TIMATION NAVIGATION SATELLITE (U)

by Mr. Roger L. Easton*

(C) TIMATION is not a system; but rather it is technology that can lead to a system. The only satellite navigation system that exists is the Navy TRANSIT system, as described at this conference by Mr. Rueger. A paper system, or what we perceive as a system, should not be confused with an actual system. It is fairly easy to do, but it is wrong. This is a program in technology; in which theoretical analysis is made; critical components shown by the theoretical analysis are developed; and measurements on satellites, needed to define a navigation system to meet classified JSC requirements, are made.

(C) The system design, again is a paper study. Quite differently from Col. Fiebelkorn, NRL found that the critical item in a satellite navigational system for unbelieveable accuracies is the ground station location. The ground station location surprisingly determines the next item, the satellite constellation. Other items in the system design are accuracy, cost, and schedule. The latter two will not be discussed in this paper because we are not really talking about this design of the system, but are merely showing what might be available in a few years if someone funds it.

(C) The places selected for the ground stations, shown in Figure 1, are Alaska, St. Croix, Samoa (American Samoa), and Guam. This is due to the Navy requirement that all ground stations should be on U.S. territory. So, that is where the stations are: farthest north, farthest south, farthest east, and farthest west.

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COVERAGE BY FOUR STATIONS ON
8 HOUR ORBIT, 5° MASK

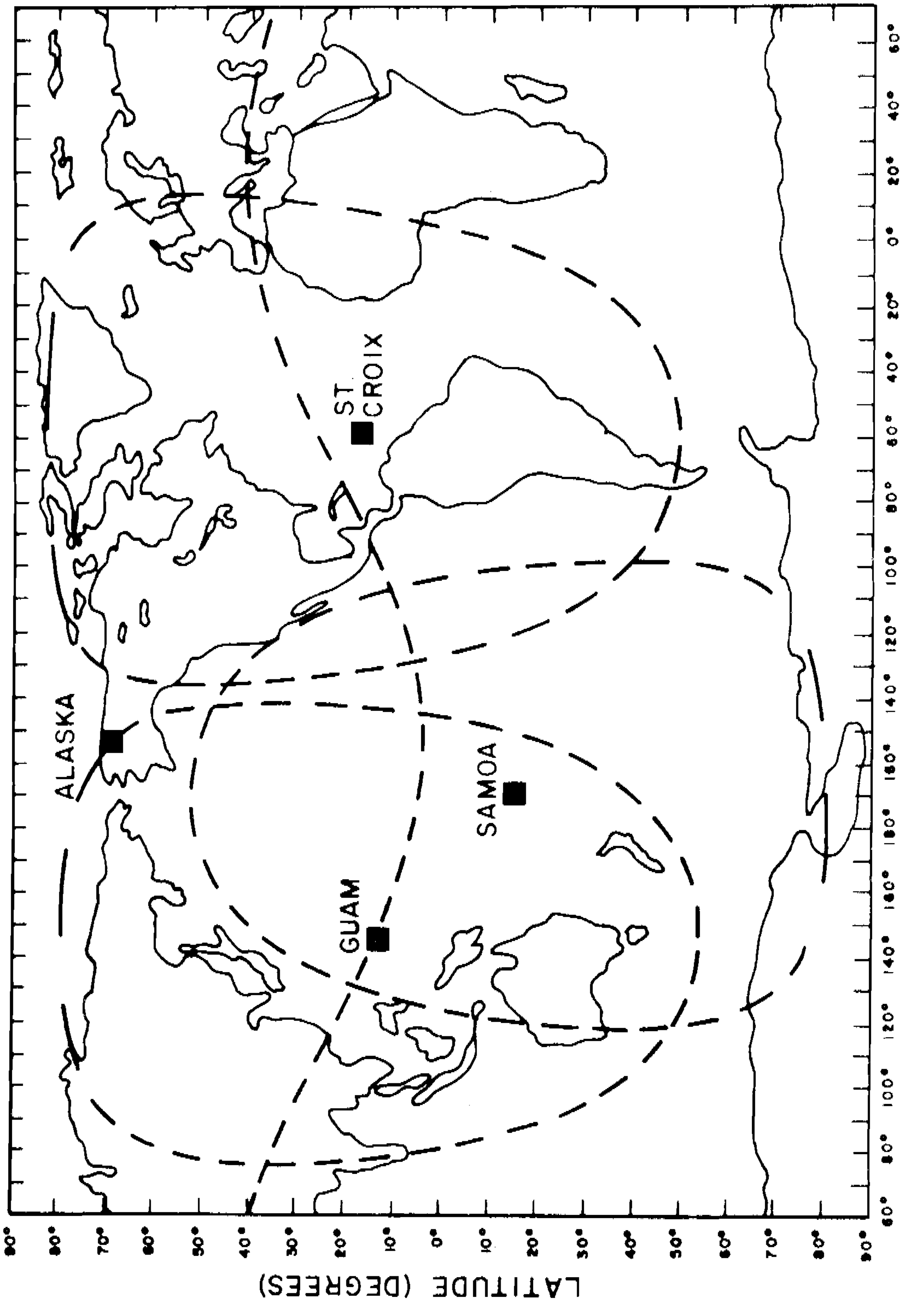


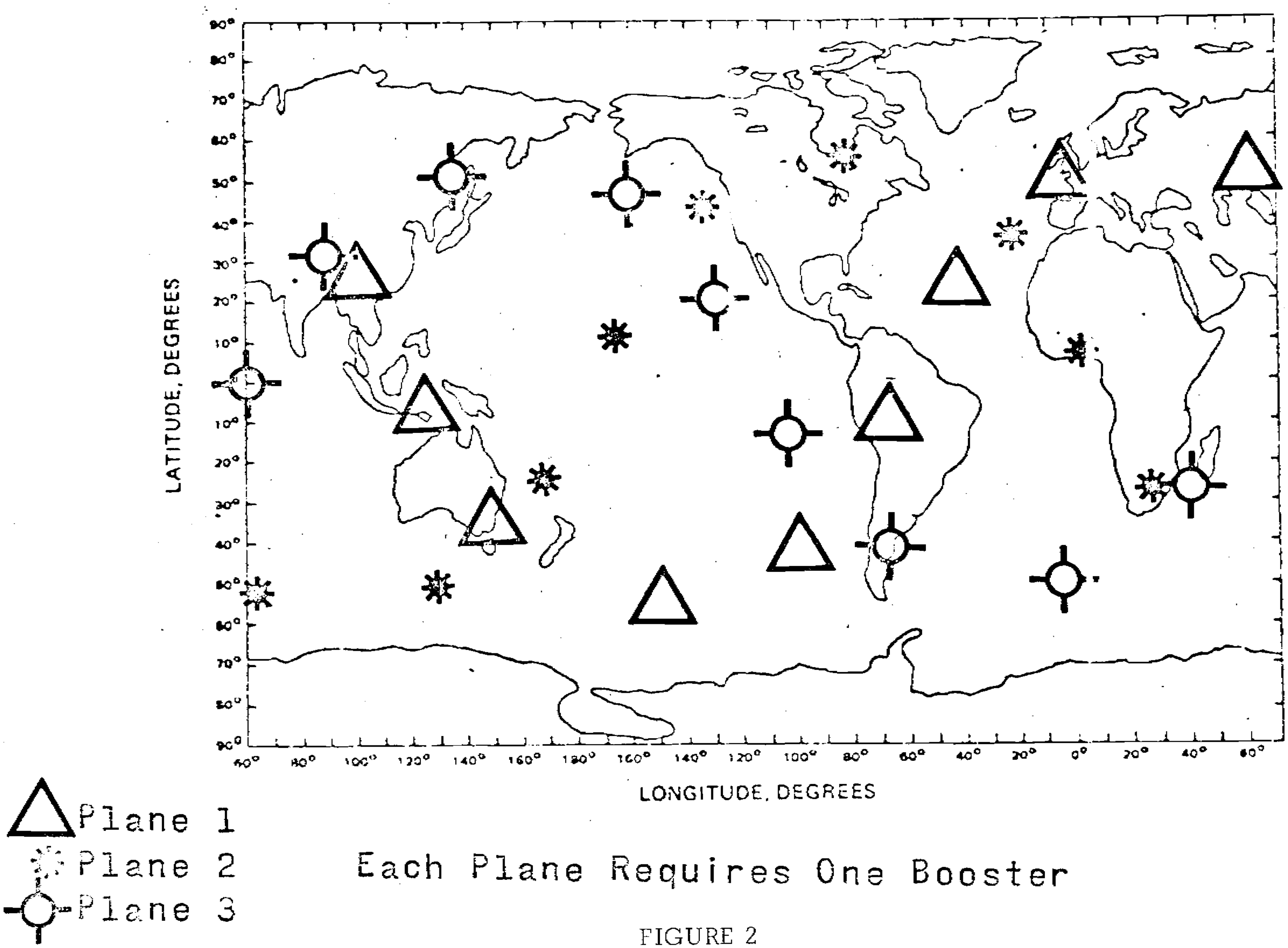
FIGURE 1

(C) Figure 2 shows the NRL constellation: three planes with nine satellites in a plane, all at 7,500 nautical miles, all launched on a single booster, TITAN-3D Burner 2. Launching them all on one booster is a big undertaking. Cost is a very large factor in the system, since this booster cost more than $15 million. Therefore, we took the minimum number of planes, which is three, and set three launches. If there is a failure on one of those launches, it is a fairly expensive proposition, much more so than for the system Mr. Rueger described.

(C) The error contours on the worst-case basis are shown in Figure 3. You will notice that there is no ground station between Guam and St. Croix, so, in this area there are times when the satellite is out of sight from any ground station. At those times, the satellite clock can drift off and it can give you errors which lead to the 53-foot maximum error shown. This is for a user who has a continuously updated clock, as in the case which Col. Fiebelkorn mentioned where you are getting xyz and time. These contours are for x, y, and z. Since the altitude is the most difficult coordinate to measure in this type system, the error is essentially the error in altitude. The errors in x and y are perhaps a third of this, therefore, x and y is about ten feet, and that should be unbelievable.

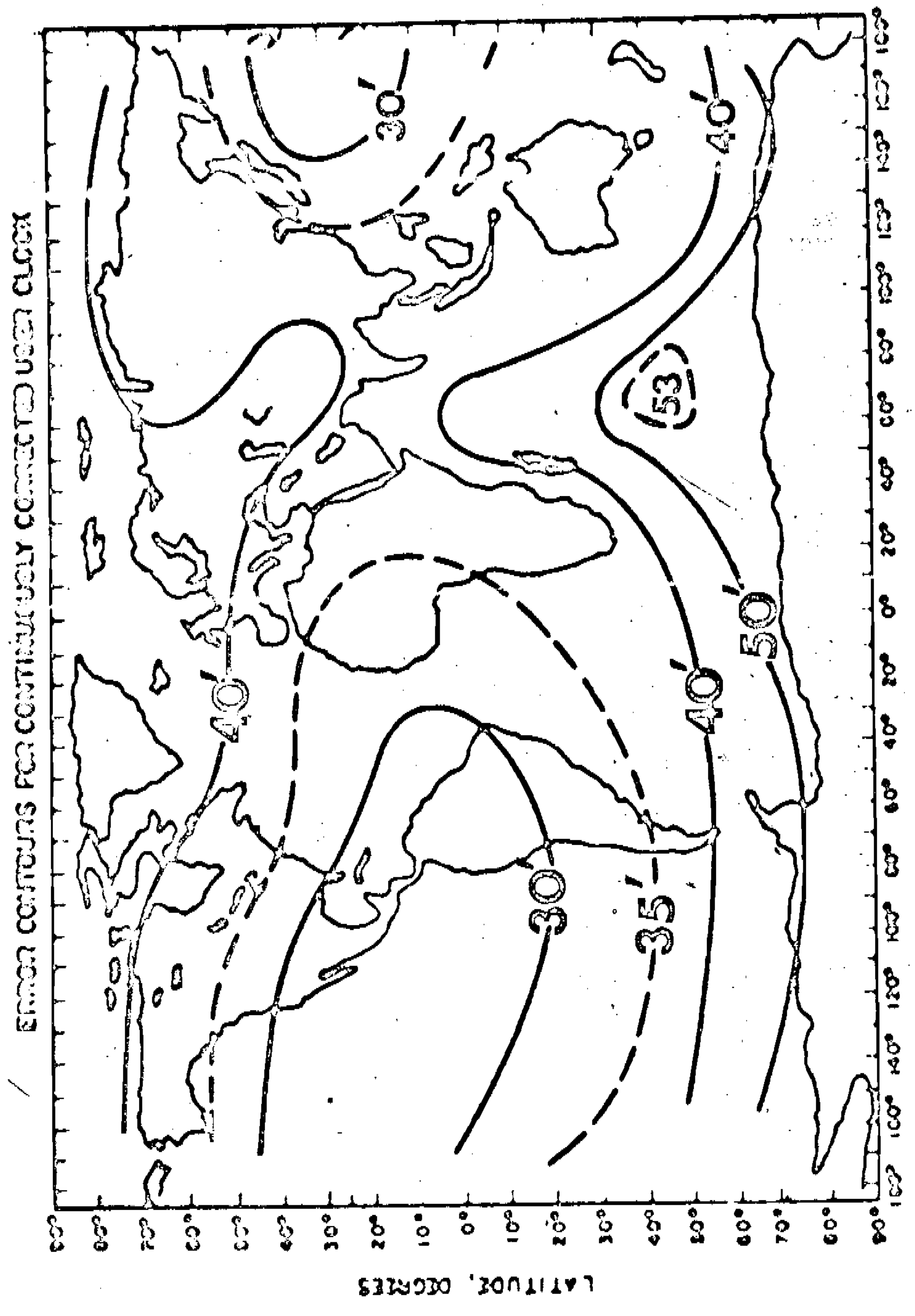
(C) If the user has a good clock (see Figure 4), we are talking stabilities like five parts in 10^{12}, the user can correct his clock when the geometry of the satellites is best. There is a minimum of five satellites in view above 10° elevation angle everywhere in the world, so that he can get xyz and time worldwide and continuously, even if one satellite is out. When the user has a good clock, as Col. Fiebelkorn suggested, he gets considerably better accuracies with a maximum error of about 30 feet. Usually he finds out that these theoretical calculated error budgets are

