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A satellite-tracking network of receiving stations and other facilities is discussed. Identified as TRANET, this network acquires and processes doppler frequency shift data from the signals of suitably equipped near-earth satellites. These data are used both in dynamical geodesy and in determining the location points on the surface of the earth. TRANET provides high-density, high-accuracy data for a large number of satellites in a form ready for the computing process. Currently, TRANET measures doppler frequency with an accuracy of one part in 10^{10} and satellite position with an accuracy of 10 meters.

TRANET

DOPPLER TRACKING SYSTEM

The tracking system known as TRANET¹ is a network of radio receiving stations and other facilities used for acquiring and processing doppler data from near-earth satellites.

The original six stations in the network were deployed in 1959 to support early Navy satellite programs utilizing the doppler shift of radio signals from a satellite. The TRANET system today includes those stations whose locations are shown in Fig. 1, and five stations in mobile vans, all of which communicate with a control center at the Applied Physics Laboratory, Howard County, Maryland, by means of a teletypewriter communication network. The system is operated for the Satellite Geophysics Project of the U.S. Naval Air Systems Command and is a primary source of data for research in both dynamical geodesy and the determination of the location of points on the surface of the earth.²

The basic physical quantity measured by a TRANET doppler station, and used as the basis of the orbital computations, is the doppler frequency as a function of time.

Since a tracking station must measure frequency and time, it must have a stable reference frequency

and standards for determining clock rate (frequency) and for setting clock epoch. TRANET stations use standard frequency VLF transmissions for frequency determination and clock carrying satellites for station clock epoch control, with HF standard time broadcasts for backup. This requires that the stations be equipped to recover satellite time data but does not require introduction of clocks in new satellites since existing Navy Navigation satellites now provide suitable satellite clocks. Precision time transfer by satellite does require that some station serve as a working standard for the purpose of calibrating the satellite clock. Clock calibration and other functions relating to time and frequency are carried out jointly by the APL Time and Frequency Standards Laboratory and TRANET Doppler Tracking Station 111.

In addition to the tracking stations proper, the other principal components of the TRANET system are the Control Center, the Computing Center, the Time and Frequency Standards Laboratory, and the communication network connecting the Control Center with the stations on one hand and the various user and service facilities on the other.

Figure 2 shows schematically the operation of the total system. The tracking stations, in response to satellite alerts (pass predictions) and observation instructions, receive doppler and satellite time data. These data, along with other optional data such

¹ R. R. Newton, "A Description of the Doppler Tracking System TRANET," APL/JHU Report TG-571, May 1963.

² W. H. Guier, "Satellite Geodesy," *APL Technical Digest*, 4, No. 3, January-February 1965, 2-12.

