used. The following satellite information is cataloged:

1) identification,
2) date and time of launching,
3) size and weight,
4) height of apogee and perigee,
5) maximum and minimum speed,
6) inclination of orbit to equator,
7) type of scientific and/or military data transmitted from satellite,
8) pertinent ancillary information.

In addition to interrogating targets on the display, it is possible to locate the track and position of any specific satellite by operating an identification switch on the panel. This action intensifies the trace of that particular orbit, thereby distinguishing it from the others. Through control switches, it is also possible to select the orbits to be displayed. In the future, when the number of satellites has increased to the point where displaying them all at once might not be feasible, it may be desirable to select satellites for display according to category, such as communications, weather, or surveillance.

Simulator Used as an Automatic Tracking System

Future developments will include the capability of making automatic corrections in the simulated orbits from live data at the detection sites. Receiving periodic corrections on all satellites, the unit could be considered an important component in a live satellite detection and tracking system.

Since the electronic function generators scan all positions of the satellites as represented on the map overlay, it is possible to sample the functions with the real-time position video signals and store the instantaneous position voltages on capacitors. The stored dc voltages would represent the latitudes and longitudes of each satellite. With appropriate gating circuits allowing the generated functions of each satellite orbit to be corrected only by the live data representing their respective satellites, the device remotely resembles a track-while-scan unit used in radar systems. Application of this technique to the automatic tracking of satellites is possible because of the repetitive nature and stability of the orbits in space.

Acknowledgment

The authors wish to thank M. Mellow, G. Reppucci, and C. Forsberg for their valuable assistance in the design and development of the electronic equipment, and for their diligent effort in conducting experiments and collecting and assembling data.

They also express their gratitude to B. S. Karasik, technical editor, for her assistance in preparing this paper.

The Navy Space Surveillance System*

R. L. EASTON†, MEMBER, IRE, AND J. J. FLEMING†, MEMBER, IRE

***Summary*—A complete system for satellite detection and tracking and for computations of satellite orbits has been built by the Navy under ARPA sponsorship. This detection system uses a CW transmitter separated from two receiving sites, all having fan-type coplanar antenna beams. The angle of arrival of the reflected signals is measured at each station by the use of an interferometer. The position of the reflecting object is inferred by the point in the fan antenna beam defined by the intersection of the arrival angles at the two receiving stations.**

Two ARPA-sponsored Space Surveillance radal (radio detection and location) devices of the type described have been installed in the southern U. S. In addition to the detecting and tracking installation the system includes data transmission lines, a data reduction center, a very high speed computer for orbit determination and predictions, and display devices.

Introduction

THE PROBLEM of detecting satellites is made difficult by their great height and velocity, and small size. The high velocity implies a short observation time but also implies great trajectory stability, so that a small number of independent observations properly separated on the ellipse serves to determine the orbit. The problem of detecting satellites is much different from that of tracking aircraft and ships for which the pulse radar was designed. For this earlier problem the target can maneuver rapidly and therefore required continuous tracking.

The detection system is shown schematically in Fig. 1. Here a transmitter antenna provides illumination in a narrow fan beam which is coplanar with similar re-

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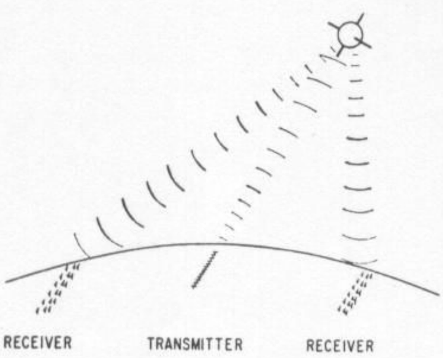

Fig. 1—The detection system used for space surveillance.

ceiving station beams. (Only that portion of the fan beam striking the satellite is shown in the figure.) The position of a reflecting object in the common antenna patterns is inferred by measuring the angle of reception of the reflected signals by means of interferometers at the two receiving sites.

