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THE GESTATION OF TRANSIT AS PERCEIVED BY ONE PARTICIPANT

Development of the Transit satellite navigation system started at APL in 1958. By 1963, Transit was providing operational service to the U.S. Navy. By now there are also an estimated 16,000 Merchant Marine users of Transit. This article is an account of some highlights of the program's early years as seen through the eyes of the project engineer who headed the APL Transit team.

INTRODUCTION

On March 18, 1958, F. T. McClure, Chairman of the APL Research Center, recommended to R. E. Gibson, Director of APL, that the Laboratory undertake to develop the satellite Doppler navigation system subsequently named "Transit." McClure explained that the idea came to him as the result of a conversation on the previous day with W. H. Guier and G. C. Weiffenbach (see their article in this issue), who had explained to him their success in determining satellite orbits by analysis of the Doppler shift. (The scientific basis of the Transit system is presented in the articles by Black and by Newton in this issue.) Seventeen days later the essential elements of the present-day Transit system were described in a 50 page proposal to the Navy Bureau of Ordnance, complete with block diagrams, power and weight estimates, and an accuracy analysis.

Throughout the summer of 1958, work continued under the informal sponsorship of the Polaris program. Formal sponsorship was provided by the Advanced Research Projects Agency (ARPA), starting in October 1958, with authorization to design and build spacecraft and ground stations. ARPA sponsorship resulted in part from the initial reluctance in some quarters of the Navy to acknowledge formally the need for an improved navigational capability. However, this reluctance soon disappeared; in May 1959, APL issued a program plan identifying an ARPA experimental phase and a Navy operational phase. The plan optimistically envisioned six launchings in the following fiscal year and eight more in the subsequent two years to achieve a full operational capability in 1962. The plan included design and manufacture by APL of launch vehicles (possibly based on an adaptation of the Polaris missile), a worldwide complex of 16 ground stations, and 18 shipboard navigating equipments.

I accept full responsibility for the design of a plan so wildly ambitious. Only slightly less astonishing than the plan, however, was its ready acceptance (including its estimated cost) by the Department of Defense.

It was possible to move much more rapidly in that period than now. Much of the present-day formalism, mercifully, was a few years in the future, and the shock of Sputnik was a potent stimulant to ambition and achievement. The work at APL was also facilitated by the rapidity with which decisions could be obtained from a streamlined DoD organization. During the first year, Roger S. Warner, Jr. was both the point of contact and the decision maker. In the following year or two, the entire DoD management team comprised only two or three individuals. The government's program managers were both highly competent and highly motivated.

SCOPE OF WORK

The original scope of work of the Transit program was the following:

1. Spacecraft (always called "satellites" whether in the shop or in orbit) — design, construction, and operation;
2. Tracking stations — design, construction, and operation;
3. Injection station — design, construction, and operation;
4. Navigation equipment — design and construction;
5. Geodesy — expansion of the then-current knowledge of the earth's gravity field;
6. Launching vehicles — design, construction, and field operations after the first few launchings.

It soon became evident that the detailed performance of all of these tasks would require an inordinately large organization at APL. Consequently, the same organizational structure previously employed in the Bumblebee missile programs was instituted. APL was to:

1. Be responsible for overall system design;
2. Design the satellites and have responsibility for certain other areas;
3. Have technical direction of associated organizations. These would be assigned broad responsibility for specific areas.

The Laboratory designed and built several tracking stations and operated one. The Naval Ordnance Test Station at China Lake and New Mexico State University were brought into the program to design, build, and operate the network of stations required for the refinement of geodesy and for the operation of orbiting satellites. Direction of the stations remained the responsibility of APL for many years. The design of the computing programs and the calculation of satellite orbits were also APL responsibilities. Because early in the operation of the tracking network it became evident that communications within the worldwide network was a major task, APL set up and operated the communications system.

The navigation subsystem initially consisted of complex equipment intended for use by Polaris submarines. The development, design, and fabrication of that subsystem were assigned to subcontractors, but the computing programs were produced by the Laboratory. Early in the program, W. H. Guier of APL conceived a novel Doppler navigation technique (the so-called integral Doppler method) that facilitated the design of much simpler equipment (although it was thought to be unsuited to the needs of the Polaris submarines because wave-wash over the antenna would frequently interrupt the integration). The descendants of this equipment are being manufactured on a large scale, both in the U.S. and abroad, and are in widespread use by both naval and commercial ships.

