TRANSIT NAVIGATION SATELLITE

by Lauren J. Rueger*

The Applied Physics Laboratory has nothing particularly spectacular to offer in the form of time transfer; however, the navigation satellite system has provided precision time from the beginning. The concept on which the system was based was formulated about 1960 and has a timing requirement-- specifically, a self-consistent time synchronization between the satellite and the ground system. This synchronization must be within 2 msecs. The navigator who uses the system can have timing errors up to about 30 seconds, which cause no inconvenience, and even errors up to 15 minutes can be handled.

The carrier frequencies to the system are important, and in the signal frequency measurements, the satellite and the navigating equipment must have local-oscillator frequency stabilities which do not depart by more than one part in 10^9 over the observation period. A correlation has been established between time/frequency errors and navigation accuracy. The relation is very nearly a linear function of the frequency and time errors. The proportional constants are 1/10 of a nautical mile error for a frequency disturbance of one part in 10^9 during the observation time, and a .004 nautical mile error for a timing error of 1 msec. The timing error corresponds directly to the distance traveled by the satellite which is moving at about 7 meters per millisecond.

This paper will present data to support the claim of 10 μsecs time synchronization with equipment for this program. The program also has

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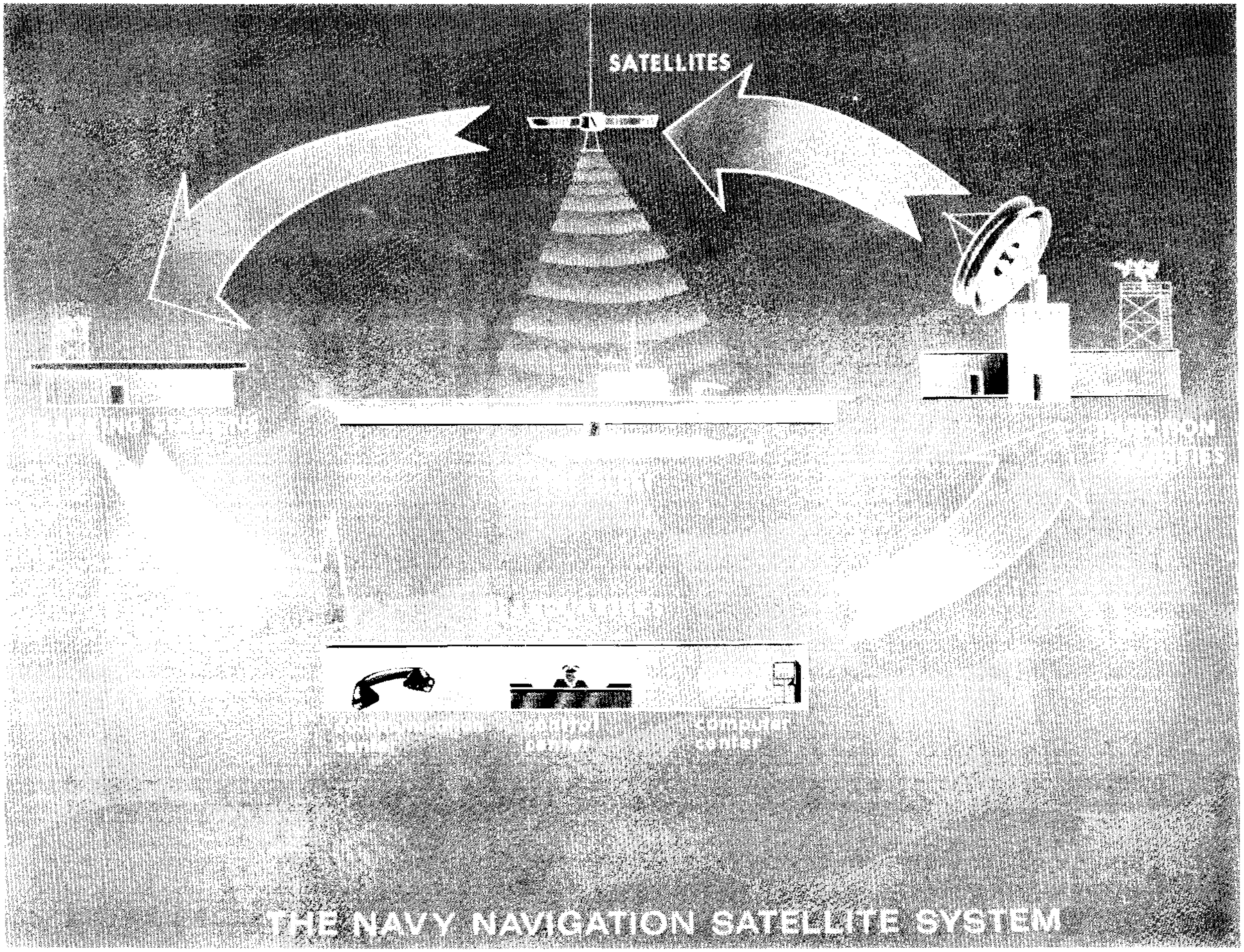
in-orbit reference oscillator stability performance of better than one part in 10^9 over an interval of 100 days, or better than one part in 10^{11} oscillator stability per day. Figures are included to explain how the system works.