GEOGRAPHICAL POSITIONS OF 3x9 CONSTELLATION



Each Plane Requires One Booster

FIGURE 2



ERROR CONTOURS FOR CONTINUOUSLY CORRECTED USER CLOCK

FIGURE 3

ERROR CONTOURS FOR USER WITH GOOD CLOCK

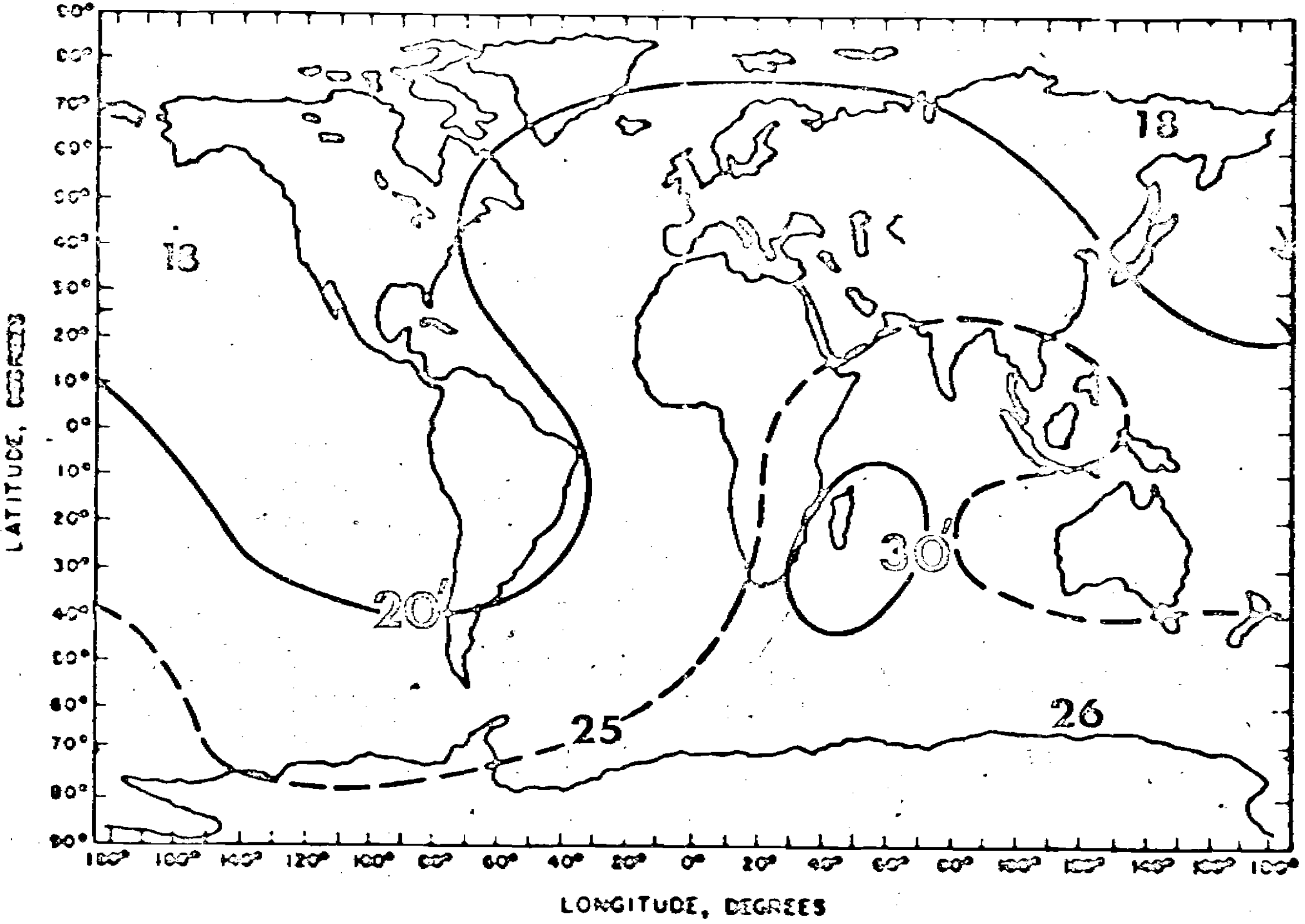


FIGURE 4

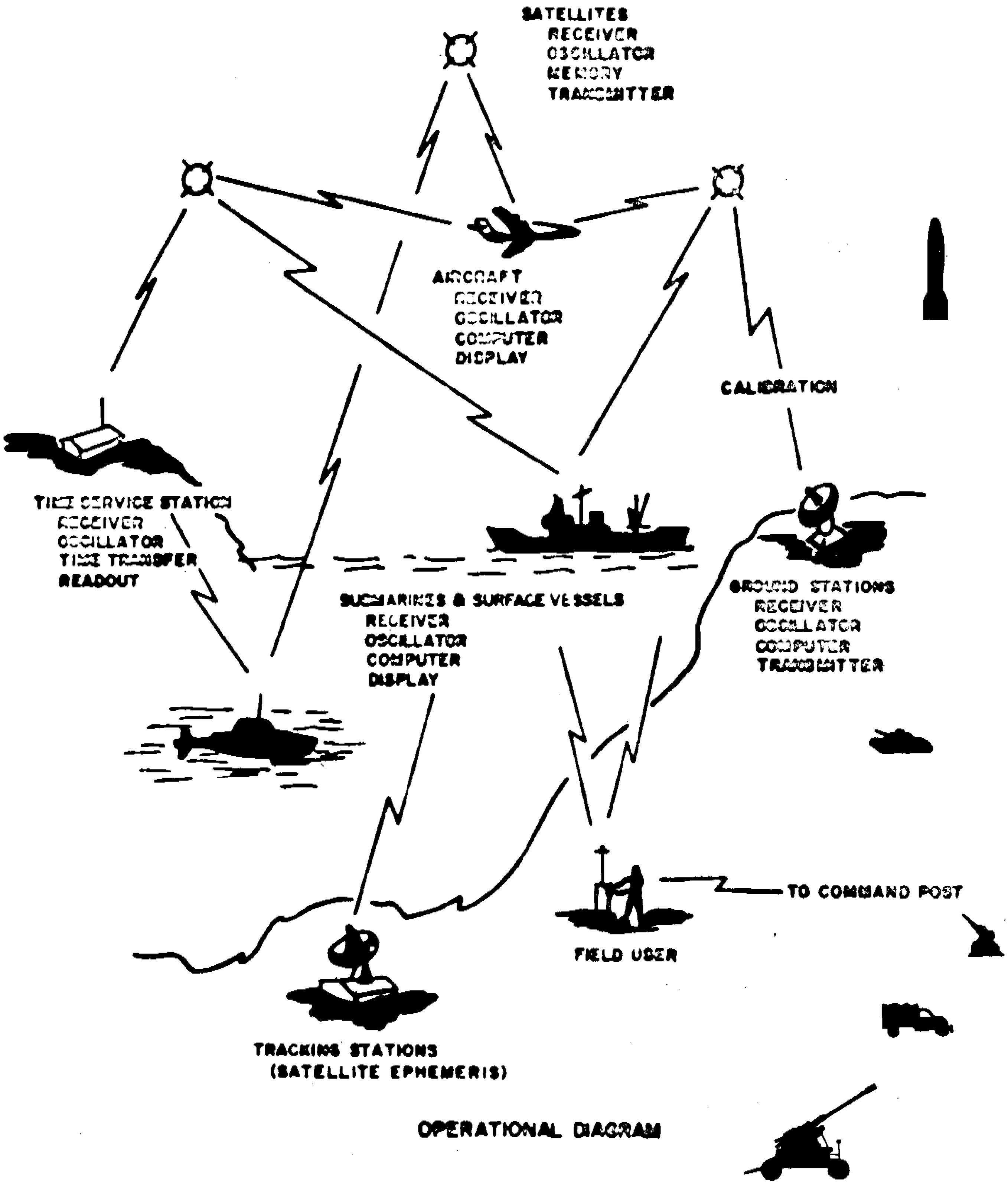
off about two to one and they are usually off the wrong way. Even so, you are probably talking considerably better than the 200 feet of 621B. This is, of course, strictly worldwide, in the Antarctic as well as anywhere else.

(C) Figure 5 shows the equipment for TIMATION. There are a number of satellites, airplanes, and time service stations; and NRL has submarines, ground stations, and tracking stations, field users, gun users, and trucks. Anyone can use this who wants to buy the equipment.

(C) The present state of technology is as follows: TIMATION now has two satellites in orbit, but only one of them is working. It has demonstrated navigation fixes, instantaneous fixes (these are xy fixes measuring both range and doppler), and running fixes. NRL has measured ionospheric refractions, is in the process of time synchronization, and is building some receivers.

(C) Figure 6 compares three satellites, two of which are real and one of which is proposed. The first one was launched over three years ago, 500 nautical miles, 70° inclination, 85 pounds, had only a single radio frequency, 400 MHz, and the maximum modulation on it was 100 KHz. The oscillator was somewhere within a few parts in 10^{11} stability. Exactly how well it functioned is not known, because it had a temperature coefficient problem. The rms of the fixes was about 500 feet.

(C) TIMATION II, which is still working, is somewhat over a year old, and has essentially the same orbit. It is a little heavier; it has more power; and it has two frequencies: one is at 150 MHz, and one is at 400 MHz, so the user can correct for ionosphere. These frequencies are just barely removed from the TRANSIT frequencies, but their equipment can be modified to receive this bird's transmission. The second satellite uses a 1-MHz modulation. The oscillator is between five parts in 10^{12} and one part in 10^{11} stability. The rms of the fixes is actually 43 meters, which is a little better than 150 feet. On the third satellite, which is proposed, the



OPERATIONAL DIAGRAM

FIGURE 5

TIMATION SATELLITES

	#1	#2	#3
Launch Date	31 May 1967	30 Sept 1969	Proposed
Altitude	500	500	7500 n.mi.
Inclination	70^o	70^o	55^o
Weight	85 lb	125 lb	350 lb
DC Power	6 W	18 W	50 W
Frequencies	400MHz	150&400	400,1600MHz
Max Mod Freq	100KHz	1 MHz	8 MHz
Osc Stab	$3pp10^{11}$	$.5\text{-}1pp10^{11}$	$1\text{-}2pp10^{12}$
RMS of Fixes	500 feet	150 feet	20-40 feet

FIGURE 6

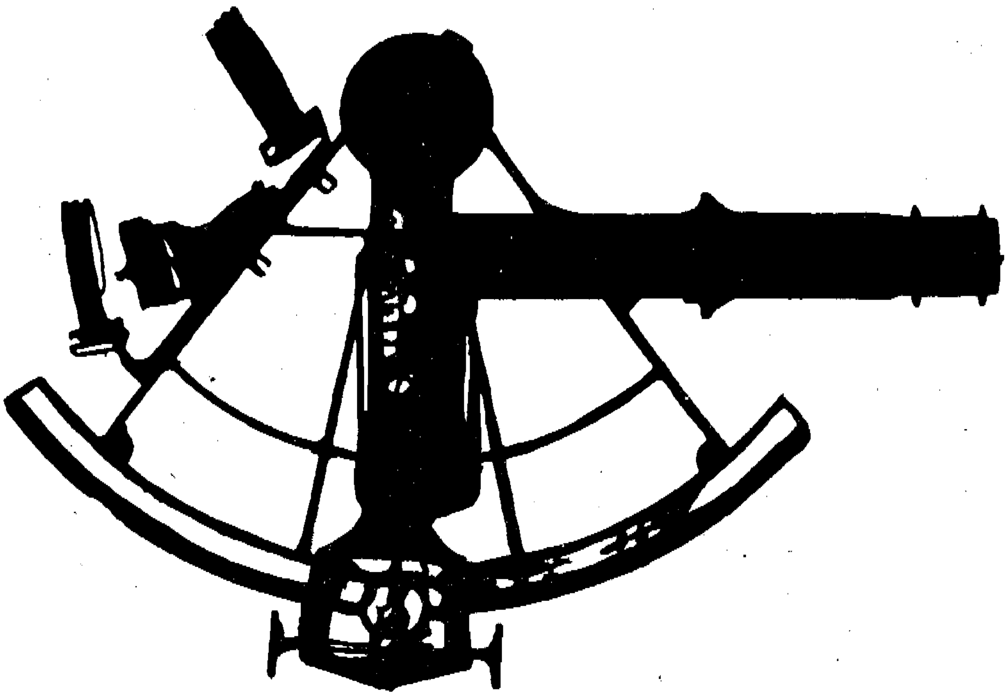
range is 7,500 nautical miles, 55° inclination (though that is not too critical, any range from 55° to 90° can be used without much loss). It will be much heavier, 350 pounds, and will have about 50 watts power from the solar cells. In frequency, the satellite will range from 400 MHz to 1,600 MHz in an attempt to correct ionosphere refractions to two feet. In modulation frequency, again the satellite will go up to about 8 MHz; in oscillator stability the hope is for about one part in 10^{12}, but two will be acceptable, and fixes will be somewhere around 20 to 40 feet.

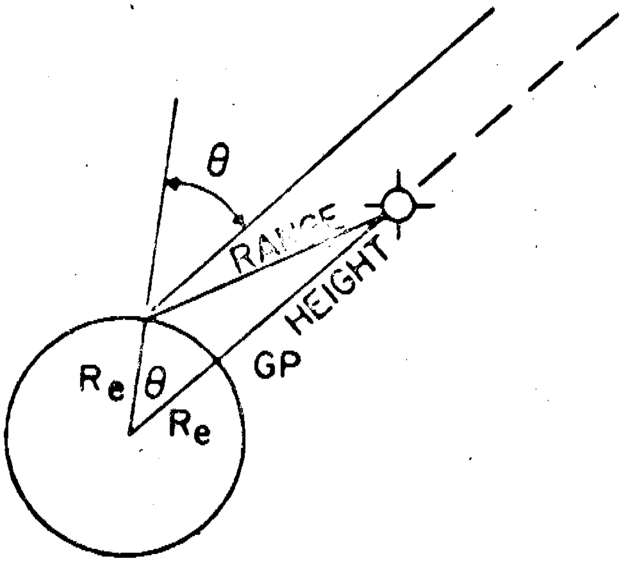
(C) When the third satellite is launched, NRL will measure geodetic constants at those altitudes, make refraction corrections, demonstrate that it can achieve the calculated prediction accuracy, and get our error budget. (It is possible to get an error budget of something like 10 feet.)

(C) Figure 7 shows a sextant, with which you measure an elevation angle to a star (though you actually use a compliment of that angle, which is the angle theta). Suppose the navigator looks out at a star that has the pictured geographical position, he will measure, or he will use this angle. Now, suppose the same navigator is at the same point and there is a satellite which has the same geographical position, he will measure the range to the satellite. That is the object of this system--to show how the range can be measured. He will know the height from the center of the earth and he will know the radius of the earth within a few meters or better if he uses Mr. Rueger's correction. So the navigator can then determine the angle. Now you can see that a range measurement satellite transforms directly to celestial navigation. The big difference, of course, is the accuracy--of seconds or fractions of seconds, compared to minutes when he measures the angle with a sextant.

(C) NRL synchronizes its satellite transmissions to the Naval Observatory time standard. They use redundant data from the satellite to synchronize the user clock, and they can then measure the time delay between the user

NAVIGATION BY MEANS OF AN ELECTRONIC SEXTANT





TRANSFORM TO CELESTIAL NAVIGATION

FIGURE 7

clock and the signal they see to infer the distance between the satellite and the navigator. It is a passive ranging system.

(C) As depicted in Figure 8, a modulation of 100 cycles is sent--it was on for ½ second for the first TIMATION. Now, let us assume that these clocks in the satellite are synchronized to clocks in the navigator. By the time that this signal gets to the navigator, the navigator's clock will move and it will have moved a portion of a cycle that infers the range to the satellite. So we measure on the phase recording 0.68 of a cycle. That is 6.8 msecs or 6,800 μsecs. The thousand cycle signal measures 92, so it is 6,920 μsecs. At the 10 kc signal it is 6,918 μsecs; the 100 kc signal, which is on all the time, reads 8.6 right where the even minute occurs, 6,918.6 μsecs.

(C) To build an intercept chart such as Figure 9 depicts, you assume a position and find your chart location. Now, you can calculate at a certain time where the satellite is with respect to this position and that at 16 minutes past the hour the satellite is going to be in this azimuth. At this point on the chart you would measure 10,870 μsecs. You then drop a perpendicular to this line and you would have a line of position. That is what an intercept chart is, a difference chart; a chart on which you calculate from an assumed position and measure the difference between your assumed position and your actual position.