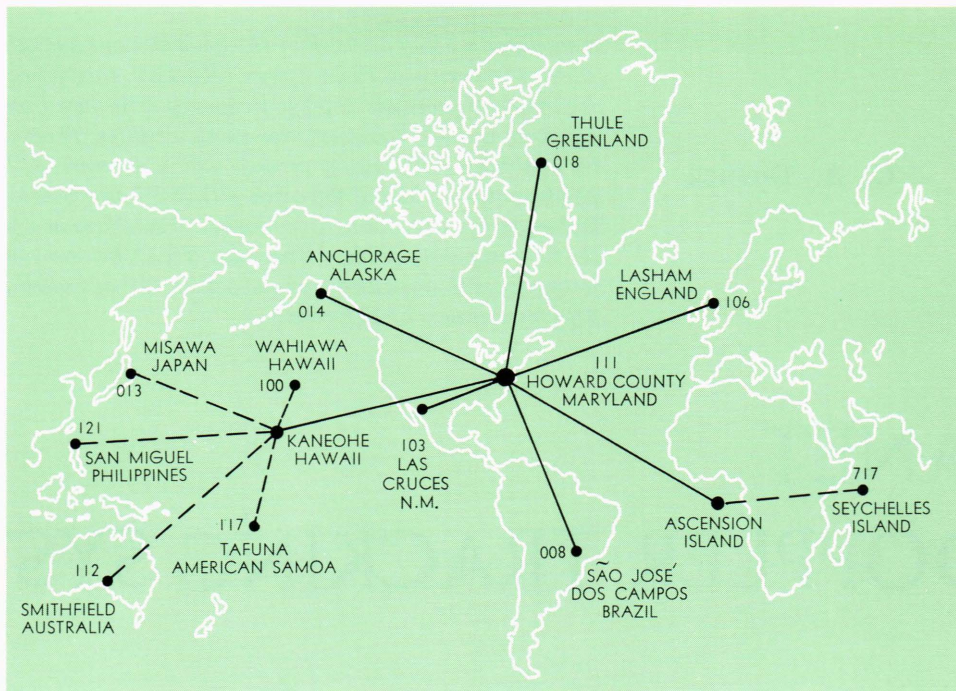


Fig. 1—TRANET station and communication network.

as surface weather data are transmitted over teletype circuits to the Control Center, Fig. 2. At the Control Center, the incoming data tapes are logged and transferred to magnetic tape. Shortly after the close of each day, this tape, containing all of the station data for the previous day, is sent to the APL Computing Center for certain preprocessing before distribution to data users, including the Naval Weapons Laboratory, Dahlgren, and the APL Space Department.

The Control Center transmits orbits and other special results to users of the system, from whom it also receives the operational requirements laid on

the system. Operational information such as alerts, station analysis reports, timing analysis reports, and a weekly technical information newsletter are also disseminated by the Satellite Control Center to the tracking stations.

The staff at each tracking station maintains continuous check on station performance insofar as it is possible. However, it is not possible for the station to be self-contained in this respect. To help in maintaining data quality and quantity, diagnostic information is of great value in maintaining the high performance of the system.

System Characteristics

A. Data Density

The system provides a high density of data for satellites in any inclination. For equatorial satellites at about 1000 km altitude, the TRANET obtains about 40 passes per day; more than this for satellites at high inclinations. The passes are well distributed in time and average about 15 minutes in duration. Thus a satellite at this altitude is under observation about 600 minutes per day. For high satellite altitudes, the total observing time increases, being divided into fewer passes of longer duration.

B. Data Processing

The doppler data produced by the station equipment is a punched paper tape in 5-level tele-

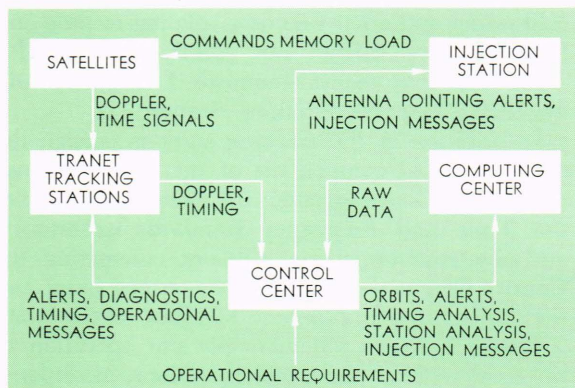


Fig. 2—Functional schematic diagram of the Tranet system.

type code. A message header identifying the data run and providing, among other information, the frequency standard error and clock time corrections is produced semi-automatically. Weather data from the site can be similarly produced and appended to the doppler data. Thus the data are ready immediately for computer processing as soon as received from the stations at the Satellite Control Center.

C. High Inherent Precision

The basic precision in satellite position measurement for satellites near 1000 km is about 10 meters for doppler data gathered during a single pass. All instrumentation errors are contained within this measure, but incomplete knowledge of the earth's gravity field limits the accuracy of an orbit determined from doppler data (a tracked orbit) to about 50 meters at the present time.

D. Station Equipment

Ground station equipment basic elements are two phase-tracking receivers, a station clock, a simple analog refraction correction device and the digital equipment necessary to develop and to punch time and period information in a standard format. Whip antennas are sufficiently sensitive for most doppler earth satellite programs. A typical station crew consists of four to six men for 24 hours a day, 7 days a week operation.

E. Volume Capability

The volume capability of the system is in the range of 40 to 50 passes per station per day or between 480 and 600 passes per day for the basic 12-station network. In 1966, the average daily yield for the basic 12-station network was 240 passes. There is redundancy in the data. A typical pass may contain 200 or more data points; a fraction of these would suffice.

Data attrition due to all causes (transmission errors, equipment malfunctions, lost passes) is below ten percent.