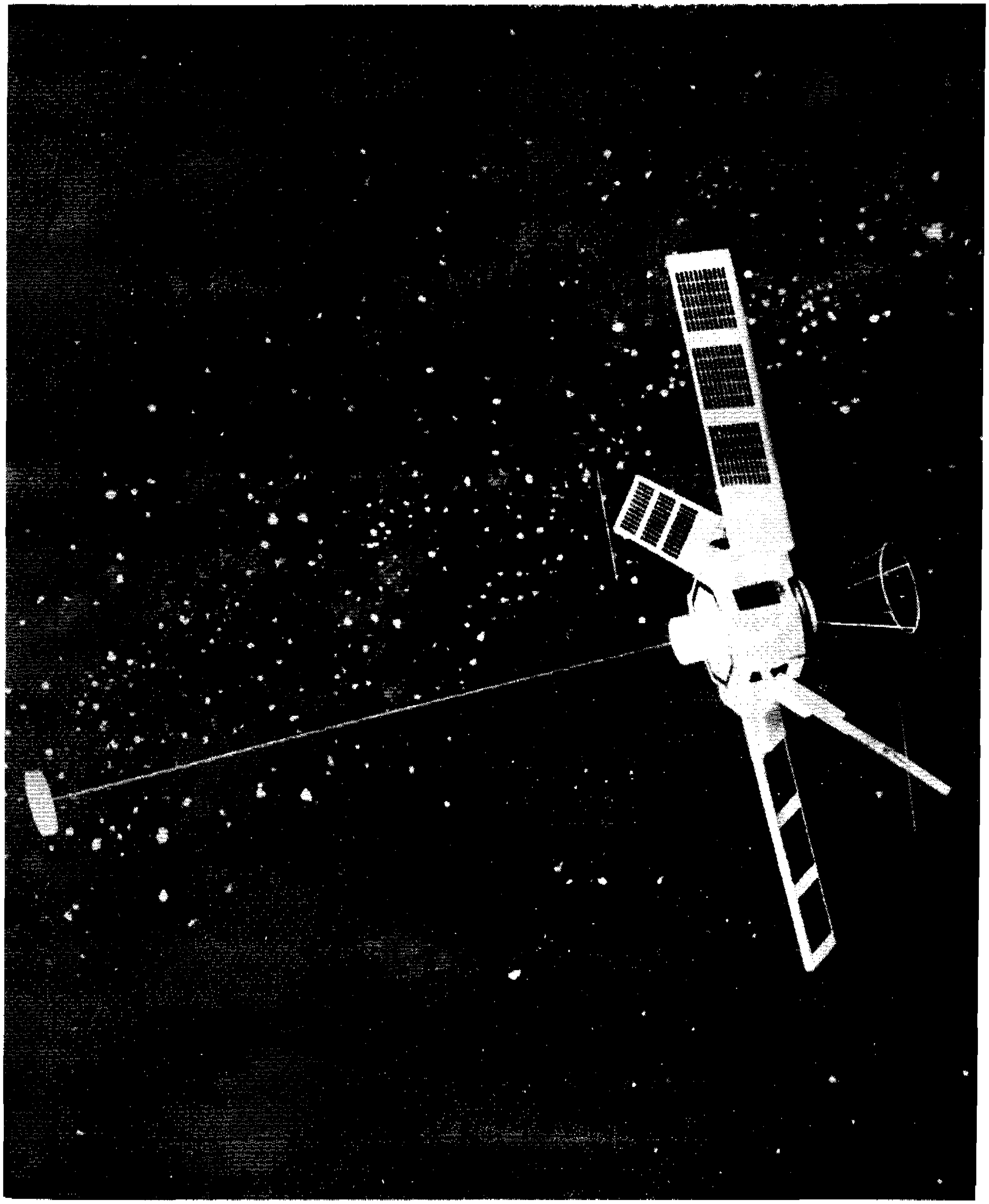
The circle can be entered (see Figure 1) at any selected place. Once the satellite is in orbit, it transmits on 150 to 400 mc, a crystal stabilized signal, which is picked up by ground tracking stations. These are located on U.S. territory. Records are kept of the frequency transmitted by the satellite as a function of time and are then transmitted to headquarters, where a central computer determines where the satellite has been traveling and predicts where it will be in the next 16 hours. That information then is injected by a signal from a ground-based transmitter into the satellite, and the satellite stores its predicted orbit for the next 16 hours. The satellite then transmits its position in a simple Kepler coordinate system plus small 3-D corrections. A navigator uses the system by recovering the orbit data from the satellite and measuring the doppler shift of the carriers. By knowing where the satellite is located, from the orbit data, and determining the geometry between the satellite and navigator from the doppler, it is possible to get a navigation fix.

Figure 2 is a picture of one of these satellites. It is not a very pretentious device--it weighs about 112 pounds when deployed in orbit; gets its power from solar cells that charge batteries; and uses a circularly polarized antenna, so that a very simple non-directional whip antenna can be used for ground-based reception. The directional antenna is aimed at the earth because there is a pendulum that makes it hang in space. It is a gravity gradient stabilized satellite.

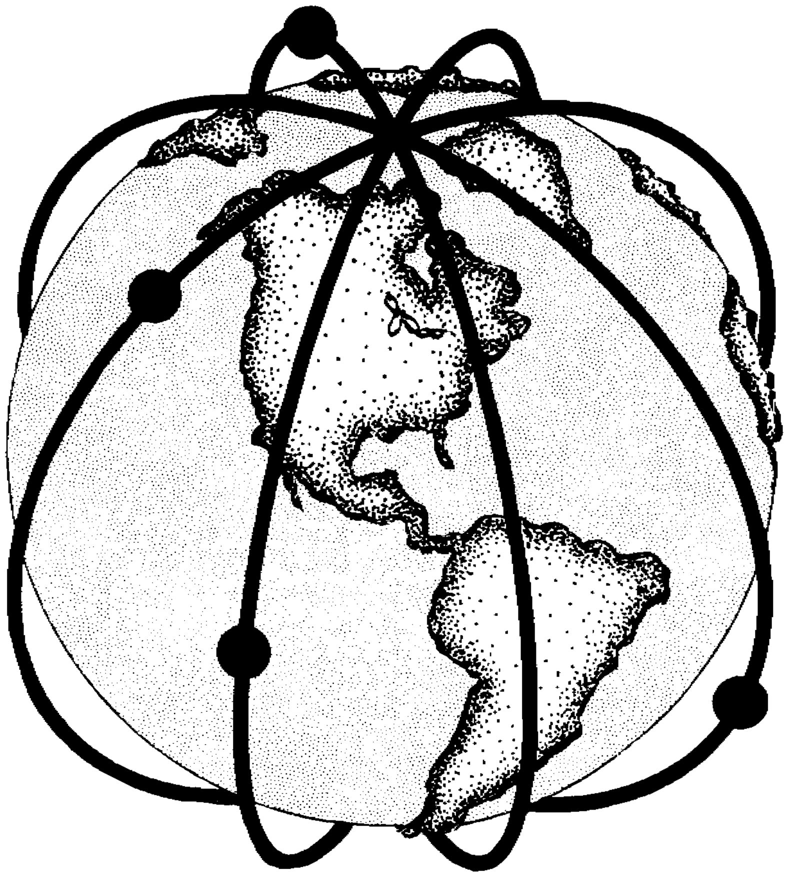
The concept of how the orbits are planned is shown in Figure 3. Any one of the satellites serves the entire world. These satellites are 600 miles above the earth and are in nearly circular polar orbits. They



THE NAVY NAVIGATION SATELLITE SYSTEM



NAVIGATIONAL SATELLITE SYSTEM



FOUR POLAR ORBITS

REV. APR. 1963

were planned to be about 45 degrees apart around the equator, but since some of these have had long service lives and were not launced into the exact polar plane,they have precessed away from the 45-degree separations. There are five in service at the present time.

Basically, Figure 4 shows what each of the satellites contains. This is a crystal oscillator and a double-proportional oven; it is a fifth overtone, 5-mc crystal, from which both the time system and the carriers are derived. This is the receiver that stores in its memory the location of the satellite. It is binary digitally encoded data that phase-modulates the carriers.

From the very start, precision time has been provided as a service. There is not an established requirement that it be UTC, however, because to use the system, the navigators do not have to synchronize to anything but system-time. Time is recovered from the satellite from a unique signal that is transmitted about every two minutes. Navigation is performed on the basis of time kept by the satellite.

