SUBMICROSECOND TIME TRANSFER BETWEEN THE UNITED STATES, UNITED KINGDOM, AND AUSTRALIA VIA SATELLITE

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ABSTRACT

During 1972 time transfer experiments were run between the U. S. Naval Observatory and the Royal Greenwich Observatory and, in 1973, between the U. S. Naval Observatory and the Division of National Mapping in Canberra, Australia.

In both cases the time transfer agent was the TIMATION II satellite, 1969-82B. The satellite ephemerides were computed by the Naval Weapons Laboratory from data provided by the Defense Mapping Agency TRANET. This net tracked the satellite's doppler transmissions.

The phase of the satellite clock was determined from knowledge of the position of the satellite and of the observer and the computed distance between the two. By monitoring the clock on successive passes the rate of the satellite clock was determined at Washington. By again monitoring the satellite clock at the distant station the satellite clock could be compared to the local clock and this local clock compared to the U. S. Naval Observatory clocks.

In 1972 the RMS of observations at Greenwich deviated by approximately 1/4 microsecond from a straight line when compared to the Naval Observatory. In 1973 the observation errors at Canberra were approximately half as great.

TIME TRANSFER

A number of time transfer experiments have been run by means of low frequency navigation systems (LORAN-C, OMEGA) and by clocks carried by aircraft and satellites.

The low frequency systems are useful and provide a large number of users with inexpensive clocks that have new atomic standard stabilities. The problem with these systems is the shifts that occur in the propagation paths.

Atomic clocks carried in aircraft are again a good solution to the problem of time transfer. This technique suffers only from the errors due to transportation time and the costs of this transportation.

The satellite carried clock suffers from a number of error sources that at first might make this technique appear inferior to the others. A closer look makes this one appear to have both the best present day capability and the best chance for improvement.

The problems with the satellite carried clock transfer method are (1) In contrast to the low frequency broadcast station and the aircraft carried clock one must now determine where the satellite (and its clock) is at the time of measurement. (2) The second problem is the instability of the satellite clocks, which are at present crystal controlled.

The first problem, that of the satellite location, is reduced by using a fact of satellite orbital mechanics. This fact is that the principal error in satellite orbits is along track. By making the measurement when the satellite is at its closest point this error becomes negligible. This satellite location error is further minimized by using a navigation satellite for which the techniques of location prediction and postdiction are well known.

The second problem of clock instability is partially solved by the high speed of the satellite. The speed reduces the effect of the instability. For instance, in some cases the satellite clock measurement was made in the U. S. barely 15 minutes before the similar measurement was made in England. A check carried by air and road would take roughly 50 times as long. From this calculation one can see that the satellite clock can have only 2% of the stability of the aircraft carried clock to have equal performance. The satellite clock has another advantage. By waiting an entire orbit and measuring the satellite clock again from the same site and thereby determine much of the clock's instability during the interval between the two previous measurements.

THE SATELLITE

The satellite used is TIMATION II, launched on September 30, 1969 and shown in Figure 1. The orbit of the object is circular, inclination 70°, and altitude 500 n. miles.

The TIMATION II satellite transmits in both the 150 MHz and 400 MHz bands. The satellite carries a clock driven by a very stable quartz crystal oscillator operating at 5 MHz.[2] Active temperature control of the quartz crystal frequency standard to within a fraction of a degree is achieved by (a) careful design of the

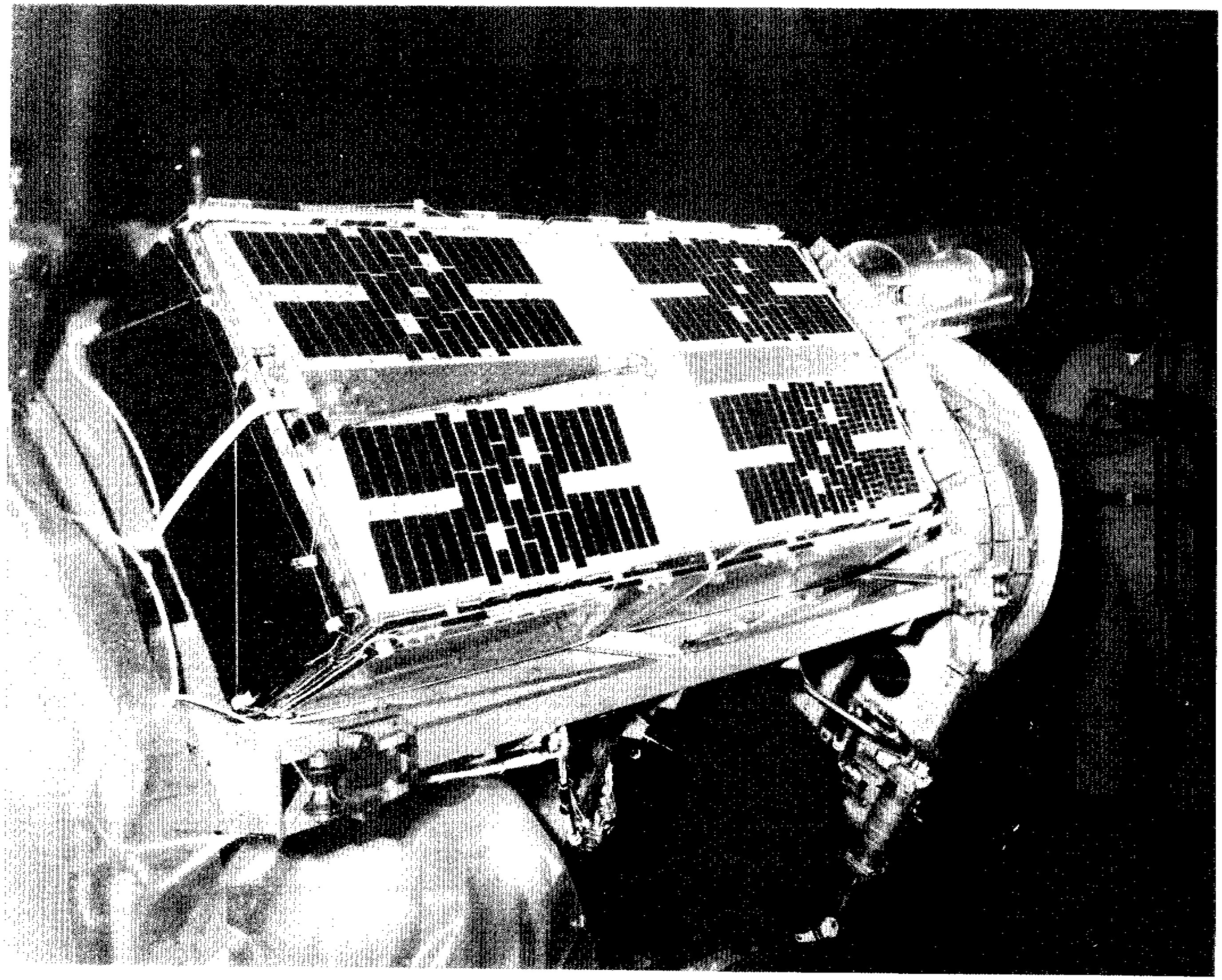

Figure 1. The TIMATION II Satellite

satellite and (b) use of a thermoelectric device for fine temperature control. The satellite antennas are kept earth-pointed by a two axis gravity gradient stabilization system.