Early in the program, the Department of Defense assigned the responsibility of launching all DoD satellites to the Air Force, so the initial idea of using homemade vehicles to launch the satellites was not pursued very far (fortunately). We simply had too much work.

From the beginning, it was recognized that different orbit inclinations were required for determining the geoid; it was even planned for a while that the operational constellation would contain a mixture of inclinations. However, the number and the variety of satellites ultimately found necessary were not anticipated at the outset. It was assumed in the first program plan that 50% of the satellites would be launched and operated successfully and that successful satellites would have an average life of one year. No allowance was made for mistakes or for the extent of the design evolution. Unfortunately, these assumptions were overly optimistic. Early on, it became evident that the Transit program would require special-purpose satellites for geodesy, radiation measurements, radioactive isotope power supply trials, and attitude-control experiments. Some of these satellites, of course, had as their primary missions the support of national objectives other than Transit. Therefore, the number of APL-built satellites directly or partially related to the Transit program grew to a total of 36 by the time the system was declared fully operational in October 1968. Eight of the satellites were victims of launch-vehicle failures and two were damaged by a high-altitude nuclear test (Project Starfish).

ORGANIZATION

The intense activity that produced a conceptual system design and a proposal was performed by an *ad hoc* team with numerous substitutions. After the formal ARPA sponsorship began in late 1958, a few staff members were assigned to a "program office" under R. B. Kershner. The engineering activities were farmed out to existing Bumblebee groups that had developed over the years to work on guided missiles. Early in 1959, a Transit mechanical design group was established in recognition of the specialized design problems associated with satellites.

By the end of 1959, it became evident that a largely self-contained project-type organization was preferable. Consequently, three Transit groups were established; research and analysis, satellite design, and ground systems. By the spring of 1961, the program magnitude and complexity were increasing. A satellite systems engineering group and a reliability organization were therefore established and a manager of launch site activities was appointed. The APL Space Department devoted most of its effort to satellite design, fabrication, and testing and to satellite orbit determination, analysis, and geodesy, whereas much of the work on navigation equipment and ground station equipment was delegated to outside organizations.

Over the next several years, the groups became unwieldy in size, and the scope and sophistication of their technical activities increased. Also, areas of technical specialization developed that were not originally anticipated, such as satellite attitude control.

During the first two or three years it was possible for the division supervisor and the project engineer to perform cost analysis, budget control, proposal writing, and progress reporting as spare-time activities. However, it eventually became evident that these administrative responsibilities required the full-time attention of several persons.

As a consequence, the Space Department organization gradually evolved so that in 1964 it had the following structure:

- Space Division Office
  - Budget Office
  - Reports Office
- Research and Analysis Branch
  - Physics and Instrumentation Group
  - Analysis and Computation Group
- Data and Control Branch
  - Operations Control Group
  - Telemetry and Command Group
- Electronics Branch
  - Electronics Systems Group
  - Radio Frequency Systems Group
- Engineering Branch
  - Power and Attitude Systems Group
  - Mechanical Design Group
  - Fabrication and Test Group
- Reliability Group

That organization and management structure prevails to the present time.

MANAGEMENT

Until the mid-1960's the Transit program and the Space Department were synonymous; therefore, the Department was managed as a project organization. During that period, the Department management staff consisted of a single person, R. B. Kershner, with some delegation of management responsibility to the Transit project engineer.

Staff proliferation was limited to special cases. For example, when Transit-related satellites (such as those employed for radiation measurements or geodesy) were constructed and operated, additional temporary project engineers were appointed as managers to avoid dilution of the mainline effort on the navigational satellites. Similarly, assistant project engineers or problem sponsors were designated to oversee the two basic types of navigation equipment, the ground station network and the radioactive thermal electric power supplies.