Description of System Components

A. Satellite Equipment

For doppler tracking by TRANET, it is necessary that a satellite carry suitable equipment. The equipment required includes a highly stable oscillator, two frequency multipliers, two transmitters and the associated power supplies (Fig. 3).

The heart of the system is the oscillator. Typically it is a dual 5 Mc/s fifth overtone oven-controlled oscillator of ultra high stability.³ Its outputs

may also be redundant, and since only one oscillator is on at a time, this allows four possible operating combinations. The buffer/converter/switch (B/C/S) converts the 5 Mc/s source to a 3 Mc/s signal and supplies a buffered, low impedance level, 3 Mc/s signal at its output. The FM/ ϕ M multiplies the 3 Mc/s signal to 54 Mc/s, where two buffers are driven in parallel to supply two coherent outputs. Each of these channels then feeds into a phase modulator, which in turn drives the output buffer-amplifier. The phase modulator is a pulse-type modulator, advancing or retarding the phase a fixed amount when driven with the corresponding signals. It is normal practice to choose a modulation format such that no phase bias is generated. The modulator is a current driven device whose input can be left disconnected if no phase modulation is required.

The power amplifiers differ only in the power level and output circuitry. Both multiply the 54 Mc/s to 162 Mc/s and amplify the resulting signal. The 324 Mc/s power amplifier then has a varactor doubler at the output.

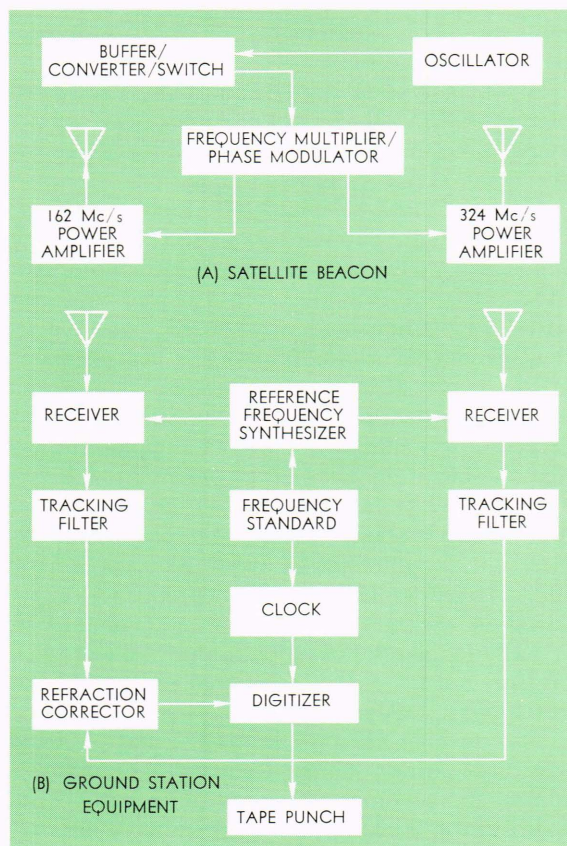


Fig. 3—Simplified block diagram of doppler tracking system.

³J. B. Oakes and R. A. Mauck, "An Improved Stable Crystal Oscillator for Satellite Use," APL/JHU Report CM-1042, February 1964.

B. Ground Station Equipment

Like the satellite, a TRANET ground station must contain a stable oscillator and a clock driven by the oscillator. The reference frequency and the epoch time shown by the clock are monitored and corrected using VLF frequency and satellite or HF time signal transmissions. The APL Howard County station uses cesium standards and a crystal controlled clock system monitored against WWV and the Naval Observatory for epoch and against several VLF transmissions for frequency. This station serves as the working standard station for calibrating those satellite clocks used for disseminating epoch time to the TRANET system.

The tracking station instrumentation currently used at TRANET stations is of two basic types. One type, used in stations characterized as Tracking Filter Stations, phase locks to the satellite signal after the signal has been heterodyned down to the 10 to 50 kc/s range. The other basic type, known as NACODE, phase locks to the satellite signal in the RF region. A third type of station instrumentation combines features of both of the previously described types and may be van mounted for portability. Five such van-mounted equipments were built to meet requirements for short-term occupancy of remote sites.

