



Development of Receivers to Characterize Transit Time and Frequency Signals

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This article describes the development of electronic receivers used to obtain precise measurements of Transit satellite signals such as Doppler shift, satellite ephemeris, and timing information. These measurements were used to determine past and future orbits of the satellites at fixed locations as well as navigation positions for receivers in submarines and ships and at other sites in an Earth-fixed coordinate system. The measurements were based on the best available standards of time and frequency. (Keywords: Navigation receivers, Time standards, Tracking receivers.)

INTRODUCTION

The quality of survey and navigation results depends on how precisely the received satellite signals can be measured. Receiving instruments must therefore be sensitive, accurate, and durable. When the Transit program began, transistors were still very new to electronic design engineers. Those transistors and other commercially available components were plagued by noise figure, power generation, and service life problems. As such problems were resolved, more accurate, more reliable, lower-powered, and smaller receivers came into service. This article discusses the scientific and technical efforts made in electronic instrumentation that resulted in the development and operation of the Transit system.

GEODESY

From the very early days of the Transit program, engineers saw the need for a gravitational potential

model of the Earth to measure and predict the orbits of satellites in the system. The use of Transit for navigation depended on accurate prediction of satellite orbits, which in turn depended on knowledge of the gravity forces acting on each satellite. A worldwide network of tracking stations was established to collect time and frequency data from the satellites to better determine the geopotential models. Each station measured signals from Earth-orbiting satellites in terms of a local time and frequency standard. The measured data were sent daily in a digitally coded format over teletype links to APL for processing.

The satellite signals consisted of two or more radio frequency (RF) carriers with digitally encoded phase modulation. Time and frequency data recovered by the receiving stations could be referenced to primary time and frequency standards maintained at APL. The calculated time and frequency in the satellite relative to APL were used to determine the time and frequency of remote tracking stations.

However, since this process of establishing time and frequency at remote tracking stations was iterative, an alternative means to enhance calculations was developed. This was accomplished by providing an independent frequency monitoring link via the reception of Navy very-low-frequency (VLF) communications signals. The VLF signals were stabilized against cesium (Cs) beam frequency standards at each VLF transmitting station. Several VLF stations (Cutler, Maine; Seattle, Washington; London, England; and a site near the Panama Canal) were used to reach all of the remote stations with strong local signals. Each station was also monitored at APL against APL frequency standards.

Anomalies in the phase stability of VLF signals often occurred because of local problems at the VLF transmitter or because of sunspot activity on the propagation path. These anomalies, when observed at APL, were identified, and warning alerts were sent to the remote tracking stations so that their standards would not be intentionally altered because of inaccurate information.

An alternate time correction method for the remote stations was provided after the development of a special portable, precision crystal oscillator with a countdown chain clock. This oscillator was calibrated in time and frequency at APL, sent by airplane to a remote site, checked against the remote standard, and then returned to APL. The drift in frequency and time during the trip would then be interpolated to set the remote station time and frequency standard.

Throughout the geodesy study, APL launched several satellites using a variety of transmitting frequencies and orbital planes. The frequencies of the earlier experiments were built on integral multipliers or dividers of the 108-MHz work started by NASA, partly because this was a nearly clear RF channel worldwide. We soon discovered, however, that satellite radio waves exhibited changes in propagation velocity when passing through the ionosphere, and such changes could impair the accuracy of geometric measurements established between the satellite and a navigation user. The study included 54, 108, 216, 324, and 920 MHz carriers. The change in propagation velocity was found to be greatest at 54 MHz. In addition, when the Transit system was initiated, it was difficult for transistors to generate RF energy at the orbiting satellite at 920 MHz.

The geodesy study established a gravitational force model describing the Earth in terms of zonal and spherical harmonics of sufficient accuracy to support Transit at a 0.1-nmi accuracy level. The study formed the basis for selecting many of the system design parameters, e.g., selection of 150 and 400 MHz for the carriers, the symmetrical \pm phase modulation of each information bit, and target power levels to be broadcast. A unique audio (beep) signal was recovered by any communication receiver at each 2-min mark. The 2-min marks

were maintained within 1 ms of the U.S. Naval Observatory (USNO) official DoD time for resetting naval chronometers at sea. However, this feature has only been used by navigation receivers to verify satellite signals and to indicate each 2 min of the satellite pass.