Two carriers are coherently derived from this signal, one at 149.5 MHz and the other at 399.4 MHz. Other frequencies are derived in the 149.0 to 150 MHz and 398.9 MHz bands to provide the nine modulation frequencies from 100 Hz to 1 MHz.

The carriers are transmitted continuously to allow doppler tracking or orbit computations. The use of two frequencies provides the data necessary to correct for both range[3] and doppler ionospheric effects and thereby insure a more accurate orbit trajectory.

The range tones are transmitted in a time sharing mode 4.8 seconds every minute. This transmission allows a user with a TIMATION II receiver, which also contains a clock, to measure the time difference between the signal received from the satellite and the ground receiver clock. This time difference includes the propagation time of the signal from satellite to ground plus the synchronization error between the satellite and ground clocks.

ORBIT DETERMINATION

Since launch the satellite has been tracked by the TRANET doppler tracking sites listed below.

Brazil	Philippines
Japan	Australia
Alaska	Seychelles
England	South Africa
New Mexico	Thialand
APL	Wake
Samoa	Cyprus

The data has been sent by the AUTODIN circuit to the Applied Physics Laboratory of Johns Hopkins University at Howard County, Maryland for preprocessing before being sent to the Naval Weapons Laboratory in Dahlgren, Virginia for use in the computation of the orbital elements. The orbit is computed using observed data over a two day span. An additional seven days of predicted minute vectors are then derived. The orbit fit in the observed region is accurate to approximately 10 meters. The further into the predicted region the more inaccurate the trajectory becomes.

COMMUNICATION LINK

The present location of the Royal Greenwich Observatory is at Herstmonceux England about 50 miles south of London. The communications link (Fig. 2) used in the experiment was primarily the General Electric commercial time share system. A Post Office (PO) telephone line was arranged between Herstmonceux and London. The GE time share system could be activated by dialing a local London telephone number and nearly immediate access was available to the computer located in Cleveland, Ohio. The only equipment necessary at the RGO site was a Model 35 teletype terminal and acoustical coupler. A similar terminal was available to personnel at NRL.

After the orbit was computed at the Naval Weapons Laboratory the minute vector trajectory date was placed into the NWL time sharing files. It was then transposed by NRL personnel into the GE files in the computer located in Cleveland. By using the terminal at RGO the data could then be retrieved from GE. The cycle could be accomplished in near real time. During the entire experiment absolutely no errors in transmission were experienced on the Cleveland to RGO link.

COMMUNICATION LINK WITH AUSTRALIA

The communications link used between the U. S. and Australia differed greatly from that used between the U. S. and the RGO. For the Australian experiment standard diplomatic circuits were used, augmented by telephone as needed. While this system did not offer the response of the direct link used between the RGO and the U. S. it was adequate once it became familiar to the participants.

EXPERIMENT CONFIGURATION

One TIMATION II receiver was located at the Naval Research Laboratory and used a cesium beam standard as a frequency source for its clock. The cesium beam is referenced to a hydrogen maser also located at NRL. The maser is kept to within a few nanoseconds of the Naval Observatory's standard. Therefore the ground clock at the NRL TIMATION site is ultimately referenced to the time standard from the Naval Observatory.

The complete NRL station configuration consisted of an analog phase receiver, a cesium beam standard and dual circular polarized helices. The receiver is a single band 400 MHz range receiver, which tracks a carrier and tone set. The lowest tone is 100 Hz and 1 MHz is the highest tone. The ratio between adjacent tone frequencies is approximately 3 to 1.

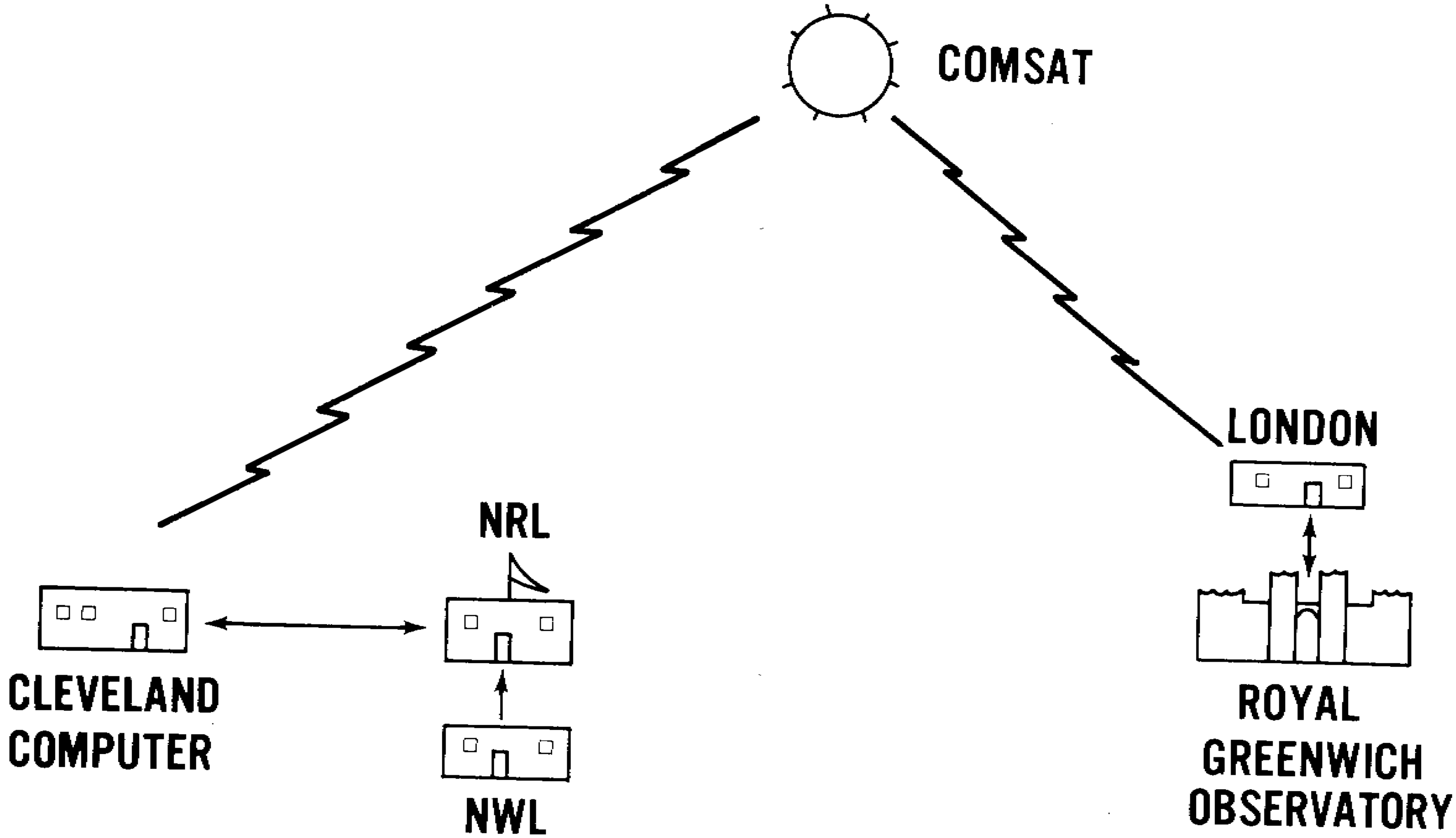

Figure 2. Communication Between RGO, NRL, NWL and the Computer

The site configuration at RGO and Australia consisted of a digital TIMATION II receiver (Fig. 3), a cesium standard supplied by the local station, a digital clock, and dual circular polarized Yagi antennas (Fig. 4). The TIMATION II receiver used automatically combined the range tones and displayed a resolved range (time once a minute when the signal from the satellite was being tracked. Adjacent modulation frequencies had a 10 to 1 ratio as opposed to the 3 to 1 ratio used in the NRL analog receiver. The lowest tone (100 Hz) and the highest tone (1 MHz) were identical to those used at NRL. This larger difference between adjacent tones required a tighter tolerance on signal to noise ratio. Consequently some minutes of data which were correctly resolved at NRL had to be filtered from the RGO system, as will be shown later.