The operation of the receiving stations is similar to that used by the system known as Minitrack[1] initiated by M. Rosen for use with Project Vanguard. The technique he suggested was similar to that used by several missile tracking systems, by radio astronomers, and by sonar. Minitrack was based largely on the missile tracking system AZUSA, built by the Convair Division of the General Dynamics Corporation. The operational principles of both systems appear to have been first conceived by Dr. H. L. Saxton of this Laboratory.[2]

Another contribution was made by Dr. J. J. Freeman[3] who analyzed this particular type of system. From his analysis it was simple to show that an interferometer system operating at a frequency of about 100 mc would require a radiated power of only a few milliwatts.

One of the problems existing in such a system is that of calibrating the angle measured electrically to the local zenith angle. Two techniques were implemented to provide the required calibration. One, involving ballistic camera photography of an airplane-carried flashing light, was demonstrated as practical by E. Habib, then of this Laboratory, and has been used as the standard calibration method for this system. The other method involved reflecting a signal off the moon. Then by knowing the local zenith angles of the moon and the corresponding electrical readings the required calibration was obtained, though with an accuracy much reduced from that obtainable with the ballistic camera.

The moon reflecting system consisted of a 50-kw FM transmitter installed to operate into a 50-ft dish at the Signal Corps Engineering Laboratories (now USARDL) at Ft. Monmouth, N. J. The transmitter was located and the work of the two laboratories was coordinated through the good offices of Lt. Col. E. J. Hagerman, Signal Corp Liaison Officer at the Naval Research Laboratory.

The moon reflection system was placed in operation in December, 1957. Early in 1958 the transmitter at SCEL was used to provide reflected signals from the remaining Sputnik (1957 Beta) into the tracking station at Blossom Point, Md., as shown in Fig. 2.

On June 20, 1958, the Advanced Research Projects Agency of the Department of Defense authorized the Naval Research Laboratory to provide one tracking complex in the Eastern United States and one in the Western United States as shown in Fig. 3. The NRL system is being expanded to form a continuous line across the Southern United States.

The first portion of the system to be placed in operation involved the stations at Fort Stewart, Ga., and Jordan Lake, Ala. This portion of the system was put in operation on July 29, 1958—less than six weeks after the ARPA Order was issued. This schedule was met by transporting the transmitter from SCEL to Jordan Lake and by modifying the Fort Stewart Minitrack station antennas to be compatible with this new system.

The Silver Lake installation became operational in November, 1958 and the Western Complex in February, 1959. The electronic equipment was built by Bendix Radio, the antennas by the Technical Appliance Company, and the transmitters were furnished by Multronics, Inc. The stations are operated by Bendix Field Operations Personnel.

THE RECEIVING SYSTEM

The receiving system has been described previously[1] so it will be discussed only briefly. Fig. 4 shows the principle of operation. After the signals from the two antennas are first amplified by preamplifiers, the output can be divided as necessary for the various phase comparisons required. By means of local oscillator circuits, the signals from the two antennas can be amplified in a single channel, thereby reducing the differential phase shift. When the combined signal is detected and compared to the difference-frequency, the resulting phase is equal to the phase difference between the signals arriving at the two antennas. The zero reading of the phase between the two signals will not normally read zero for an equal phase signal at the antenna. The difference between the phase read and the phase present at the antennas is found by means of a system of calibration.

CALIBRATION

As was mentioned, an interferometer system requires calibration and the most accurate means of calibration is the ballistic camera method. With the size of antennas used for space surveillance, however, the far zone of the antenna is many miles high—too high for conventional aircraft.

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[1] J. T. Mengel, "Tracking the earth satellite, and data transmission, by radio," PROC. IRE, vol. 44, pp. 755–760; June, 1956.

[2] H. L. Saxton, NRL Rept. No. 4003, July, 1952. (Confidential.)

[3] J. J. Freeman, "Principles of Noise," John Wiley and Sons, Inc., New York, N. Y., pp. 271–274; 1958.

