TRANSMISSION OF DATA BY RADIO FROM U.S. SATELLITES

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All of the United States satellites have used radio transmissions from the satellite to ground receiving stations for precision tracking of the satellites and for the transmission of telemetry data from measurements taken within the satellite. In addition, a ground-to-satellite radio link has been used in some satellites to command the satellite to "read-out" telemetered data taken during an entire orbit whenever it passes over a ground station. This last function is provided to allow continuity of satellite measurement of such effects as X-ray and ultraviolet radiation levels, by recording these measurements on a slowly advancing satellite magnetic tape recorder for a period of as long as $2\frac{1}{4}$ hr, and then playing this record back within 5–10 sec, whenever the satellite passes over an appropriately instrumented ground station.

For the tracking of the United States satellites, a dual system of radio and optical tracking stations was established, in order to provide a high probability of establishing and determining the precise path of the satellite, and to predict the future path of these satellites. Initial acquisition of the satellite, and tracking during the first few weeks of its lifetime, is done by a radio tracking system, using a transmitter carried within the satellite which sends signals continuously during flight. In this way radio reception at a ground station from the satellite is obtained whether it is day time or night time, fair or cloudy weather, with a probability of at least two passes over a station per day per satellite. In contrast, the optical tracking system uses reflected sunlight to illuminate the ground observation stations, a condition which limits operations to two periods of approximately one hour each, just before dawn and just after dusk each day, and even then only when the seeing conditions allow such observations. In addition, the relationship of the orbital period and the times of occurrence of sunrise and sunset may "beat" so that periods of several weeks or more may go by for a given satellite without providing a passage over a given observation station during these desired periods. Based on these considerations, it is estimated that proper optical observations occur at about once per ten days per station per satellite.

A second requirement is also met by the radio tracking system—that of proving that the satellite is in a useful orbit. Proof of this is provided by giving the actual orbit,

(1) in the form of the orbital elements which actually define the orbit mathematically,
(2) in the form of a prediction ephemeris which provides future times of passage over given locations on the Earth, and
(3) in the form of day-to-day equatorial crossing predictions, which, together with the orbital elements, allows a fairly precise determination of the look angles for a given passage as a function of time at any station.

In addition to these predictions, a basic book of "minute vectors" is provided every day for each satellite, which gives the actual position of the satellite every minute of time, to an accuracy of a few milliseconds, in the form of x, y, and z co-ordinates centered on the center of the Earth. This book is of great application in post-analysis studies of the position of the satellite for geodetic work, or for correlation of scientific data taken in the satellite with latitude, longitude and altitude.

Based on these predictions, the data on each orbit is passed on to the optical tracking system as soon as the orbit is determined, and continuously thereafter for the period that the radio transmitter within the satellite continues to function (usually three weeks at the least). During this period, the Smithsonian Astrophysical Observatory at Cambridge, Massachusetts, the agency responsible for the optical tracking system, determines the look angles, angular rate, highest elevation angle and times for each predicted passage of the satellite near each of its optical tracking stations. It provides this information to these stations so that, weather conditions permitting, they can then photograph the passage of the satellite on their Baker–Nunn Super Schmidt telescopes with precise time correlation. A network of twelve of these stations are now in operation, each of which has the capability of providing the angular satellite position to about 5″ of arc with a time accuracy of a few milliseconds.

The radio tracking system used for determination of the initial orbits is named the "Minitrack" system, denoting a tracking system requiring minimum weight and size components within the satellite. The ground stations are not minimum size however; they utilize an antenna field of eight separate antenna arrays, four of them 60 × 10 ft in size. These antennas are connected in pairs, so that each pair, with its associated electronics, measures the difference in the time of arrival of the radio signal from the satellite at each antenna of the pair, and thus the angular position of the satellite with respect to the baseline joining the antennas. Use of five baselines provides the complete angular position of the satellite for the period that it is within the beam pattern of the antenna arrays. This pattern was selected to provide a broad north–south pattern to permit a series of strategically located stations to form a north–south fence that would offer a maximum probability of intercept of a satellite passing from west to east. The east–west antenna pattern was made rather narrow (about 10°) to offer as high an antenna gain as was possible in order to permit a lower power transmitter within the satellite.