A fourth type of station, the small, hand-portable GEOCEIVER, is currently under development at APL. GEOCEIVER sets will ultimately replace the much larger van-mounted stations.

Figure 3 shows schematically the operation of a tracking station. Satellite signals on two frequencies which are coherent and related by simple ratios (1:2, 3:8, for example) are received and compared with frequencies synthesized from the station's frequency standard, giving a beat frequency in the range of tens of kilocycles. The satellite oscillator is deliberately offset by an amount that exceeds the maximum expected doppler shift, so that the beat frequency never passes through zero. This offset has ranged from 35 to 85 parts per million in APL-built satellites. The maximum doppler shift for satellites at about 1000 km is about 25 parts per million. The beat frequency is produced in the receiver detector and contains the desired doppler information, phase modulation if present, and noise. It is this signal which is tracked in the phase lock tracking loop.

The tracking filter is essentially a narrow band-pass filter whose center frequency automatically adjusts to the input frequency. The input bandwidth to the tracking filter is typically 20 kc/s and the effective tracking bandwidth is 10 cps. The ratio of the square root of the tracking bandwidth to the input bandwidth is a measure of the ratio

of the root mean square (RMS) output phase noise to the RMS input noise. The outputs from the tracking filter are nearly noise free doppler signals, and signals produced by the phase detectors consisting of modulation and timing information.

The signals received from the satellite have been subjected to (a) doppler frequency shift, (b) frequency shifts due to ionospheric refraction, and (c) frequency shifts due to tropospheric refraction. Making use of the frequency dependence of the refractive effect of the ionosphere, the ionospheric refraction correction system combines the outputs of the two tracking filters in such a way as to eliminate, to first order, the refractive effects of the ionosphere. Outputs from the refraction corrector are the corrected doppler signal and the first order refraction error signal, which is usually displayed as a tuning aid and which may be recorded for studies of the ionosphere.

The corrected doppler output of the refraction unit is digitized. Present practice is to sample the doppler frequency every 4 seconds. Every 4 seconds, the digitizer counts a preset number of cycles and determines the time in microseconds (or $0.2 \mu\text{sec}$) required for such a count, beginning at the first positive going zero crossover of the doppler signal after an integral second, and ending at the positive going zero crossover of the N_c th cycle, where N_c is the pre-set number of cycles counted. The metering frequency is 1 or 5 Mc/s, depending on the equipment, and the pre-set count is almost continuously variable between 1 and 99,999. The pre-set count is chosen to make the period count just under 1 second at the beginning of a pass, when the beat frequency is lowest.

All of the TRANET stations are also equipped to receive timing signals, in the form of a "timing word," recovered from the phase modulation on Navy Navigation Satellites, which broadcast a timing word every 2 minutes. When a timing word is recognized, the equipment produces a pulse at the appropriate time, which causes the station digitizer to form and punch an 11-digit satellite time data point. These time data points are recorded on 5-level teletype code paper tape, in place of a doppler data point. In the pre-processing of data in the 1410 computer at APL, all of the timing data points for a pass are extracted from the data message for subsequent separate handling. The timing data may be used in several ways; it is current practice to compute the RMS of the timing points and the indicated station clock offsets every day, and to feed this information for selected days back to the tracking stations, where it is used to adjust station clock epoch. Through the use of this tech-

nique, the tracking stations are able to maintain station clock timing accuracies to better than 0.3 msec.

The GEOCEIVER⁴ differs from present TRANET stations in several respects: (a) GEOCEIVER uses the integrated doppler counting technique, in which a measure of the *change* in satellite to station range is obtained by counting the number of doppler cycles received between successive one-minute markers; (b) GEOCEIVER is much smaller and lighter than current TRANET station equipment; (c) the data format results in at least a 10-to-1 reduction in the number of data points from a satellite pass; (d) the requirement for calculation of clock errors and clock corrections by station operators is obviated by obtaining epoch from Navy Navigation Satellites automatically in the course of tracking operation; and (e) the GEOCEIVER is adaptable with few changes to a semi-automatic mode of operation.