Another category of positions, called "project scientist," was initiated in about 1962. Project scientists came in two general varieties. The function of some was to act as separate technical monitors of key activities, independent of the project engineers, who necessarily divided their efforts between program management and technical matters. The function of other project scientists was analogous to "principal investigators," who are the users of the technical results of an experiment or test. In some cases, an individual functioned as both project engineer and project scientist. In all cases, the project scientists were "dual listed," working part-time as project scientists and part-time in a line organization capacity.

The management technique employed was very simple. Dr. Kershner issued one vote to each of the "*n*" people who were parties to a given matter and gave them a fair hearing. However, he always reserved "*n* + *1*" votes for himself for use when needed. The Navy almost never overruled any of our decisions.

TECHNICAL PLANNING

Of the various hardware elements of the Transit system, the satellites were the most ambitious design task, proving to be more difficult and more time-consuming than any other portion of the system.

The satellite block diagram as presented in the program plan of May 1959 is shown in Fig. 1. We predicted that the operational satellites would weigh about 50 lb and have an average useful life of about five years. These predictions seemed to many persons to be wildly optimistic. The satellites that were developed and are still in use weigh about 110 lb. Most of this extra weight is attributable to redundancy and to other safeguards in the satellite subsystems that were not originally planned but that have more than justified their cost in weight and power. Possibly the most dramatic achievement in the development program is the reliability and longevity of the satellites. The two oldest satellites in the present operational Transit constellation were built by APL; each has accumulated about 13 years of continuous operational service, unique in all DoD and NASA spacecraft experience.

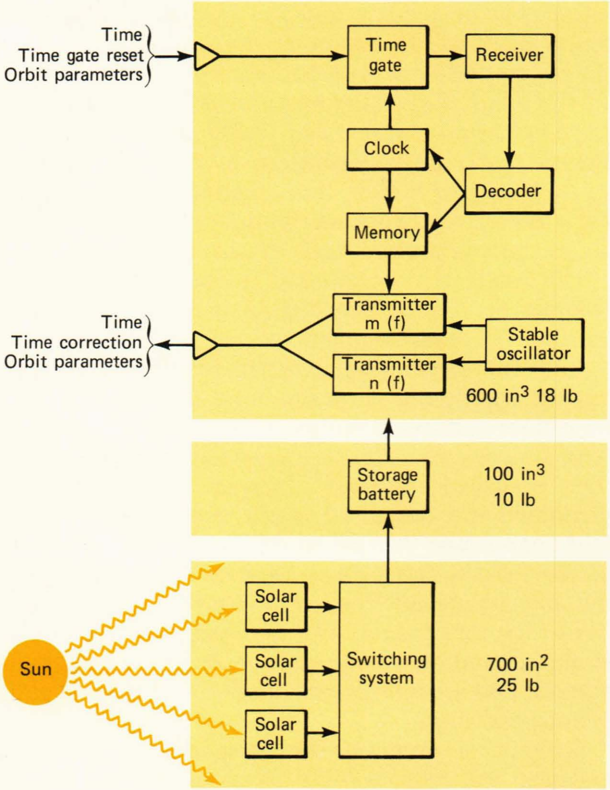

Fig. 1—Block diagram of the Transit satellite as conceived in 1959.

Oscillator

The stable oscillator was recognized to be a crucial element. It was expected that a short-term frequency stability of 1×10^{-9} could be obtained with a commercial crystal contained in three Dewar flasks of rather massive metal construction to provide thermal inertia. Early in the game, it was found that getting crystals with the desired short- and long-term stability wasn't all that easy. However, a very conscientious supplier who selected crystals carefully was found and has been our source ever since.

The Dewar flask assembly collapsed in vibration test, to our great dismay. Fortunately, however, we ran across an article on cryogenic insulation in a chemical engineering journal that described a multilayered material, invented years before as a domestic refrigerator insulating material (alternate layers of aluminized mylar and fiberglass mesh), that provided the equivalent of hundreds of Dewar flasks in series and also protected the assembly against launch vehicle vibration and acceleration. This superb insulating material has always been named "Kropschot" at APL in mistaken attribution to the person who invented it; however, Kropschot[1] credits Dewar with the invention. The provision of a large thermal time constant was not the only trick used in the oscillators. A number of technical improvements were required (e.g., active proportional thermal control, crystals having very low frequency-temperature dependence) before we reached the currently available stability of 10^{-10} to 10^{-11}.