(C) Figure 10 is an example in which several lines of position were measured and came out in a perfect fix.

(C) On the next measurement, shown in Figure 11, things did not come out so perfectly, and the result was an arc of a circle. The observation at the center of the circle and at the radius of the circle is the time error between the observer's clock and the satellite clock; this is what is meant by taking extra data and getting time out of it. The observer can then put a correction into each one of these readings until he comes up with the

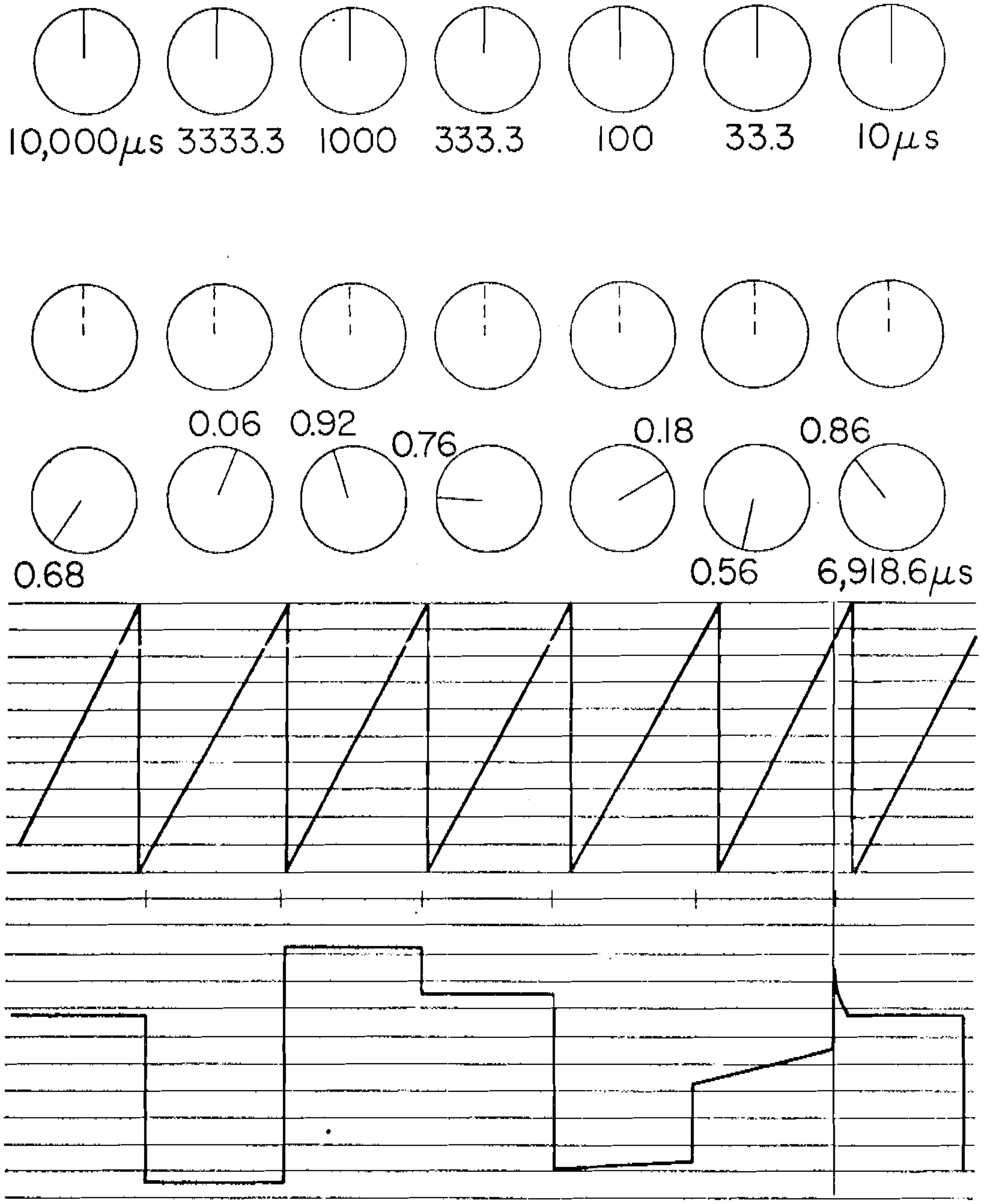
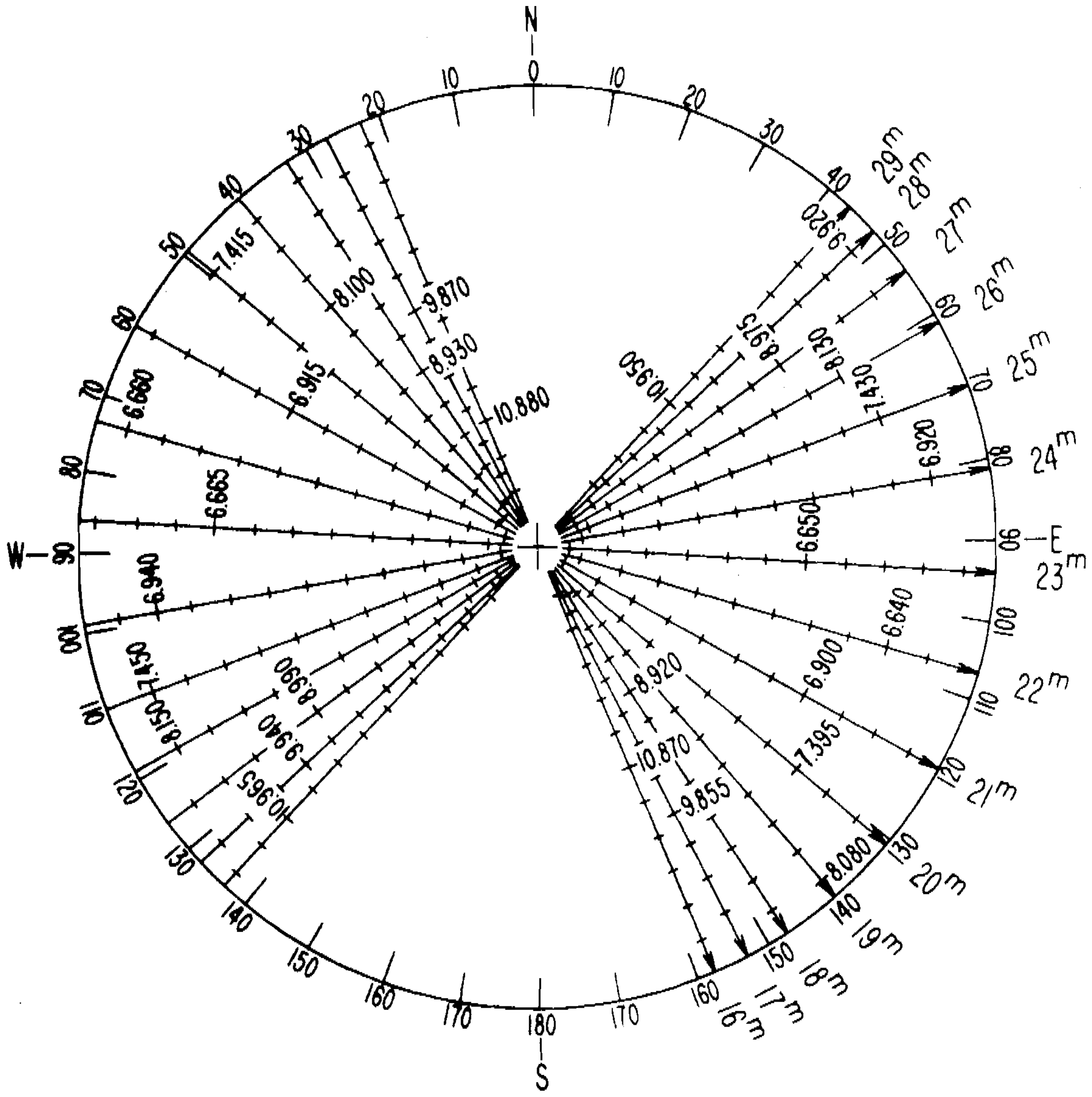
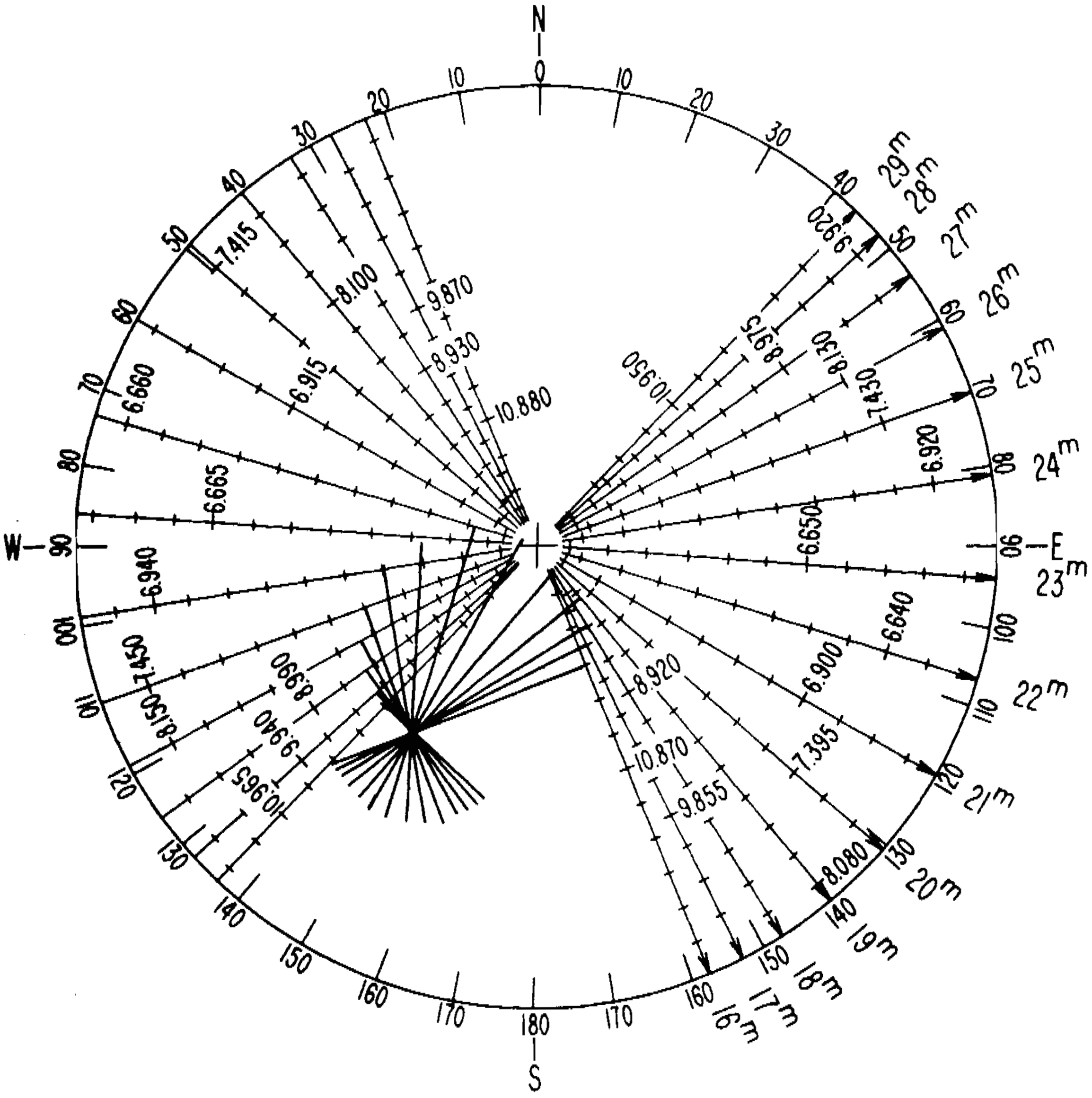

10,000μs
3333.3
1000
333.3
100
33.3
10μs
0.06
0.92
0.76
0.18
0.86
0.68
0.56
6,918.6μs

FIGURE 8



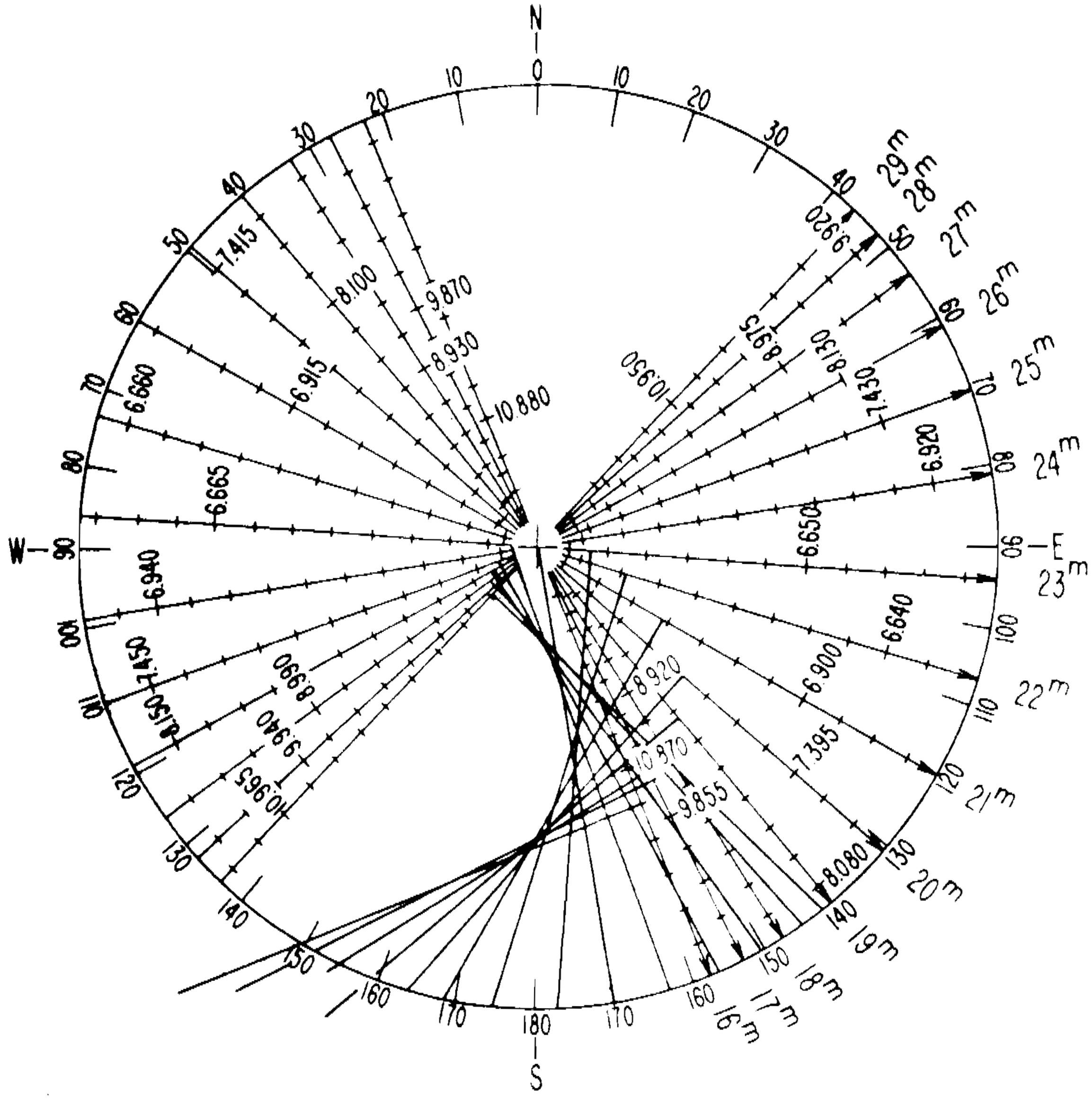
PRECOMPUTED INTERCEPT CHART

FIGURE 9



FIX DETERMINED ON INTERCEPT CHART

FIGURE 10



INTERCEPT CHART SHOWING EFFECT OF SYNCHRONIZATION ERROR ON PLOT

FIGURE 11

best fix, and he will then have a measure of the time error between his clock and the satellite clock. If you must do this in two different places over the world, you can transfer time from one place to another using the satellite.

