project and field level (top), management of tracking and data acquisition has been stable for eleven years, save for the transfer of Vanguard to NASA. At the bottom, NASA Headquarters management of the same functions also shows long-term stability. All tracking and data acquisition was centralized under the Office of Tracking and Data Acquisition on Nov. 1, 1961.

At NASA Headquarters, in Washington, where Agency-wide operations were to be coordinated, the tracking and data-acquisition functions were handled by the Assistant Administrator for Space Flight Operations in the person of Edmond C. Buckley, who reported to the Associate Administrator for Space Flight Programs. (Figure 10) With some minor changes in titles, this arrangement persisted until Nov. 1, 1961, when an Agency-wide Office of Tracking and Data Acquisition was established.[43] Edmond C. Buckley assumed the title Director, Office of Tracking and Data Acquisition at this time; becoming, in 1966, Associate Administrator, Tracking and Data Acquisition. This organization has been retained through 1966.

In comparison with industry and even other Government agencies, NASA's organization for managing the Minitrack and STADAN functions has been extraordinarily stable.

When NASA absorbed Minitrack and assumed the responsibility for tracking non-military satellites, it also inherited the problem of finding money for operating Minitrack and for financing the development and purchase of new equipment. During the Vanguard Program, money had been allocated to the National Science Foundation and then passed on to the Naval Research Laboratory. In the case of NASA, Congress appropriates money directly. NASA Headquarters assembles all the monetary requirements for new facilities, research and development, and operation of all its networks. These requirements are related to the total NASA program; a budget is prepared and presented to Congress. Funds appropriated for STADAN flowed originally through the Office of Space Flight Operations to Goddard Space Flight Center, the field center with the operating responsibility for STADAN. After the creation of the Office of Tracking and Data Acquisition in 1961, it has served as the source of STADAN funds within NASA.

DOD Interfaces and Coordination

After its formation, NASA moved rapidly to assimilate all nonmilitary space activities as well as military operations it deemed important to its mission, particularly von Braun's organization at Huntsville and the JPL team. With the acquisition of JPL, NASA had central control over all scientific satellite work and had absorbed the JPL Microlock stations. NASA also took over direct control of the South American Minitrack stations from the Army in early 1959.[44]

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[43] Robert Rosholt, An Administrative History of NASA, 1958-1963, NASA SP-4101 (1966). p. 221.

[44] NASA Memo 4132-8: JPC: mlk, Feb. 2, 1959. A request from NASA to the Chief, Army Communication Services Division, to turn over all station responsibilities. (In NASA Vanguard files)

In the post-Sputnik era, DOD was rapidly building up its own tracking facilities; i.e., SPASUR. The framers of the Space Act were concerned over duplication of facilities if NASA and DOD went their separate ways. Section 204 of the Space Act provided for a Civilian-Military Liaison Committee. In actual practice, this Committee was little used and eventually atrophied completely. Significant duplication was actually prevented by DOD's primary interest in detecting new, potentially threatening objects in space rather than acquiring scientific data from satellites or obtaining orbital elements with high precision. SPASUR and other DOD facilities must keep accurate traffic counts of what passes over. Today DOD's National Range Division and Satellite Control Facility possess some tracking and data-acquisition capabilities, but there has been no attempt to duplicate STADAN. More effective coordinating groups and Congressional attention have precluded this.[45] In fact, NASA and DOD have shared their facilities to a greater and greater extent. NASA provides NORAD with tracking data and tracks Air Force scientific satellites carrying Minitrack beacons. NASA also acquires telemetry data for many DOD satellites.

Minitrack Operation — 1958-1962

This was a period of few major changes — one might call it a plateau — in Minitrack capabilities. More and more satellites were launched as NASA scientific programs began to materialize in hardware form. But the satellites were not large, there were not too many of them in orbit at one time, and their orbits usually were within the reach of the Minitrack net. It had to be this way, obviously, because the tracking and data-acquisition network was the horse that had to precede the cart. As NASA laid plans for the Observatory series of satellites, polar satellites, and satellites circling in highly eccentric orbits, NASA planners and engineers at Headquarters and Goddard had to keep one jump ahead with facilities that would do the required job.

When NASA took over the Nation's scientific space programs, the IGY had only three months to go; Vanguard had had one success and many disappointments; and there had been three successful Army Explorers and two failures — hardly a burden for Minitrack. During 1959, four more scientific satellites went into orbit. Some satellites, such as Vanguard I, kept on transmitting for lengths of time that began to worry those who looked ahead in a Malthusian way and feared that the sky would soon be so full of transmitting satellites that ground facilities would be saturated. Cutoff or "killer" timers began to be installed on

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[45] The Space Flight Ground Environment Panel of the Aeronautics & Astronautics Coordinating Board (AACB), with separate subpanels on Network Plans and Development effectively control this particular NASA-DOD interface today.

satellites to counter this trend. But by 1960, most recognized that Minitrack, despite its great victory over the nay-sayers of 1955-1956, would have to be enhanced in several ways within two or three years. This preparation and deployment of today's STADAN is the subject of the next chapter.

Network Modifications and Changes

Some Minitrack site changes were made during the 1958-1962 period to improve geographical coverage and data acquisition. Stations were added at College, East Grand Forks, St. John's, and Winkfield. A few stations were closed down or shifted; for example, the move of the Havana equipment to Ft. Myers, and the shutdown of Antigua. These changes did not add any radically new capabilities to Minitrack.

Some changes in telemetry and command antennas were made during this period, and supporting electronic equipment was improved. The "rockinghorse" antenna of Vanguard days was superceded by a manually pointed 9-Yagi array (Figure 11) and then by a few 16-Yagi arrays to improve telemetry reception and command transmission. The fundamental frequency of Minitrack was upped from 108 Mc to 136-to-137 Mc in 1960 to escape from local interference at the lower frequency and meet International Telecommunication Union (ITU) requirements. This change required relatively minor modification of the Minitrack interferometer. Unfortunately, complete frequency conversion was impossible between 1961 and 1965 because several active satellites were still telemetering useful data at 108 Mc.

Another rather interesting change to Minitrack involved the modification of the calibrating astrographic cameras for optical satellite tracking in May 1960. The resulting cameras did not have the precision and acuity of the SAO Baker-Nunns, but the larger satellites could be tracked and, in addition, used for Minitrack calibration in the place of aircraft. Collectively, the new cameras formed the Minitrack Optical Tracking System (MOTS).[46]

Summarizing this short chapter: In the first four years after NASA's creation in October 1958, Minitrack changed but little. There was no larger need — yet — satellites were few, far between, and relatively simple. Major changes were in the offing, however.

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[46] David W. Harris, et al, "MOTS — The Minitrack Optical Tracking System," Photo. Sci. Eng., VII (March 1963), 73.

Figure 11. A 9-Yagi, 136-Mc STADAN antenna.