Transmitters

Sputnik I-II had employed 20- and 40-MHz transmitting frequencies, which were sufficiently close to the 15 and 7.5 meter ''ham'' bands to alert a worldwide network of receivers to the Soviet accomplishment. The selection of frequencies for Transit was influenced by the necessity for measuring the ionospheric refraction of the radiated signals and for eliminating that source of error from the data. The refractive effect decreases with frequency and, moreover, instrumentation for its measurement is simplified if frequencies can be selected that are harmonically related to each other. Having been used on Vanguard I, 108 MHz had tacit national, if not international, approval as a space frequency. That frequency, plus the harmonically related ones of 54, 162, and 216 MHz, became standard in the early experimental Transit satellites. Subsequently, 108 and 216 MHz were dropped and 324 MHz was added.

At about the time those frequencies were being selected, the World Advisory Radio Committee was meeting in Geneva and, for the first time, the subject of international frequency assignments for space applications came up. The U.S. members were caught without a position on the subject. The Navy member of the U.S. delegation, with whom the Laboratory had discussed the Transit experimental frequencies, immediately queried us on the frequency selection for the operational Transit system. It was clear that the higher the frequency, the more accurately the refraction effect could be handled. On the other hand, anything above 400 MHz could not produce an adequate power output in the newly developed transistor. Therefore, 400 MHz was selected as the higher of the two frequencies. Because 200 MHz had already been assigned to the VHF-TV band and was unavailable, 150 MHz was selected as the lower, even though the two frequencies did not have an integer relationship. The selected pair was communicated to the U.S. delegation and, with the approval of the USSR members, became the first space frequencies to be assigned on an international basis. The Russian navigation satellite system, which has not been publicized, also utilizes the 150/400 MHz pair. The Russians have also copied many of the other characteristics of the Transit system. We know that 35 to 40 Russian navigation satellites have been launched.[2]

Memory

The memory was envisioned as a magnetic core device. However, industry was unable initially to produce core storage memories as dense as required. For the first two years, polyaperture and magnetostriction delay line memories were used as temporary expedients.

The first concept envisioned transmission of the memory contents intermittently as a pulse modulation on one of the two navigation frequencies. However, as the amount and format of the ephemeral readout became better defined, it was recognized that continuous readout was necessary. Fortunately, a phase modulation scheme was devised that permitted continuous modulation of both RF carriers without corrupting the Doppler data.

UNFORESEEN PROBLEMS WITH HAPPY ENDINGS

A few major areas of spacecraft technology were either overlooked or underrated in my (and probably all our) initial technical planning. Among those areas were power systems, thermal design, and attitude determination and control.

Power Systems

The design concept of the power system was fairly straightforward — an array of solar cells, a storage battery, and a few commandable switches. We and the other organizations engaged in spacecraft design had no experience and little appreciation for the space environmental effects on solar cells and of the idiosyncrasies of nickel-cadmium storage cells. When one succeeded in penetrating the barriers of proprietary information erected by the suppliers, it became evident that they were not much more knowledgeable. For example, there was little agreement among the experts on the preferred operating temperature, depth of discharge, rate of charge, operating life, storage life, memory effect, etc. of nickel-cadmium cells.

Another problem was obtaining delivery of nickel-cadmium cells. We placed a $12,000 order for cells that were of an off-the-shelf commercial design but defined by a fairly rigorous specification. When the delivery date came and went with no sign of the urgently required cells, we visited the president of the company and informed him in guarded terms of the critical contribution of the Transit program to national defense. He was duly impressed and promised cooperation but explained patiently that his stockholders would take a dim view of his jeopardizing a $10 million per year business in rechargeable cells for tooth brushes, shavers, etc. in favor of our little order. However, he did come through finally with a fine product. Once we learned the niceties of the care and feeding of nickel-cadmium storage cells, their life in orbit exceeded our fondest hopes.