Figure 5 shows the diversity that the program has undertaken in its years of service. It started off as a navigation aid to the POLARIS submarine. The instrumentation includes a receiver, a computer, and a lot of peripheral gear to keep records, as well as to make the computer programming more sophisticated as the geodetic knowledge expands. The Laboratory developed a small unit for the surface equipment which has been used for over five years by surface units. The military version is just taking its place this year. The satellite navigation program got off on some tangents because it was found that the earth really was not well enough defined in the geodetic form for an observer to tell precisely where a satellite was going to be in the future. The geodetic program requires data from many locations. The figure shows a very small receiver for taking geodetic-type information, suitable for operation anywhere in the world for good surveying data. Also on the figure is a piece of back-track

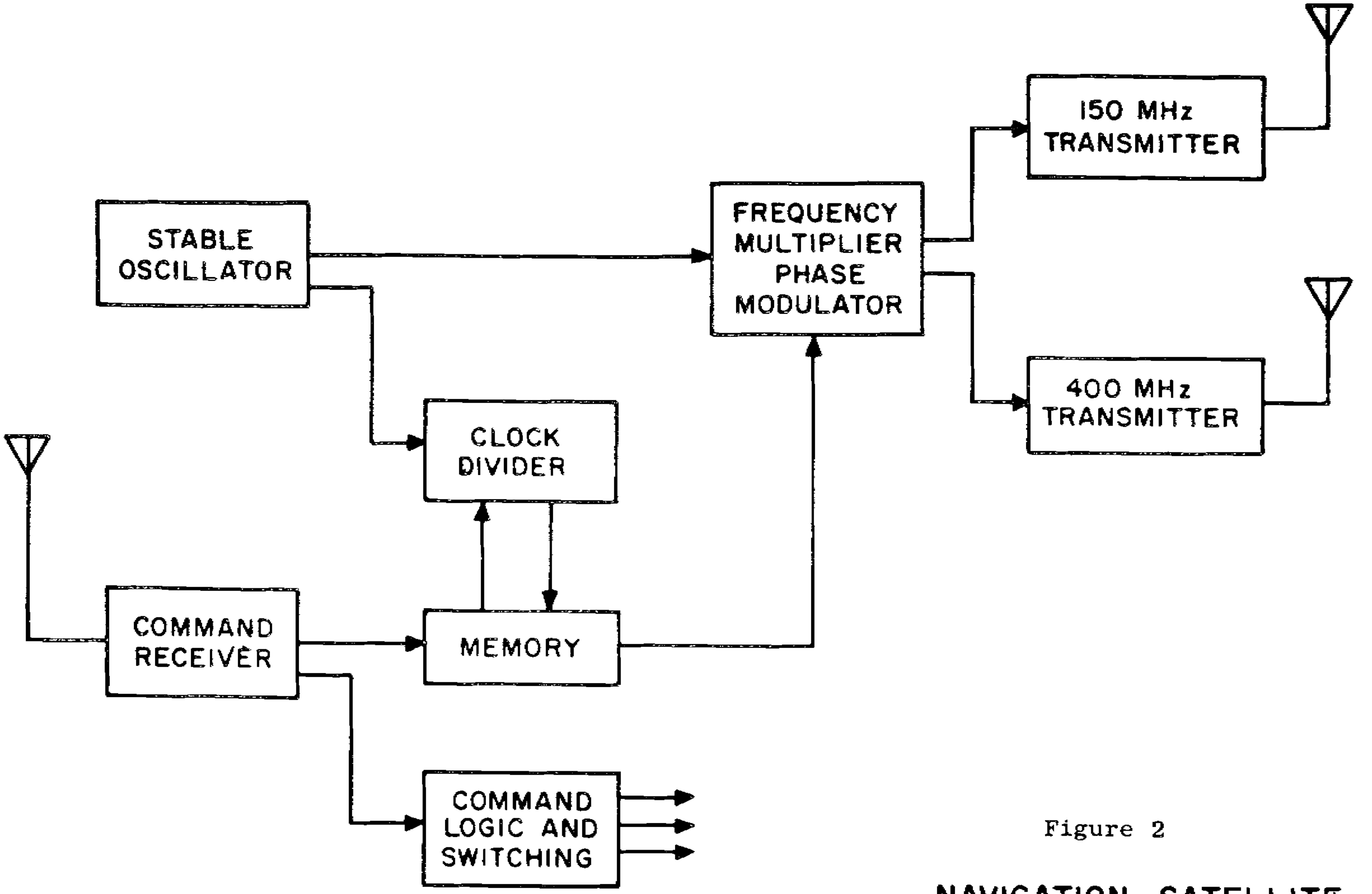
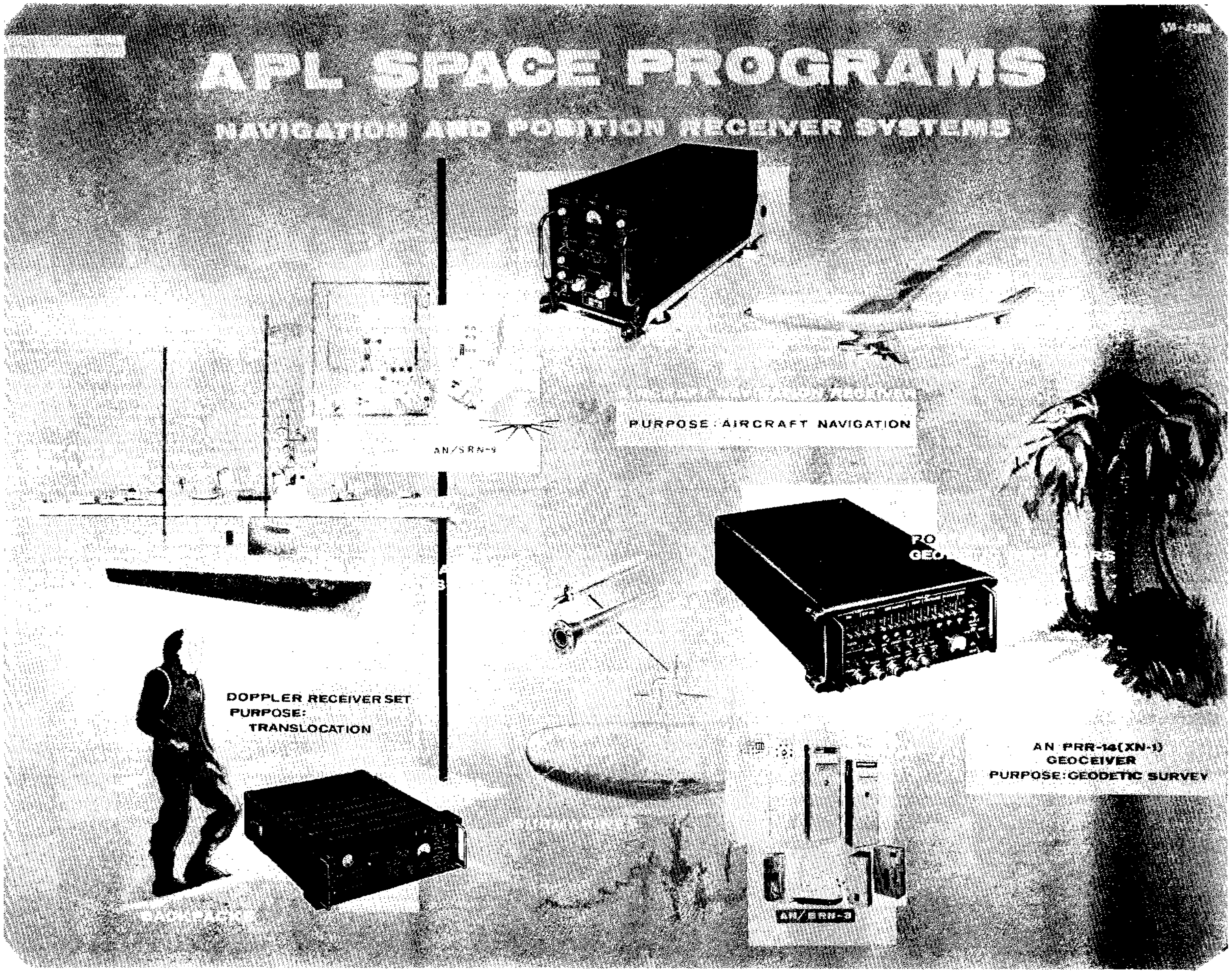