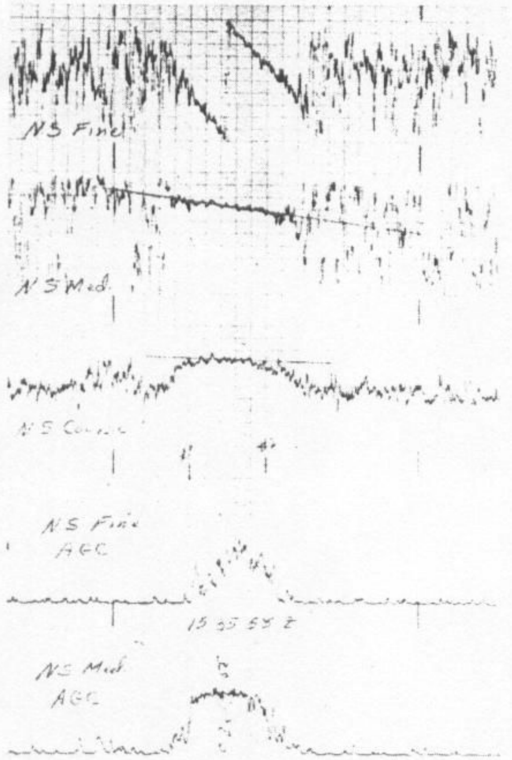

Fig. 2—Reflected signal obtained from 1957 Beta satellite.

Fig. 3—Location of tracking stations.

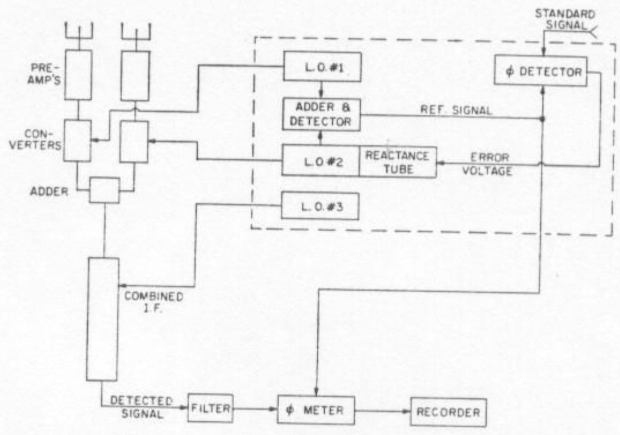

Fig. 4—Block diagram of receiving system.

For calibration a distant source in a known position is required. A device that meets this requirement is the Vanguard I satellite, 1958 Beta, whose position is well known from the orbit computed by NASA. Even though the orbit of this satellite is the best known of any, the data for calibration purposes must still be obtained from post flight rather than predicted data. Once the data is obtained the calibration is made by comparison with the electrical data. Since the orbital data is obtained by calibrating the Minitrack stations against the stars, the Space Surveillance stations are also calibrated against the same standards—though with diminished accuracy.

SIGNALS

Fig. 5 shows the signal obtained from the calibration satellite, 1958 Beta. The inclination of this satellite is nearly the same as the latitude of the Space Surveillance line, so its signals remain in the antenna beamwidth for a considerable time. In general the signal reflected will appear similar to a very small portion of this direct signal, though the reflected signals are much noisier than the direct signals. A reflected signal from another satellite is shown in Fig. 6.

In addition to signals reflected from satellites many extraneous signals are present. They appear as reflections from meteorite trails, from aircraft, and as direct signals from radiating satellites, electrical storms, radio stars, direct feedthrough from transmitter to receiver, and man-made interference. One of the most prevalent interfering signals is due to meteorites. Fig. 7 shows one of the signals obtained during a time of high meteorite activity.

The simplest means of reducing meteorite reflections is illustrated in Fig. 8. Here the polarization of the transmitting antenna is opposite to that used on the receiving antenna. The record also shows a receiving antenna having the same polarization as the transmitter. A count of incidences on the two receiving channels shows that approximately only 5 per cent as many signals appear on the receiving antennas having the opposite polarization to the transmitter as appear on the antenna having the same polarization as the transmitter.