The radio frequency selection for use with the Minitrack system was made largely on the conflicting requirements of maximum power conversion efficiency within the satellite and minimum refraction error in the transmitted signal due to the ionosphere. The first requirement indicated a low frequency, on the order of 50 to 150 Mc/s. This requirement also provided the maximum gain for the ground antennas while still not restricting the antenna patterns to values too small to be used. The second requirement indicated as high a frequency as practicable—at least 100 Mc/s (the effect of the ionosphere in refracting or bending a radio wave is inversely proportional to the square of the frequency). At the time the compromise solution for the system was being determined, it became apparent that a third element was being added—transistors were becoming available that would give the 5 to 25 mW power levels required at frequencies up to 135 Mc/s. This was in mid-1955. On this basis, a frequency allocation was requested for use during IGY between 100 and 135 Mc/s. A parcel between the upper end of the commercial FM broadcast band assignment in the United States and the start of a series of aeronautical band assignments was allocated—at 108 Mc. This frequency has proven to be a particularly good choice, in that minimum size and weight crystal controlled transistor oscillators are easily obtained for use in the satellite and because ionospheric effects are reasonably low. It was initially predicted that this frequency would result in 10% of the satellite passages being measured to an angular accuracy of 30″ of arc, and that the worst error would be about 8 min because of ionospheric errors. Results on 1958 Beta 2 (Vanguard) indicate a tracking accuracy of about 3 min or less over several one-week periods which would appear to bear out these predictions for this system.

Figure 1 shows a world map with the locations of the stations of the Minitrack Network. The stations along the west coast of South America (Santiago, Chile; Antofagasta, Chile; Lima, Peru, and Quito, Ecuador) plus the stations at Havana, Cuba; Fort Stewart, Georgia, and Blossom Point, Maryland in the U.S.A. provide the so-called fence for satellites launched at orbital inclinations of 30° to 40°. Station antenna patterns are such that these seven stations offer about an 80% probability of signal pick-up for a satellite altitude of 200 miles, without slipping between adjacent station patterns. Additional stations are provided at Essalen Park, South Africa, and Woomera, Australia for greater spread in longitude to improve the computational accuracy in determining the orbit of the satellite. The station at Antigua Island in the British West Indies was established for initial signal pick-up after the orbit had been obtained after its launch from Cape Canaveral, Florida, and the station at San Diego, California was established to provide the initial signal

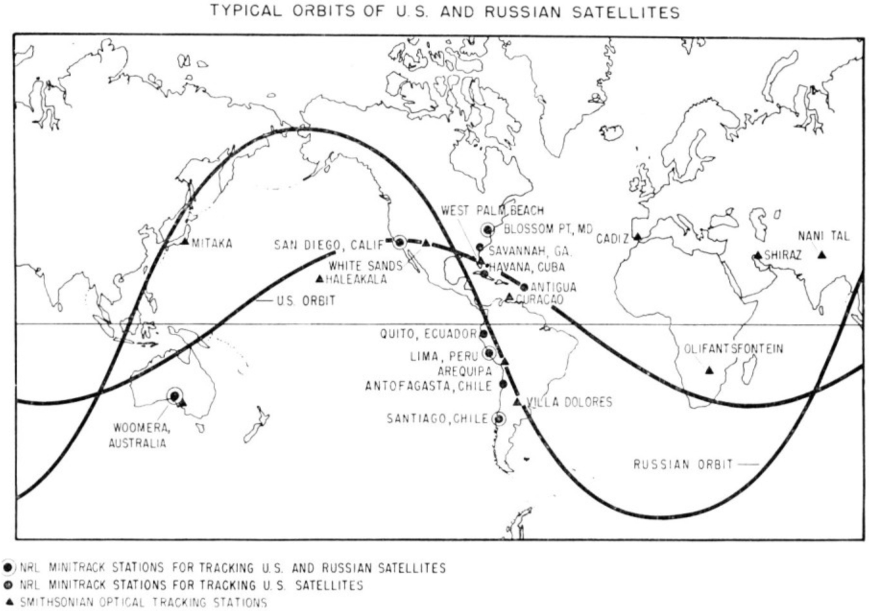

FIG. 1. Typical orbits of U.S. and Russian satellites

pick-up after completing of its initial orbit. Both of these last stations provide continuing tracking data after the initial orbit in the same manner as the other network stations.