Figure 2

NAVIGATION SATELLITE
BLOCK DIAGRAM



APL SPACE PROGRAMS

NAVIGATION AND POSITION RECEIVER SYSTEMS

equipment so small that people can take their positions on a man-portable set. These things are real hardware; they work, but they are not yet available in large quantities. This geodetic effort turned out to be more significant than the Laboratory expected.

Figure 6 shows what was found out about the earth--it really is not round any more. If you describe the earth from the mathematical function as an oblate spheroid, the little contours represent about 10-meter departures from that mathematical function. This type of information was essential in order to realize the kind of precision that is being obtained from the navigation system. It was necessary to set up a world-wide tracking network to keep track of the very small permutations of the orbit as the satellite went around the earth.

Figure 7 shows the positions of stations operated in support of this work. There are about 12 permanently located stations which have been in service for periods longer than five years, and which generate the data base that has been acquired by tracking satellites. Satellites in orbits of different inclinations and altitudes have provided the data base on which the present world geodesy is formulated.

Figure 8 lists the stations which have station numbers assigned to them. This gives an idea of the timing residuals received in some of the stations in their time synchronization on a routine basis. (This happens to be for the month of April for one of the operational navigation satellites.)

The observers take a number of timing data points each time the satellite goes by, and then they compute the rms residual of that group of points, (e.g., for two satellite passes, the rms errors were 10 μsecs or less for station 008; that station is located in Brazil). The local station in Howard County, station 111, is one of the better frequency and time control stations, and these measurements show that the timing residuals are very low. One of the operational stations, station 330, which is operated by

SITES OCCUPIED BY DOPPLER TRACKING EQUIPMENT
1959 - DEC 1968

DISTRIBUTION OF APL TIMING RESIDUAL RMS FOR SATELLITE 1967-92A, 1-30 APRIL 1970

Station	RMS (Milliseconds)															Total
	.01	.02	.03	.04.	05	.06	.07	.08	.09	.10	.11	.12	.13	.14	.15*	
008	2	1		2	3											8
013	1	2	2	4	1											10
014	10	7	1	1												19
018	5	11	14	17	8	5	2	1		2					1	66
019	5	20	21	11	4	1	1									63
020	4	4	5		1											14
103	7	6	5		1											19
106	5	1	7	4	4	2										23
111	20	3														23
112	1	4	12	5		1										23
115	1	6	7		2											16
117	2	6	5	2	1			1								17
121	3	5	3	5	2											18
330	16															16
700			1													1
733	12	1														13
765	1	2	5	4	2	3		1								18
766	1	1	4		2											8
895			2	1		1	3	2								9
896	12	19	8	6												45
898		4	3	6	6	4	1	1		1						26
911	5	2														7

*0.15 or over.

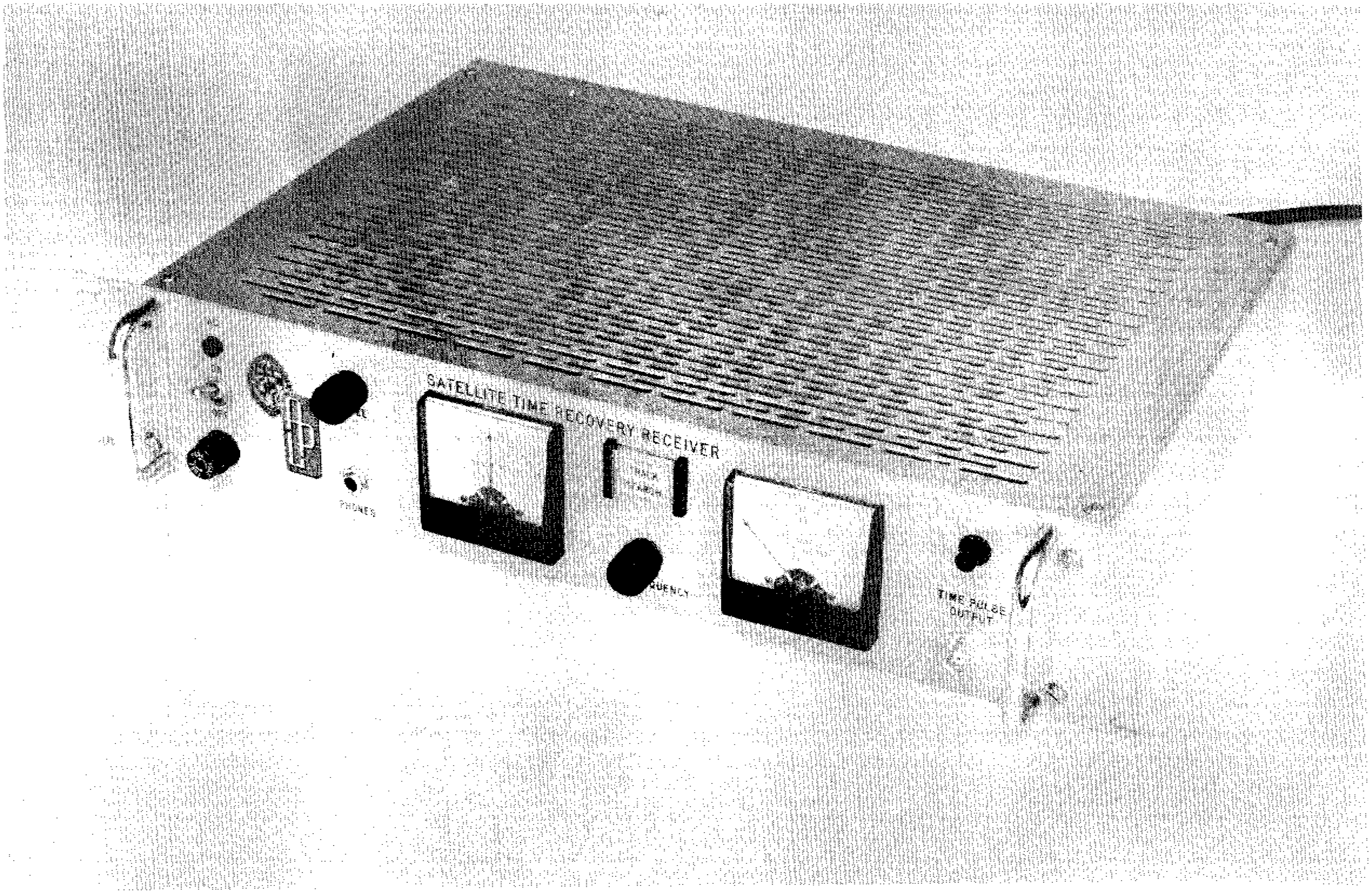
the Navy on the West Coast, is shown on the figure. Others are located in various places, such as Australia 112, 115 in South Africa, and 117 in the Seychelles.