The Atomic Energy Commission (AEC) was anxious to promote the use of radioactive isotope power supplies (RIPS) as an alternative to the solar cell/battery arrangement. Since it was not at all clear that we could meet our five year life expectancy with batteries and solar cells, we pursued that alternative for several years. Transit 4A was designed to incorporate a small RIPS as a supplementary power supply. The RIPS was to be delivered to Cape Canaveral for installation after the satellite was checked out. The State Department heard of the plan and remembered that, a short time before, due to a launch failure, one of our Transit's had fallen on Cuba and provoked loud complaints from Fidel Castro. Accordingly, State vetoed the use of the RIPS. Late on a Friday evening, Glenn Seaborg — then head of the AEC — called President Kennedy away from his dinner to appeal the State Department veto. The President overruled the State Department. The launching was scheduled for the following Monday and the Transit was already installed on a fueled Thor-Able-Star launch vehicle. Since Washington was shut down for the weekend, both the AEC and the Navy found it impossible to schedule an airlift of the RIPS to Cape Canaveral in time for the launching. I borrowed a Marine Corps attack plane (I couldn't tell "for security reasons" why I needed the plane) and flew the RIPS to the Cape in time for the launching. Fortunately, the AEC was willing to ignore the violations of their airlift regulations (single pilot, single-engine aircraft, instrument flying conditions). This would, of course, cause a storm of protest today.

Thus, as the result of rather extreme measures, we were first to use any form of nuclear power in space.

Launching Vehicle Compatibility

Although we expected initially to use a solid-propellant launch vehicle derived from the Polaris missile, the launchings through 1961 utilized the three-stage Thor-Able and the two-stage Thor-Able-Star. Since those vehicles were capable of putting bulky configurations weighing several hundred pounds into the required orbit, we were under no pressure to conserve weight or restrict volume. Moreover, we had no need for "unfolding" the satellite once it was in orbit.

This made our initial tasks easier but necessitated a costly, time-consuming redesign when it was decided after 1961 that we were to use the much smaller Scout launching vehicle. The satellite body had to be reduced to about an eighth of the previous volume, the weight had to be halved, and solar power panels had to be folded for launching. Simultaneously, more redundancy, more safeguards, and more sophisticated subsystems were being incorporated. As a consequence, radically different electronic packaging, a more complex power system and thermal design, deployable structures, more complex attitude control, and more complex in-orbit operations became necessary. Although meeting these requirements was traumatic at the time, they eventually resulted in a greatly superior Transit design. In the process, the Space Department developed the design capabilities for compact satellites that have been the basis of much of our subsequent spacecraft work. The high-density electronic packaging that the Scout decision forced on us, in turn, forced us to weld rather than solder the circuitry together. That radical change in circuit assembly technique resulted in a substantial improvement in circuit reliability, thus repaying the investment in time, money, and turmoil many times over.

Figures 2 and 3 show typical Transit satellites before and after the Scout decision.

Thermal Design

Until the Transit satellite had to be miniaturized to fit the Scout launching vehicle, thermal design was so simple and easy that we were lulled into a false sense of confidence. However, the move to Scout made the thermal designers key members of the team and, for-