(C) Figure 12 depicts the TIMATION I satellite. After eight months in orbit,the boom apparently kinked and the satellite turned over. It was turned back several times, and after about 18 months it became useless, but it did provide a lot of data.

(C) Figure 13 is TIMATION I before it went up as a secondary payload on the aft-rack of an Agena.

(C) NRL used the TRANSIT that Mr. Rueger described (see Figure 14), or four stations of it, for its orbit prediction system, in which this satellite was treated exactly as though it were a doppler satellite. It does put out a doppler signal. NRL modified its stations in Alaska, Lasham, Las Cruces, and APL to receive the data from this satellite--this was the only 400 MHz signal. All the data is sent to APL, APL sends it to the Weapons Lab, and the Weapons Lab tells NRL where the satellite was and where it is going to be. It works quite well.

(C) Orbit accuracies on TIMATION I were about 100 meters (shown in Figure 15) with which several time transfers were made between the station here at the Laboratory and the station in Alaska, and the results were roughly $\frac{1}{2}$ μsec rms. At the station in Fort Collins, Colorado, on the grounds of radio station WWV, NRL got about 2/3 μsec. WWV had a way of getting into the system and making some problems. The same situation existed in Texas, again giving only about 2/3 μsec. In Florida, results were about 1/3 μsec, but it is roughly $\frac{1}{2}$ μsec time transfer.

(C) The internal heart of the satellite, as far as time transfer goes of course, is the crystal oscillator. The crystal in TIMATION I was an ordinary glass Bliley crystal; in TIMATION II it was a metal-enclosed

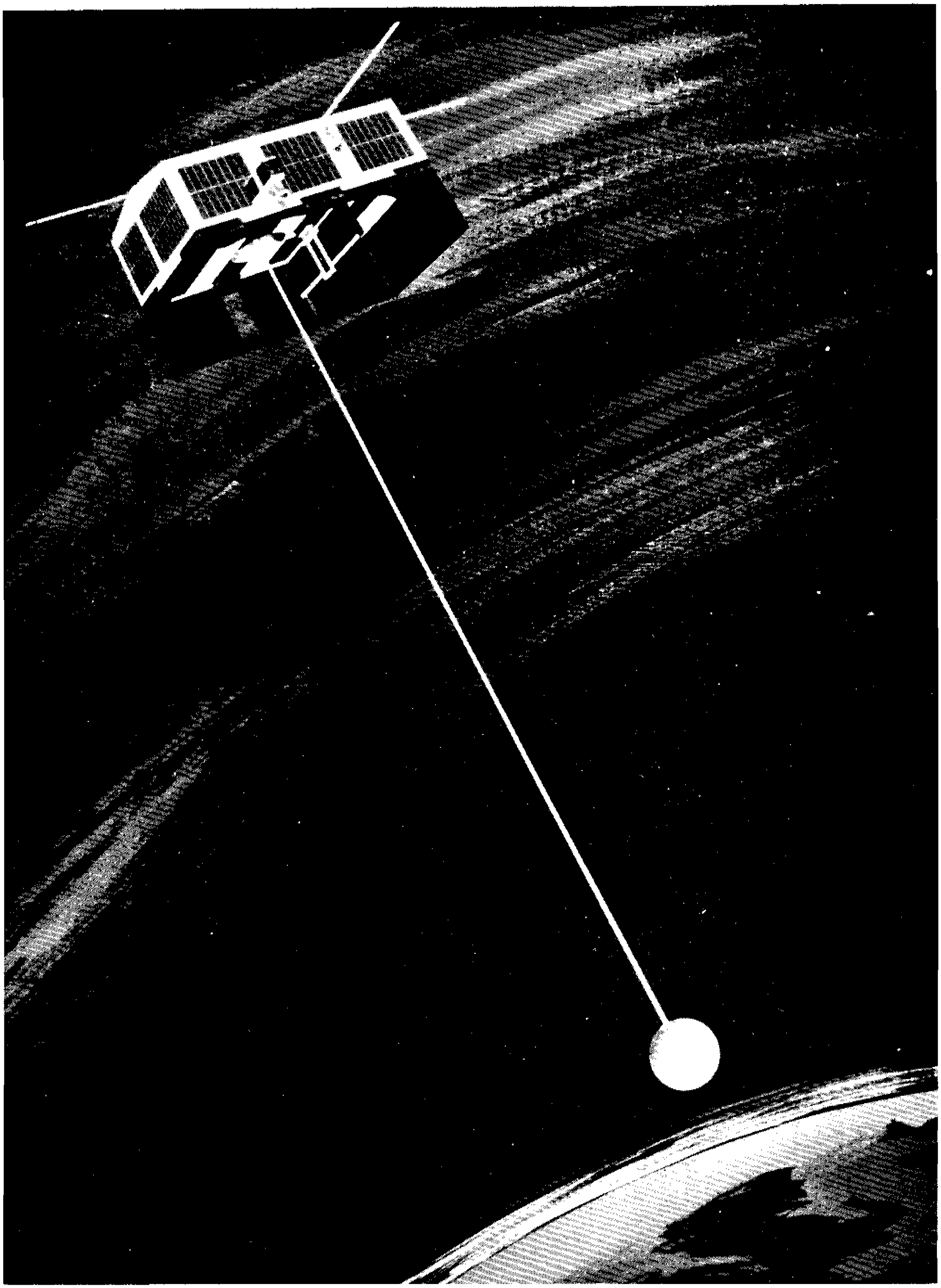


FIGURE 12

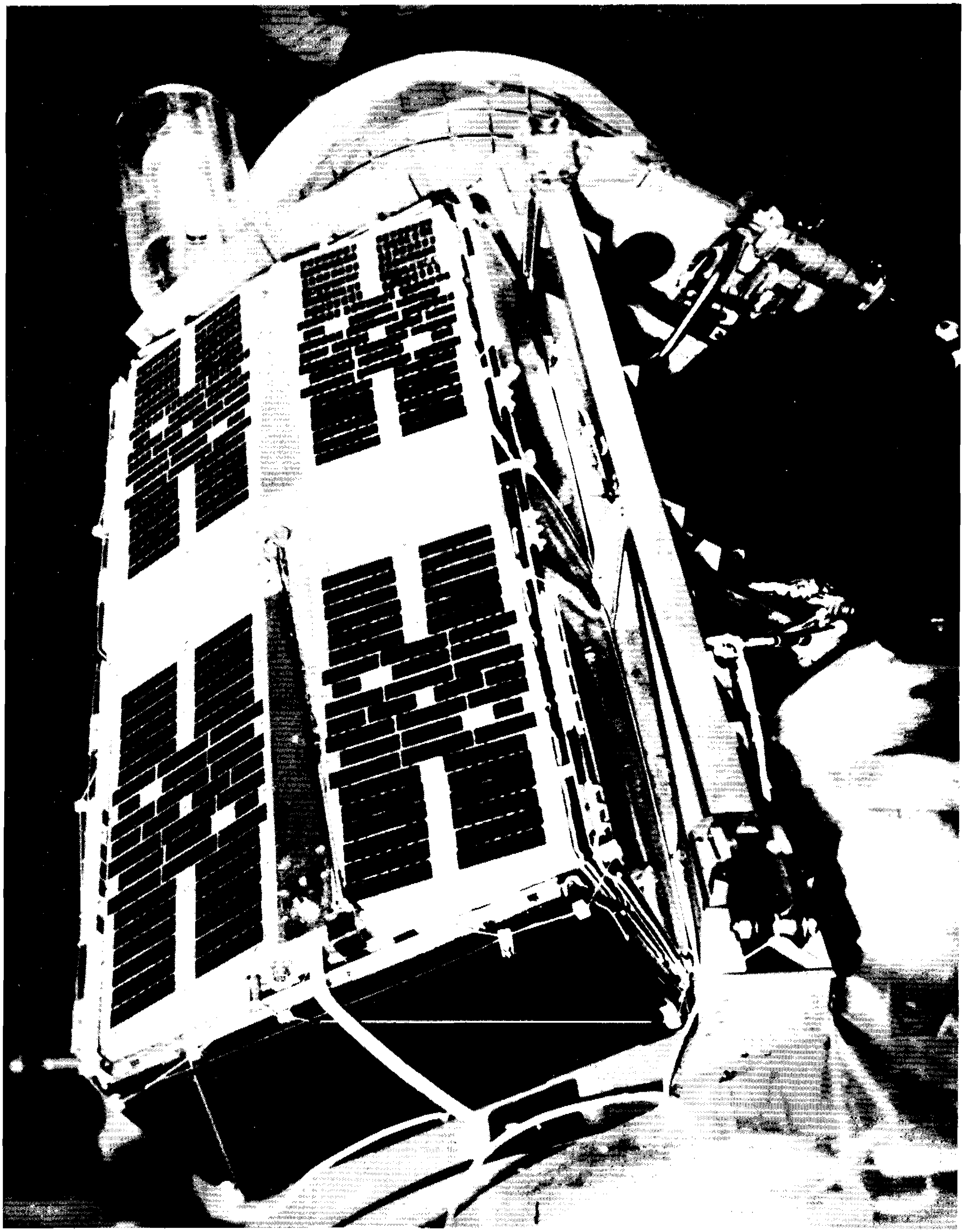


FIGURE 13

ORBIT PREDICTION NET (TRANET)

FIGURE 14

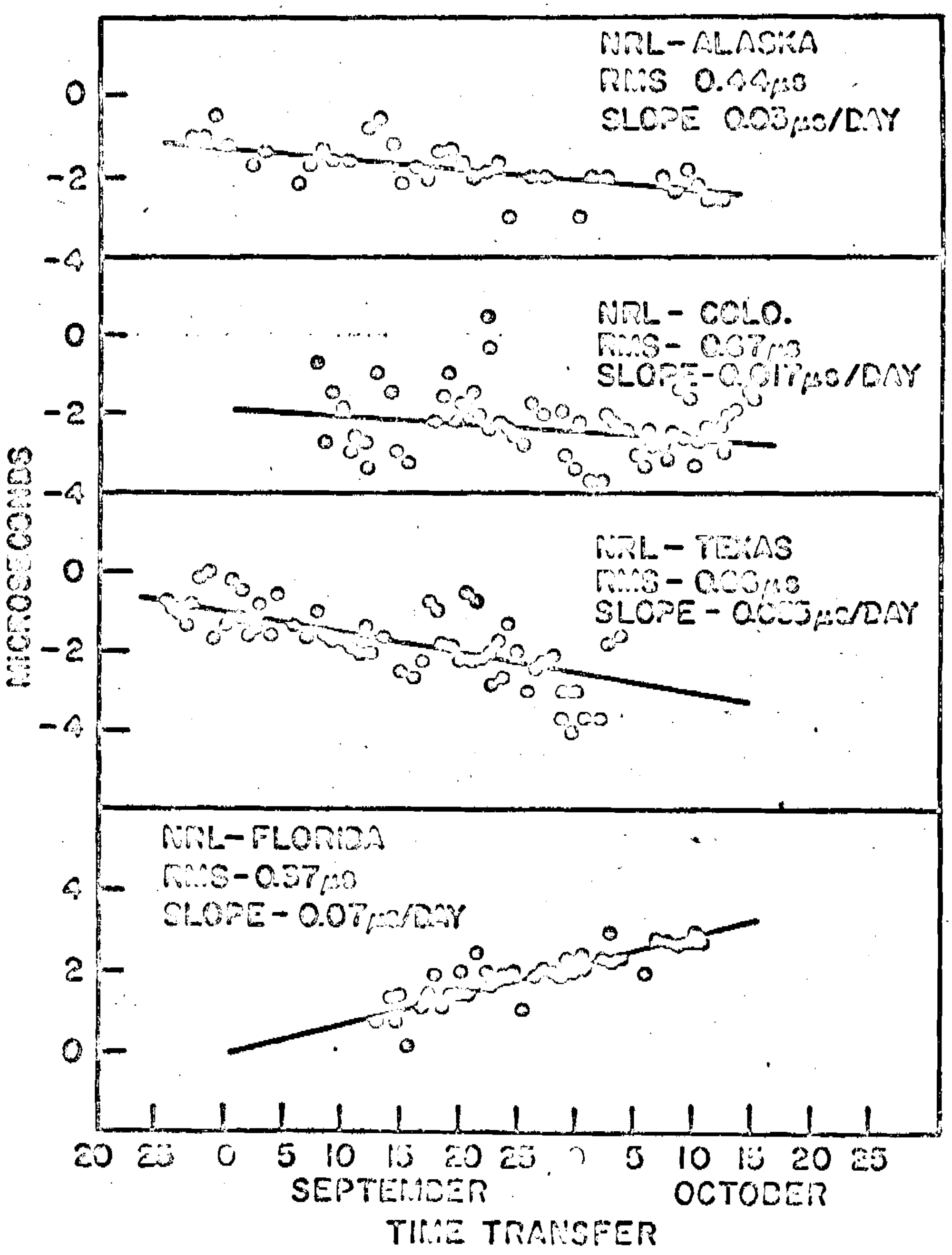

NRL-ALASKA
RMS 0.44μs
SLOPE 0.03μs/DAY
NRL - COLO.
RMS - 0.67μs
SLOPE-0.017μs/DAY
NRL - TEXAS
RMS - 0.66μs
SLOPE - 0.035μs/DAY
NRL-FLORIDA
RMS-0.37μs
SLOPE - 0.07μs/DAY
MICROSECONDS
0
-2
-4
4
2
20
25
0
5
10
15
20
25
0
5
10
15
20
25
SEPTEMBER
OCTOBER
TIME TRANSFER

FIGURE 15

high bake-out, high temperature, high vacuum, super-smooth crystal. The oscillator of Figure 16 is tuneable from the ground; it has some little motors that gear down to turn the capacitors and tune the oscillator. TIMATION II also can be changed in phase; TIMATION I could be tuned only in frequency.

(C) Figure 17 shows a history of TIMATION I. The temperature of the satellite followed percentages of sunlight quite well; the peaks came when it went into and came out of 100 percent sunlight, because of the albedo of the earth and 100 percent sunlight. The frequency also shifted, because the ovens had not been adjusted in vacuum and that was what gave it a rather large change of frequency with temperatures.