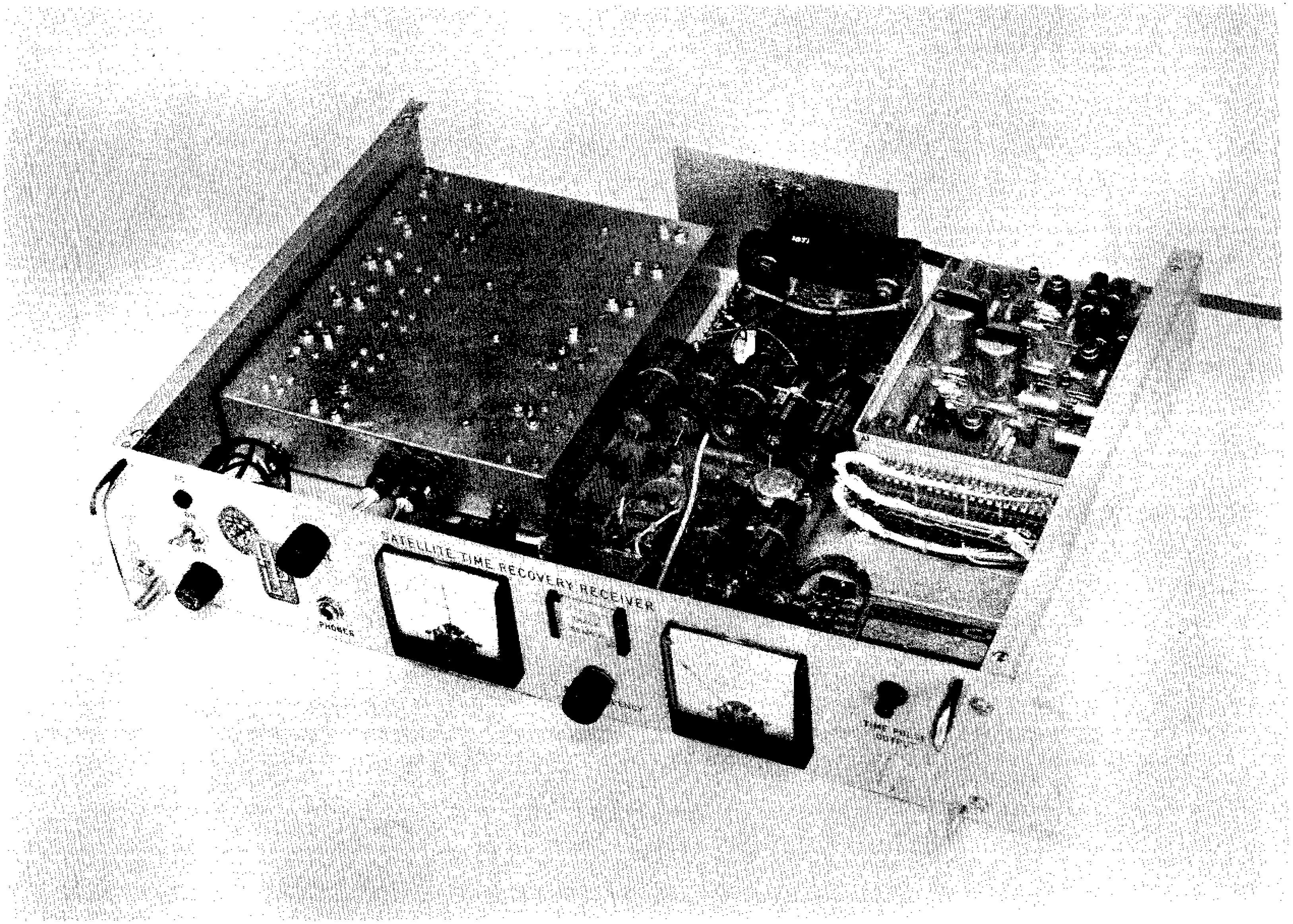
The people operating the tracking station at the APL site have had to be on duty 24 hours a day, 7 days a week, so they have had some spare time on their hands. These operators worked up a design for a satellite time recovery receiver that is quite small. Figure 9 is a picture of one of these units, however, it does not represent a state-of-the-art engineering effort.