CHAPTER V

METAMORPHOSIS OF MINITRACK INTO STADAN

The preceding chapter hinted at major changes brewing beneath the calm surface of the 1959-1962 time period. To understand how and why Minitrack evolved into STADAN, let us first look at the pressures NASA's satellite plans exerted on its tracking and data-acquisition facilities. The total picture can be best visualized with the help of a cause-and-effect table:

-Cause- Pressure Due to Planned Program	-Effect- Major Additions to Basic Minitrack
Tracking requirements of polar-orbit satellites and geodetic satellites.	Extension of geographical coverage to Alaska. See Appendix A for details.
Data-acquisition requirements of Observatory-class satellites and communications and meteorological satellite programs	Installation of 85-ft and 40-ft parabolodial antennas at Gilmore, Orroral Valley, and Rosman.[47] Installation of SATAN telemetry antennas.[48] Addition of high capacity data links to Goddard.
Tracking requirements of synchronous satellites and those in highly eccentric orbits.	Goddard Range and Range Rate tracking systems installed at several STADAN sites and on mobile equipment.
Need for better command capability for complex Observatory-class satellites and large meteorological satellites.	SATAN command antennas with high-powered transmitters.

The picture of Minitrack changing into STADAN evokes the question of how the whole thing was planned. How did NASA's tracking people know what kind of

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[47] An antenna is only an obvious external feature. A great deal of new electronic gear supports each new antenna.

[48] SATAN = Satellite Automatic-Tracking Antenna.

antennas to develop and where to place them? Formal long-range plans laying down tracking and data-acquisition requirements were rarities during the early days of the U.S. space program. Paperwork was at a minimum. The already-told story of the birth of Minitrack showed no step-by-step plans. Instead engineers, such as John Mengel and Roger Easton, sitting down over a cup of coffee, looked at the Vanguard satellite, figured out how big a transmitter they could afford and how much money they had, and then decided how many Minitrack stations to put where. As plans and funding changed, Minitrack changed—all with a minimum of paperwork.

With the advent of NASA, funding levels jumped from millions to billions, and the sheer magnitude of the Nation's space effort demanded a more rigorous approach. If tracking and data-acquisition equipment was to be developed and installed in time for a new satellite program, a forecast of satellite launchings had to be available. NASA's first formulation of a comprehensive plan was embodied in a secret document entitled "NASA Long Range Plan," prepared in December 1959 by the Office of Program Planning and Evaluation.[49] This plan was primarily a forecast of what NASA could do given certain budgetary constraints and reasonable extrapolations of the state of the art in launch vehicles—the pacing facet of space technology at that time. Plans such as this were continually modified, particularly under the pressure of the Soviet feats in space.[50] Despite their ephemeral character, these plans gave tracking engineers targets to shoot at, such as the planned Observatory-class satellites and synchronous communications satellites. To meet such requirements, Goddard engineers had to predict the state of the art two or three years in advance. Various technical solutions were studied and tried out in the laboratory. Finally specific approaches were selected and developed into operational hardware, such as the Goddard Range and Range Rate equipment.

In STADAN, as in most other technical enterprises, there has been no predictable, cut-and-dried engineering response to administrative plans. Someone with foresight gets an idea, develops it, and sells it up the administrative chain of command. Really significant ideas, such as the DAF, backed by good salesmanship frequently changed plans and budgets in their favor.

In the paragraphs that follow, some of the key technical and historical features of these additions will be related. Separating out and listing the major

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[49] Robert L. Rosholt, <u>An Administrative History of NASA, 1958-1963</u>, NASA SP-4101 (1966), p. 130.

[50] Perhaps the sharpest perturbation occurred on May 25, 1961, when President Kennedy announced that it was time for a "great new American enterprise" — landing a man on the Moon in the decade of the sixties.

additions to the basic Minitrack, we have:

- Site additions and shifts
- The new 85-ft and 40-ft dishes
- The Goddard Range and Range Rate tracking equipment (RARR)
- SATAN telemetry antennas and SATAN command antennas
- Enlargement and automation of the ground-based communication links between STADAN stations.

All these changes and additions have converted Minitrack into what is now called STADAN (Space Tracking and Data-Acquisition Network.)[51]

Station Site Changes

The early Minitrack sites were geographically constrained by the short range of the tiny Vanguard transmitter and the lack of precision tracking during the satellite injection phase downrange. No one was sure just where a satellite would pop over the horizon. Minitrack stations were thus deployed, rather close-spaced, along the now-familiar detection fence on the 75th meridian. Today, with downrange tracking ships and much better injection tracking, rough orbital elements are available even before the satellite leaves the vicinity of the launch range. Spacecraft, too, are more sophisticated and can carry beacons that send out strong signals. The Minitrack "detection-fence" approach has been abandoned in favor of fewer better-equipped stations located all over the world. The table in Appendix B confirms this trend. First, though, there was the elimination of redundant Minitrack sites, such as Antofagasta. These changes were offset by the addition of new Minitrack sites well outside the 75th-meridian fence, e.g., Winkfield and College. In 1966 a few Minitrack sites were being phased out altogether; examples are Blossom Point and East Grand Forks. Some, such as College, were being consolidated with other STADAN stations. The fact of today is that tracking is not the most important function of STADAN, as it was with Minitrack; data acquisition has assumed prime importance. STADAN is no longer characterized by an interferometer fence but instead by well-separated, high-data-rate paraboloidal antennas.

As the list of sites (Appendix B) with 40-ft and 85-ft antennas indicates, every continent except mainland Eurasia possesses such a site. (Actually the

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[51] Frequently, the word "Space" in STADAN's acronym has been changed to "Satellite," but this unnecessarily limits STADAN's utility with semantics. STADAN has been used for lunar purposes; viz., the Anchored IMP's (IMP's D and E).

Alaska STADAN station can be thought of as an Eurasian outpost.) This distribution is necessary because today's satellites run the gamut in inclination from the equatorial Syncom to the Polar Orbiting Geophysical Observatories. Originally, as the station vignettes in Appendix A testify, there existed a more specific reason for placing a station away from the 75th meridian. The first Australian station at Woomera, for example, was placed there for geodetic purposes during the IGY. The new Australian STADAN station in Ororral Valley, however, possesses an 85-ft dish and conforms with STADAN consolidation philosophy that data acquisition is STADAN's prime reason for being.

To summarize then, the geographic evolution of STADAN has consisted of three overlapping phases:

- The Minitrack 75th-meridian fence
- Geographically dispersed Minitrack stations
- Fewer, better-instrumented, well-dispersed STADAN stations.

The Big Dishes

The first 85-ft antenna went into operation at the Alaska STADAN station in March 1962.[52] The main stimulus behind its design and construction was the Nimbus meteorological satellite program, which officially began at NASA in 1960. Minitrack data-acquisition capabilities were obviously inadequate for receiving the flood of cloud-cover pictures that Nimbus would generate. One or more wide-band, high-data-rate antennas were required. A large, pointable antenna (Figure 12) is an expensive affair-roughly $910,000 for the design, engineering, fabrication and erection of the Alaska 85-ft dish. John Mengel recalls that, in 1961, Dr. T. Keith Glennan, then Administrator of NASA, said never to ask him again for any more such equipment.[53] The 85-ft dishes have obviously been well worth their price; NASA now owns four of them and operates a fifth which belongs to ESSA. (See Appendix B)

Since the equipment at the STADAN sites is described in great technical detail in readily available NASA documents, only events of historical interest are covered in this chapter.[54]

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[52] Sites with 85-ft dishes were originally termed DAF (Data-Acquisition Facility) sites, but are now part of STADAN.