The reason for the reduction in meteorite reflections is understood when it is realized that the meteorite trails in general are formed below the ionosphere and that the most usual excitation of the meteorite trail is the one due to the indivudual electrons oscillating in the polarization of the exciting element. Since the excitation of the transmitting antenna is not subject to Faraday

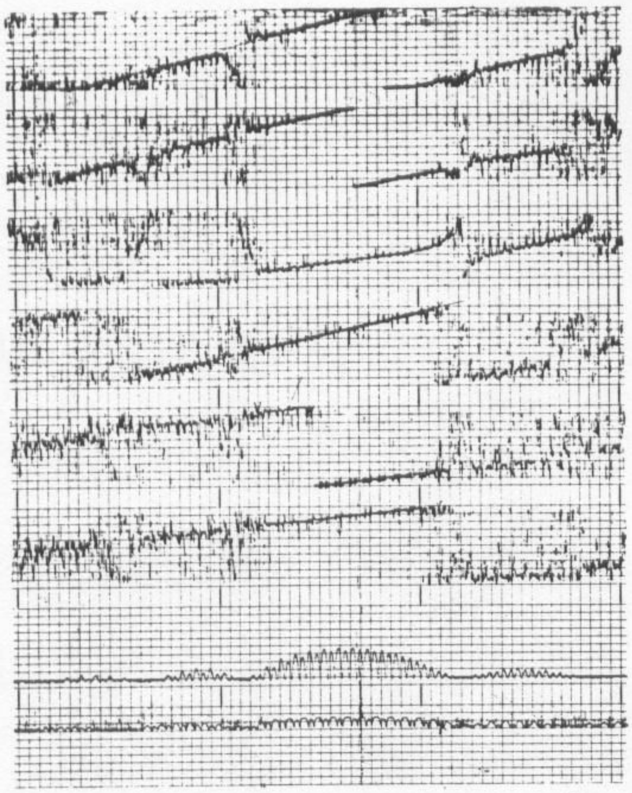

Fig. 5—Direct signal from 1958 Beta 2 (Vanguard I) satellite.

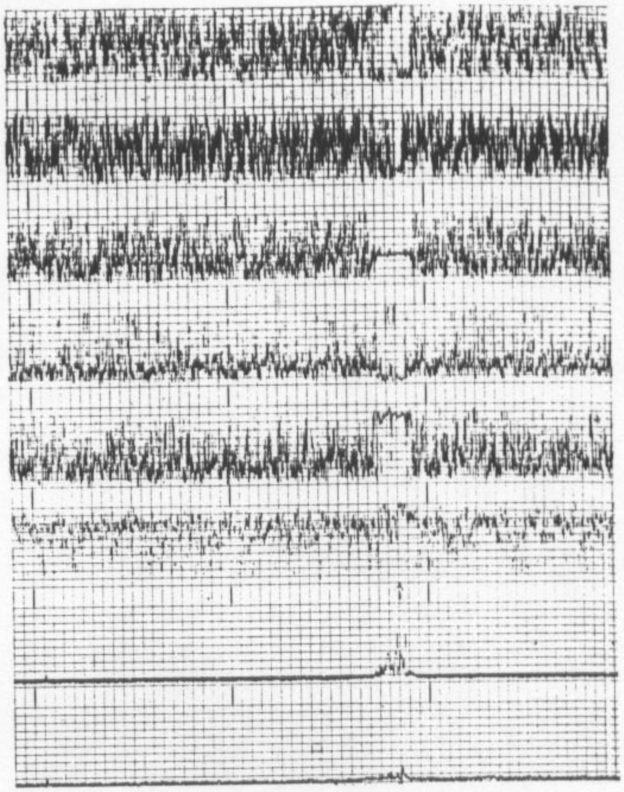

Fig. 7—Reflected signal from meteorite trail.