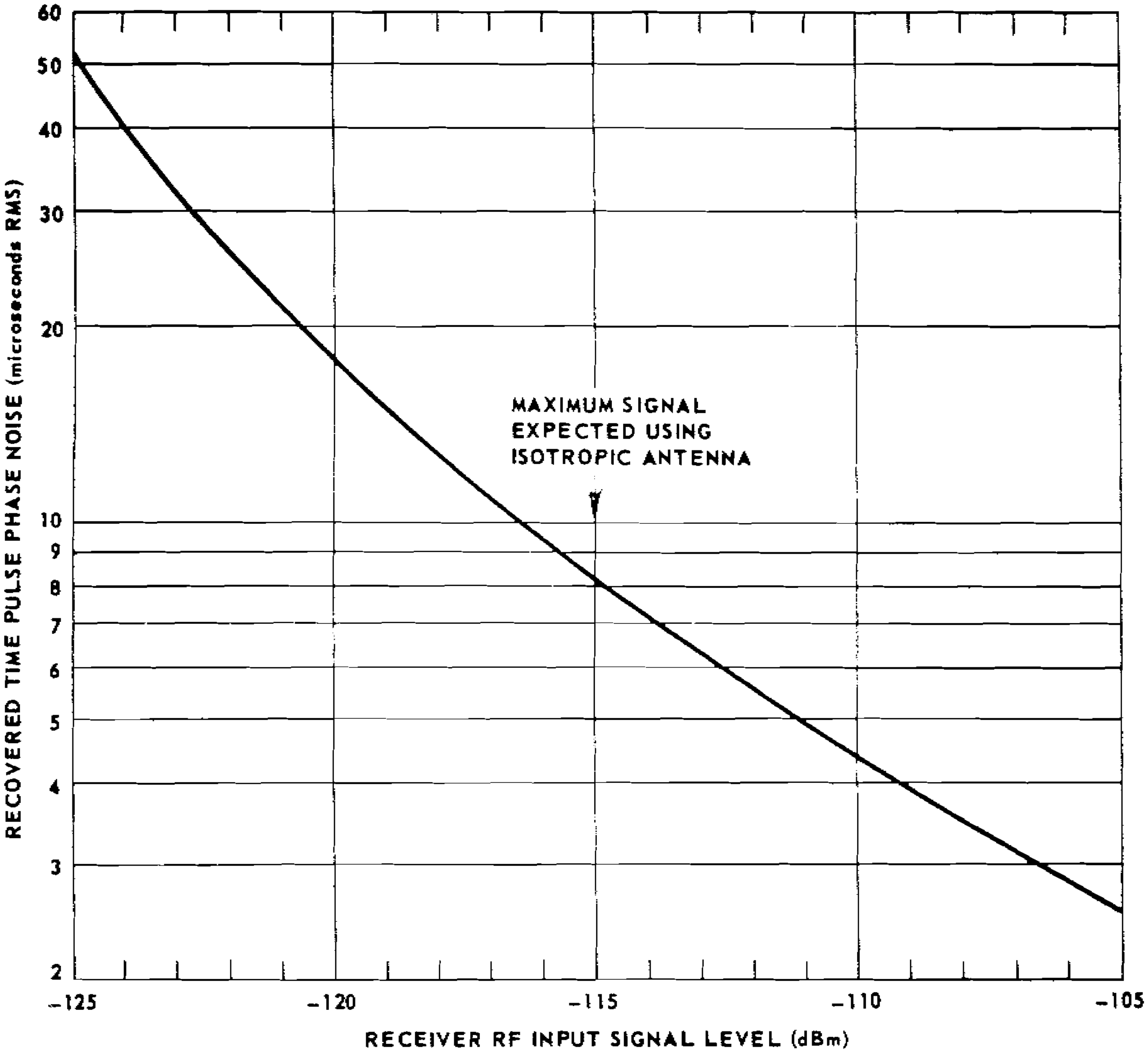
Figure 10 shows the inside of the satellite time recovery receiver, which is a tracking filter-type receiver at 400 MHz, and some digital logic. These are integrated circuits, TO-5 cans, and also a power supply.

Figure 11 shows the performance that is being realized by this instrument. The phase noise in the receiver is plotted as a function of signal-noise signal-level. It operates normally on a non-directional antenna. Normal satellite signal levels are about -115 db which represents an instrumentation error of about 8 μsecs in time recovery by this instrument.

Figure 12 shows some of the pertinent parameters regarding the model shown in the previous figures. This data relates to the first model built. There is an improved model that has a little better signal-noise ratio and an instrumentation error of about 5 μsecs. The signal is at a frequency of 400 mc -80 parts per million and has a doppler shift of ± two parts in 10^5. The phase-locked loop in this unit is 15 cycles wide and the timing output is a 10-volt spike with a 2/10 μsec rise time. It occupies $3\frac{1}{4}$ inches of panel space, weighs 15 pounds, and uses 10 watts average power. APL is not in a position to manufacture these items in quantity, so the Coast Guard has put in an order to a small company in the Annapolis area for a quantity of ten. They sell for about $2500.


SATELLITE TIME RECOVERY RECEIVER
PHONES
TRACK
SEARCH
QUENCY
TIME PULSE
OUTPUT


SATELLITE TIME RECOVERY RECEIVER
PHONES
TIME PULSE OUTPUT



NAVIGATION SATELLITE TIME RECOVERY RECEIVER FIDUCIAL TIME RECOVERY PHASE NOISE

NAVIGATION SATELLITE TIME RECOVERY RECEIVER

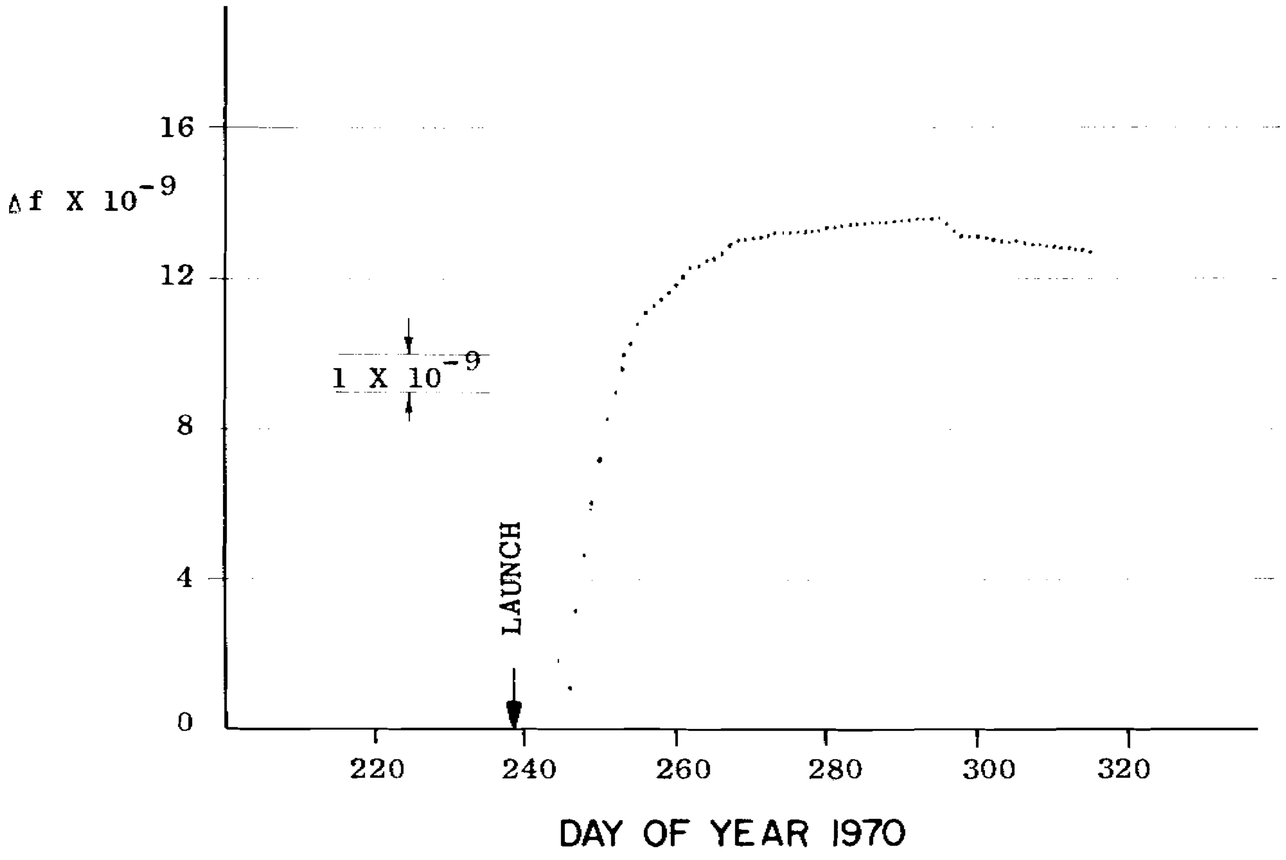
1. FIRST MODEL: 8 μ second rms @ -115 dbm SIGNAL/NOISE = 6 db
2. SECOND MODEL: 5 μ second rms @ -115 dbm SIGNAL/NOISE = 3 db
3. OPERATING FREQUENCY: 400 MHz - 80 PPM (±2 X 10^{-5} DOPPLER)
4. INFORMATION BANDWIDTH OF PHASE LOCKED LOOP: 15 Hz
5. OUTPUT: PULSE - 10 VOLTS WITH 0.2 μ second RISE TIME EVERY 2 MINUTES
6. SIZE: 3½" PANEL SPACE; 19" RELAY RACK WIDTH; 15 POUNDS
7. POWER: 10 WATTS @ 60 ~
8. COST: ABOUT $ 2500 IN QUANTITIES OF TEN