[53] Interview with John T. Mengel, April 28, 1966.

[54] The most descriptive reports are: Satellite Instrumentation Network Facilities Report, Goddard Rpt. X-530-62-3, April 1962 (note the early acronym—SIN); Satellite Tracking and Data Acquisition Network Facilities Report (STADAN), Goddard X-539-64-159, June 1964; and Space Tracking and Data Acquisition Network Facilities Report (STADAN), Goddard X-530-66-33, December 1965.

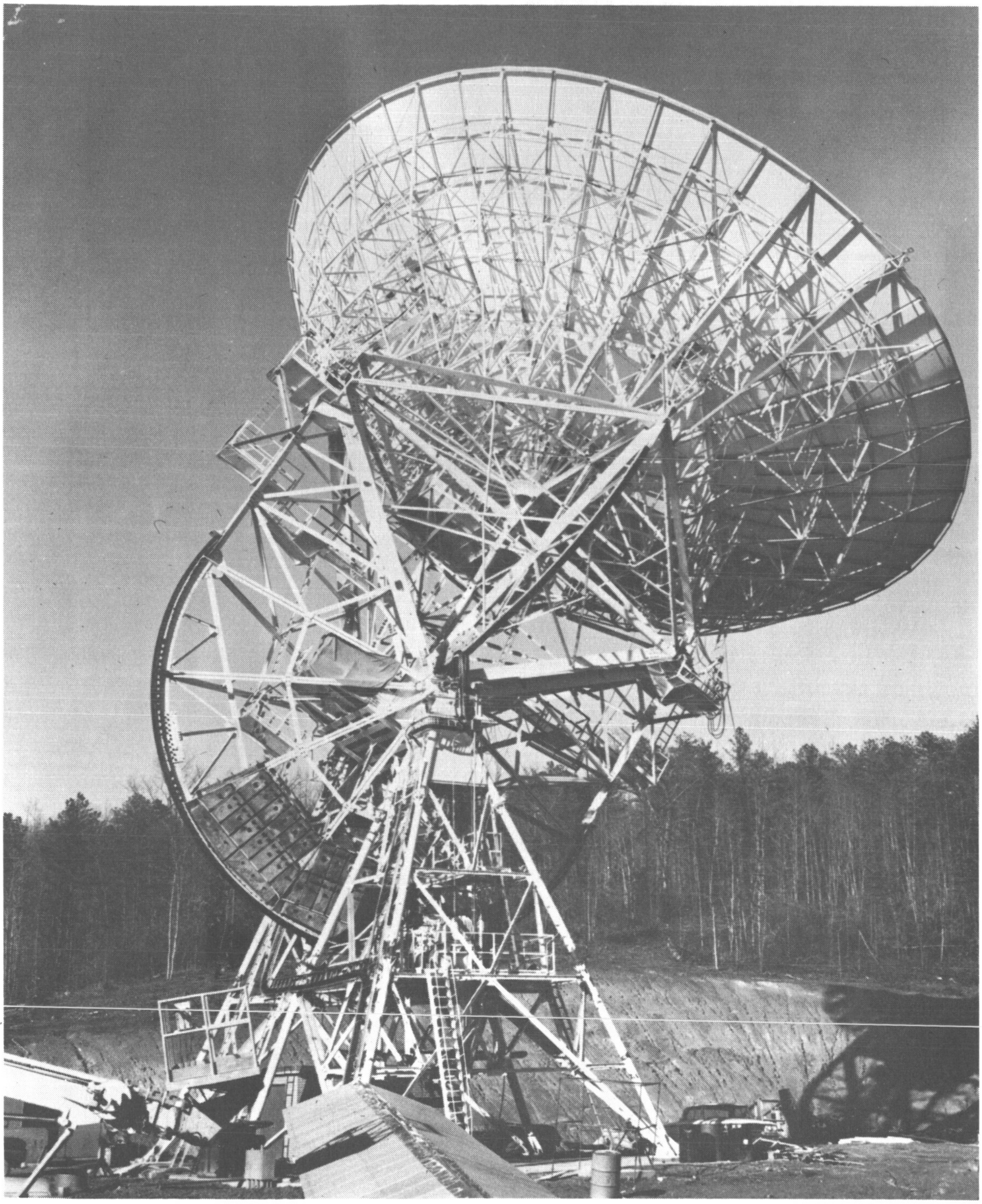

Figure 12. Photograph of the first Rosman 85-ft Data Acquisition Facility Antenna

The price of the first Rosman 85-ft antenna was brought down to $760,000, less for additional ones, but NASA decided to install cheaper 40-ft paraboloids at sites where smaller antennas were adequate. (Figure 13) The first of these new antennas went into operation at Quito in December 1963.

STADAN seemed by 1966 to have reached an instrumentation plateau, just as Minitrack did at the end of the IGY. Data-acquisition facilities were then adequate for the satellite programs planned by NASA. Indeed, satellite science was being caught in a budget squeeze by the higher-priority Apollo program. Furthermore, there seemed to be a trend away from complex, high-data-rate Observatory-class satellites to larger numbers of smaller scientific satellites. The recent creation of the SSS (Small Standard Satellite) program illustrated this trend. According to John Mengel, the next task for STADAN would be one of automation, wherein antennas and associated electronic equipment are automatically pointed and switched over to the desired satellites as they appear over the horizon. There is a growing traffic problem in space that causes station operators considerable trouble as they quickly try to switch from one satellite to another, each with different frequencies and priorities.

Goddard Range and Range Rate Equipment (RARR)

Although STADAN's primary mission has become data acquisition, the tracking function is no less vital than it was in the Vanguard days. Tracking, in fact, has become a great deal more difficult as NASA's programs have expanded to embrace Syncom, IMP, and EGO. The problems are two:

- In synchronous or stationary orbits the satellite being tracked moves very slowly — perhaps not at all — with respect to the ground-based tracking station. Minitrack interferometry is powerless here because it cannot generate a precision orbit without many separate observations at well-separated spots. Minitrack yields only direction cosines and not the range and range rate directly, yet these are critical parameters in jockeying a synchronous satellite into orbit.

- Minitrack angle tracking is of little use when satellites are near apogee in an eccentric orbit. In this region, angles vary slowly but range and range rate change quickly.

These tracking problems were recognized by NASA before 1960, when the essentials of RARR were laid out by Edmund J. Habib, at Goddard, and Eli Baghdady, of Adcom, Inc.[55] In essence, RARR sends a signal to the spacecraft,

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[55] Edmund J. Habib, George C. Kronmiller, Peter D. Engels, and Henry J. Franks, Development of a Range and Range Rate Spacecraft Tracking System, NASA TN D-2093, June 1964. (The three coauthors of Habib were part of the original Goddard RARR design team.)