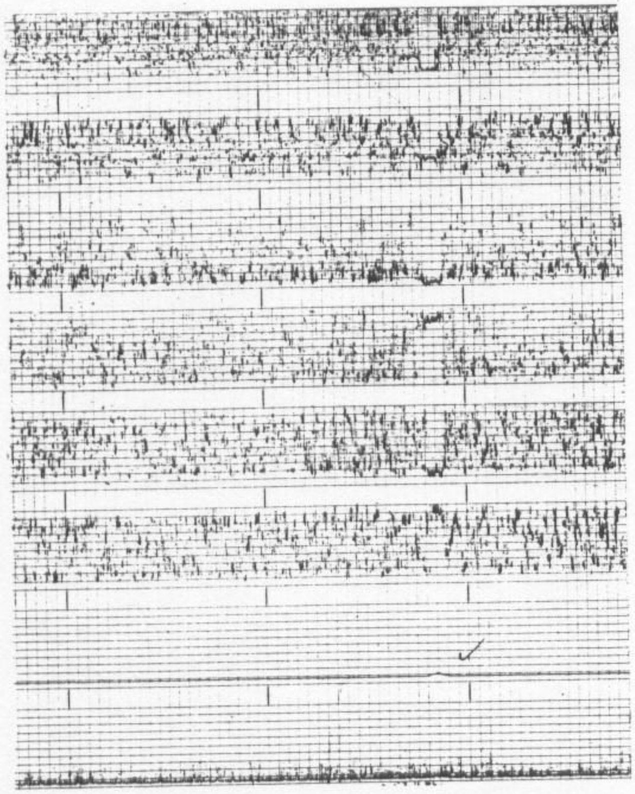

Fig. 6—Reflected signal from satellite.

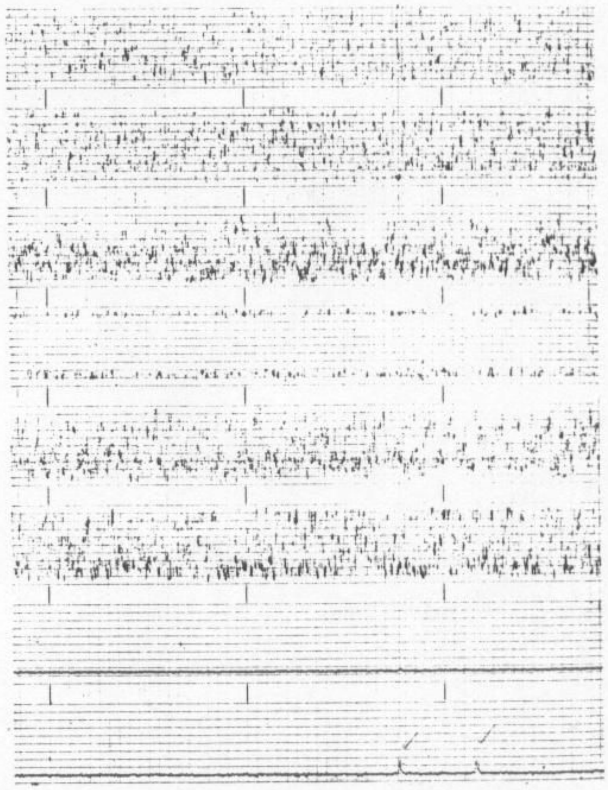

Fig. 8—Reduction in reflections due to meteorite trails by cross polarizing transmitting and receiving antennas. (Bottom trace shows the output of a receiver having the same antenna polarization as the transmitter; the next trace above shows the output of a receiver having the antenna polarization crossed to that of transmitter.)

rotation at the usual height of meteorite trails, the type of reflection described above will be cross-polarized to an antenna having a polarization crossed to the transmitter. Under these conditions the response from meteorites can be expected to be low. Reflections from satellites occur from within or above the ionosphere and the polarization of such signals is subject to Faraday rotation so the polarization of the received signal can be expected to be random.

STATIONS

The stations involve large antenna installations. The Jordan Lake transmitting site is shown in Fig. 9. The Fort Stewart installation is considered the R&D receiving station and hence is larger than the other receiving sites. At each receiving station the information from the phase meters is placed on direct reading recorders and is also placed on phone lines for real time transmission to the Naval Research Laboratory and to the Naval Weapons Laboratory at Dahlgren, Va. The data is sent using standard FM telemetry subcarriers directly on a standard telephone line.

SPACE SURVEILLANCE OPERATIONS CENTER

During the experimental phase of system operation, the Space Surveillance Control Center is located at NRL. It is normally operated on an 8-hour day and 5-day week. An experimental operations center is also located there both for the development of improved operational techniques and for serving as a backup for the Space Surveillance Operations Center at Dahlgren, Va., which is in operation around-the-clock seven days a week. The analog data representing phase and signal-level information of interest are read manually immediately after they are recorded at Dahlgren. The observations are used for improving the predictions of known satellites and determining the orbits of unknown satellites crossing the Space Surveillance line.