All of the Minitrack network stations, with the exception of the station at Essalen Park in South Africa, include telemetry receiving and recording equipment, and provision for the ground interrogation of the

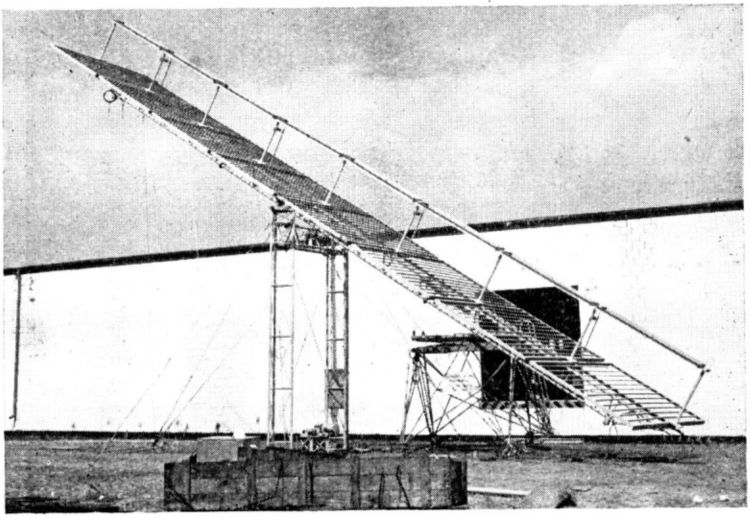

FIG. 2

satellite to turn-on the telemetry circuits as required. This equipment includes a telemetry antenna, shown in Fig. 2, which includes a 60 ft by 10 ft antenna array mounted so that it can be directed to follow the satellite passage from an angular position of 60° west of the zenith to 60° east of the zenith. Figure 3 shows the telemetry receiver, the Ampex seven channel FR-107 magnetic tape recorder, and the two Collins 200 W v.h.f. command transmitters. The South African station has provision for telemetry recording and reception on an abbreviated two-channel magnetic tape recorder, using simpler yagi receiving antennas, and with no provision for telemetry command interrogation.

Telemetry data is transmitted in several ways in the United States satellites. First, the Minitrack telemetry receiving stations were designed to receive and record amplitude modulation of the r.f. carrier at frequencies between 2600 and 20,000 c/s. The frequencies below 2500 c/s

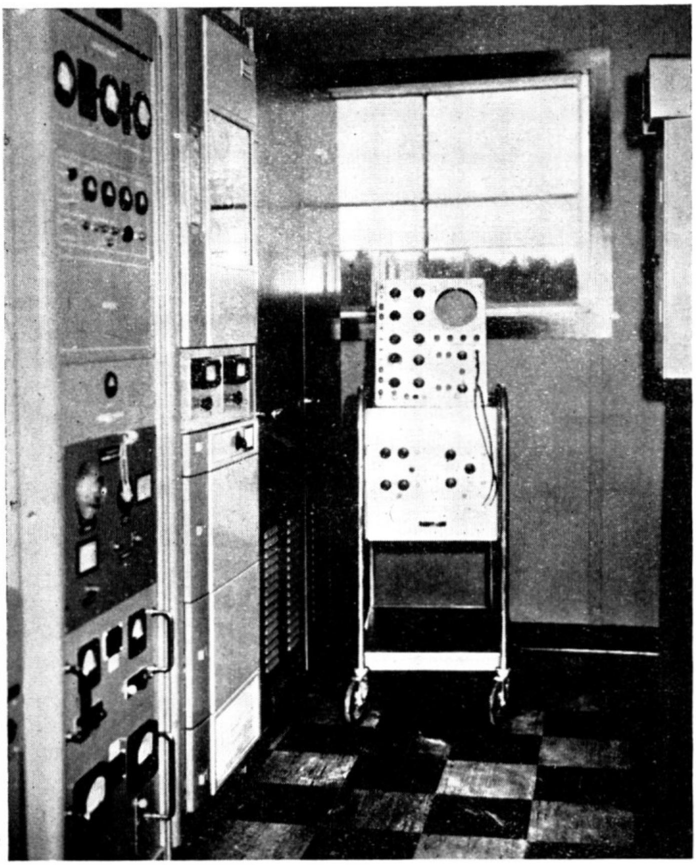

FIG. 3

were not used in order to eliminate interference with the Minitrack tracking ground receivers. Second, for the 1958 Beta 2 (Vanguard) satellite, a number of these stations were modified to permit the precise measurement of the unmodulated carrier, this frequency being controlled by a precise quartz crystal whose temperature/frequency characteristic was accurately calibrated. Measurement of this frequency, and correcting this frequency for the Doppler shift, permits a measurement of the temperature of this satellite in a simplified telemetry technique. Third, another type of receiving system using phase locked oscillators at the receiving stations, has been in use during the last several months at numerous locations. These are designated by the name "Microlock," and permit small deviation phase-modulation of the r.f. carrier with no attendant amplitude modulation. They can thus be used with frequencies below 2600 cps with no bad effect on the Minitrack receivers. This system has been used in the Explorer satellites (1958 Alpha, Gamma, and Epsilon).