DEVELOPMENT OF TIME STANDARDS

The best standards available when the Transit program began were maintained by two government agencies with varying research activities and missions: the National Bureau of Standards (NBS, now the National Institute of Standards and Technology), which provided national standards of time and frequency for the industrial needs of the United States, and the USNO, whose mission was to provide time, frequency, and navigational star tables for all DoD activities. APL obtained time and frequency signals from both the NBS and USNO to calibrate and establish its own standards, which were essential to develop precision oscillators for time and frequency references in each spacecraft and to qualify standards for the receivers needed for orbit tracking and navigation.

For many years, time was defined by the Earth's rotation, i.e., solar time. In 1954, the USNO and the United Kingdom made careful measurements of the Earth's rotational rate in terms of the frequency of an atomic Cs frequency standard. The stability of this standard was determined to be better than the stability of the Earth's rotational rate and was promoted as a new reference of time.

In 1959, APL acquired two Cs commercial atomic standards. The first measurements revealed both the NBS and USNO to be 4 to 5 ms out of sync, and the signal from the NBS station in Beltsville, Maryland, had a diurnal frequency shift of about 5 parts in 10^8 . At APL's request, both deviations were revised: the time standard was corrected to 5 μ s, and the diurnal frequency variation was corrected by voltage regulation of the power fed to the NBS crystal oscillator tube filaments.

In the 1960s, an international time system called Universal Time (UT) was agreed upon. For this time to be related to the observed variation in the Earth's rotation, the value of a second was assigned each year in relation to the Cs frequency. Many users of precision time objected to this yearly change in the value of the second.

In 1972, an international compromise was struck to give the second a constant year-to-year value and to make up the difference in the Earth's rotational rate by introducing a leap second every 6 to 18 months. The offset of the second in terms of the Cs frequency standard was chosen so that a leap second would be needed to keep the Earth's rotational rate and atomic time in

sync. This time system is called Universal Time Coordinated (UTC) and is kept by radio links between the standard laboratories of nations worldwide. In the early days of UTC, only those laboratories capable of simultaneous observation of long-range radio navigation (loran C) signals were qualified to contribute to the definition of the coordinated time system, which was maintained at the Bureau International des Poids et Mesures in Paris, France.

Through the years, the RF links from APL to the USNO progressed through loran C, line 10 TV channel 5, common view of the Transit satellite, and common view of Global Positioning System (GPS) satellites. The time synchronization also used portable clocks for many years to make weekly trips between APL and USNO; transfer errors of less than 1 μ s eventually were reduced to less than 1 ns.

The technology in frequency standards based on crystal oscillators improved by about a factor of 10 every 7 years, from 1 part in 10^{-9} to 1 in 10^{-13} . For a frequency instability of 10^{-9} over the period of a satellite pass, the associated navigational error is about 0.1 nmi and is proportionally less as the reference stability improves; 10^{-11} relates to 0.001 nmi (6 ft). Therefore, a relative stability of 10^{-11} in frequency over a pass is needed to provide survey data at the 2-m level. Statistically, this number improves for multiple passes at the rate of $N^{-1/2}$, where N is the number of passes. Worldwide survey sites were established using Transit by recording 15 to 20 passes at a given location, then using tracked orbits for the same passes. This procedure provided survey accuracies of about 1 m in latitude, longitude, and height.

The frequency standards available to APL were upgraded as the technology improved. Four generations of Cs frequency standards and three generations of hydrogen masers spanned the years from 1959 to 1988,¹ starting with 5 parts in 10^{10} stability on the first Cs standard to about 2 parts in 10^{15} for the best continually tuned hydrogen maser. During 1996, 49 standard laboratories contributed data from nearly 200 atomic frequency standards via common view of GPS signals.²

RECEIVERS

Tracking Receivers

Tracking receivers for Transit orbit determination were initially

commercial, general-purpose radio receivers followed by audio tracking filters and digital data recordings. A reference oscillator frequency was introduced at the receiver input to heterodyne with the satellite's incoming signal, the heterodyne note was successively amplified in two intermediate frequency (IF) amplifier stages and rectified to get the audio note, and the tracking filter reduced the noise level in the audio note to less than a 10-Hz noise bandwidth. Figure 1 shows the components of the experimental tracking station at APL in 1962.