The Space Surveillance Operations Center has been established at the Naval Weapons Laboratory (Dahlgren, Va.) so that it could take advantage of the NORC (Naval Ordnance Research Computer) and of the NWL staff. The NORC computer is especially well suited for orbit computations since it has both a high precision (13 significant decimal digits plus sign and exponent) and a high speed (15,000 operations per second). A picture of the NORC is shown in Fig. 10 and a table of its operating characteristics is as follows:

Number system:	Decimal (Automatic floating point).
Word size:	16 digits and check digit.
Instructions:	3-address.
Storage capacity:	2000 words (electrostatic). 20,000 words (magnetic core) being added.
Storage access time:	8 μsec.
Multiplication time:	31 μsec.
Addition time:	15 μsec.
Magnetic tape units:	8 operating at 70,000 characters per second.
Printers:	2 mechanical operating at 300 characters per second. 1 optical printer operating at 15,000 characters per second.

Fig. 9—The Jordan Lake transmitting site.

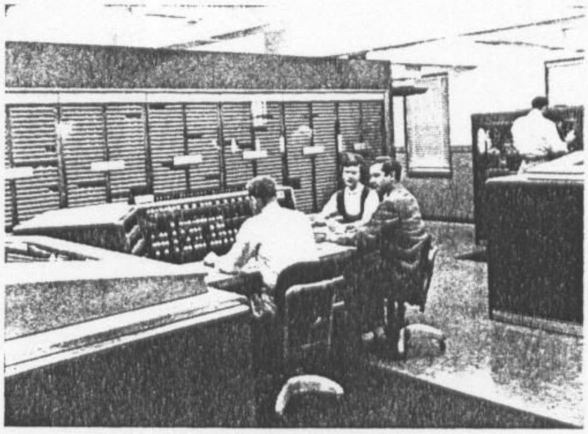

Fig. 10—The Naval Ordnance Research Computer (NORC).

ORBIT COMPUTATIONS

The mathematical formulation of the orbit-computation programs has been the responsibility of Dr. P. Herget (Director of the Cincinnati Observatory) under contract to NRL and of Dr. G. M. Clemence and Dr. R. L. Duncombe, both of the U. S. Naval Observatory. The analysis, programming, and some of the mathematical formulation are being done by NWL.

The orbit computations required for satellites are divided into two parts: a) determination of the orbital elements from the observations, and b) prediction of future satellite positions from these elements (compilation of an ephemeris). For initial orbit determination and prediction, Cowell's method of numerical integration[4] is used; for large numbers of observations, the method of general oblateness perturbations[5] is employed. Six elements are needed to describe an elliptical orbit at some given time T_0 (called the epoch). These elements are derived from the observations when there is sufficient information available to be equivalent to a position vector and a velocity vector at a given time.

The orbital elements are refined automatically on the NORC by successive application of a differential correction procedure until the residuals between all the observations and the positions computed from the ele-

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[4] P. Herget, "The Computation of Orbits," 1958. (Published by the author.)

[5] P. Herget and P. Munsen, "A modified Hansen lunar theory for artificial satellites," *Astronomical J.*, vol. 63, pp. 430–433; November, 1958.

ments have become small. The best available set of elements is used to compute a position vector in geocentric inertial space for the satellite for every minute of time in the future (for days or weeks, depending on the type or orbit) for predictions. Both in orbit determination and prediction, the position of the satellite as computed from the elements is corrected for perturbations due to the earth's oblateness and atmospheric drag. Depending on the requirements of the user, predictions as needed are computed in the form of a world map (longitude and latitude of the subsatellite point on the earth and the height of the satellite above the earth), or of local station predictions (range, bearing, and elevation information at frequent time intervals for optical instruments or narrow-beam radars to view the satellite), or of beam-crossing predictions (time, height above the earth, and zenith angle) for Space Surveillance stations.