C. APL Time and Frequency Laboratory

The time and frequency laboratory provides a monitoring and advisory service to the TRANET stations with respect to standard time and frequency transmission. Continuous VLF frequency comparisons and periodic time checks using a hand portable precision clock serve to relate the APL time reference to those at the National Bureau of Standards and the Naval Observatory to an accuracy of a few microseconds. The satellite clock, in turn, is used to compare Station 111, which serves as the standard station, against the individual tracking stations in the TRANET.

D. Control Center

The Control Center serves both as the hub of TRANET system communication and the locus of current information on the status of satellites and of the ground tracking network. Each station is linked to the Control Center by the teletype network shown in Fig. 1. The volume of message traffic handled in the Control Center since 1961 is shown in Fig. 4. The Control Center is manned continuously by teletype operators and by a supervisory duty officer whose duties include that of assuring that there is an appropriate response in all situations affecting the satellites or tracking network requiring decision or action.

Soon after each pass at a station, a data message containing a header, data, and optionally a weather and narrative message is transmitted to the Control Center. At the Control Center, each received pass is checked off against the pass prediction or "alert"

and observation instruction for that station; all missing passes are accounted for and statistics are assembled on station compliance. The transmission of data requires about 15 minutes for each pass on 60 wpm teletype circuits. After checkoff, the data passes are transferred to magnetic tape.

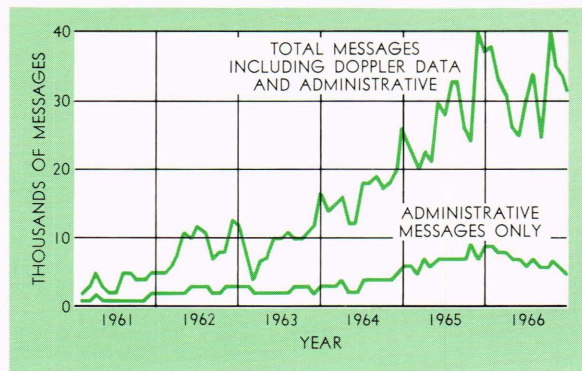


Fig. 4—Volume of message traffic handled in the Control Center since 1961.

E. Computing Operations

At 0500Z each day, the magnetic tape containing the previous day's data is delivered to the Computing Center, where the first step in the computing operation is performed on an IBM 1410. The raw data are checked for correctness of header and of data format. Timing points are separated from the data message and all data are reformatted to a common data format. One output of the 1410 is a computer input tape containing all of the data ordered by satellite along with accompanying header and weather information. Other outputs are the format checked raw data prepared for transmission to Naval Weapons Laboratory, Dahlgren, raw satellite timing data, header listings, weather and flag messages, and missed pass listings.

Subsequent computing is carried out at APL on an IBM 7094 and at NWL on an IBM 7030 in orbital improvement programs. In APL computing, Fig. 5, the data are first converted from period count to frequency in the CONVERTOR, and the epochs given in the raw data are adjusted to the epoch at which the derived frequency should apply.

The data then enter the DATA EDITOR, whose purpose is to delete spurious data or occasional gross errors that may result from tracking, frequency, or timing errors. EDITOR first eliminates any data points that are outside the range of any possible doppler frequency. Then a least squares fit of the experimental frequencies observed to the theoretical frequencies from a previous orbit, is made over the span of the data, with the station coordinates θ , λ and the satellite frequency f as the

⁴ T. A. Stansell, "GEOCEIVER: An Integrated Doppler Geodetic Receiver," APL/JHU Report TG-710, July 1965.

variable parameters. The fictitious station locations thus determined are discarded, but the individual data points can now be tested for variations which exceed predetermined stripping levels. The output of the DATA EDITOR includes a first estimate of the satellite frequency and information relative to noise and other factors indicative of probable quality of each pass.