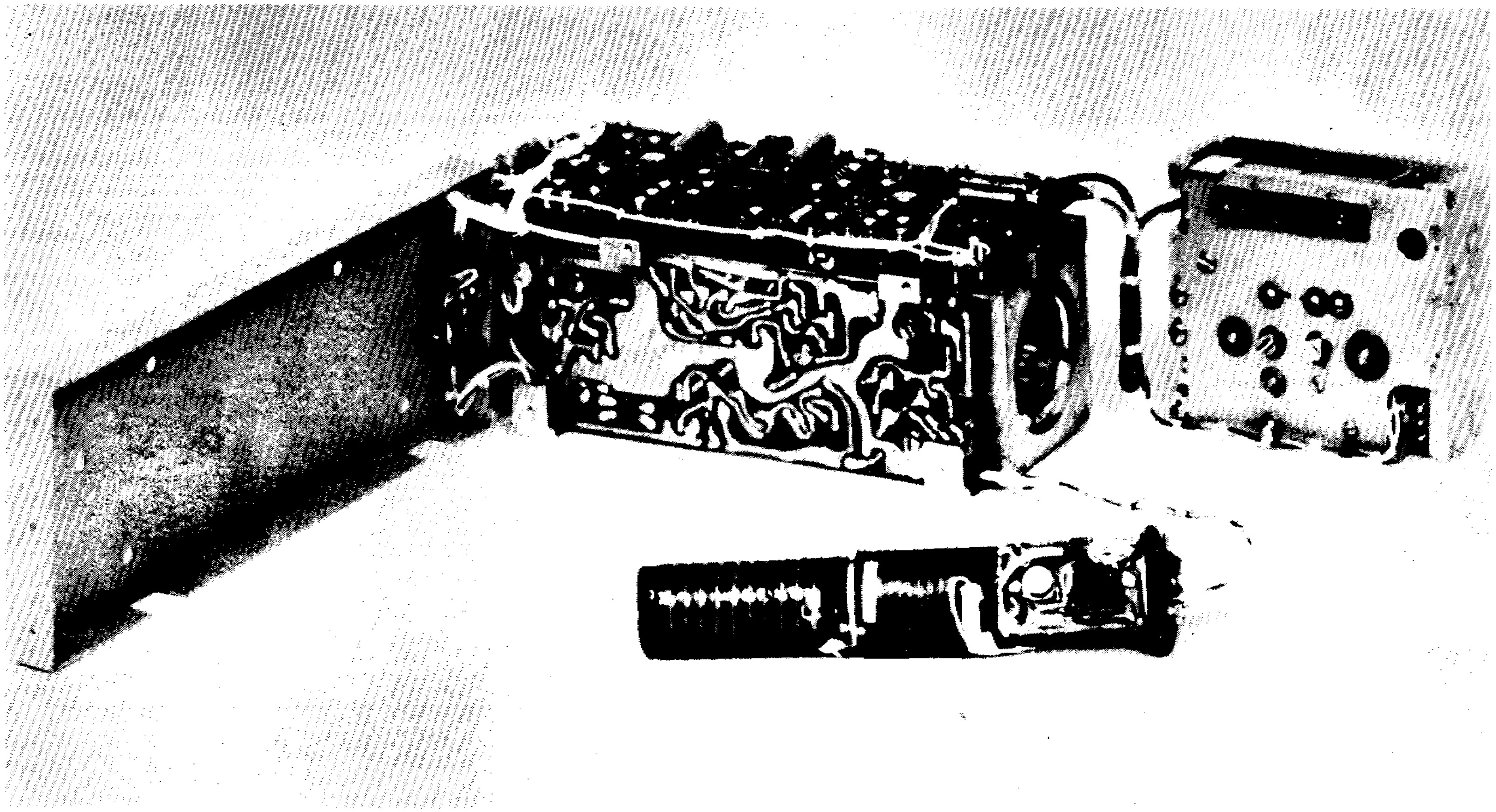
(C) On TIMATION II there is a temperature control on the base of the oscillator. It cools when the satellite is too hot and heats when it is too cool, and keeps it within a tenth of a degree at all times (see Figure 18). There have been no changes or frequency changes due to temperature on this satellite.

(C) Figure 19 shows some of the adjustments that were made on TIMATION II; NRL brought the frequency down, then brought it down again, then had to bring it up, and now they always have to adjust the frequency up.

(C) If they took out those adjustments, the frequency went positive for a while, then it went negative, and now it is running a negative 3.6 parts in 10^{11} per day due to radiation effects on the crystal (see Figure 20).

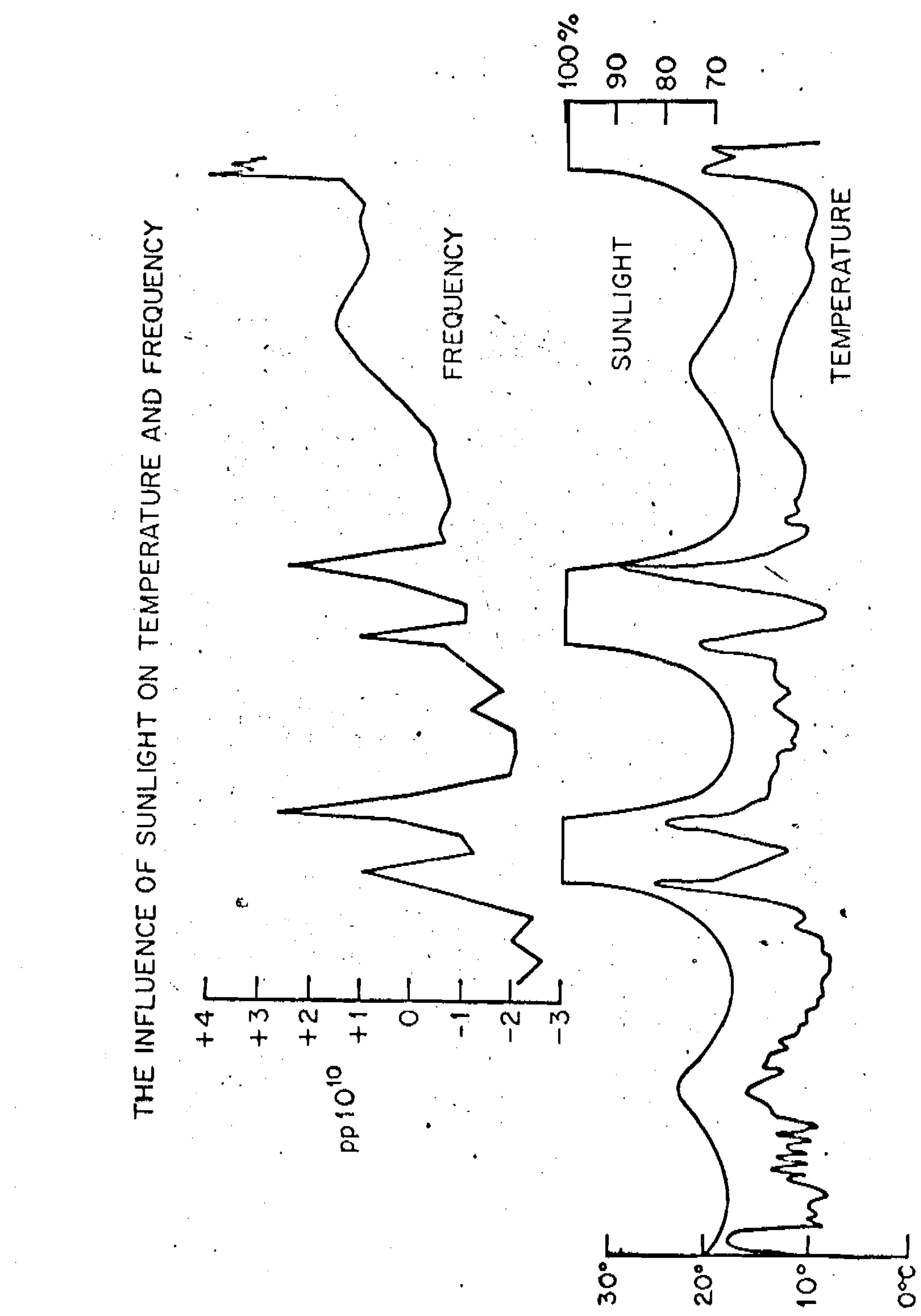
(C) For the next satellite, of course, NRL hopes to have the better crystal (see Figure 21). Crystals this good have been measured in the Laboratory, two parts in 10^{12}. At this time, the integration time in which they are interested is about 12,000 seconds. Part of this problem is in the rubidium standard.

(C) TIMATION II fills up the rack (see Figure 22) again for the secondary payload.



DISASSEMBLED VIEW OF SATELLITE FREQUENCY STANDARD

FIGURE 16



THE INFLUENCE OF SUNLIGHT ON TEMPERATURE AND FREQUENCY

FIGURE 17

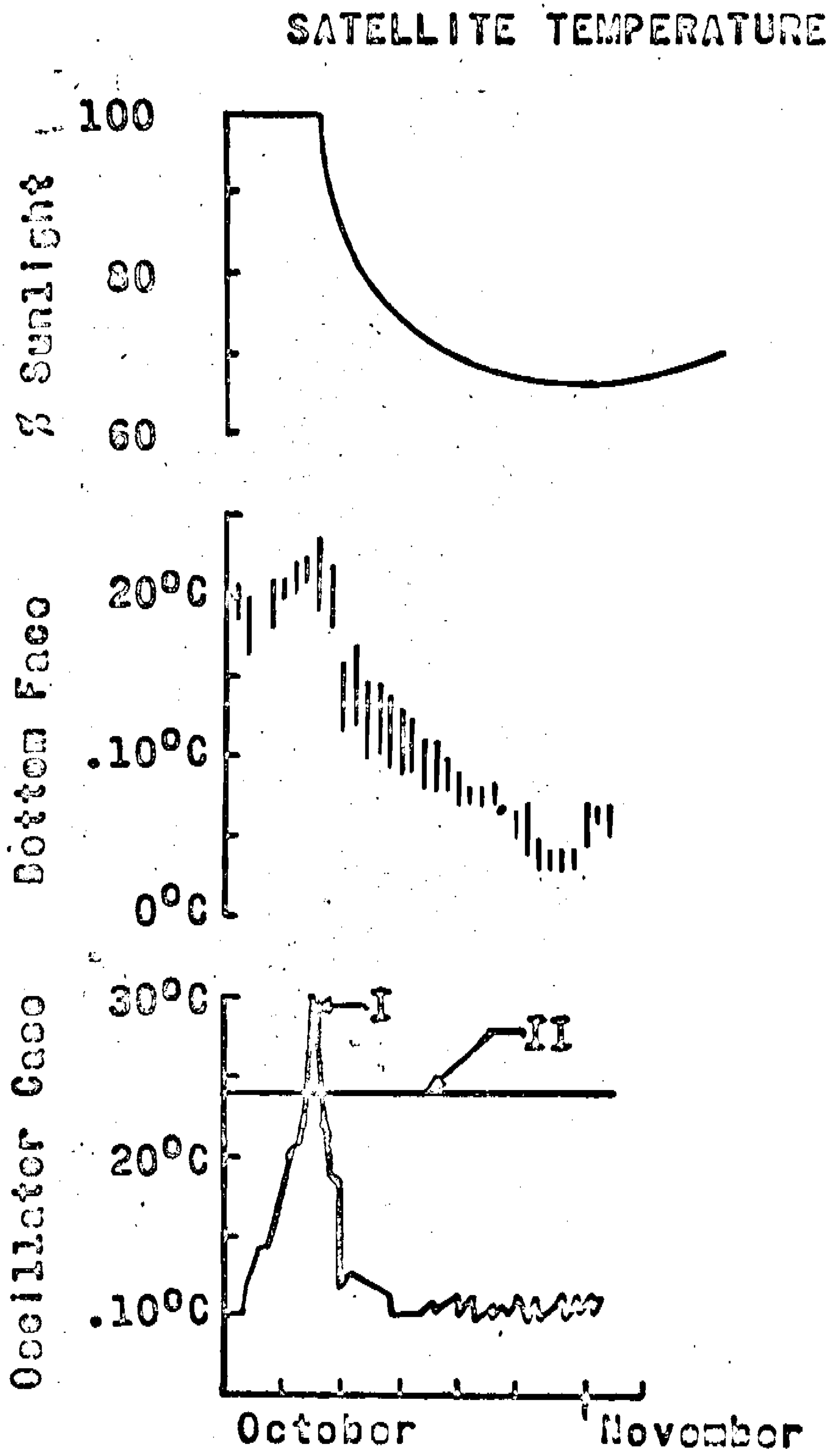

SATELLITE TEMPERATURES
% Sunlight
100
80
60
Bottom Face
20°C
10°C
0°C
Oscillator Case
30°C
20°C
10°C
I
II
October
November