The six elements needed to describe an elliptical orbit at time T_0 (epoch) may be given as follows:

Semimajor axis (a)
Eccentricity (e)
Inclination (i)
Right ascension of ascending node (θ_0)
Argument of perigee (ω_0)
Mean anomaly at epoch (M_0).

The epoch is given as the year, month, day, hour, minute, and second in universal time. The semimajor axis of the ellipse is measured in earth's equatorial radii (equatorial radius is 3963.34 statute miles based on the international ellipsoid for the shape of the earth[6]). The eccentricity is a ratio which is always less than unity for an ellipse and is equal to zero for a circle. The inclination (see Fig. 11) is the angle measured in degrees from the equatorial plane of the earth to the orbital plane at the ascending node (that is, where the satellite crosses the equator in a northward direction). The right ascension of the ascending node is measured in degrees eastward along the earth's equator from the vernal equinox to the ascending node. The vernal equinox establishes the x-axis for the geocentric inertial coordinate system, the z-axis passing through the earth's North pole, and the y-axis lying in the equatorial plane to form a right-handed coordinate system. The argument of perigee (point of closest approach to the earth) is the angle in degrees measured in the orbital plane from the ascending node to the perigee. The mean anomaly at epoch is given in degrees and represents the position of the satellite in the orbit with respect to the perigee.

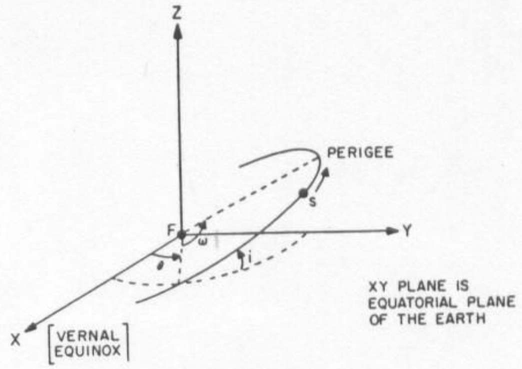

Fig. 11—Coordinate reference system.

If there were no disturbing forces exerted on the satellite, its orbit would not change with time and predictions of future satellite positions would be made simply on the basis of an ellipse fixed in inertial space. For most artificial earth satellites, there are two major disturbing forces which must be taken into account: one resulting from the shape of the earth (the equatorial bulge), and one resulting from the presence of the atmosphere. Because of the distribution of the mass of the earth, there is motion of the perigee in the orbital plane and motion of the node in the equatorial plane. Because of the energy removed from the orbit by atmospheric drag on the satellite, the orbit collapses with time, the apogee (farthest point from the earth) shrinking many times faster than the perigee. These perturbations are taken into account both in orbit determination and prediction.

An example of a complete set of elements and related information is given for the satellite 1958 Beta 2 (Vanguard I) as released from the Vanguard Computing Center as follows:

Epoch	October 22, 1959	122700 UT
Anomalistic period	134.04899	Minutes
Period decay	−0.0001	Minutes per day
Inclination	34.249	Degrees
R.A. of ascending node	191.613	Degrees
Motion of node	−3.023	Degrees per day
Argument of perigee	182.671	Degrees
Motion of perigee	4.415	Degrees per day
Latitude of perigee	−1.503	Degrees
Mean anomaly at epoch	160.459	Degrees
Eccentricity	0.18963	
Semimajor axis	1.36030	Earth radii
Perigee height	405.6	Statute miles
Apogee height	2,450.3	Statute miles
Velocity at perigee	18,371	Miles per hour
Velocity at apogee	12,514	Miles per hour

The anomalistic period is the time for the satellite to make a complete revolution from perigee to perigee. Depending on the orbital elements, the motions of node and perigee are only a few degrees a day at most. For a polar orbit ($i=90°$), there is no motion of the node; and for an orbit having an inclination of $63\frac{1}{2}°$, there is no motion of the perigee. The perigee and apogee heights

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[6] "The American Ephemeris and Nautical Almanac for the Year 1959," U. S. Naval Observatory, Washington, D. C.; 1957.

are measured from the surface of the earth, which is taken to correspond to the equatorial radius in this case.