ANALYSIS OF RESULTS OF THE RGO EXPERIMENT

Time difference measurements between the clock in the satellite and the clock at each ground station are taken when the satellite is above the horizon at each ground station. An epoch time transfer can be performed using just one simultaneous measurement from each ground station, however, the precision of the time transfer can be improved by using more observations collected over a large span. For this experiment data were collected for 1 week. The inclusion of data over a 1 week span allowed a determination of the frequency difference between RGO and USNO in addition to the epoch transfer. The repeatability of the time transfer via satellite was demonstrated and the contribution of several error sources was reduced by using redundant measurements.

Time difference measurements at each site were obtained using ranging receivers at 400 MHz. The use of measurements at only one frequency prevented an accurate correction for the group delay to the signal due to the ionosphere. The contribution of the ionospheric effect to the time transfer was minimized by collecting data for the 1 week period, which caused any bias in the time transfer due to this error source to approach zero, however the variance of the time transfers measurements was not reduced.

The observed time difference is given by

$$O_{obs} = t_{prop} + (t_{sat} - t_g) + \Delta t_{iono} + \Delta t_{trop} + K + \epsilon \quad (1)$$

where

(1) O_{obs} is the measured or observed time difference.

(2) t_{prop} is the free-space propagation delay along the line-of-sight from the satellite to the receiver.