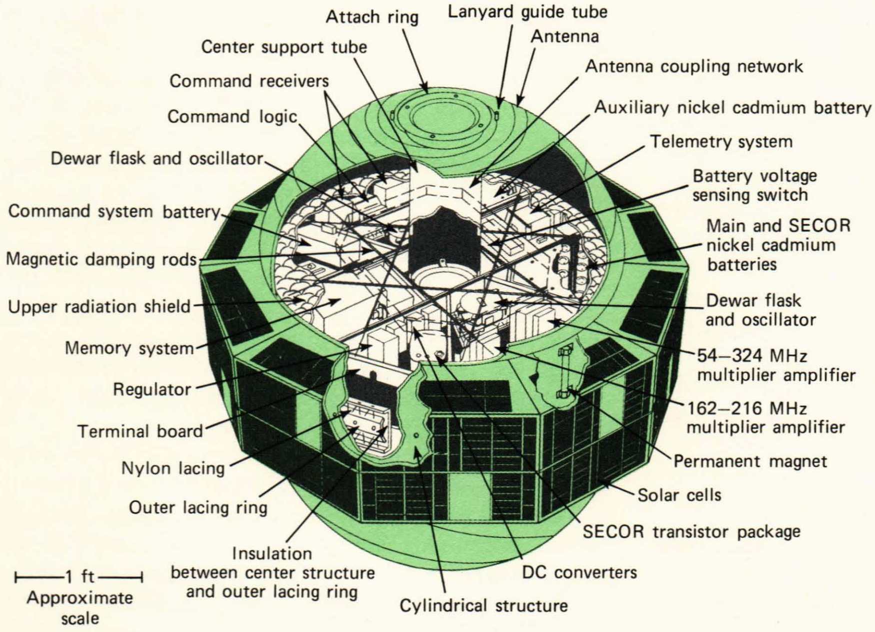

Fig. 2—Cutaway view of Transit satellite 3-B, (launched by Thor-Able-Star).

tunately, they rose to the occasion. By happy coincidence, gravity-gradient attitude control was introduced along with Scout launching, thereby allowing the use of an earth-pointing radiator for heat rejection. Otherwise, the thermal design would have been substantially more difficult.

Attitude Control

Initially, attitude control was not included in the design concept of Transit satellites. The antennas, which were silver-pigmented epoxy paint spirals on the spherical body of the early satellites, provided approximately isotropic patterns. Because the launchings employed the Thor-Able, which had a spin-stabilized third stage, it was recognized that the satellite must be despun after separation to avoid modulation of the signals. The "yo-yo" despin technique for the transfer of the angular momentum to separable masses was invented independently at APL and at the Jet Propulsion Laboratory for that purpose.

When the second satellite was being built, it was realized that the signal levels at the tracking stations would be improved if the orientation of the satellite was controlled enough to roughly point one of the satellite antennas at the station, that is, "down." Moreover, controlling the attitude removes an error in the Doppler data caused by uncertain motion in attitude. Control with a permanent magnet was selected as a simple, stop-gap means.

The yo-yo despin technique resulted in modest uncertainty as to the amount of residual spin, which would impair the quality of the attitude control provided by the magnet. Two well known damping techniques, energy dissipation by magnetic hysteresis and by shorted coils, were selected to augment the yo-yo despin.

As the extensive redesign proceeded to adapt Transit to the Scout, it became evident that an earth-pointing directional transmitting antenna would be necessary. Gravity-gradient attitude control was the logical choice. Because a satellite over the north magnetic pole is within line of sight of APL, the magnetic attitude control we had been using was a handy way of establishing the initial vertical attitude needed for extension of the gravity-gradient stabilization boom. After gravity-gradient "capture" was accomplished, the unneeded control by the electromagnet was turned off.

The yo-yo and magnetic hysteresis rods (by now metal-jacketed rather than provided with coils) were retained for despin after separation from the Scout. However, it was feared that the rods would be effective only about one axis of the libration motion in gravity-gradient stabilization, thereby allowing the satellite's antenna pattern to oscillate about the other axis. Since magnetic hysteresis worked so well, it was suggested that mechanical hysteresis, in the form of a lossy spring at the end of the boom, might be used to ensure libration damping about both axes. The tricky problem of deploying the spring was solved by embedding it in biphenyl, which had the useful property of gradually subliming in space and ever so gently releasing the spring. So far so good.

Use of this arrangement in orbit provided some unexpected excitement in the form of satellite gyra-