The quality of Doppler measurements from orbiting satellites greatly depends on eliminating as much receiver noise as possible and also on the stability of the receiver reference oscillator during the measurement period. Eventually, single-sideband receivers were developed that immediately eliminated noise from the unwanted sideband at the first mixer.

To reduce the size of instrumentation that had to be carried to remote places for site survey operations, a special-purpose receiver called the Geceiver was developed by the Magnavox Corporation (Fig. 2). This self-contained instrument was slightly larger than a briefcase and combined single-sideband receivers for the Transit operating frequencies, a standard frequency oscillator, and a data reduction system to provide a data record for each satellite pass. APL used this data record along with tracked orbital data to determine a site survey.



Figure 1. Experimental tracking station at APL (1962): 1 = antenna monitor, 2 = spectrum display, 3 = WWV (call letters) receiver, 4 = receivers and tracking filters, 5 = antenna positioner, 6 = meters, 7 = transistorized digital data system, 8 = refraction correction unit, 9 = recorder, 10 = antenna time recovery system, 11 = satellite time recovery system, and 12 = PB-250 computer.

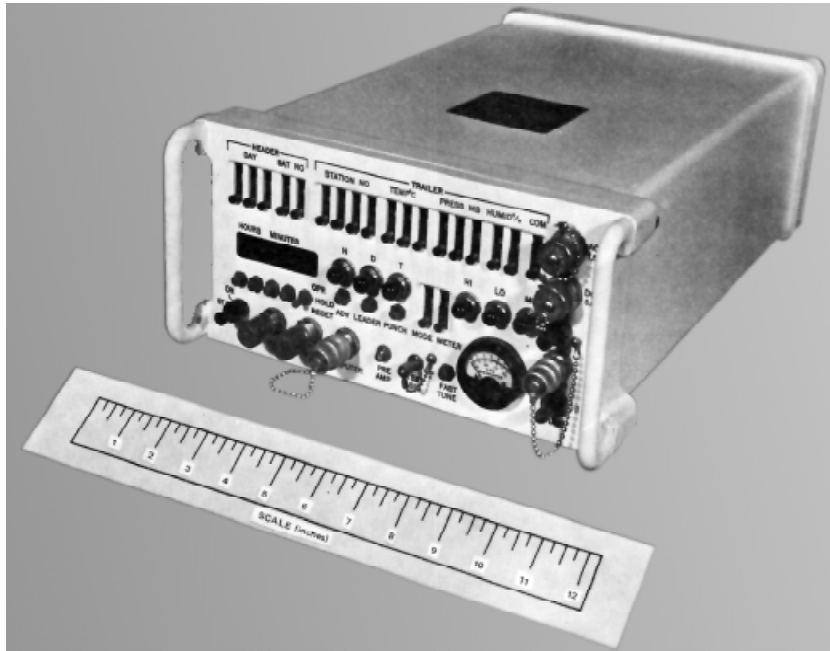


Figure 2. The Geoceiver AN/PRR-14.

Navigation Receivers for Fleet Ballistic Missile Submarines

The primary effort to develop a navigation receiver was in support of Fleet Ballistic Missile (FBM) submarines. The Laboratory established detailed specifications for this purpose and distributed them for competitive bidding to U.S. businesses knowledgeable in radio receiver design and manufacture. More than 50 companies responded. Westinghouse Electric Corporation won the competition for the receiver, and Ramo Wooldridge was declared the winner of the data processor and computer portion of the system.