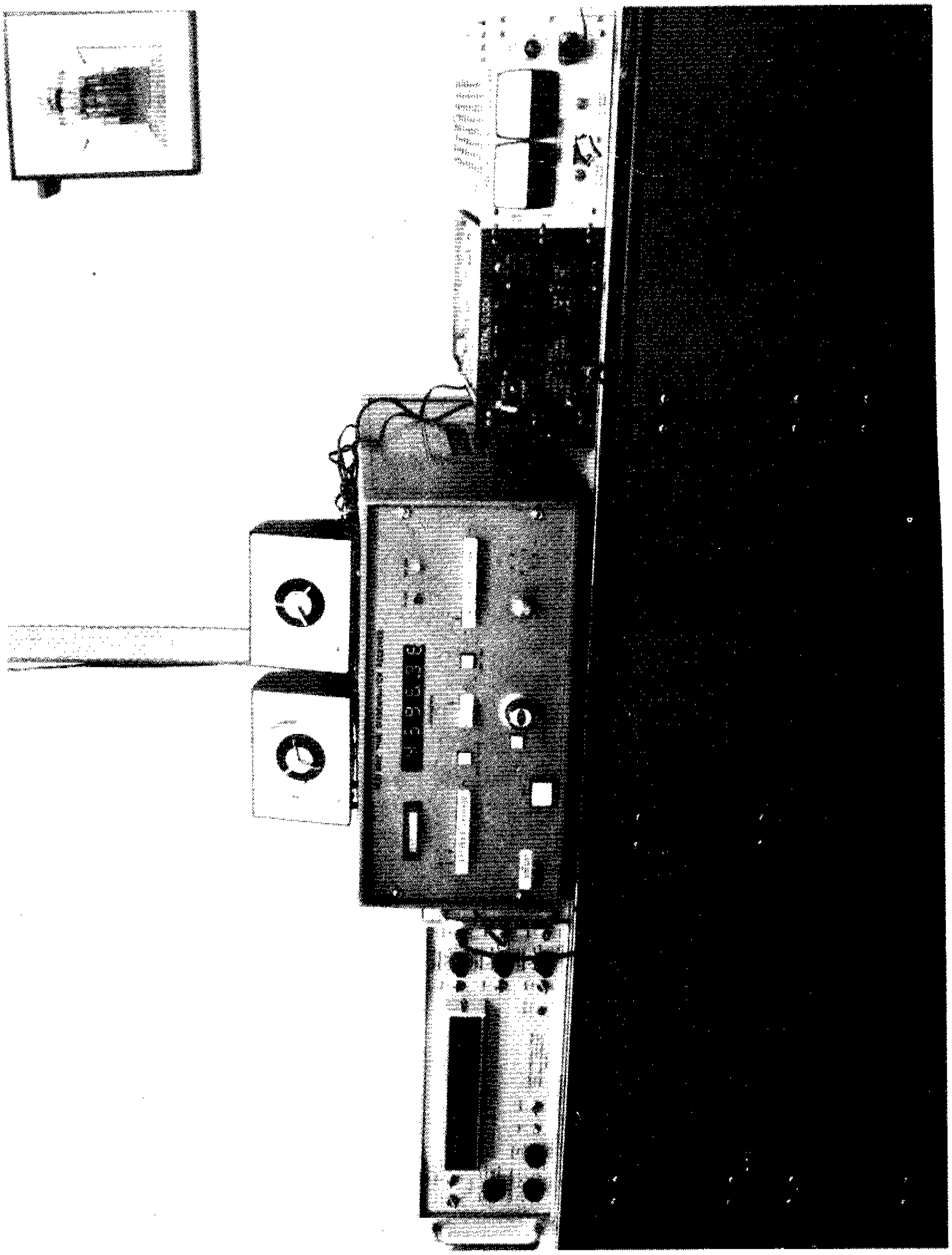

Figure 3. Receiving Equipment Used at RGO and in Australia

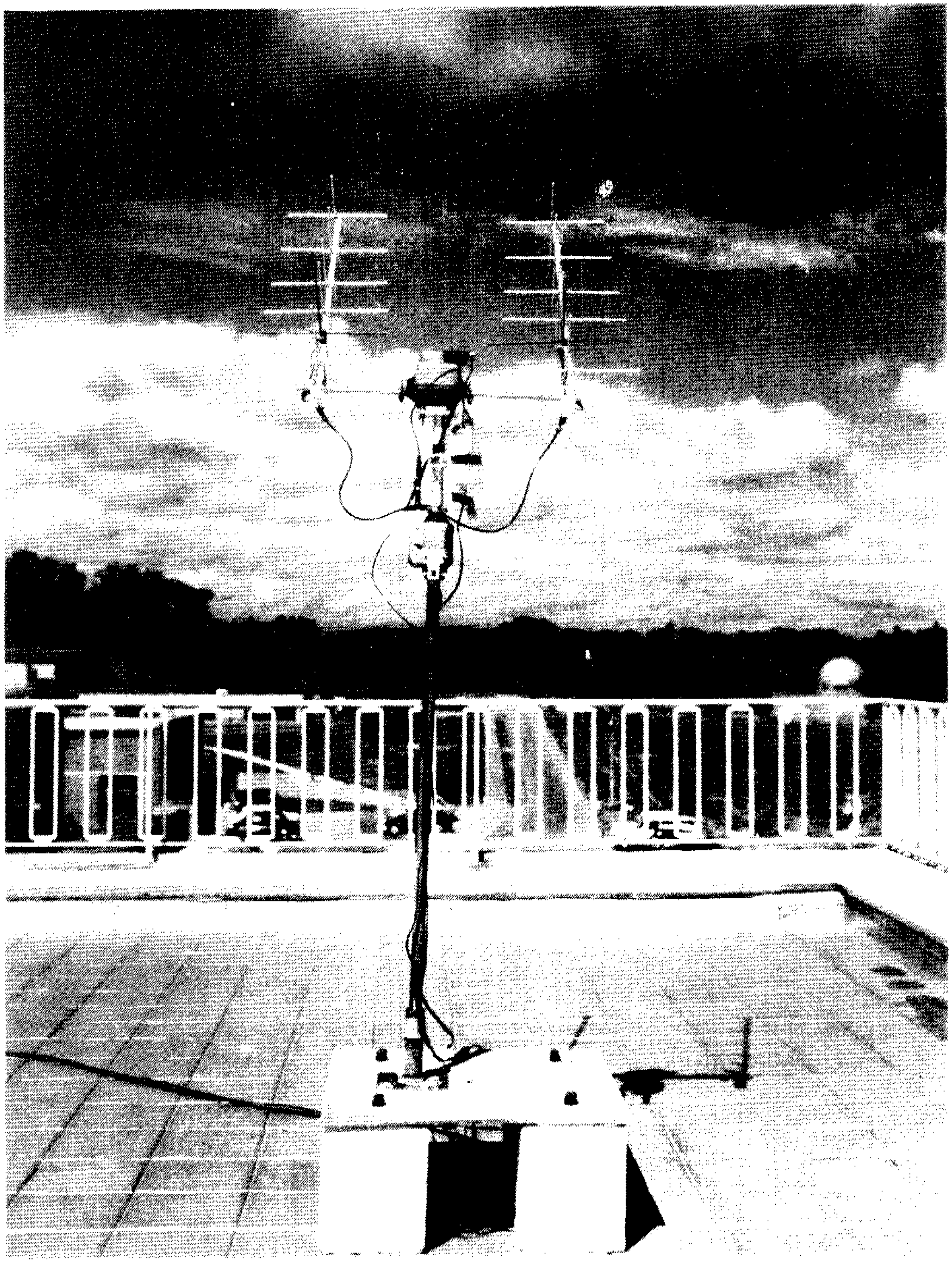

Figure 4. The Antenna Installation at RGO. The same antenna was used in Australia.

(3) $(t_{sat} - t_g)$ is the time difference between the satellite clock and the ground station clock.

(4) Δt_{iono} is the ionospheric group delay at 400 MHz.

(5) Δt_{trop} is the delay through the troposphere.

(6) K is the delay from the antenna through the receiver which is either calibrated to zero or precisely measured.

(7) ϵ is the random and unmodeled error in each observation.

The term t_{prop} is of the form R/c where R is the range from the satellite to the receiver antenna and c the speed of light in vacuum. The calculated value of R is influenced by the accuracy of the satellite ephemerides as well as the knowledge of the observer's geographical position. The largest component of uncertainty in satellite position is along the track of the satellite. The error in t_{prop} due to this component can be minimized by taking the time difference observation when the satellite is near TCA (Time of Closest Approach) to the receiver. At TCA the satellite is a maximum elevation and is therefore moving normal to the line of sight. Since the elevation angle is at a maximum, the contributions due to the troposphere and ionosphere are also minimized.

The satellite ephemeris is used with the receiver antenna position to calculate theoretical values of the time differences denoted by T or T_i for the "i" th point. Then a correction is calculated using the observed time differences which is denoted by (t-O) or (T-O)i. The (T-O)'s may be designated for RGO, NRL or USNO by (T-O)RGO, (T-O)NRL or (T-O)USNO.

The Naval Observatory UTC time, denoted by t_{USNO}, is transferred to NRL by (a) a microwave relay link or (b) a traveling clock. Hence the (T-O)NRL values may be reference to the Naval Observatory by Equation 2.

$$(T\text{-}O)USNO = (T\text{-}O)NRL + (t_{USNO} - t_{NRL}) \qquad (2)$$

The NRL clock was corrected before each satellite pass to agree with UTC, hence there is no significant bias between the two clocks, and the second term in Equation 2 approaches zero (to within a few nsec). The two (T-O)'s may be combined to give (T-O)RGO - (T-O)USNO which yields the epoch transfer. The slope of the time transfer curve during the 1 week data span then yields a measure of the frequency difference between the ground station clocks at RGO and USNO.

The TIMATION II satellite clock is driven by stable 5 MHz quartz crystal frequency source and is used to derive the satellite time base which is designated by t_{sat}. The satellite clock is tunable in both frequency and time, however for this experiment no corrections were applied during the data span. The quartz crystal exhibits a low aging rate with respect to the UTC time base, hence t_{sat} may be ultimately related to UTC by Equation 3.

$$t_{sat} = T_0 + f_0 (t_{USNO} - t_0) + 1/2\, a_0 (t_{USNO} - t_0)^2 \tag{3}$$

The terms T_0, f_0 and a_0 represent the time, frequency and aging rate differences between the satellite clock and the USNO time base at some epoch t_0. If simultaneous observations are taken, then the satellite clock is eliminated when the difference (T-O)RGO - (T-O)USNO is computed using Equation 1. The satellite clock was a factor in this experiment because the TCA's from RGO and NRL were separated by about 15 minutes in time for the same revolution of the satellite.

Figure 5 shows a typical pass taken from the NRL site. The (T-O) values were biased for convenience in producing the computer plots. These (T-O)'s exhibit a slope which is partially due to orbit inaccuracies. Taking the reading of the (T-O) for each pass at the maximum elevation point minimizes the contribution of several error sources.

Figure 6 shows a pass taken from the RGO site. A bias was inserted for convenience in making the RGO computer plots, as is noted in Figure 6. For this pass three points were filtered and two points show a jump of approximately 1 microsecond with respect to the majority of the observations. As mentioned previously, this can occur for the digital receiver used at the RGO site because of the 10 to 1 ratio between adjacent tones. The NRL analog receiver (which used approximately a 3 to 1 tone ratio) and the digital receiver were calibrated at NRL before this experiment to insure that the time differences measured represented the actual time delay.

All passes collected over the 1 week period are presented in Figure 7. The lowermost plot gives the (T-O)USNO values which are obtained from the (T-O)NRL values through the use of Equation 2. The middle plot gives the (T-O)RGO values directly* because their time standard was used to drive the

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*A four microsecond offset was inserted for convenience, hence the final values require a four microsecond correction.