Figure 13. Photograph of the STADAN 40-ft Data Acquisition Antenna at Quito.

which replies through a transponder. In a process called "sidetone ranging," time of signal transit to and from the satellite yields distance and Doppler measurements give range rate.

Space Technology Laboratories built the first piece of RARR equipment for the NASA Syncom program in 1961. Motorola, GE, and General Dynamics/Electronics have since constructed additional units. The table in Appendix B indicates when and where RARR units have been deployed in STADAN.

SATAN Equipment

The early evolution of the "rockinghorse" and Yagi telemetry antennas was described in Chapter III. The installation of the big 85-ft and 40-ft wideband, data-acquisition paraboloids did not diminish the need for better telemetry antennas to handle the smaller satellites. The big dishes can be used for the smaller Explorer-class satellites, but it is a waste of their capability if an Observatory, a Nimbus, or some other large satellite is also within station range. The purpose of the SATAN antennas is to complement the data-acquisition and command functions of the big dishes, replacing the small, often hand-pointed, 9- and 16-element Yagis of Minitrack vintage. The SATAN antennas also perform as acquisition aids for the narrow-beam-width paraboloids. At sites with no big dishes, the SATAN antennas will of course be the prime data-acquisition and command antennas.

There are two types of SATAN antennas: one for telemetry reception and another for command—the down-link and up-link, according to current terminology. (Figures 14 and 15)[56] Although the early Yagi antennas did not have automatic tracking capability, all recent versions do. Automatic tracking is, of course, inherent in the name of the antenna. SATAN telemetry-reception antennas operate in the 136-to-138 Mc range, and the command antennas transmit in the 123-Mc and 147-to-150-Mc bands.

Inhouse development of the SATAN antennas began at Goddard soon after the Center was created. By 1960, a developmental model tower and pedestal, servodrive system, and 108-Mc receiving-antenna array were installed at Blossom Point. Based on this development work, NASA held a competition for SATAN production. On August 17, 1962, NASA selected Dalmo-Victor Company and Amelco, Inc., to negotiate for R&D and production services for the SATAN program. The history of SATAN antenna deployment is summarized in Appendix

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[56] Goddard Space Flight Center: Data Systems Development Plan, Satellite Automatic-Tracking Antenna Network (SATAN), Revision 2, Sept. 23, 1965.