The AN/BRN-3 receiver (Fig. 3) was contained in two cabinets, each $2 \text{ ft}^2 \times 5 \text{ ft}$ high, that were bolted and cabled together and could be installed through the submarine personnel hatch. The antenna comprised a pair of fat dipoles stacked in a vertical array, which was enclosed in a green fiberglass cylinder 4 in. in dia. \times 4 ft high and mounted atop a movable periscope that was exposed above the water when receiving satellite signals. When first installed, a dual preamplifier was housed in a water-pressurized container just under the antenna to preserve the system low-noise figure. However, maintaining the service life of these preamplifiers became such an effort that the 3-dB signal loss associated with running a cable directly from the antenna to the receiver cabinet was found to be acceptable with the system performance margins realized in actual service.

The FBM receiver included the antenna preamplifier described previously, the frequency standard, and the RF, IF, and video amplifiers for the two operational frequencies (150 and 400 MHz). The output Doppler

frequencies were analog-combined in frequency multipliers and dividers to create a single refraction-corrected Doppler signal.

The receiver also included test instrumentation to verify its ability to recover a weak satellite test signal and to investigate countermeasure signals. A tuned input transmission filter was provided with shunt varactors that would detune the filters if signals at damaging burnout levels were encountered. The RF, IF, and video amplifiers were designed to operate without overloading in the presence of interfering signals 60 dB stronger than the desired satellite signals; as an interfering, fixed-frequency signal entered the skirts of the IF bandwidth, the receiver was designed to sequentially lower the tracking circuit bandwidth from 30 Hz to 10, 3, and 1 Hz if necessary. The coast



Figure 3. Fleet Ballistic Missile submarine receiver AN/BRN-3.

circuits and computer-aided control loop functions would then easily reacquire Doppler signals once the interfering signal passed out of the intermediate bandwidth.

Computer-aided control loop functions also were used for initial acquisition of satellite signals and recovery of signals following signal loss due to waves washing over the periscope antenna (wave wash). This problem dictated taking the Doppler data in about 1- to 1.6-s samples, which could be coherently added up to 5-s data spans. The feature of adding adjacent data samples averages out the short-term instabilities of the satellite and receiver reference oscillators, thus permitting Doppler signal measurements to a resolution of 0.001 Hz.

When first installed in the FBM submarines on 31 December 1963, the AN/BRN-3 included a commercial Borg frequency standard mounted within the receiver cabinet. This standard was based on extensive crystal oscillator research done at the Bell Telephone Laboratories for Standards for American Telephone and Telegraph. The signal from the reference crystal in the Borg oscillator was subject to frequency drift with time. Provision was made to measure and recover from this drift whenever it exceeded 5 parts in 10^9 because that amount of frequency error would generate local time errors that not only made it harder to predict when a satellite would be within radio range but also the starting Doppler frequency. When the Borg 5-MHz signal was multiplied to the local oscillator frequency, a significant loss in the signal-to-noise ratio (SNR) resulted, which Westinghouse overcame by introducing an oven temperature-controlled crystal transmission filter at the 5-MHz input to the receiver. This fix was so effective that Hewlett Packard added the filter to one of its better oscillators (HP-104) and marketed it for several years. Later in the FBM program, a Hewlett Packard Cs standard was installed in the FBM navigation center to replace the Borg oscillator. This eliminated the need for frequency and time corrections because the Cs standard typically remains within 5 parts in 10^{12} over its operational service life.

The modulation of the satellite signals was recovered in the AN/BRN-3 from whichever channel (150 or 400 MHz) was being received with the best SNR. The modulation provided 6103 bits of information every 2 min and a beep-time index every 2 min, decomposed into 156 words of 39 bits. Every sixth word was sent in the clear and was available for commercial or naval ship users. The remaining words were encrypted and made available only to FBM submarines. The words in the clear were enough to describe the approximate Kepler orbit of that transmitting satellite and to provide three-dimensional corrections to the Kepler orbit at each 2-min point. To find the same satellite a second time, a ship would have to record these Kepler data and

calculate when the satellite would be in range again. On the other hand, the FBM could recover all words sent, both in the clear and encrypted. The encrypted message contained repetitions of the fixed-orbit parameters as well as Kepler data for every other satellite currently in service. This feature, similar to the GPS's limited access, was designed into the system so that Transit could truncate the Kepler data given in the clear. This would deny precision navigation but would provide truncation corrections in the encrypted data for full navigation precision. Truncated data were accidentally transmitted from one satellite for less than 1 day and were never again employed.