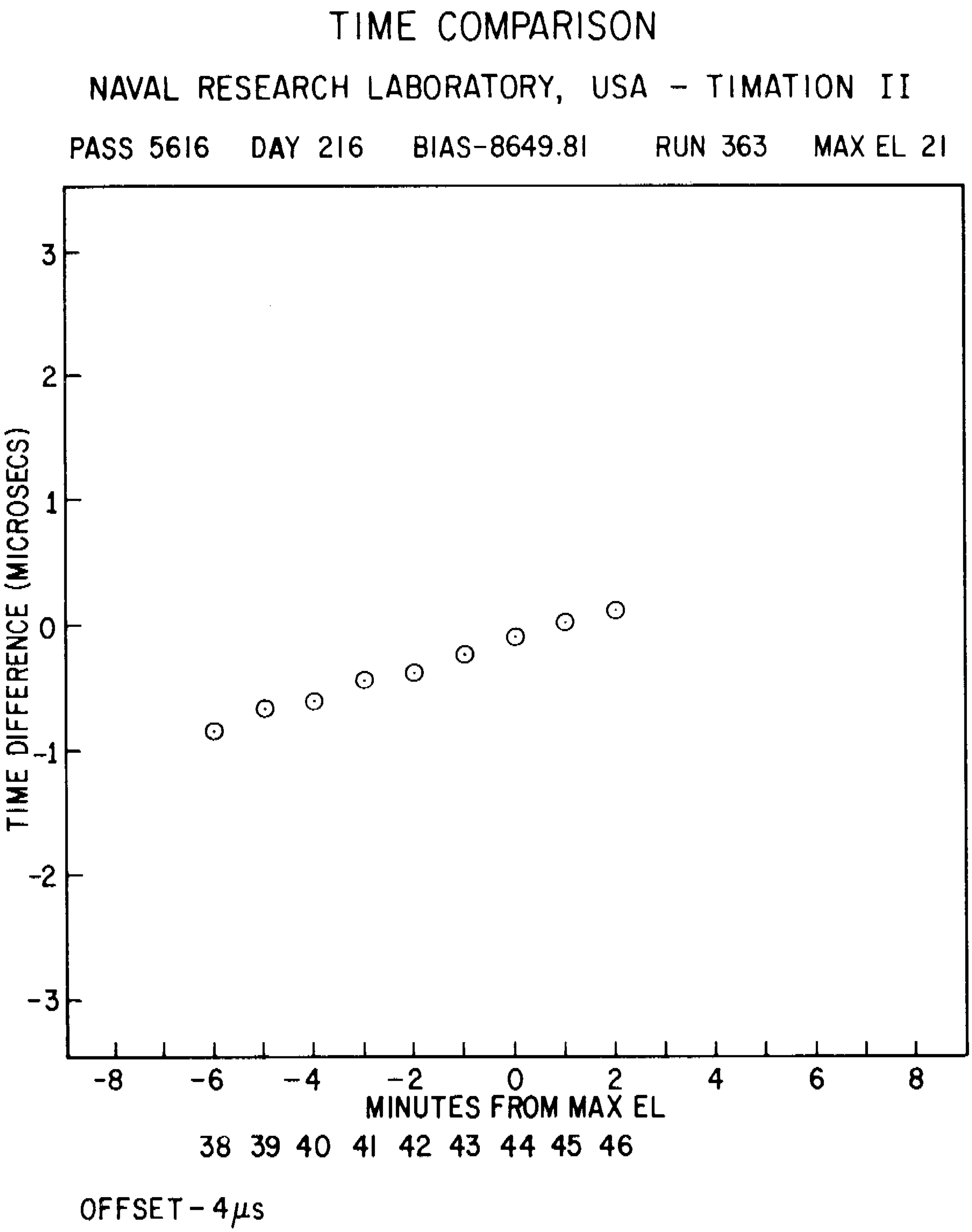

Figure 5. Data From a Typical NRL Pass

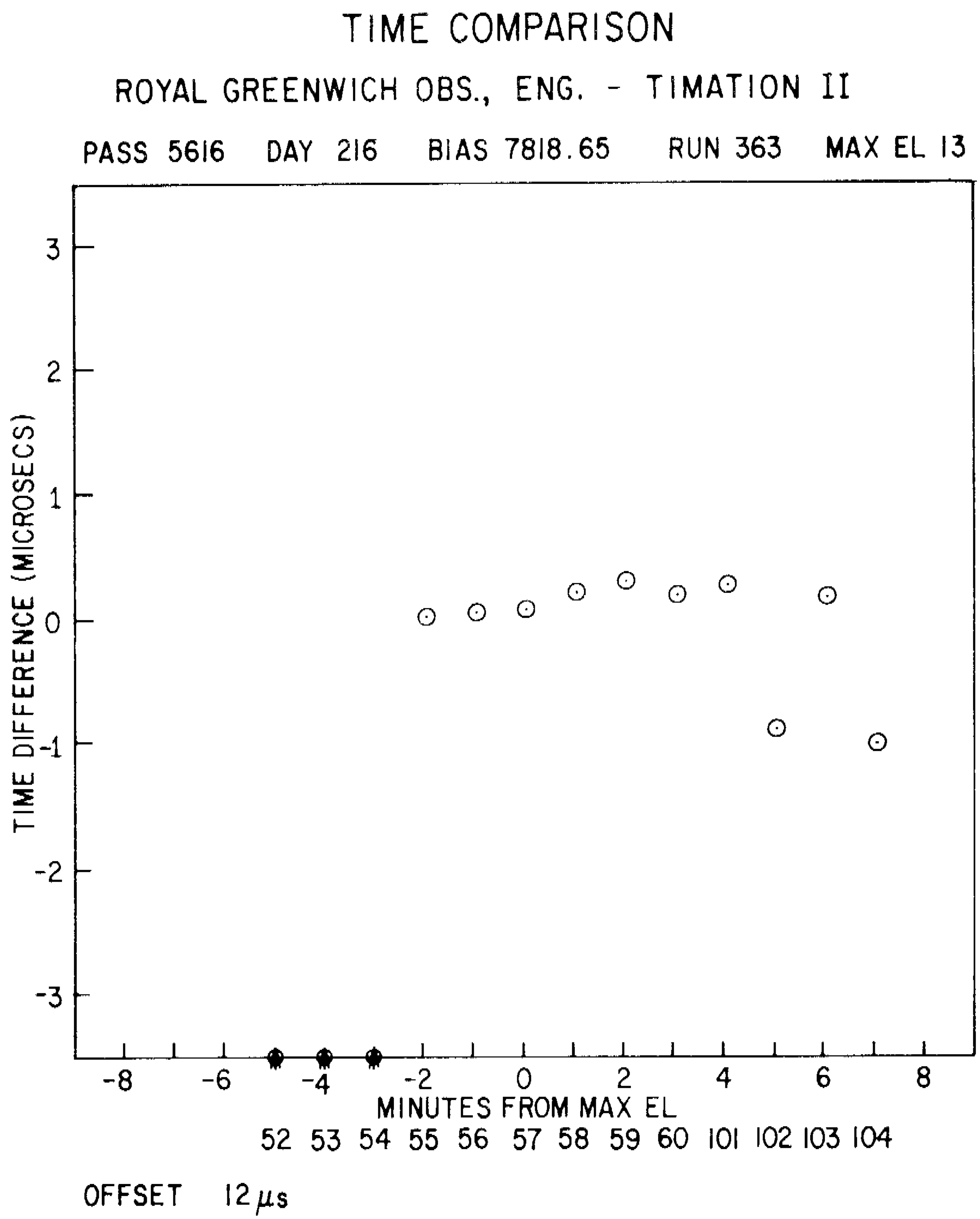

Figure 6. Data From a Typical RGO Pass

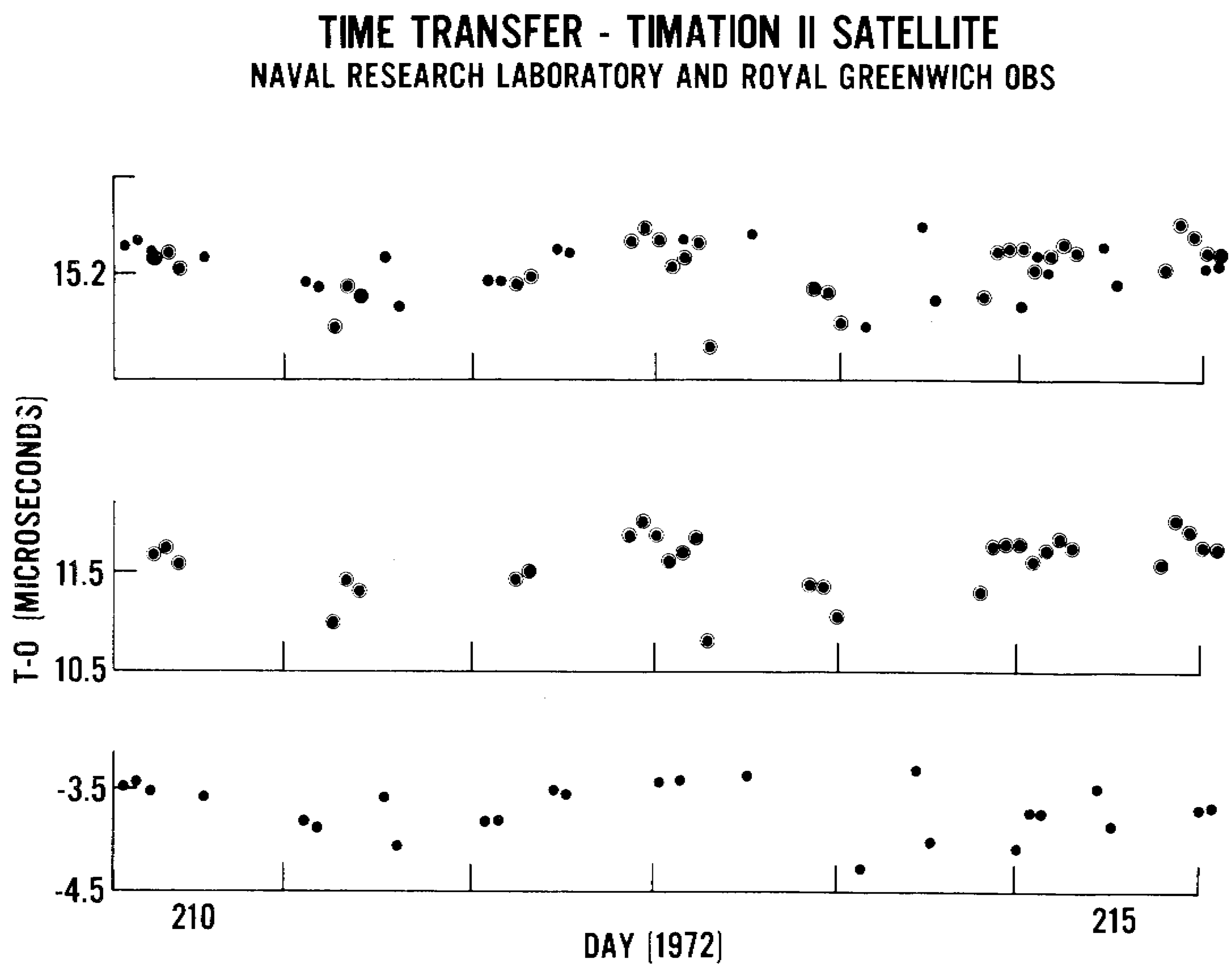

Figure 7. Individual and Combined RGO-NRL Passes Taken Over 6 Days in 1972

digital receiver. The effect of the satellite clock has been removed from Figure 7. The (T-O)'s can be subtrated to produce the final (T-O)RGO - (T-O)USNO plot on the top of Figure 7. This yields the time transfer on a pass to pass basis between RGO and USNO.

CONCLUSIONS

RGO has two different methods of clock synchronization with USNO, firstly the traveling clock experiment which is performed approximately every 6 months and secondly, daily comparison with LORAN-C. Figure 8 shows the traveling clock closure made about 4 months before the TIMATION time transfer experiment and again 3 months after the experiment. It is seen that a constant 1.5 microsecond difference was present between LORAN-C and the traveling clock. Figure 9 compares the results for August 2, 1972 which shows agreement to less than 0.5 microsecond, assuming the same bias for LORAN-C. The frequency difference between RGO and USNO is given by the slope of the (T-O)'s in Figure 13 and yields a value of less than 5×10^{-12}. The RMS noise level was ± 0.3 microsecond.

	TRAVELING CLOCK	LORAN C	Δ
4 - 17 - 72	7.9	9.5	1.6
11 - 3 - 72	11.8	13.3	1.5

Figure 8. UTC Differences Made Between RGO and the USNO

THE AUSTRALIAN EXPERIMENT

The Australian experiment was aided by knowledge obtained at RGO. After the completion of the RGO experiment the digital receiver was recalibrated using a large number of satellite passes. The phase adjustments on the several sidetone frequencies were used until the adjustments produced the minimum number of resolution faults. The readings on this receiver were then adjusted to be equal to those obtained on the analog receiver at NRL.

