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 TRANET 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.

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 as:

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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-
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 ovens 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/DM 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.

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) fre-
quency shifts due to ionospheric refraction, and (c) frequency shifts due to tropospheric refraction.
Making use of the frequency dependence of the refraction error signal, 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 cor-
rector are the corrected doppler signal and the first order refraction error signal, which is usually dis-
played 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 μsec) 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 Nc th cycle, where Nc is the pre-set number of cycles counted. The meter-
ing frequency is 1 or 5 Mc/s, depending on the equipment, and the pre-set count is almost con-
tinuously 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 tim-
ing 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-
technique, the tracking stations are able to maintain station clock timing accuracies to better than 0.3 msec.

The GEOCEIVER 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
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 nominal 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, defined roughly as containing all the factors that affect the quantity and quality of the data which are the inputs to the analysis program. 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 systematic 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 $\Delta t$ 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

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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 μsec 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 10^8 per day, corresponding to negligible position errors due to this effect.6


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.