FIGURE 18

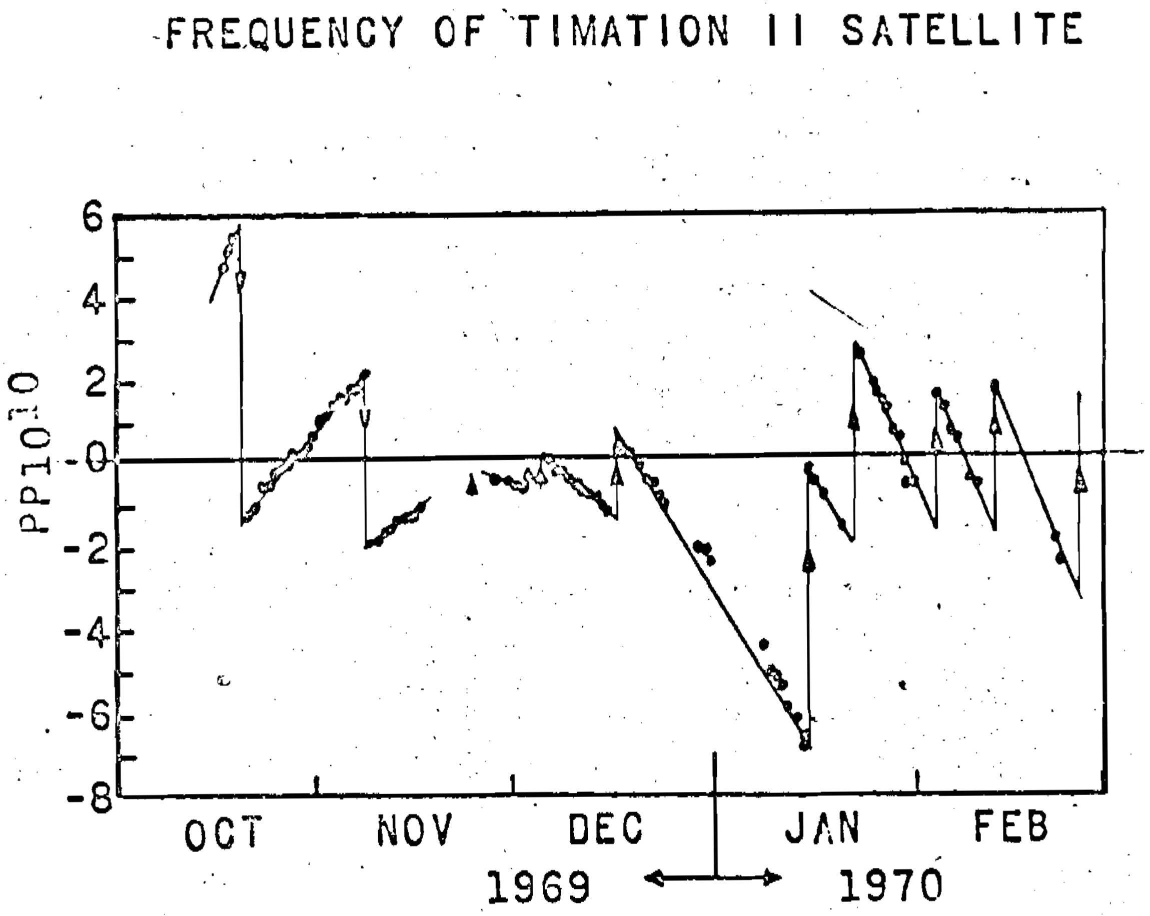

FREQUENCY OF TIMATION II SATELLITE
PP10^{10}
6
4
2
0
-2
-4
-6
-8
OCT
NOV
DEC
JAN
FEB
1969
1970

FIGURE 19

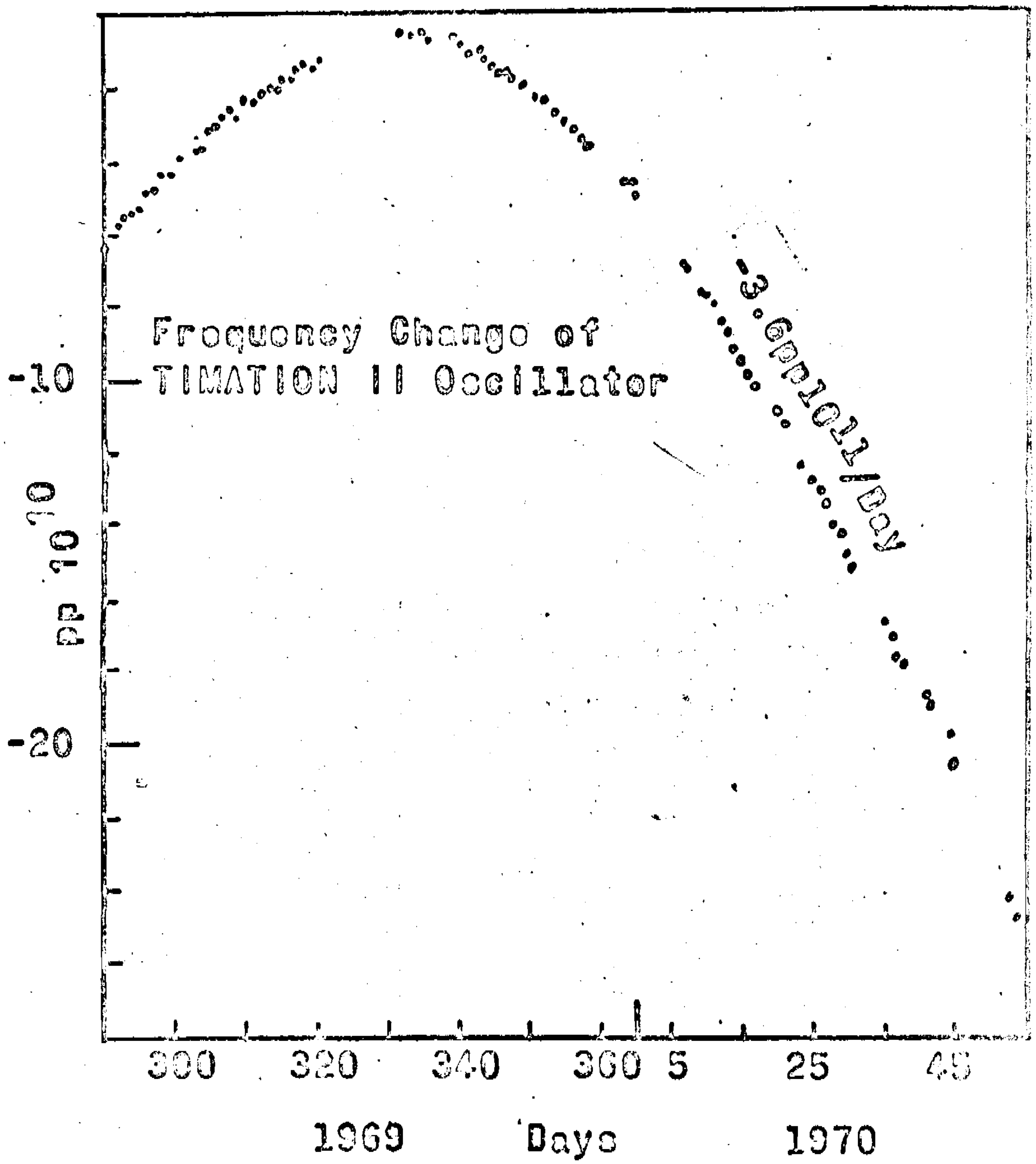

Frequency Change of
TIMATION II Oscillator
-3.6pp10^11/Day
-10
-20
pp 10^10
300
320
340
360
5
25
45
1969
Days
1970

FIGURE 20

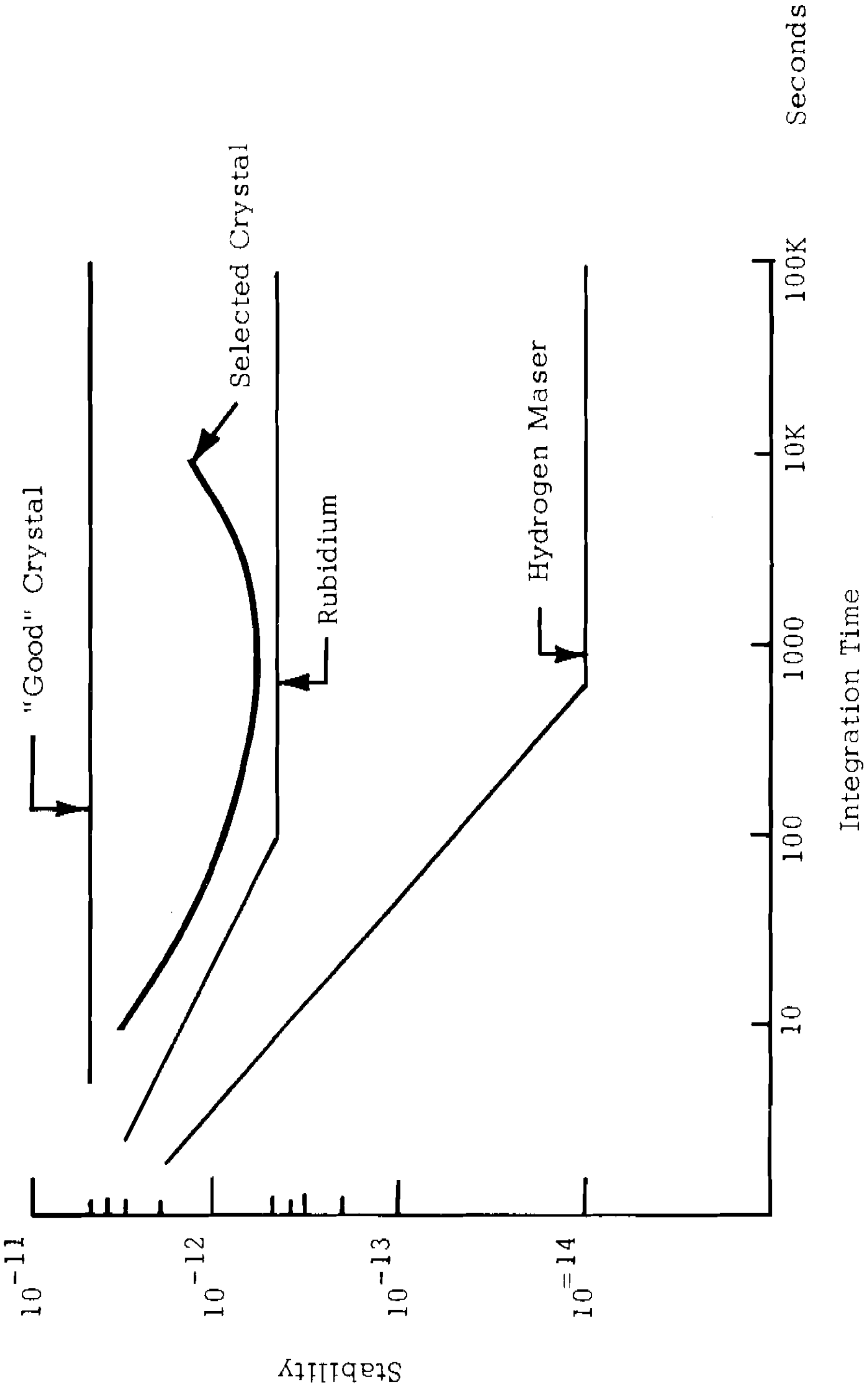

Stability
10^{-11}
10^{-12}
10^{-13}
10^{-14}
"Good" Crystal
Selected Crystal
Rubidium
Hydrogen Maser
10
100
1000
10K
100K
Seconds
Integration Time