Figure 10 shows the results of the first run at the Australian site. In this case the data shown is a direct comparison of each station with the satellite clock.

8-2-72	
UTC (RGO) - USNO (Loran C)	-11.1
UTC (RGO) - USNO (Traveling Clock)	- 9.6
UTC (RGO) - USNO (TIMATION 11)	- 9.8

Figure 9. RGO - USNO Time Transfer Results

The U. S. station is the solid line and the Australian is dashed. The time difference between the two scales is twenty microseconds. When the difference between the data lines is added to this 20 microseconds the chart shown in Figure 11 is obtained. The chart shows a systematic drift of approximately 0. 1 microsecond per day and the data deviation is 0. 11 microseconds about this drift line.

Two months after these data were taken the Australian group produced the data shown in Figure 12 and Figure 13. These graphs have RMS deviations approximately three times higher than previously. Presumably this higher value exists because the orbits were made using a single 400 MHz signal in contrast to previous orbits made by means of both 400 and 150 MHz signals.

Figure 14 shows the relationship between the two sets of data. It is seen that the average drift of the two standards is 0. 087 microseconds per day. These data were extrapolated further to compare it to the USNO traveling clock measurement made on 6 December. The difference between this extrapolated and the measured value was 0. 09 microseconds.

FUTURE MEASUREMENTS

Further measurements are being made in Australia. It is expected that the next satellite of this series will provide improved data for worldwide time transfer.