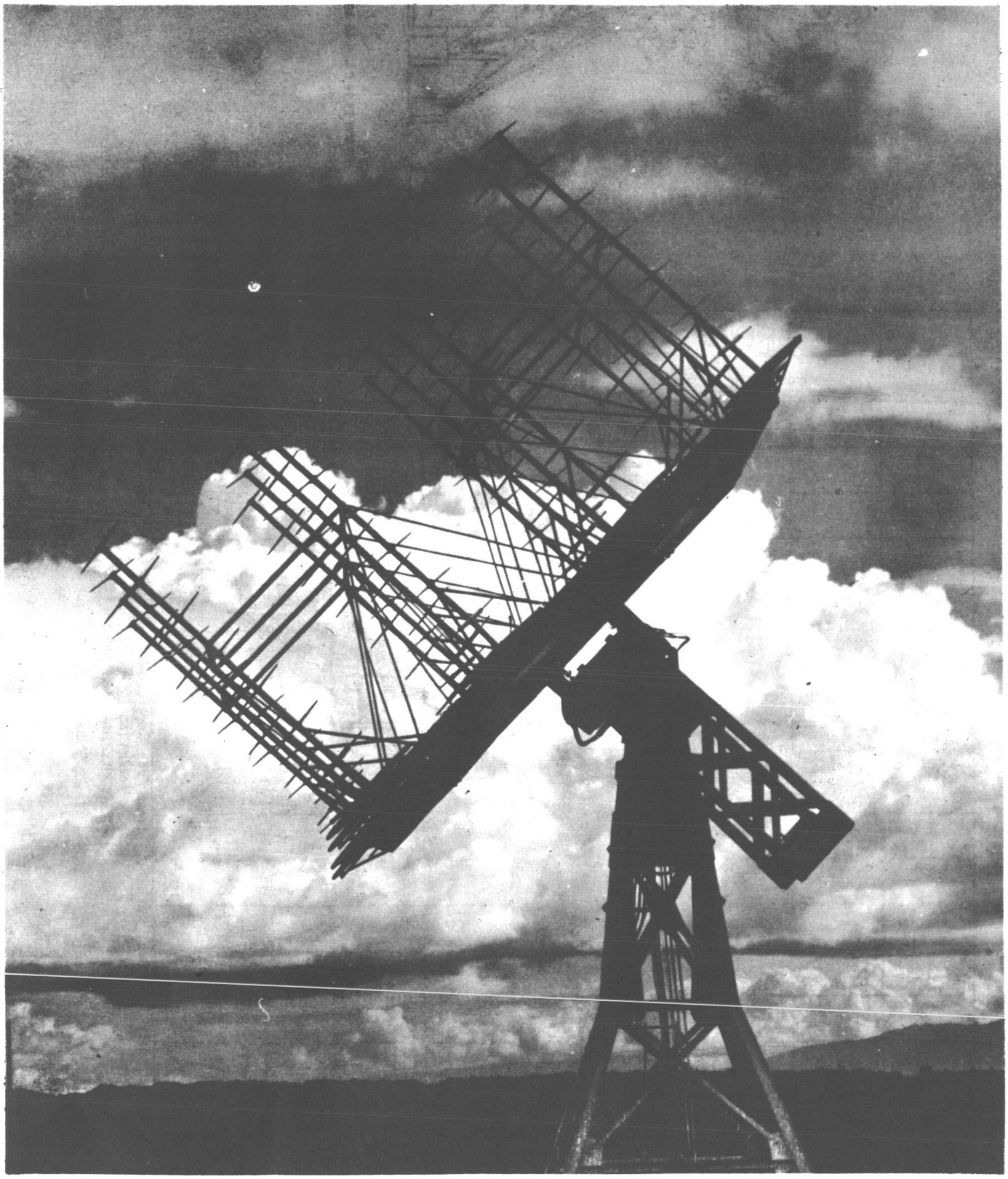

Figure 14. Photograph of a SATAN Telemetry Reception Antenna

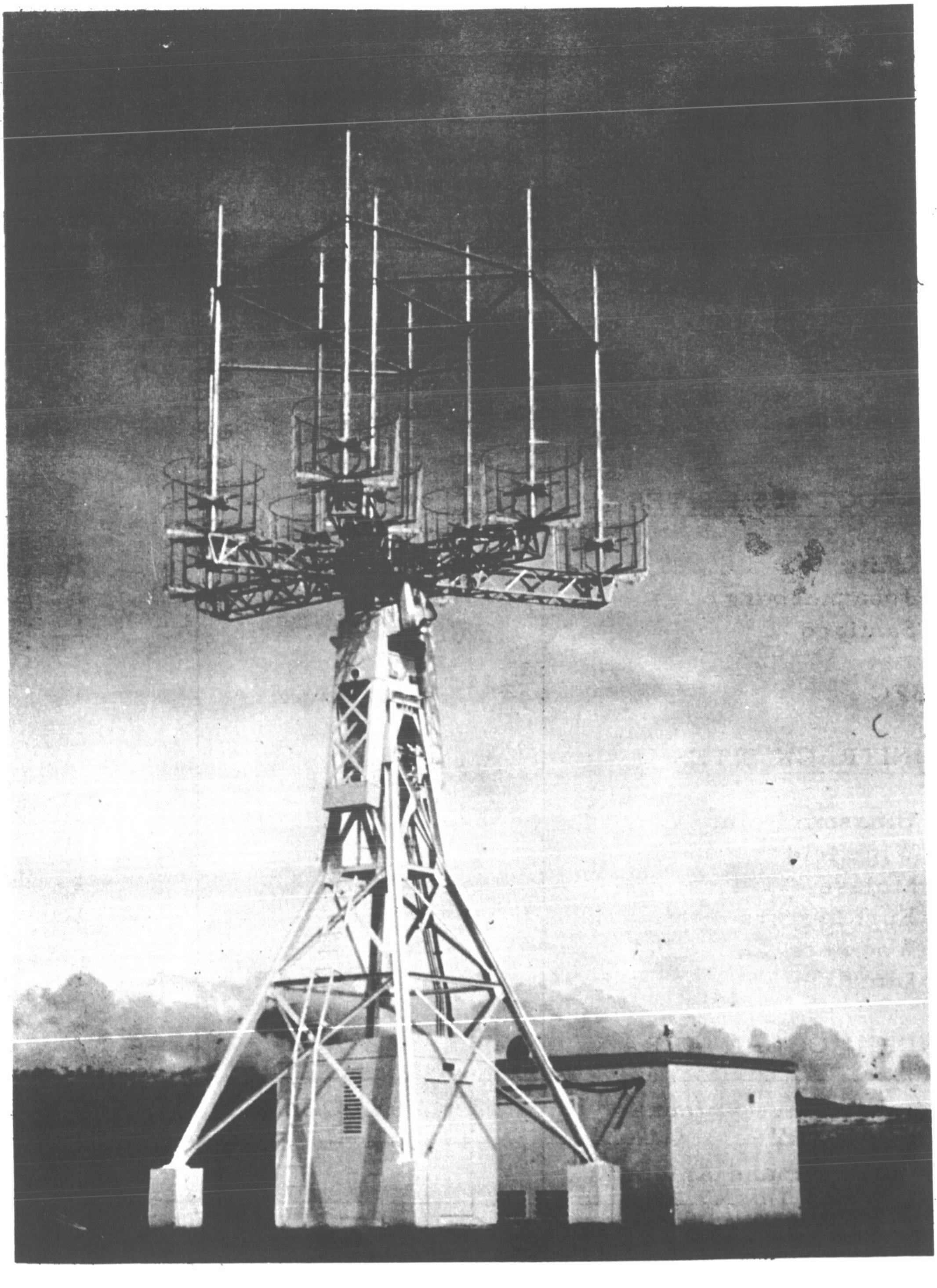

Figure 15. Photograph of a SATAN Command Antenna

B. By the end of 1966, 18 SATAN telemetry and 16 SATAN command antennas were installed at STADAN sites.

STADAN Communications

A worldwide tracking and data-acquisition network is of little avail unless there is a corresponding communication system tying the stations to the control and data-processing center. Not only must the millions of data words recorded from several dozen satellites each day be transmitted back to waiting computers, but instructions must be sent from the central control point to individual stations for relay to the proper satellites. Goddard Space Flight Center, the control point for STADAN, may wish, for example, to change data-acquisition priorities for the satellites passing over Santiago.

In the Vanguard days, teletype circuits were the main method of communication between Minitrack stations and the Vanguard Control Center. (Figure 8) With just a few primitive satellites, teletype circuits could handle most of the data. A modern OGO, however, may spew out a few full-length books of data at each pass over a station. With a few dozen active satellites in orbit, each making a circuit of the globe in about two hours and filling up its tape-recorder memory each trip, ordinary teletype circuits could not handle the load. For most satellite data, reels of tape (some 40+ miles of tape per day) plus the international postal system form the logical communication link. High priority data, "real-time" data, satellite commands, and satellite status data can be sent by teletype where necessary.[57] Voice communication between field stations and the NASA control centers was added for Project Mercury.

All NASA tracking, data-acquisition, and command stations including all three major networks (STADAN, DSN, and MSFN), are linked together by NASCOM, a far-flung integrated grid of landlines, undersea cables, and radio links (Figure 16). An integral part of NASCOM is SCAMA (Switching, Conferencing, and Monitoring Arrangement), which handles all voice communications.[58] Continuing with the acronyms: NETCON stands for Network Control, where STADAN operational scheduling is originated; OPSCON equals Operations Control Center.

NASCOM has been built up link by link over NASA's entire history. It would detract too much from the overall STADAN story to recount all the additions and changes over the last eight years. Two "snapshots," (Figures 8 and 16, show the network at two well-separated points in time.

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[57] The early Minitrack stations, particularly those in South America, used to contact one another via amateur radio to discuss mutual problems and pass the time away between infrequent satellite passes.

[58] R. H. Bidlack, "The 304 Conference Switching System," Bell Laboratories Record, XLIII, (Jan. 1965), 9.