FIGURE 21

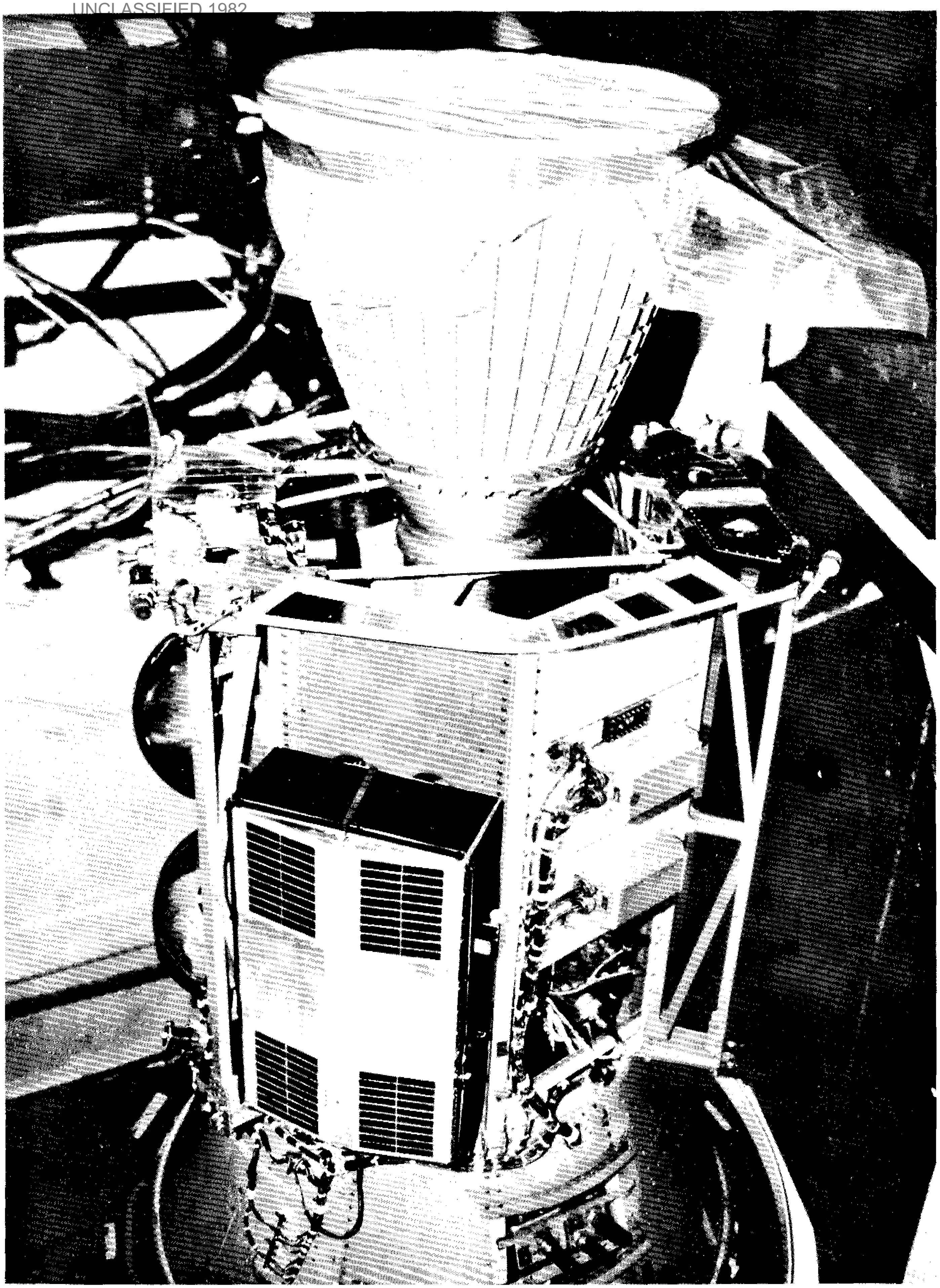


FIGURE 22

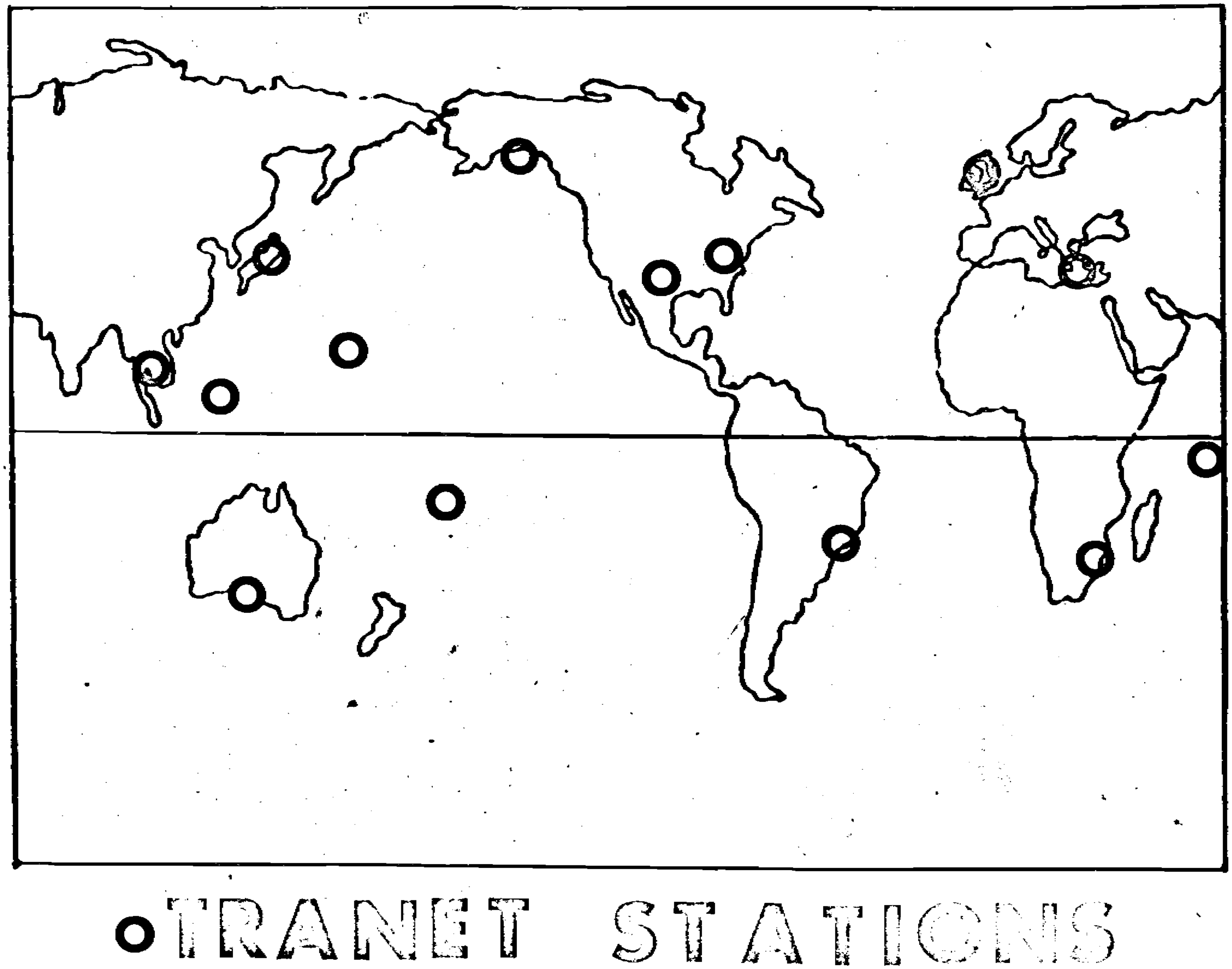


FIGURE 23

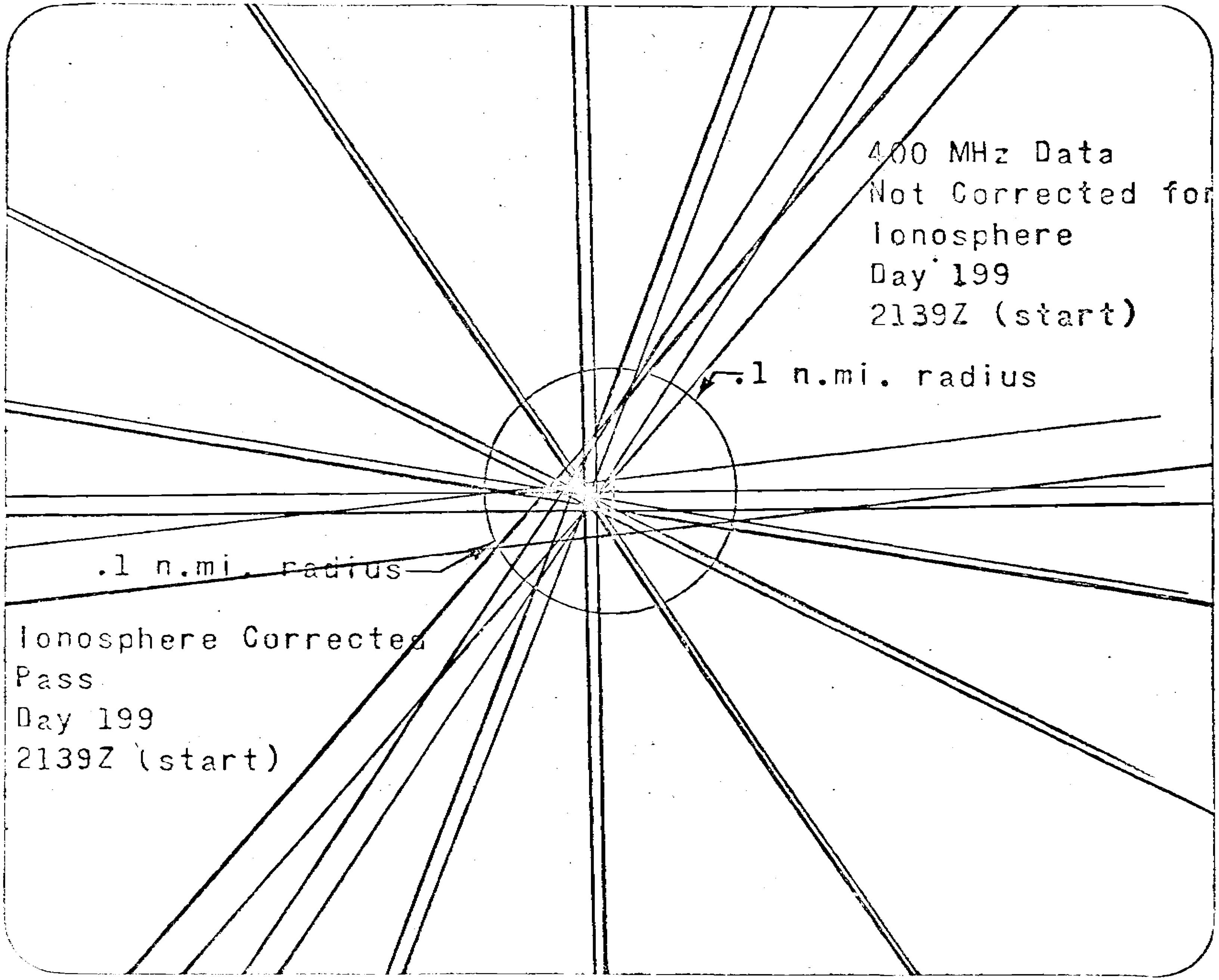

400 MHz Data
Not Corrected for
Ionosphere
Day 199
2139Z (start)
.1 n.mi. radius
.1 n.mi. radius
Ionosphere Corrected
Pass
Day 199
2139Z (start)

FIGURE 24

FIXES DETERMINED FROM TWO FREQUENCY RANGING DATA

33 Points
100' CEP

Mean Lat. 15'
Mean Long. 27'

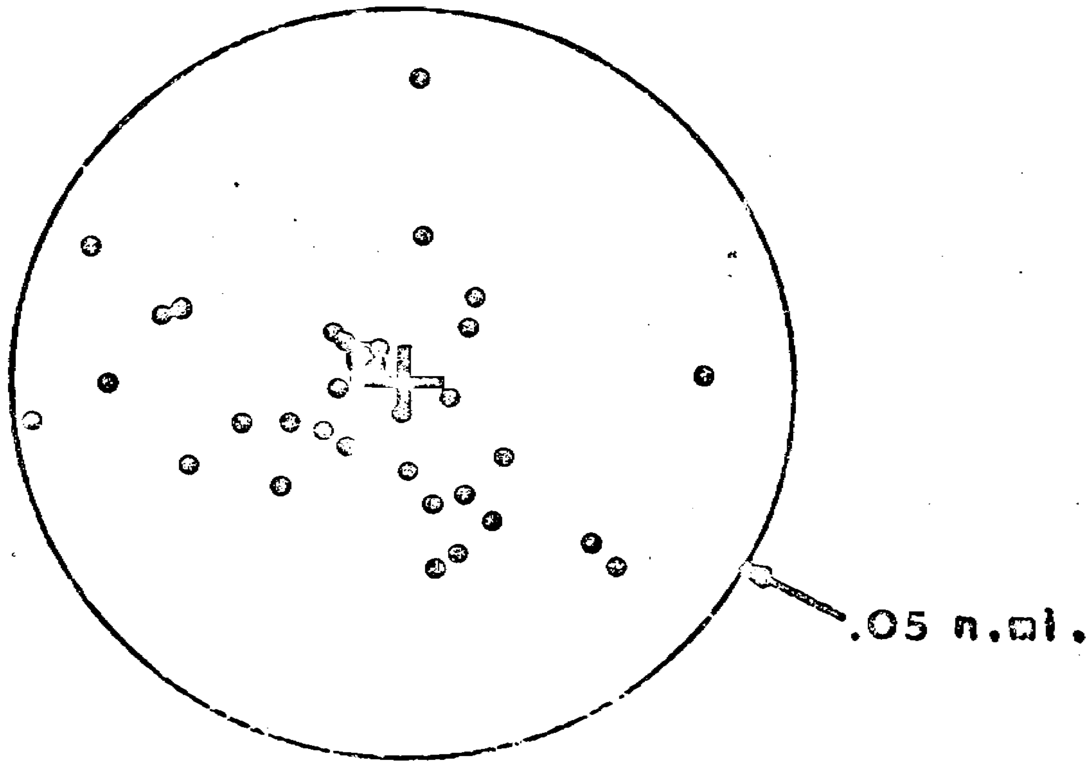


FIGURE 25

NRL TIMATION II SATELLITE

(Launched 30 Sept. 1969)

150-400 MHz NAVIGATION FIXES

DAY 72-105	DAY 133-154	DAY 155-173
RMS 68 M.	RMS 58 M.	RMS 54 M.