After the data from each pass are edited, the total set of retained data is used in the orbital improvement program. In this program the nom-

ined roughly as containing all the factors that affect the quantity and quality of the data which are the inputs to the analysis program.⁵ The former include neglected components of the earth gravity field and residual refraction effects. Neglected gravity field components are the dominant error sources and in fact the primary object of geodetic research using artificial earth satellites. Refraction effects are of less consequence and can in any case be overcome through proper choice of frequencies and other techniques. Observational errors include sys-

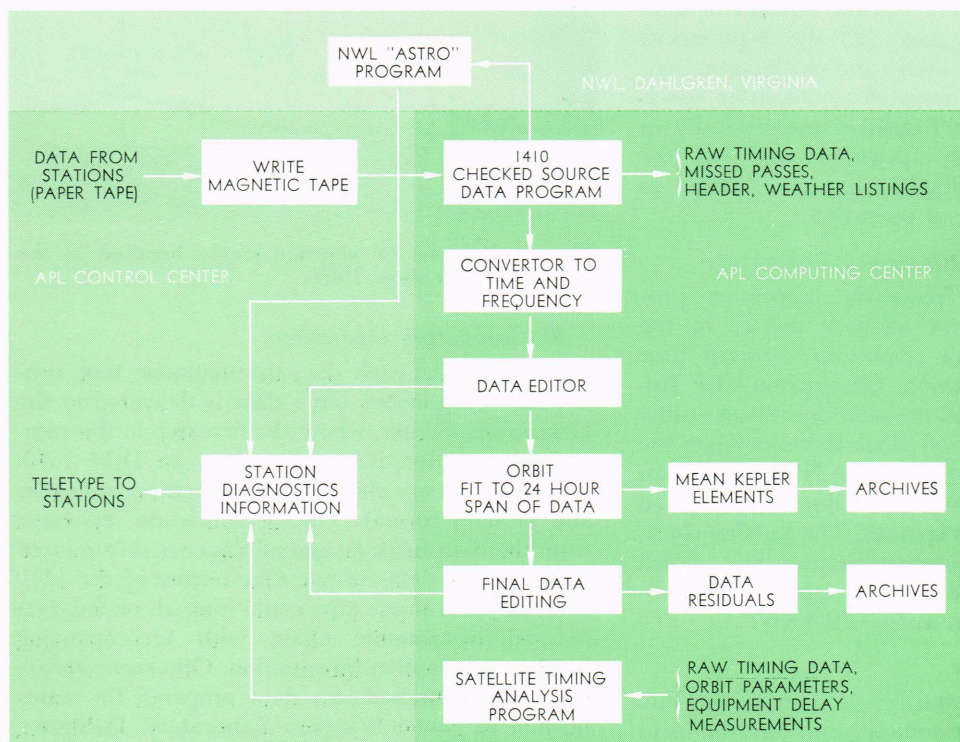


Fig. 5—Diagram of computing operations.

inal station coordinates, rather than the fictitious ones found in the EDITOR are used, and the unknown quantities are the six orbit parameters, plus the average satellite frequency for each pass. The details of the calculation are described elsewhere. The output of the tracking program is a set of orbital parameters which are placed in data archives for geodetic studies, and which may be used for other purposes such as the computation of station alerts, antenna pointing alerts, ephemerides and sunshine predictions.

Accuracy of the System

System accuracy is influenced by errors of two general types: (a) analytical errors, defined as including those phenomena that affect the analytic results but which are not included in the analysis for some reason, and (b) observational errors, de-

tematic errors in time and frequency measurement, the span and distribution of the data, and (by definition) noise.

Errors in station clock epoch result in systematic position errors along the satellite track amounting to approximately $7.5 \delta t$ meters, where δt is in milliseconds. Since the advent of clock-carrying satellites, the level of accuracy with which TRANET stations maintain epoch time has improved and currently equals or exceeds that required for geodetic work. In the course of tracking clock-carrying satellites the timing data from such satellites is recorded, and is later processed in computing programs which remove propagation times, calibrate

⁵ W. H. Guier, R. R. Newton, and G. C. Weiffenbach, "Analysis of the Observational Contributions to the Errors of the Navy Satellite Doppler Geodetic System," APL/JHU Report TG-653, January 1965.

the satellite clock against the standard station, and compute the error in the station clock epoch relative to the standard station. Measuring error is limited by the signal to noise ratio associated with the received timing signals and is presently about 30 μ sec RMS for the data received on a single pass.

Frequency errors which are constant throughout a satellite pass produce no errors in the computed position of the station or satellite. Oscillator drift during a pass, however, may produce a small error in the minimum range, similar to that which would be produced by an along track velocity error. Frequency standards currently in use typically have drift rates of a few parts in 10^{11} per day, corresponding to negligible position errors due to this effect.⁶

⁶R. R. Newton, "The Navy Navigation Satellite System," *Proc. COSPAR 7th International Space Science Symposium*, May 1966.