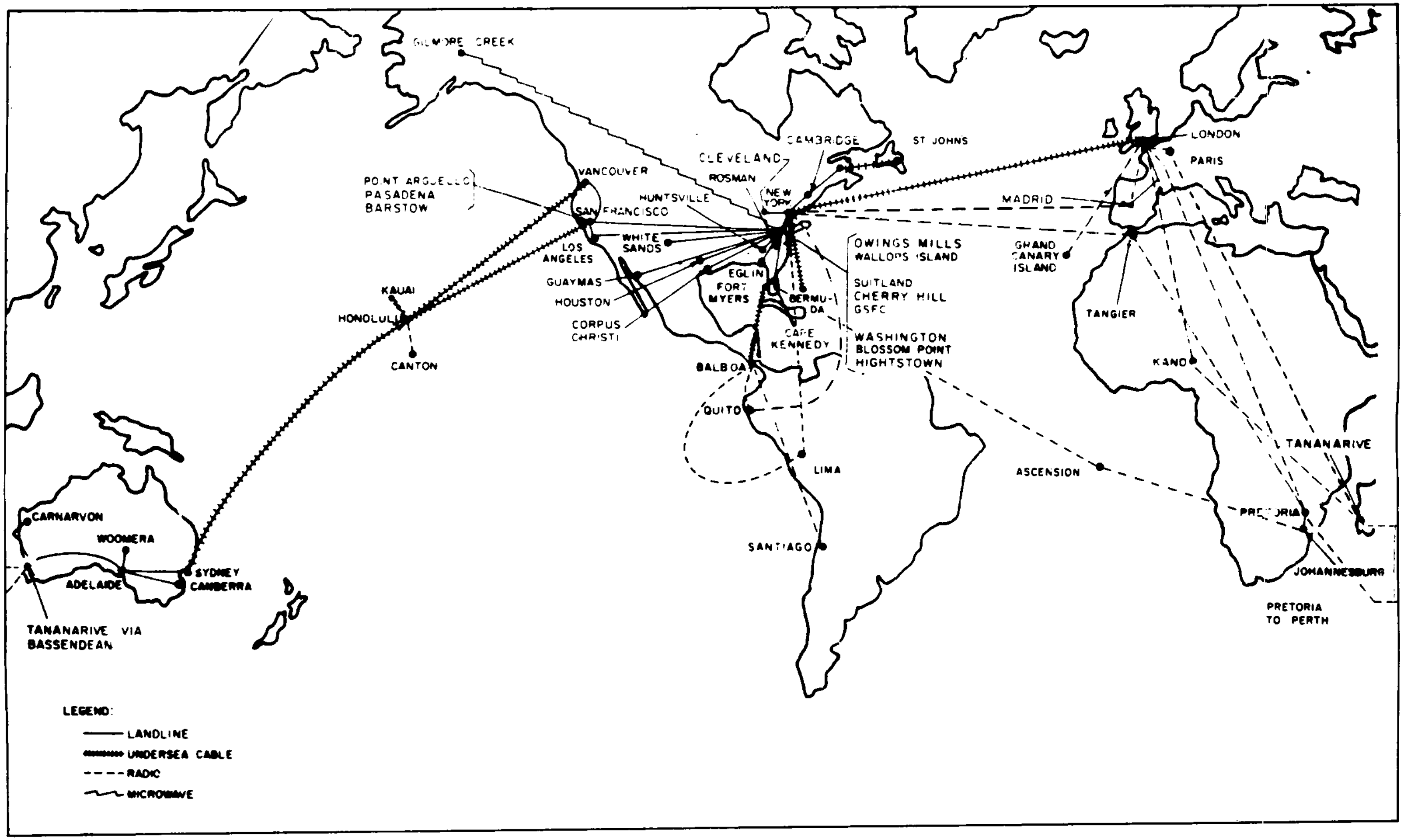

Figure 16. Map of NASCOM Network

CHAPTER VI

HISTORICAL SUMMARY

The twelve-year history of NASA satellite tracking, stretching from the concept of Minitrack to the STADAN of today, can be summarized by seven points:

1. The insight of the NRL group into the importance of satellite electronic tracking helped them win the official U.S. program over Orbiter in 1955.
2. Two buildups and two plateaus characterize Minitrack/STADAN history. (Figure 17)
3. The requirements of synchronous and high-eccentricity satellites made it necessary to supplement interferometer tracking with RARR tracking during the early 1960's.
4. The primary mission of STADAN changed from tracking to data acquisition in the mid-1960's. The 85-ft and 40-ft dishes and SATAN antennas were added to cope with this increased requirement.
5. Since 1963, there has been a trend toward fewer but better-instrumented stations.
6. The total worth of STADAN facilities in 1966 is approximately twenty-five times that at the end of the IGY in 1958 (See Appendix C).
7. NASA centralized its management of tracking and data acquisition early in its history and these functions have always reported well up in the NASA organization (Figure 10).

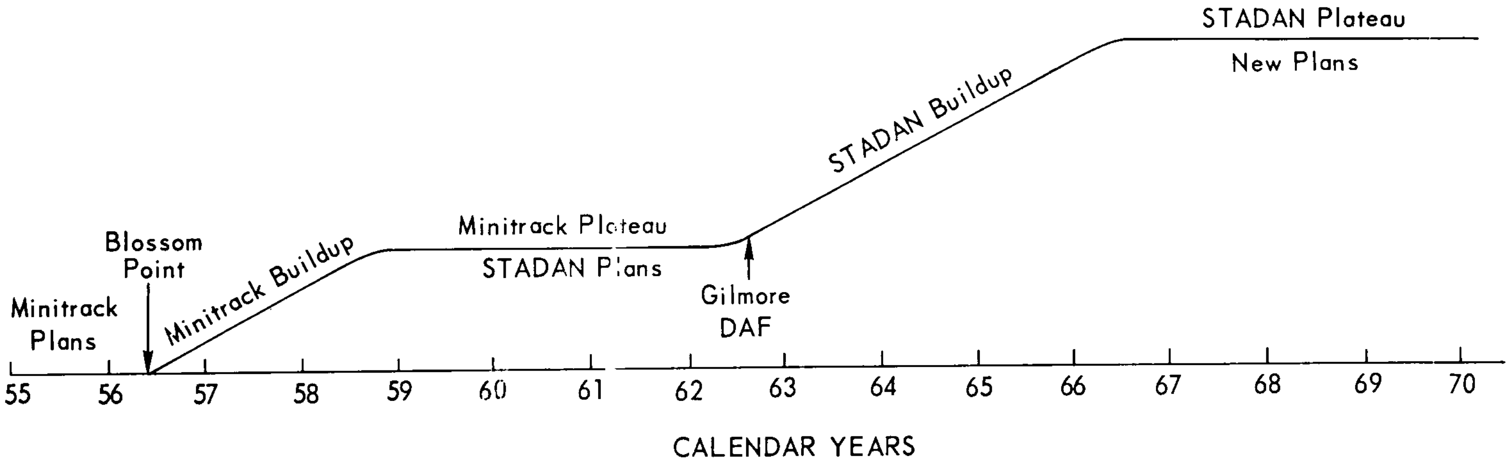

Figure 17. Sketch Showing "Idealistic" View of Minitrack and STADAN Evolution

EPILOGUE

Through the ages, communications have been the prologue to discovery. Whether by feeble smoke signals or high speed electronic signals, communications have been essential in the exploration of new frontiers. Today, these frontiers reach beyond our own planet. In fact, man's electronic signals are already preceding him to the Moon and to other planets. Already, although the Space Age is in its infancy, man has made remarkable strides in penetrating the atmosphere surrounding his planet—and even ventured into space. Scores of made-on-Earth objects have been launched into space, many to roam the solar system forever. We stand now on the threshold of a new era of discovery.[59]

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[59] "Sinews From Space," by Edmond C. Buckley in Rensselaer Review, Fall 1965.

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APPENDIX A

DESCRIPTIVE VIGNETTES OF MINITRACK AND STADAN STATIONS

ALASKA

Synonyms: Officially called Ulaska (for University of Alaska) before 1961. Also called Fairbanks, a more general appelation, which includes the Gilmore and College sites.

Location: Gilmore Creek, 13 miles north of the city of Fairbanks, Alaska. An old placer mining site. The Gilmore site is only 3000 ft away. Alaska was the first DAF site, with an 85-ft antenna becoming operational in March 1962. The high-gain, multiple-frequency antenna was required for the polar-orbiting Nimbus satellites, the POGO's, and the EGO's. A 40-ft antenna was added in August 1966. In late 1966, the Minitrack array at College was moved to Alaska to consolidate Alaskan tracking operations. The site is on NASA-owned land.

ANTIGUA

Location: Antigua is a small island (108 square miles) in the British West Indies. Tracking facilities were at Coolidge Field, where the U.S. conducted military operations.