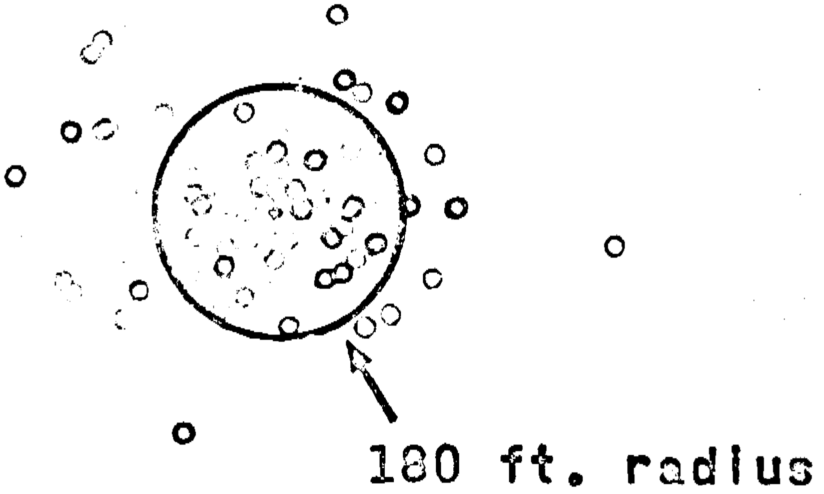


FIGURE 26

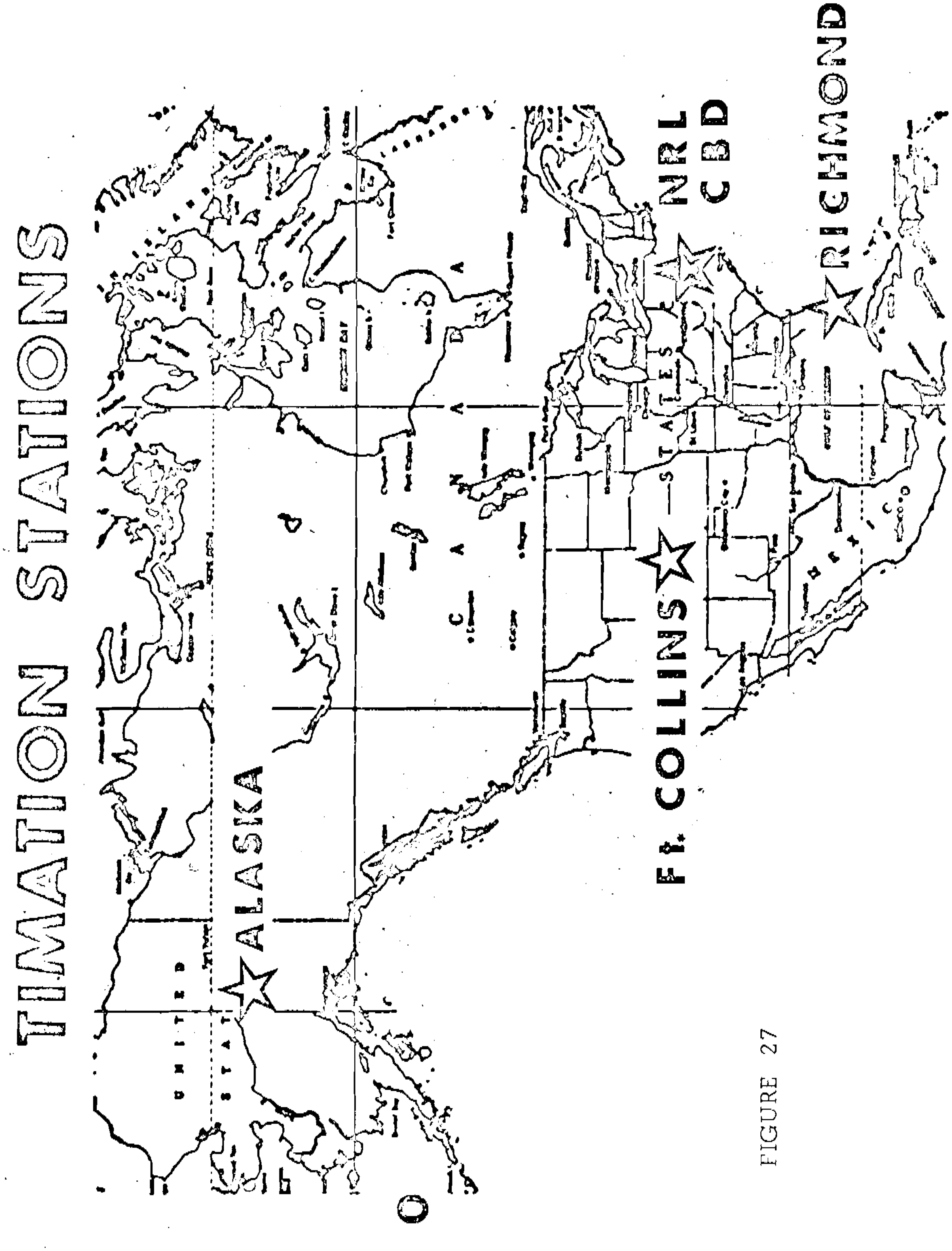

TIMATION STATIONS
ALASKA
Ft. COLLINS
NRL
CBD
RICHMOND
UNITED STATES
CANADA
UNITED STATES
MEXICO

FIGURE 27

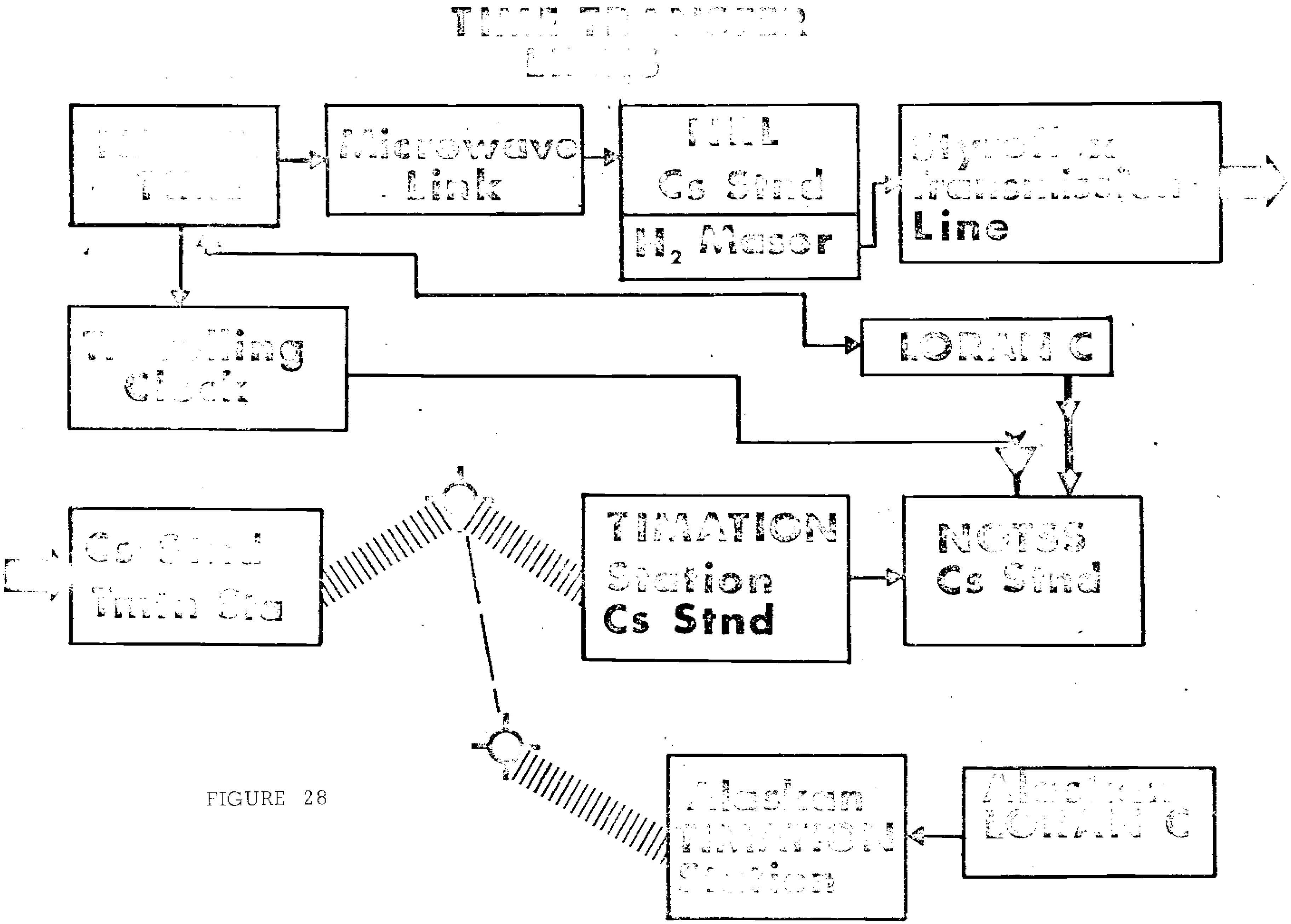

TIME TRANSFER
LINKS
Microwave
Link
NRL
Cs Stnd
H_2 Maser
Styroflex
Transmission
Line
Traveling
Clock
LORAN C
TIMATION
Station
Cs Stnd
NCTSS
Cs Stnd
Cs Stnd
Tmtn Stg
Alaskan
TIMATION
Station
Alaskan
LORAN C

FIGURE 28

through the styroflex transmission line (used to compare with NRL standards); it goes to the satellite; from the satellite it goes down to the TIMATION station in Richmond, Florida; that station's cesium standard is compared with the Naval Observatory's time standard substation in Richmond. Each one of these actions is a phase comparison. In order to go to Alaska, NRL goes to the satellite for about 15 minutes, the satellite transmits to the Alaskan station which also receives the Alaskan LORAN-C transmissions.

(C) When the Laboratory maser's output was compared to NRL's cesium beam in Florida, the result was a sigma of about 0.14 sec (see Figure 29).

(C) Figure 30 shows a signal going all the way from the Observatory to NRL to the satellite to Florida, and on to the Florida substation. The result was a sigma of 0.15 μsec, and over this ten-day period there was a change of about $\frac{1}{2}$ μsec. This was all done on a single frequency of 400 mcs. NRL was not doing the 150 and the 400 on this data, and they were quite pleasantly surprised to get this level of value. Dr. Winkler says this shows that the Florida clock has a rate. They had to check that rate against the result.

(C) In Figure 31, the signal goes the other way; from the Observatory to the LORAN-C station in Alaska by way of the satellite. The result was an even better sigma on this one. It is actually an unbelievable one and it shows that the LORAN-C time standard, according to NRL's measurements, must be a very good one, again $\frac{1}{2}$ μsec variation in ten days--a very good standard deviation of measurement. Of course, this sigma has to be used with a little caution, but it gives you a rough idea of how well you are doing.

(C) The next step (see Figure 32) is to reduce the number of comparisons. It would be nice to go directly from the Observatory microwave link to the stations to the satellite and keep the station synchronized to the Naval Observatory time standard substation oscillator, so there were not quite so many places for error.


Fla. (NRL)-NRL Maser
via
b
+1
0
-1
Microseconds
290
Day 1970
300
σ=.14 µs.

FIGURE 29

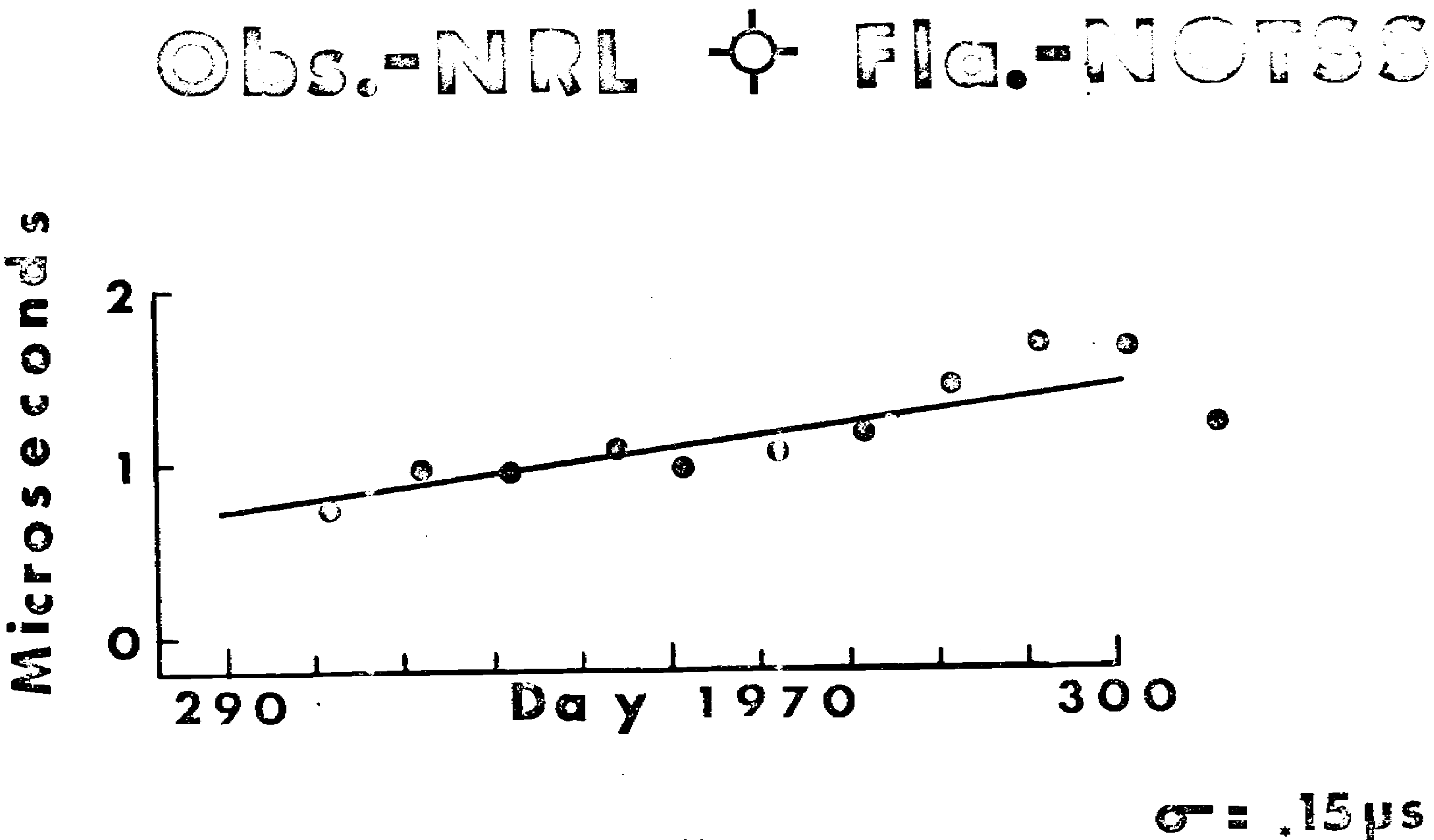


FIGURE 30

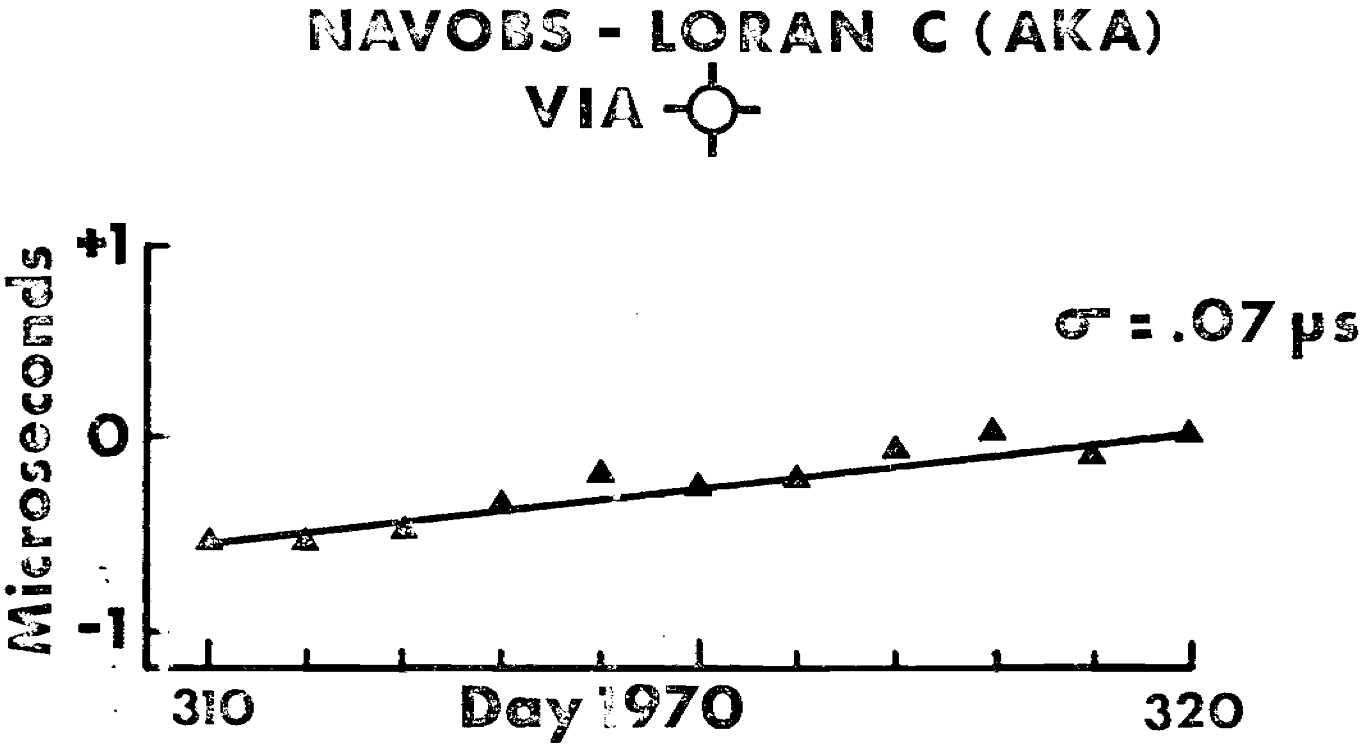

NAVOBS - LORAN C (AKA)
VIA
σ = .07 μs
Microseconds
+1
0
-1
310
Day 1970
320

FIGURE 31

PROPOSED TIME TRANSFER LINKS

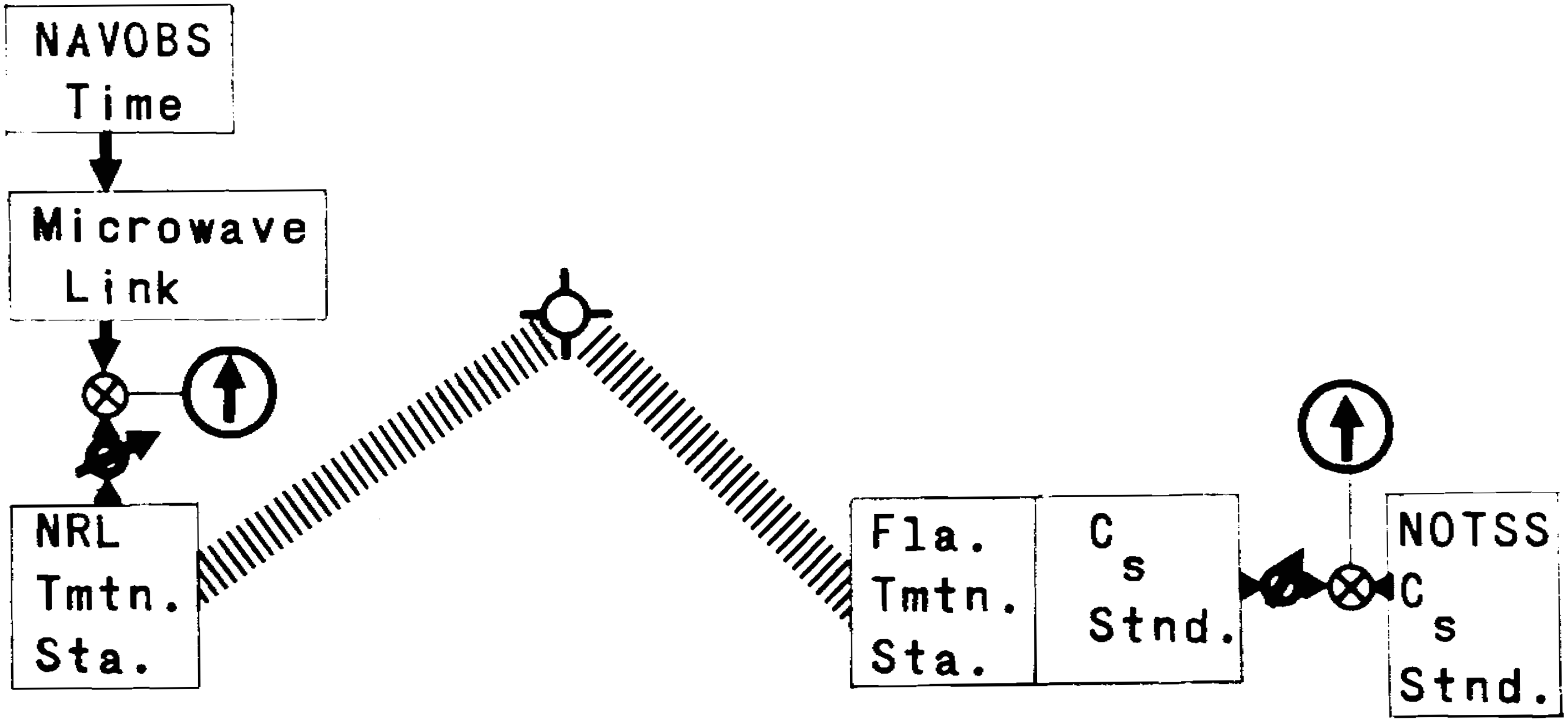


FIGURE 32