A catalog of all satellites is maintained by the NORC computer and can be displayed as subsatellite positions projected on a world map. Fig. 12 illustrates the appearance of the display, called SPASCORE, for which the film is normally projected at one frame per minute in "real time" but may be run forward or backward at 20 frames per second. The map overlay on the projection screen is a modified cylindrical projection of the earth. The subsatellite positions are calculated by the NORC and automatically recorded on 35-mm film from a Charactron cathode-ray-tube output device, which is also used as an optical printer for alphanumeric data output. This equipment provides great versatility in displaying the computer output; it can be operated on-line with the computer to project the output in real-time with a delay of as little as eight seconds or to record the output on film at 40 frames per second for later development and projection.

The most important output of the Space Surveillance System is information on nonradiating satellites. Orbital elements can be computed and predictions of future satellite positions can be given to those authorized to receive such information. The System also has been used to augment the observations of radiating satellites.

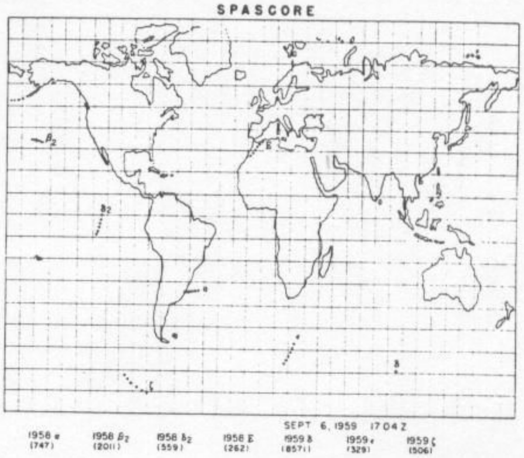

Fig. 12—NORC output display (SPASCORE).

Discussion

The radal (radio detection and location) system described differs from a pulse radar in principle and in detail differs greatly. Pulse radar[7] uses a single installation from which energy is transmitted and received. The location of reflecting objects is inferred from the angle of arrival and from the time delay between transmission and reception. Previous to and during World War II the angle of reception was derived from the antenna direction. The monopulse radar,[8] also developed at this Laboratory, derives its angular information from several simultaneous observations of the angle of reception of the incident wave. Pulse radars were developed for detecting and tracking ships and aircraft, objects which have great maneuverability but low speeds.

The radal system is designed to detect and locate objects having great speed but very limited maneuverability. For such objects a great range capability but a modest number of sightings serves to determine the path of the object for days to come.

To satisfy the requirement of detection at great ranges the system has been designed to maximize range capability. Since a larger average power can be generated economically at CW than with pulses, a CW system is indicated. To use antennas having large capture areas without unusably small beamwidths, a low frequency is used. The antenna beamwidths are designed to detect over a large angle in one direction and a very narrow angle in the other. This technique permits detection of objects passing through an area of large dimensions but small volume.

An integral part of the Space Surveillance System is a high-precision, high-speed digital computer to process the observations with a minimum time delay. Thus a catalog of all orbiting objects within range of the system is maintained to produce predictions of their future positions for the use of authorized customers.

The present system has demonstrated itself to be effective and reliable. Improvements are planned and will be installed as time and funds allow. An additional transmitter is expected to be located in the central portion of the line in the near future. The present system of analog data transmission and manual data reading is expected to be replaced by a digital transmission system to permit fully automatic data handling by the computer.

Acknowledgment

The authors wish to acknowledge their indebtedness to Dr. C. E. Cleeton, Superintendent of the Applications Research Division, and Captain W. E. Berg, Senior Program Officer for Military Applications of Satellites, U. S. Naval Research Laboratory, Washington, D. C., for their continuing helpful guidance on the Space Surveillance project, which has engaged the talents and interest of a large part of the Division. Above all, they wish to acknowledge the tireless efforts of their colleagues, to whom they attribute the success of the project.

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[7] A. H. Taylor, "Radio Reminiscences: a Half Century," Naval Research Lab., Washington, D. C., pp. 294–308; 1948.

[8] R. M. Page, "Monopulse radar," 1955 IRE Convention Record, pt. 8; pp. 132–134.