The Navy sponsored development of a receiver system for the operational tracking stations for 2 years and then decided to use the AN/BRN-3 in several tracking sites: Winter Harbor, Maine; Rosemont, Minnesota; Point Mugu, California; and Oahu, Hawaii. The second IF amplifier bandwidth for these sets was widened to better accommodate reception of other telemeter signals. Those specific modules were painted red so that the supply and repair facilities would not return the modified units to FBM users. This decision to use the AN/BRN-3 in ground sites guaranteed availability of spare parts over the 33 years of operational service through the FBM supply system.

Navigation Receivers for Surface Ships

When primary responsibility for the Transit program shifted to the Special Projects Office of the Navy, there was no urgency to develop receivers for the surface Fleet, and the cost of the AN/BRN-3 system seemed too expensive to duplicate. Therefore, APL undertook the development of a simpler design for surface ship use. This system (Fig. 4) was designated the AN/SRN-9(XN-5), and it used only the message information sent in the clear. Because the antenna was not subjected to signal dropouts caused by wave wash, it was mounted high in the ship's superstructure with a clear view of the sky and radio line of sight to the satellites, and the Doppler recovery was tied to 2-min data spans. Data from the satellite message were printed out on a paper ribbon adding machine that had solenoids to operate the numerical keyboard.

A Navy procurement effort was initiated for the AN/SRN-9(XN-5), but delivery was not expected until 1972. In response to an urgent need for the receiver, APL built 25 sets and, over a period of at least 5 years, installed these units in surface ships and moved them from ship to ship as needs were identified. These sets were used on the Apollo recovery ships to pick up returning astronauts. During one recovery, the receiver temporarily malfunctioned but was repaired in time for the pickup; thereafter, an APL field engineer was stationed aboard every recovery ship.

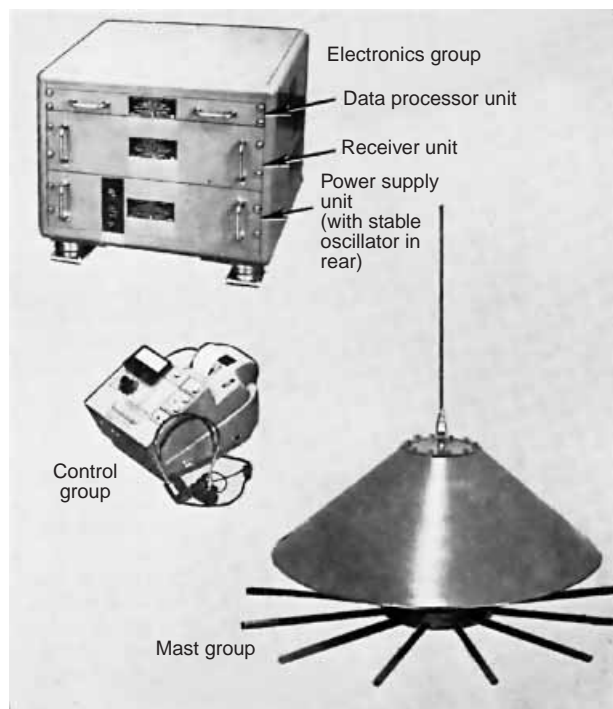


Figure 4. The AN/SRN-9(XN-5) surface ship receiver.

Navigation Receivers for Aircraft

The APL-developed Transit receiver for aircraft (Fig. 5) was designed to provide navigation corrections to the inertial platform of an airplane used to map the world's geomagnetic fields. On one mission near the South Pole, an aircraft lost electrical power in flight. When power was restored, the aircraft's inertial platform had lost its settings. Fortunately, a Transit pass was obtained, and the platform was reset, enabling the aircraft to return to a safe airbase with less than 1 hour of fuel remaining.