Because of the need for additional channels, and to permit amplitude modulation of a carrier at frequencies below 2600 c/s without affecting the tracking carrier, frequencies of 108 Mc/s and 108·030 Mc/s have commonly been used in the United States satellites.

The first U.S. satellite consisted of a cylinder approximately 6 ft long and ½ ft in dia. containing transmitters for experiments as well as tracking. The second U.S. satellite ventured into the field of utilization of solar energy for operation of the tracking transmitter. This Vanguard satellite is now in its sixth month of orbiting the earth and the solar powered transmitter is still emitting a strong clear signal with no signs of diminishing. The third and fourth U.S. satellites with a variety of instrumentation are now having their telemetered data analysed and evaluated. Table I shows various data for the earth launched satellites.

In conclusion, radio has provided the major method of contact with the United States satellites—both for tracking and for telemetry. The orbits of all of these satellites have been available continuously to all interested activities needing this information, and specific look angles and times have been issued regularly to those activities having narrow beam devices such as radio-telescopes or optical telescopes that have to be directed to track the satellites. To date, 1265 data messages have been sent to the computer for 1958 Alpha, 1477 for 1958 Beta, 994 for 1958 Gamma, and 213 for 1958 Epsilon. In addition, 52 data messages were sent in for 1957 Alpha, 20 for 1957 Beta, and 254 for 1958 Delta, the Soviet satellites. Telemetry was provided for 1958 Alpha, 1958 Beta, 1958 Gamma, and 1958 Delta. To date over 3410 rolls of ½ in. magnetic tape have been provided to the various user groups. Over 752 interrogations and telemetry data command read-out operations were made on 1958 Gamma. It can truthfully be said that radio provides the method and the means for communication, tracking, and control of the satellites of today and the space vehicles of tomorrow.

TABLE I

Data on satellites

	Sputnik I (1957–Alpha)	Sputnik II (1957–Beta)	Explorer I (1958–Alpha)	Vanguard I (1958–Beta)	Explorer III (1958–Gamma)	Sputnik III (1958–Delta)	Explorer IV (1958–Epsilon)
Launched	Oct. 4, 1957	Nov. 3, 1957	Jan. 31, 1958	Mar. 17, 1958	Mar. 26, 1958	May 15, 1958	July 26, 1958
Weight (lb)	184	1,120	30·8	3·25	31·0	2,925	38·43
Shape	sphere	complex	cylinder	sphere	cylinder	cone	cylinder
Dimensions	22·8 in. dia.	—	80 in. long 6 in. dia.	6·4 in. dia.	80 in. long 6 in. dia.	11 ft. 9 in. long 5 ft. 8 in. wide (base)	80 in. long 6 in. dia.
Shell material	aluminum alloys	aluminum alloys	steel with 8 aluminum oxide strips	aluminum	same as Explorer I	aluminum alloys	steel
Radios	20·005 and 40·002 Mc/s	20·005 and 40·002 Mc/s	108 and 108·03 Mc/s	108 and 108·03 Mc/s	108 and 108·03 Mc/s	20·005 Mc/s	108 and 108·03 Mc/s
Experiments	internal temperatures and pressures	dog; radiation temperatures and pressures	radiation; meteorites; temperatures	temperatures	radiation; meteorites; temperatures	wide variety of instruments	radiation at 625 miles plus
Power supply	chemical batteries	chemical batteries	mercury batteries	mercury batteries, 6 groups of solar converters	mercury batteries	chemical and solar batteries	mercury batteries
Radio lifetime	23 days	7 days	1–2 weeks; 1–4 months	1–3 weeks; 1 will work "indefinitely"	about $2\frac{1}{2}$ months	—	—
Satellite lifetime	3 months (died 1/4/58)	$5\frac{1}{3}$ months (died 4/13/58)	3 to 5 years	about 200 years	3 months (died 6/28/58)	unknown	unknown
Orbital details:							
Perigee (mi.)	142	140	224	404	118	130	178
Apogee (mi.)..	588	1038	1573	2465	1740	1167	1,368
Period (min.)	96·17	103·75	114·8	134·29	115·9	106	110
Inclination (°)	64·3	65·4	33·5	34·25	33·37	65	51
Speed at perigee (m.p.h.)..	18,000	18,000	18,400	18,400	18,860	18,337	18,000
Speed at apogee (m.p.h.) ..	16,200	15,100	13,700	12,400	13,450	14,637	14,000