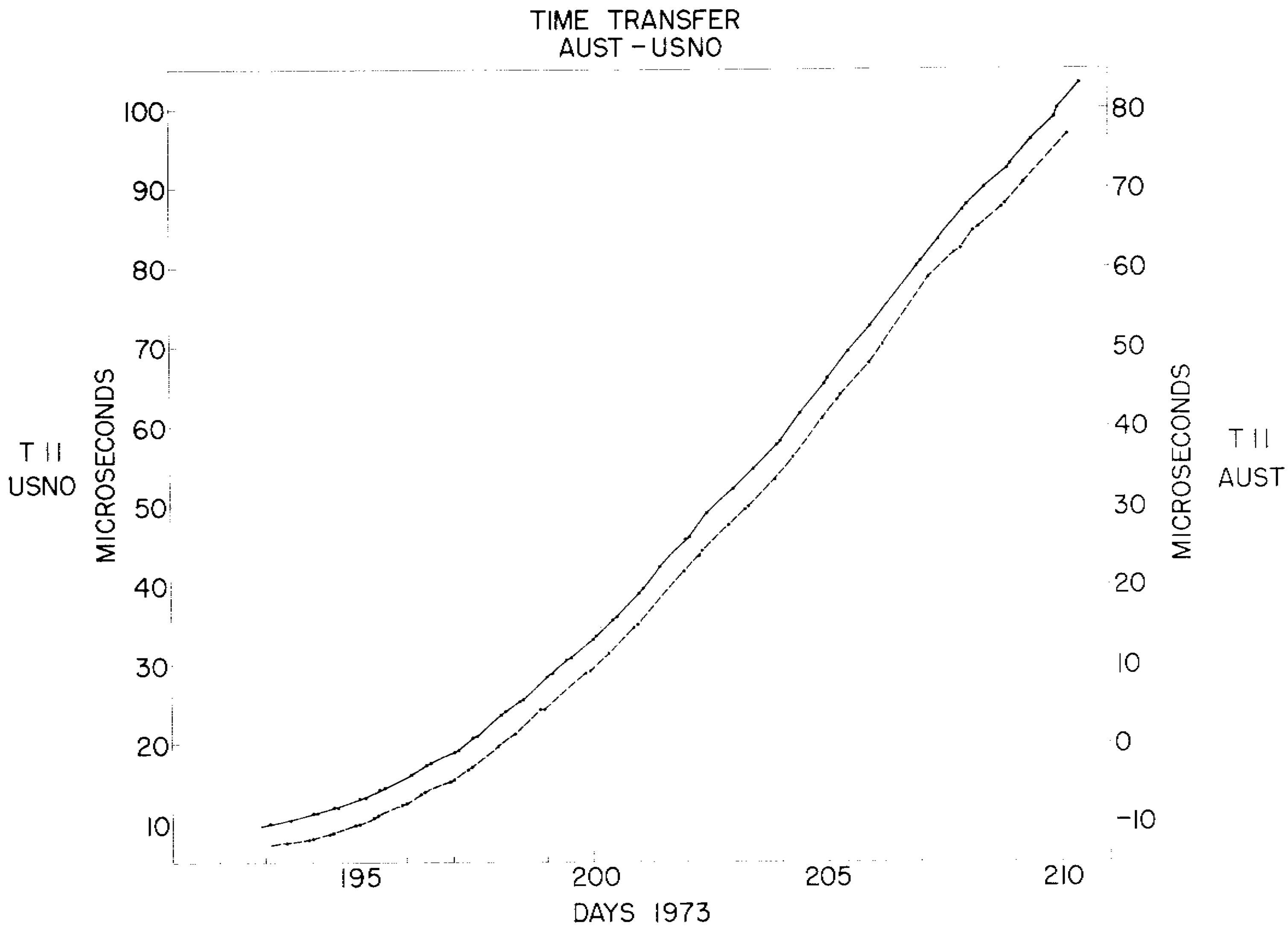

Figure 10. Results of First Australian Run

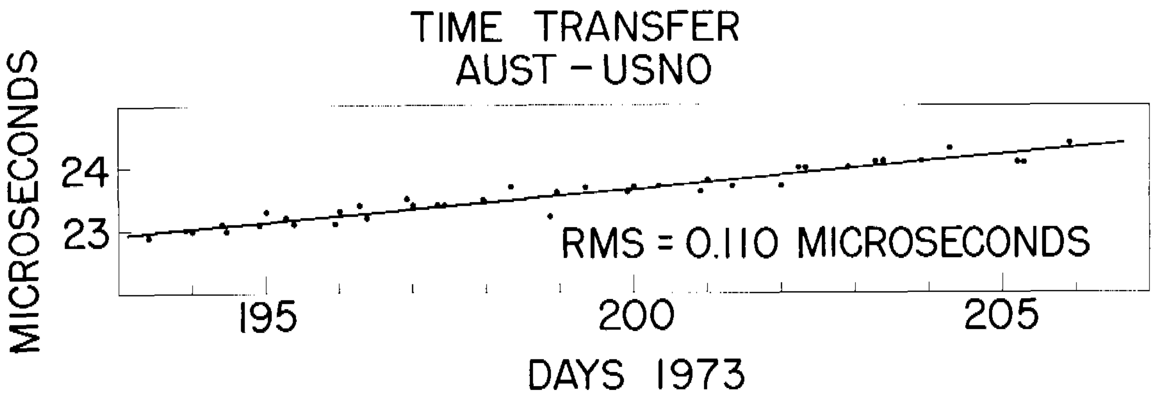

Figure 11. Time Differences Obtained from Figure 10

ACKNOWLEDGEMENTS

Experiments like those described require the help of many people in many organizations. The following list contains a number of those involved.