Other Receivers

In 1967, Vice President Hubert Humphrey announced that the Transit system was available for worldwide use. In response to this news release, the technical information was made available, and several commercial organizations built navigation receiver sets. The market quickly found an interest in commercial shipping at about \$25,000 per set. However, when the price dropped to about \$5000, owners of pleasure boats bought the systems. Surveys conducted by the Navy identified as many as 14 manufacturers and 100,000 users. Units were made both in the United Kingdom and in Japan, with a British firm offering them for as low as about \$1000 (U.S.).

The AN/SRN-19 was one of the last navigation sets designed at APL. This small, single-frequency (400-MHz) set used in-the-clear data from the satellite and

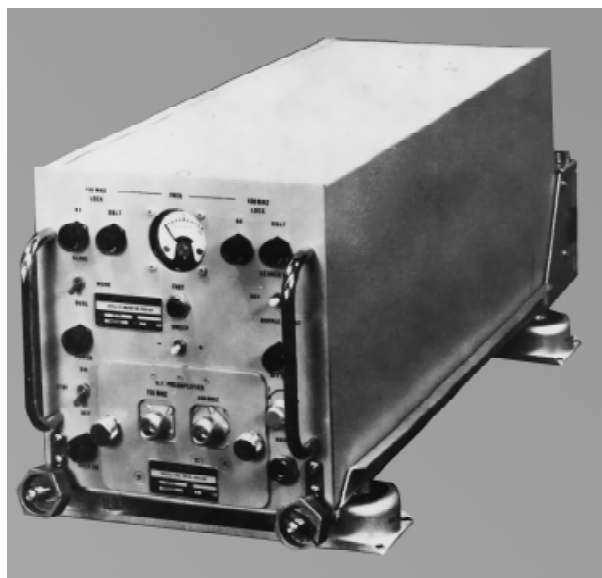


Figure 5. Transit DRS/A aircraft receiver.

was specially adapted for small shipboard service. The unit recovered satellite time and performed dead reckoning between satellite passes.

In addition, backpack navigation sets were developed for use by the Army in advising close support gunfire. Covert army observers could get a fix on their position and give accurate position data on nearby targets back to a gunfire site located safely away from the target but within firing range.

Other sets were used for a service called "co-location," in which two sets observed the same satellite pass but at some distance apart. The calculated difference in positions provided a much better measurement than either set's independent measurement since errors in the predicted position of the satellite as well as propagation effects cancel. For site separation of 1 to 50 mi, the separation measurements had errors of only a few feet. Co-location has also been used effectively in positioning oil wells in the North Sea. Another application resulted in a method to measure azimuth: two antennas, tied to the same receiver but separated by 600 ft, would resolve the fixed geometry to provide better than 1° uncertainty in the direction to north. However, no operational use resulted from this effort.

CONCLUSION

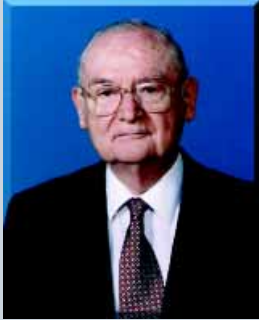
APL has successfully developed receivers and data analysis methods to measure signals from orbiting satellites with sufficient precision to support satellite orbit prediction and navigation service to user submarines and ships. Fixed-site measurements provided worldwide precision survey data at the 1-m level in latitude, longitude, and height.

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LAUREN J. RUEGER received a B.Sc. in engineering physics and an M.Sc. in physics from Ohio State University in 1943 and 1947, respectively. A specialist in precision frequency measurement and electronic systems engineering, he joined APL in 1953 and subsequently worked on many system projects, including radar matching techniques, electronic countermeasures, the atomic frequency standard facility, Transit, the GEOS-C radar altimeter, and the hydrogen maser. From 1978 to 1988, Mr. Rueger served as a U.S. delegate to the Geneva sessions of the International Radio Consultive Committee Study Group 7 on time and frequency. He is a Fellow of the Institute of Electrical and Electronics Engineers and a member of the American Physics Society, American Association for the Advancement of Science, and Photographic Society of America. He retired from APL in November 1988.