Antigua was one of the original Minitrack sites installed during the IGY. Interferometer arrays were installed to track Vanguard launch vehicles approaching and leaving along the Atlantic Missile Range. The site was operated jointly by the U.S. Navy and Air Force. A Microlock station with interferometry and Doppler tracking was also installed on Antigua. The site was closed in July 1961.

ANTOFAGASTA

Location: A Pacific port in north Chile. The tracking station was located at a spot called Salar del Carmen.

Antofagasta was one of the original, prime Minitrack IGY sites set up along the 75th meridian. On Chilean soil, the station was initially operated by the Army and then by a joint NASA-Bendix-University of Chile team. With the improved capabilities at Santiago and Quito, Antofagasta became redundant and was closed in July 1963.

BARBUDA

Location: A small island in the Leeward group southeast of Puerto Rico; once important in the slave trade.

Barbuda was suggested as a Minitrack site in the early NRL reports and proposals; (see NRL Memo 548). Because of difficult terrain (logistics) Antigua and Grand Turk were chosen instead as downrange Minitrack sites.

BLOSSOM POINT

Location: At Blossom Point, Maryland, on the Potomac River, 40 miles south of Washington, D.C.

Blossom Point was the first operational Minitrack station. It was ready at the time of the first Sputnik, in early October 1957. In fact, a special 40-Mc cross array was quickly installed at Blossom Point to track the Sputniks. Blossom Point has been called the "prototype" Minitrack station and has been used for much research, development, and equipment testing. The Minitrack crews were trained there during the IGY days. On a site leased from the Army, Blossom Point was first operated by Navy personnel and then taken over by a Bendix crew. Blossom Point was closed in the fall of 1966 and its equipment was transferred to Network Test and Training Facility (NTTF) at Goddard Space Flight Center.

CANAL ZONE

Location: Canal Zone.

A Canal Zone Minitrack station was proposed by NRL in the Vanguard proposal. Sites in Panama proper were also examined (see Panama); but because of electronic interference and poor sites, no tracking stations were built either in Panama or the Canal Zone.

CARNARVON

Location: In northwestern Australia.

Carnarvon is the site of a Goddard Range and Range Rate tracking unit. At present, there is no other STADAN equipment installed. A MSFN station is also located at Carnarvon.

COLLEGE

Synonyms: Also called Fairbanks, a more general appelation that includes Gilmore and Alaska sites.

Location: A state-owned site six miles north of the city of Fairbanks. College was added to the original IGY Minitrack network in 1960 when it became necessary to track high-inclination satellites, such as Nimbus and POGO. The station has been operated by personnel from the University of Alaska. In late 1966 the Minitrack equipment was transferred to the Alaska site.

EAST GRAND FORKS

Location: 14 miles northeast of East Grand Forks, in northwestern Minnesota.

The East Grand Forks Minitrack station was added to the original Minitrack network in 1960 to track high-inclination satellites. The equipment was on a leased private site and was operated by Bendix personnel. This station was phased out in the fall of 1966 as part of NASA's program relying on fewer, better-instrumented tracking stations.

FT. MYERS

Location: 7 miles south of Ft. Myers, on the Gulf Coast of Florida.

The Ft. Myers Minitrack site was added in 1959 to replace the Ft. Stewart station that was converted to an Active Minitrack (SPASUR) station for Air Force use. Ft. Myers received most of its equipment from the Havana station when it was removed after the Cuban revolution. The site is on leased private land and is operated by Bendix personnel.

FT. STEWART

Location: Georgia

Ft. Stewart was the site of one of the original IGY Minitrack arrays. In 1958, the site was modified for use by the Air Force in the East-West Active Minitrack fence (SPASUR). The passive Minitrack equipment was transferred to Saint Johns, Newfoundland, in 1959.

GILMORE

Synonyms: Often called Fairbanks in the literature and sometimes Alaska (in error). The name "Fairbanks" actually includes all Alaskan STADAN facilities.

Location: See discussion under Alaska.

Gilmore is the site of a second Alaskan 85-ft antenna, which was built in 1962 for the U.S. Weather Bureau (now part of ESSA). The Gilmore antenna is now used extensively by ESSA in the Tiros Operational Satellite (TOS) program. Eventually ESSA will probably assume complete responsibility for operating this facility.

GRAND TURK

Location: A small island southwest of Florida in the Bahamas group.

Special Minitrack equipment was installed on Grand Turk during the IGY to track the Vanguard third stage. The equipment consisted of an array of Yagi antennas looking downrange. Grand Turk was phased out in 1961 as other tracking equipment on the Atlantic Missile Range took over during the ascent phase of satellite launches. A Microlock station was also installed on Grand Turk and tracked military vehicles as early as 1956.

HAVANA

Location: At Batista Field, 32 miles west of Havana.

One of the IGY prime Minitrack stations was installed at Havana in 1957. Anticipating harassment and interference after the Cuban revolution, NASA moved the station's equipment to Ft. Myers in 1959.

JOHANNESBURG

Synonyms: Esselen Park, Pretoria, Hartebeesthoek, and Olifantsfontein have all been used to designate NASA tracking facilities in the Johannesburg area. The reasons for this confusion are evident in the following discussion.

Location: All STADAN equipment is now located at Hartebeesthoek thirty-eight miles northwest of Johannesburg.

Minitrack equipment was installed at Johannesburg during the IGY to pick up satellites as they were placed in orbit along the Atlantic Missile Range. At first the equipment was placed at Esselen Park, 18 miles northeast of Johannesburg, where it was operated by the National Telecommunications Research Center, temporarily located at the National Railway College. When the Minitrack equipment was converted to 136 Mc in 1960, the site was moved to Hartebeesthoek. The original Esselen Park site was close (4 miles) to the Olifantsfontein site of the one of the SAO Baker-Nunn cameras. Hartebeesthoek is also the location of DSN equipment.

KANO

Location: Kano is a city in northern Nigeria.

ISIS telemetry and command equipment is installed at Kano to get better geographic coverage during this ionospheric research program. A MSFN station is located here.

KAUAI

Location: Kauai is one of the Hawaiian Islands.

ISIS telemetry and command equipment is installed at Kauai to get better geographical coverage during the ionospheric research program. A MSFN station is located here.

LIMA

Location: The Minitrack station is at Pampa de Ancon, 20 miles northwest of Lima, Peru.

Lima was the site of one of the prime IGY Minitrack installations along the 75th meridian. Originally run by the Army, the equipment is now run by a team made up of NASA, Bendix, and scientists from the Geophysical Institute of Peru. Lima was one of the sites where special antennas were installed to track the Sputniks, which transmitted at 20 and 40 Mc instead of the 108-Mc Minitrack design frequency.

MAYAGUANA

Location: An island in the Bahamas group.

Originally Mayaguana was slated to receive a modified Minitrack station to track the Vanguard third stage, but since the Antigua and Grand Turk sites seemed adequate, the station was eliminated from the network in September 1957. The equipment that was destined for Mayaguana was sent to San Diego.

MOJAVE

Synonyms: The Mojave STADAN site is often referred to as Goldstone or Barstow in the literature.

Location: The nearest important town is Barstow, California, 50 miles southwest. The site is in the Goldstone Lake area in the Mojave Desert near NASA's DSIF installation.