Figure 13 shows an example of the frequency stability in one of the satellites from launch time. The days at the bottom represent the calendar year of 1970, and the scale of the frequency resolution of the chart, one part in 10^9 is as indicated. A satellite was launched the last part of August, and within two or three days, it was ready to be used. These measurements are one day apart. Since navigation is possible when the frequency error is less than one part in 10^9 over a 10 to 15 minute period, it is seen from this data that navigation quality operation is attained 12 to 16 hours after launch. Note that by 10 or 15 days later, the stabilities are well below one part in 10^{10} per day.

Figure 14 shows an oscillator which has been operating in the same time period. As a matter of fact, that is the slowest drifting oscillator APL has in orbit. This has been in service three years, and you can see a change for 100 days of less than one part in 10^9. The instrumentation for measuring includes an iterative fitting routine with a measurement sensitivity of two parts in 10^{10} on a single measurement.

The Applied Physics Laboratory has been funded to put up another series of satellites. One of the items planned for this series is an improved way of keeping the time to the UTC standard. Presently, time is set in 10-μsec jumps, which seems to be a very generous time resolution for a 2-msec system requirement. Now that needs are developing for a higher resolution, it may be possible to implement some of the ranging propagation approaches which have been previously mentioned. In order to provide a more uniform time scale, a device called an incremental phase shifter is planned for one of these satellites. It is a synthesizer that goes between the oscillator and the input to the timing and transmitting chain. It has two objectives, as shown in Figure 15: (1) to take out the frequency drift that exists in the oscillator, and (2) to adjust the epoch. The initial design for this next satellite will have a course time resolution

SATELLITE 30190
FREQUENCY HISTORY



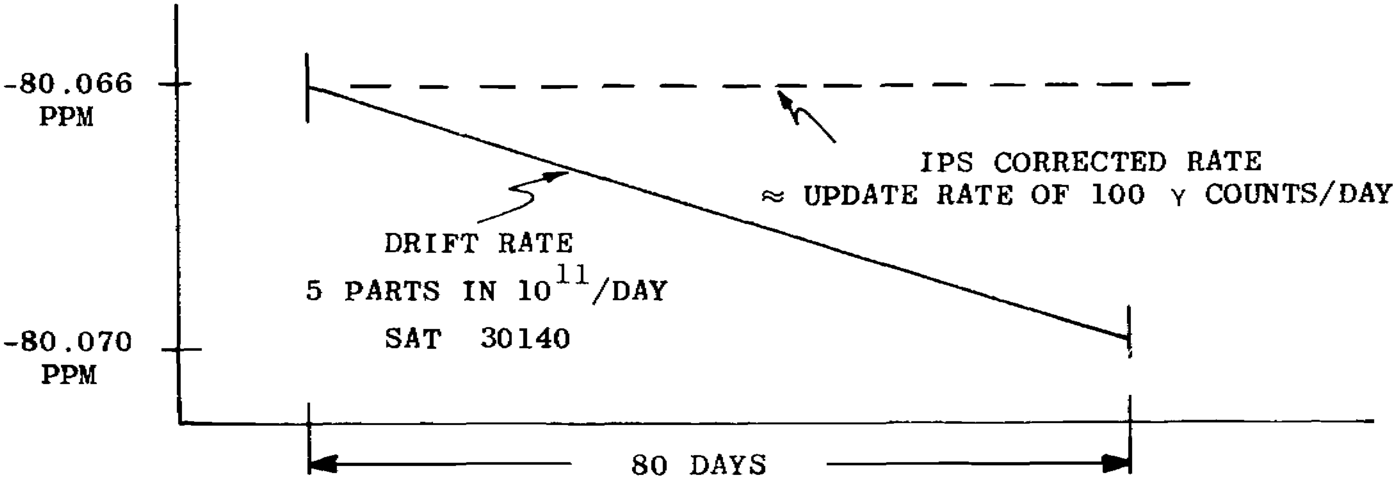
FREQUENCY ADJUSTMENT

TYPICAL SATELLITE OSCILLATOR LONG TERM DRIFT IS PARTS IN 10^{11} PER DAY

IPS SYSTEM RESOLUTION IS:

8 PARTS IN 10^{13} FOR THE 84.48 PPM OFFSET

6 PARTS IN 10^{13} FOR THE 145.51 PPM OFFSET



MAJOR PERFORMANCE CHARACTERISTICS OF THE IPS

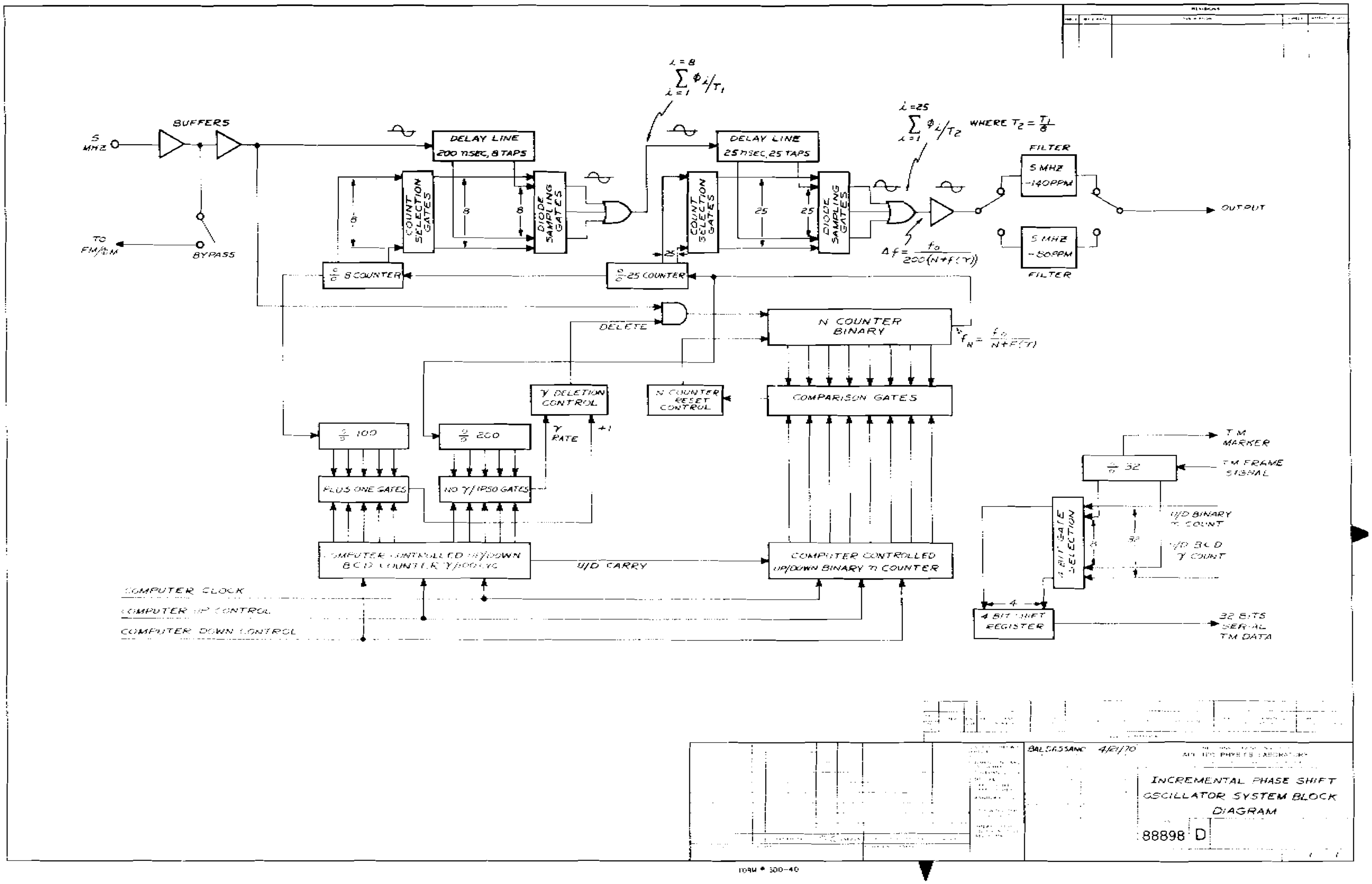
THE TWO OBJECTIVES OF THE IPS SYSTEM ARE:

1. TO CORRECT THE LONG TERM FREQUENCY DRIFT OF THE SATELLITE OSCILLATORS (-80 PPM AND -140 PPM) TO A PRECISION OF PARTS IN 10^{13}
2. TO ADJUST EPOCH WITHIN THE PRESENT 200 NANOSECOND WINDOW TO A PRECISION OF ONE NANOSECOND

of 200 nsecs which is the period of one cycle of the 5-mc oscillator. Time adjustments will provide a timing error less than 1 nsec.

The design parameters were picked as shown in Figure 16, to give a resolution of about eight parts in 10^{13} per adjustment step. The phase is shifted continuously to remove the frequency error of the oscillator. Two frequencies will be possible for operating the satellite; one at -145 parts per million for use on an experimental basis and the other at -84.48 parts per million, the operational value. There will be an operational capability in this satellite. The odd offset operational frequency is tied back to the selection of some system parameters--6,103 bits for a two-minute interval works out to provide a simple integer frequency divider chain derived from the offset 5-mc signal.

Figure 17 generally shows how this incremental phase shifting is accomplished. The input oscillator signal goes through a 200-nsec delay line with eight taps, each tap being a step of 25 nsecs in epoch. The analog 5-MHz signal is gated from each tap by diode bridges. This output goes through a 25-nsec delay line with 25 taps. Each of these taps provides a 1-nsec phase adjustment or time adjustment. The gating is also through diodes. Since this jumping between diode switches introduces noise on the signal, the output spectrums must be cleaned up by crystal filtering. These filters can be several hundred cycles wide at the 3 db pass band limits. The transfer function from the input to the output frequency is an exactly known function of the parameters with the known settings of the digital instrumentation which are all going to be set by ground command. As you can see, a signal of 5 mcs comes in and goes into a counter. Every time this counter overflows, it advances the phase shifter 1 nsec. Presently, that counter is run until it reaches a number held in a register. The register will contain a number like 70 to 90 which can be set from the ground. Unfortunately, that does not provide the resolution desired, so a million steps have been provided in another binary



INCREMENTAL PHASE SHIFT OSCILLATOR SYSTEM BLOCK DIAGRAM system between each counter integer. One step in this million unit makes a frequency adjustment of eight parts in 10^{13}. The stepping of the fine frequency adjustment will follow a programmed sequence to take out first or second order drift rates of the oscillator. Consequently, counting registers can go up or down to accommodate both up and down drifting oscillators, and each time the one million unit overflows, it moves the course register over one. It is a continuous system. There is no recycling; the system smoothly progresses over its entire adjustment range, advancing with steps of the finest resolution.

With regard to the future requirements for precise time and time interval for the NAVSAT program, APL does not establish any of these requirements. However, if a requirement is established, APL would be most happy to comply with the requirement. APL has a working frequency standard which is now within eight parts in 10^{13} of the Naval Observatory in the UTC time system. The timing epoch at our Laboratory is held within $\frac{1}{2}$ μsec, relative to the Naval Observatory's time system. Common monitoring of the LORAN-C system is being used in order to hold the value. Clock transfers have been provided to establish and calibrate. Synchronization to the Naval Observatory has been done on a routine basis for a good many years. Instrumentation in our own development programs can make synchronization measurements internally to the Laboratory to about 2 nsecs. Some of the receiving instrumentation has been checked out that will provide synchronization measurements of 10 nsecs between roof-mounted antennas and reference signals inside the Laboratory.