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James Wilcox

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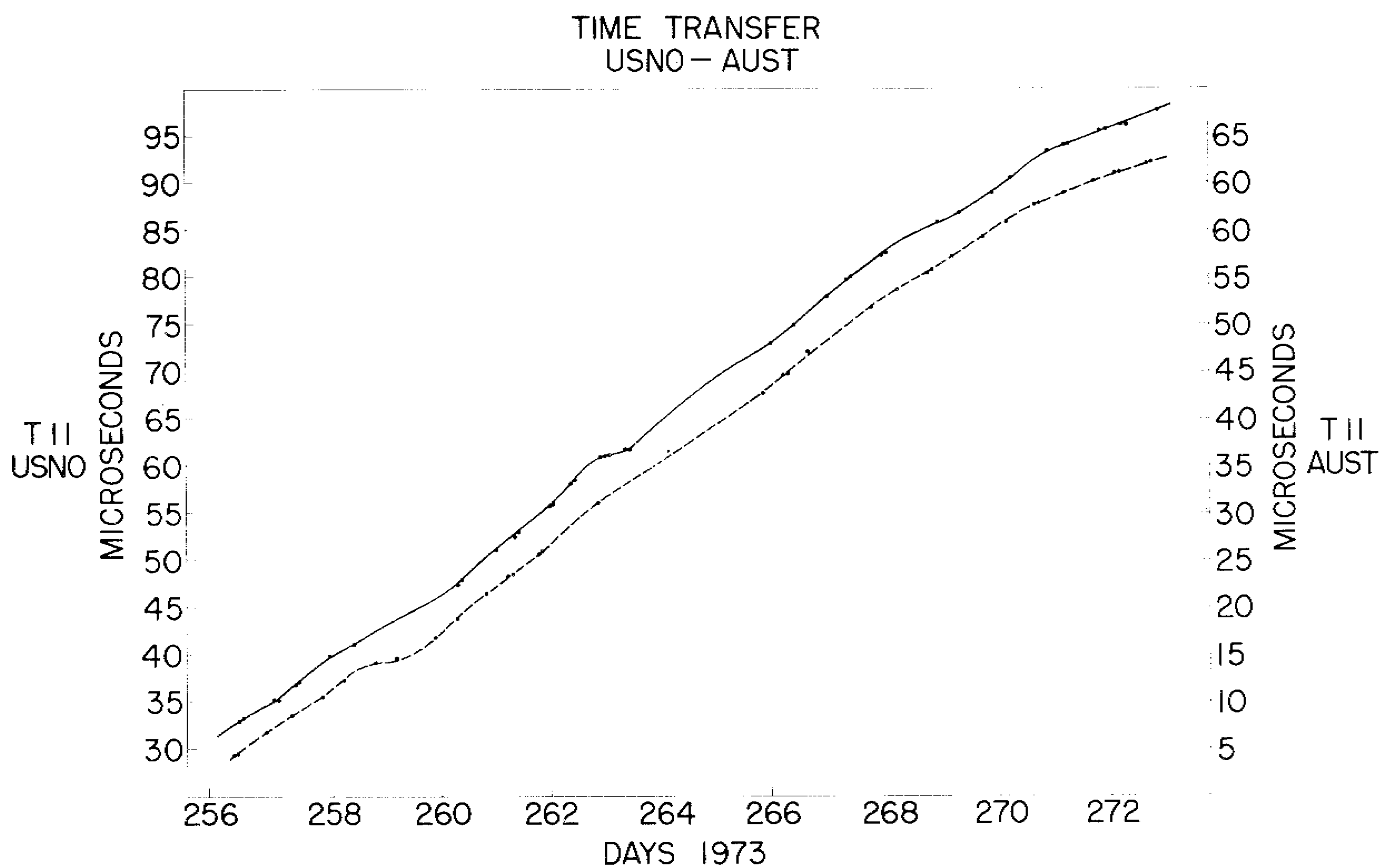

Figure 12. Results of Second Australian Run

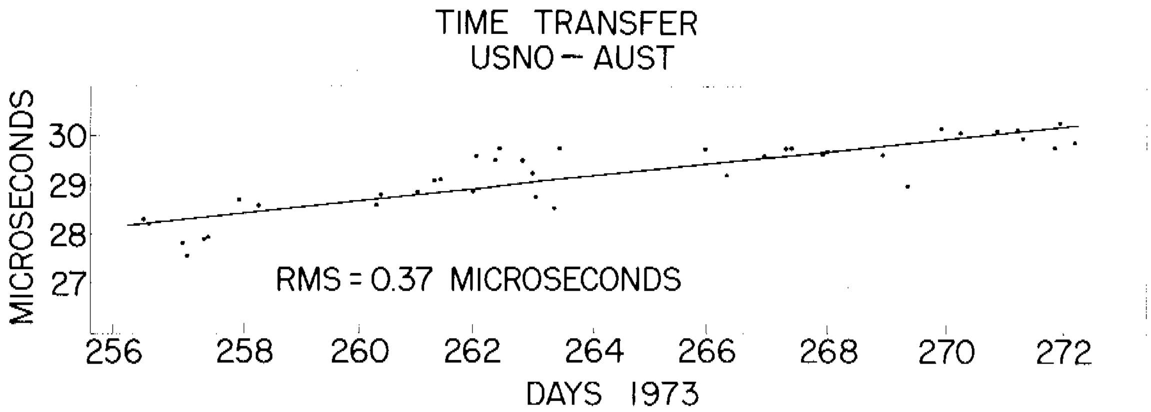

Figure 13. Time Differences Obtained from Figure 12

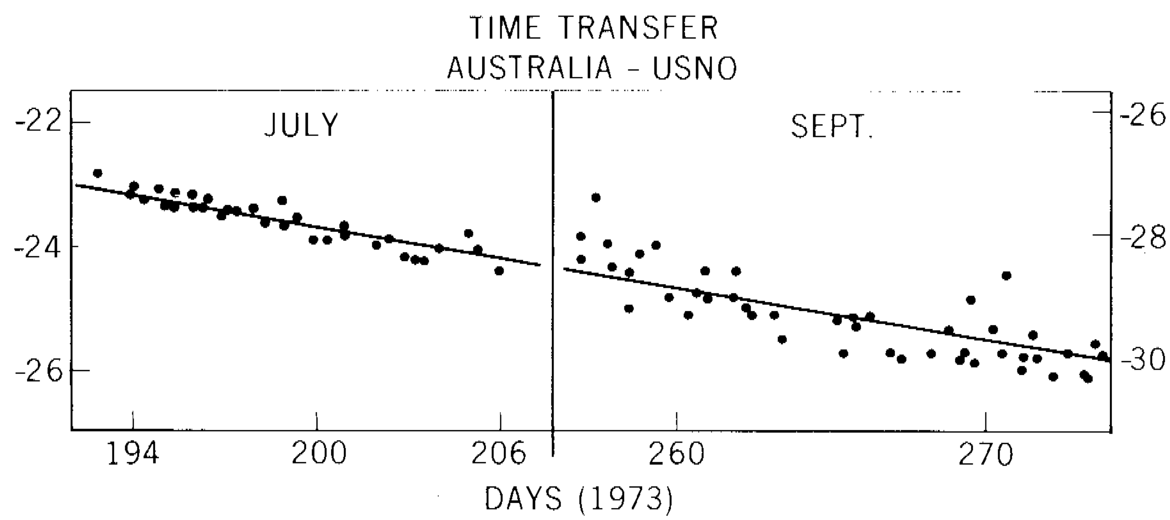

Figure 14. Combined Time Differences from the Two Australian Runs

QUESTION AND ANSWER PERIOD

DR. WINKLER:

Dr. Peter Morgan, from the Australian Time Service, in Canberra is extremely enthusiastic about this direct link which he has now with the rest of the world. Of course, I am also most optimistic that this system, particularly after you are going to have some more satellites in the not too distant future. It will become a most important link to many users, and I may stress that I personally see no competition between, for instance, this system and the SATCOM transfer which is entirely different.

SATCOM is a two-way simultaneous time transfer, using the wide band communications link. It is by its very nature a time transfer which you can compare to a trunk line in telecommunications service; you go to major areas which then are used as local time reference stations.

You cannot put a SATCOM ground station everywhere you need time. It is impossible, the cost and the operational inconvenience would be prohibitive.

But you may be able, and I hope you will be able to use ground timing receivers of considerably less complexity for a NAV-satellite if the receivers are just designed for time recovery rather than the navigation.

I think it may be useful at this planning conference to put something right up into the air and to say that we are planning tentatively to develop ground receivers for the coming — Timation 3 Navigation Technology Satellite.

We ought to know all those requirements for ground receivers which can be anticipated at this moment. It is clear to everyone that they all must be consolidated.

So, I want to encourage you, as of this moment, to get into contact with Mr. Easton or with myself, and hopefully in writing, make your anticipated requirements known.

DR. WINKLER:

Well, no more questions?

(No response.)

DR. WINKLER:

Then thank you very much, Mr. Easton.