Barstow was not one of the original, prime Minitrack IGY sites. It did not become operational until 1960, when the Minitrack equipment originally installed at Brown Field Naval Auxiliary Air Station at Chula Vista, California, was transferred out to the Goldstone area in the electronic quiet of the desert. A 40-ft antenna has since been installed. Mojave is on NASA land and is operated by Bendix personnel.

ORRORAL VALLEY

Synonyms: Sometimes called Canberra.

Location: 35 miles southwest of Canberra, Australia.

The Orroral Valley site was added to STADAN in 1965, when an 85-ft DAF dish was placed in operation. Like the other Australian tracking installations, Orroral Valley permits more frequent telemetry readout of satellites and also helps determine the precise shape of the Earth with geodetic measurements from the South Pacific. Minitrack equipment from the Woomera site was moved to Orroral Valley in late 1966.

PANAMA

Location: At Rio Hata, Panama.

The Panama site was to have been one of the prime Minitrack stations along the 75th meridian during the IGY. The Panama government wished the site located at a military base, where there would have been serious electronic interference. This fact, combined with frequent thunderstorms, reduced the desirability of a site in Panama. When it became apparent that the Antigua and San Diego stations would suffice for tracking and data acquisition during satellite passes over this region, the Panama station was abandoned. The Minitrack equipment was sent to Woomera, Australia.

QUITO

Location: At Mt. Cotopaxi, near Quito, Ecuador.

Quito was one of the prime IGY Minitrack stations along the 75th meridian. The station is on a leased private site. Originally set up and run by U.S. Army personnel, it is now operated by Bendix. In addition to the Minitrack interferometer, there is now a 40-ft dish installed.

ROSMAN

Location: Near Rosman, North Carolina, about 30 miles southwest of Asheville.

Rosman is one of the newer STADAN stations. The first 85-ft DAF dish went into operation in July 1962, the second in August 1964. The site was established specifically for receiving high-data-rate telemetry from Observatory-class satellites. Rosman also has Range and Range Rate equipment and is an ATS site, but there is no Minitrack interferometer.

SAN DIEGO

Location: Station was located at the Brown Field Naval Auxiliary Air Station, Chula Vista, California.

The prototype Minitrack equipment manufactured by Bendix was installed at San Diego in 1957. Navy Electronics Laboratory personnel operated the station for NRL. The imminent closure of Brown Field stimulated the move of the station to Mojave in 1960. San Diego also received modifications that permitted reception of the Sputnik 20 and 40-Mc signals in late 1957.

SANTIAGO

Location: Station is located at the Peldehune Military Reservation, 52 miles northeast of Santiago, Chile.

Santiago was one of the prime Minitrack sites established along the 75th meridian during the IGY. It has been enlarged considerably with the addition of a 40-ft dish, Range and Range Rate equipment, and, in 1957, modifications to permit the tracking of Sputnik 20- and 40-Mc signals. The station is on Chilean land. The U.S. Army originally operated the station, but the operating team is now made up of NASA, Bendix, and University of Chile personnel.

ST. JOHN'S

Location: The station site is 14 miles north of St. John's, Newfoundland.

This Minitrack station was added to the network in 1960. The station, on Canadian land, is operated by Canadian personnel.

TANANARIVE

Location: 18 miles west of the city of Tananarive, in central Madagascar (now the Malagasy Republic).

The recent addition to STADAN increases tracking and data-acquisition coverage in the southern hemisphere. Range and Range Rate equipment was installed in 1965. In 1966, SATAN Minitrack equipment, and a 40-ft antenna were added.

TOOWOOMBA

Location: About 80 miles west of Brisbane. Transportable ATS equipment is installed here.

WINKFIELD

Location: At Winkfield, 20 miles southwest of London.

Winkfield is a Minitrack station established in 1961. It is the only European STADAN station. The equipment is located on a British site and operated by British personnel.

WOOMERA

Location: The U.S. tracking facilities are located about 8 miles southeast of the Australian town of Pimba, in Southern Australia. The major Australian rocket facilities at Woomera are northwest of the U.S. facilities.

The Woomera station was installed during the IGY to get tracking data from the southern hemisphere for geodetic purposes. The Minitrack equipment originally intended for Panama went to Woomera. The site is owned by Australia and the operators are all Australian. In late 1966, the Minitrack equipment was moved to Orroral Valley. The Woomera site received modifications in 1957 so that the Sputnik 20- and 40-Mc signals could be received. Woomera also has a DSN station and an SAO Baker-Nunn camera station.

MOBILE STATIONS

There are a number of portable pieces of STADAN equipment that are moved to various spots for various programs; viz., portable telemetry and command equipment at Darwin, Australia, for the OGO program, and the shipboard Range and Range Rate equipment at Lagos, Nigeria, during the Syncom program.

APPENDIX B

HISTORY OF MAJOR EQUIPMENT CHANGES AT STADAN SITES

	Minitrack		85-ft Antenna		40-ft Antenna		SATAN Telemetry		SATAN Command		Range and Range Rate	
	in	out	in	out	in	out	in	out	in	out	in	out
Alaska	11-66		3-62		8-66		5-65		6-65			
Antigua	8-57	7-61										
Antofagasta	9-57	7-63										
Blossom Point	7-56	9-66							7-64			
Carnarvon											64	
College	60	11-66										
E. Grand Forks	60	9-66										
Ft. Myers	59						2-66		1-66			
Ft. Stewart	9-57	59										
Gilmore			5-63									
Goddard	9-66						4-66					
Grand Turk	9-57	61										
Havana	9-57	59										
Johannesburg	58				2-64							
Lima	57						9-66		8-66		64	
Mojave	60						1-66		12-65			
Orroral Valley	11-66						10-64		11-64			
Quito	9-57				12-63		6-64		11-64			
Rosman			7-62				5-64		12-64		64	
Rosman			2-64									
San Diego	9-57	60										
Santiago	9-57				1-64		2-65		1-65		64	
St. John's	60											
Tananarive	66				66		12-65		11-65		65	
Winkfield	61											
Woomera	10-57	11-66							10-64			

APPENDIX C

STADAN FINANCIAL SUMMARY, FY 1956 THROUGH FY 1967[60]

(in millions of dollars)

	FY 61 and prior[61]	FY 62	FY 63	FY 64	FY 65	FY 66	FY 67
Operations	17.3	10.0	12.3	23.2	24.8	29.0	33.7
Construction and equipment	18.0	13.2	18.2	22.7	19.2	16.9	15.2
Total	35.3	23.2	30.5	45.9	44.0	45.9	48.9
Cumulative investment in construction and equipment	18.0	31.2	49.4	72.1	91.3	108.2	123.4

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[60] Data provided by Roland Theisen, NASA Headquarters, June 1, 1966.

[61] Preliminary Vanguard budget for "tracking and telemetering": FY 56, 2.1; FY 57, 0.7; FY, 58, 0.1. Total IGY expenditures for these functions: 2.9. No programs beyond Vanguard were contemplated. From NRL Letter C-7100-143/55: emc, Sept. 30, 1955. (In NASA Vanguard file.)

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