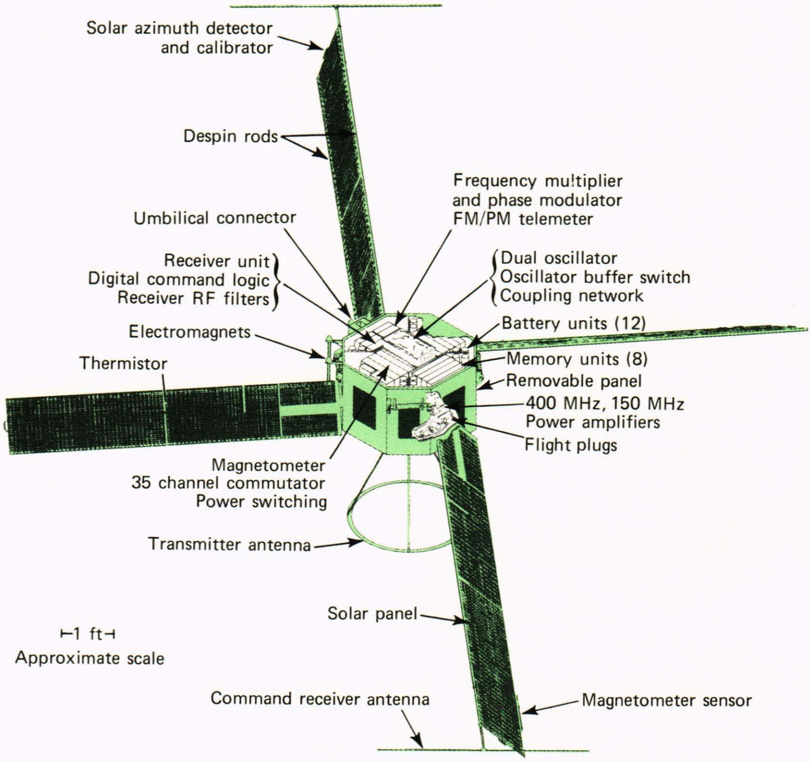

Fig. 3—Cutaway view of Transit satellite 5C-1 (launched by Scout).

tions as the spring deployed. Nevertheless, gravity-gradient capture was obtained the first time it was tried. However, the second satellite exhibited violent motions and eventually came to rest upside down. The situation was fairly tense in the Space Department. In the process of trying to unravel why the first satellite worked and the second was jinxed, we finally realized that the discharge of the biphenyl vapor at the end of the boom was acting as a miniature, berserk rocket. The position of the sun, which heated and sublimed the biphenyl, relative to the orbit plane was crucial in determining the effect of the torque produced by the escaping vapor.

Fortunately, one of the project members had noticed that a Christmas tree ornament of a spiral construction exhibited a most peculiar type of vibration — alternately back and forth in the transverse planes — and recognized that the gravity-gradient stabilization boom had a similar spiral construction. This suggested that, as the result of mechanical cross-coupling, the magnetic hysteresis rods should be equally effective in dissipating libration motions about any axis. Unfortunately, this hypothesis of what was termed the "screwy boom" by the late J. L. Vanderslice defied all attempts at analysis. Finally, it was decided that only a trial in orbit would prove or disprove the idea. A satellite was launched with means for a two-week delay in initiation of the spring deployment after boom extension. Well before the two weeks were up, the libration motions were beautifully damped and, on the strength of that demonstration, the spring was omitted from all future Transits.

LESSONS LEARNED

The military profession has the useful practice of producing an "After-Action Report" following a battle or other action. One of the important purposes of the report is to critique the operations of both sides. These conclusions are contained in a section commonly titled "Lessons Learned." The medical profession, at least in major hospitals, has an analogous practice. It might be desirable if a similar practice were employed in the other technical professions.

What, then, are the lessons learned (more precisely, relearned) from the Transit program?

I think the most fundamental lesson is that an effective (probably the most effective) way to accomplish a task is to assign reponsibility and authority for the entire task to a single, competent, highly motivated organization with capable and dedicated management. If, for technical reasons or because of the size of the task, some aspects of the task must be performed by supporting organizations, then those other organizations should be placed under the technical management of the primary organization but given considerable freedom in their work.

A similar policy should apply to the individuals within an organization. Assign authority and responsibility for pieces of the task to competent, enthusiastic individuals and then give them plenty of elbow room.

The mechanism for protection against misplaced trust is oversight by experienced personnel who are competent in the subject at hand, but not oversight so pervasive as to smother initiative. When trust is found to have been grossly misplaced, as it inevitably will be occasionally, the best corrective action is speedy replacement of the erring organization or individual.

The corollary is to recognize promptly tasks well done by means of rewards, both tangible and intangible.

Another lesson learned is that when a novel, technically challenging task is commenced, there should be a frank understanding between the sponsor and the executor of the task that the estimates of the time and money that will be consumed in performing the tasks are just that — estimates — and that, since a learning process is involved, the rate of accomplishment cannot be guaranteed.

It was our good fortune in the Transit program to have managers within both the government and the Laboratory who had already learned these two lessons.

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