Summary

The TRANET system is capable of providing high-density, high-accuracy doppler data for a large number of satellites in a form ready for immediate computer processing.

The TRANET system is capable of measuring the doppler frequency received from a satellite with an accuracy of 1 part in 10^{10} and the satellite position with a precision of 10 meters. Accuracy of orbit determination is limited to about 50 meters by incomplete knowledge of the earth's gravity field.

It is estimated that the TRANET system could reliably handle as many as ten near-earth satellites in full time operation with maximum accuracy. With lessened accuracy requirements the number of satellites which the system could be called on to track would be greatly increased.

ADDRESSES

The listing below comprises the principal recent addresses made by APL staff members to groups and organizations outside the Laboratory.

- A. A. Westenberg, "Application of ESR Spectroscopy to Gas Phase Chemical Kinetics," *5th Aerospace Sciences Meeting of the AIAA*, New York, N.Y., Jan. 23, 1967.
- R. A. Farrell, "The Lattice Gas—Phase Transitions," *Physics Department Seminar, Catholic University*, Washington, D.C., Mar. 3, 1967.
- A. A. Westenberg and R. M. Fristrom, "Structure and Chemistry of Flames," *751st Meeting, Chemical Society of Washington*, Arlington, Va., Mar. 9, 1967.
- P. M. Bainum, "Design of Satellite Attitude Control Systems by Lyapunov Techniques," *Department of Engineering Control Systems Seminar, The Johns Hopkins University*, Baltimore, Md., Mar. 16, 1967.
- F. F. Hiltz, "Neuron Simulation and Data Processing," *Training Symposium on Mathematical Modeling and Analysis of Biological Systems*, Kensington, Md., Mar. 17, 1967.
- K. S. Bonwit (APL) and R. E. Rasche (Sperry Gyroscope Company), "CESSAM: Conversion Equipment System, Surface-to-Air Missile," *IEEE International Convention*, New York, N.Y., Mar. 20–23, 1967.
- M. L. Moon, "Surface Missile Systems," *U.S. Naval Reserve Research Company 5–11*, Annapolis, Md., Mar. 21, 1967.
- I. Katz, J. J. Hicks, and T. G. Konrad, "Radar Experiments with Chaff for Measuring Atmospheric Properties," *Conference on Physical Processes in the Lower Atmosphere, University of Michigan*, Ann Arbor, Mich., Mar. 20, 1967.
- I. Katz, "Probing the Clear Atmosphere with Radar," *Joint Session of IEEE Antennas and Propagation and Geoscience Electronics Groups*, Washington, D.C., Mar. 21, 1967.
- M. T. Miyasaki, "Using Hot Wire Anemometers for Airborne Meteorological Measurements," *International Symposium on Hot Wire Anemometry, University of Maryland*, College Park, Md., Mar. 21–22, 1967.
- R. A. Makofski, R. W. Henderson, and F. F. Mark, "A High-Pressure Hypersonic Gun Tunnel," *Fifth Hypervelocity Techniques Symposium*, Denver, Colo., Mar. 16–17, 1967.
- J. C. Murphy and J. Bohandy, "Growth of PbS Crystals in Silica Gel" and "ESR of Mn^{2+} and V in Strontium Tartrate," *March Meeting of the American Physical Society*, Chicago, Ill., Mar. 28, 1967.
- J. H. Martin (APL), R. L. Statler (NASA), and E. L. Ralph (Heliotek Corporation), "Radiation Damage to Thin Silicon Solar Cells," *Photovoltaic Specialists Conference*, Cocoa Beach, Fla., Mar. 28–31, 1967.
- Jane Olmer, "APL Information Processing System," *National Federation of Science Abstracting and Indexing Services Annual Meeting*, Philadelphia, Pa., Mar. 29–30, 1967.
- D. K. Anand and J. M. Whisnant, "Stability and Dynamic Response of Thermally Bent Booms Subjected to Varying Radiation Pressure," *Structural Dynamics Conference*, Palm Springs, Calif., March. 29–31, 1967.
- M. L. Hill, "Materials for Small Radius Leading Edges for Hypersonic Vehicles," *AIAA Structures*