INTERNATIONAL TIME TRANSFER BETWEEN USNO AND RGO VIA NTS-1 SATELLITE

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ABSTRACT

Time transfer data was taken at NRL and RGO during July–August 1975. The NRL station was reference to USNO via portable clock and Loran-C. The data indicates continuous sub-microsecond clock synchronisation during the experiment.

INTRODUCTION

The only operational system at present generally available for continuous precise time comparisons between clocks in different locations is provided by the chains of Loran-C navigational emissions which now furnish the link between participating agencies and the Bureau International de l'Heure for the formation of TAI, the international scale of atomic time. A serious disadvantage is that good clocks at establishments outside the present Loran-C coverage area are automatically excluded. It is also obviously desirable that fully independent checks should be made to confirm the synchronisation of the various chains. Such checks can be made periodically by the physical transport of clocks between the various locations but such procedures are expensive and cannot be operated continuously.

In 1963 Study Group VII of the International Radio Consultative Committee referred to the advantages, which might be expected to accrue from the use of time signal emissions from artificial earth satellites, and urged studies of the technical factors involved. (1). In 1970 R L Easton of the U S Naval Research Laboratory reported on the use for time synchronisation of the Timation satellites employed in navigational experiments. (2). Following successful experiments between sites in the U S A, the low-altitude satellite Timation II was used for a brief period for time comparisons between the U S Naval Observatory and the Royal Greenwich Observatory. The frequency difference between RGO and USNO was observed to be less than 5×10^{-12}. The standard deviation of the individual time measures was $\pm$ 0.3 microsecond. After servicing at NRL the receiver was sent to Australia where in more extended tests the standard deviation was reduced to approximately $\pm$ 0.1 microsecond. (3).

Timation III

The NRL Timation project was merged in 1973 with the U S Air Force 621B project to form a combined Department of Defense (DOD) programme called the NAVSTAR Global Positioning System (GPS) and the NRL Timation III satellite was redesignated GPS Navigational Technology Satellite 1 (NTS-1). Our interest here is restricted to the potentialities of the system in a world-wide precise time synchronisation facility. The satellite moves in a nearly circular orbit with a radius 3.13 times the equatorial radius of the Earth and with an orbital inclination of 125^{o}. The period of revolution is 469 minutes. The satellite motion is monitored by Doppler measures at 5 stations and the orbit calculated at the U S Naval Weapons Laboratory (NWL). Predicted positions are made available at reception points through a data link to a central computer. NTS-1 incorporates rubidium gas cell standards, a quartz oscillator, and a retroreflector panel to permit direct measure of range.

Two programmes of particular relevance in timekeeping have been planned. One is to make direct comparisons between the USNO and RGO both via Loran-C and via NTS-1 and to check these by occasional travelling clock trips. In this way it is hoped to determine if there are any significant seasonal variations and to estimate the accuracy of the two systems in practice. Another experiment involves the intercomparison of standards in USA, Australia, New Zealand, Hawaii, Japan and the UK. The present report is an interim discussion of the results obtained in the first month of the USA/UK comparisons.

Clock Comparisons

Time differences between the satellite clock and the clock at the ground station are made by a sequence of phase measures made at ten related frequencies. (4). The comparison frequencies are emitted each minute between seconds 55 and 60. It is normally possible to commence a series of measures shortly after the satellite appears above the horizon, and to continue measures throughout the pass until the satellite disappears below the horizon. All transmission frequencies are of the order of 330 MHz and, in order to derive the lower frequencies necessary for the phase comparisons covering the range 10^{-3} to 10^{-9} second, an additional frequency in the same wave band is transmitted. This is known as the satellite reference frequency and it is transmitted over the whole five seconds in which the ten side tones are radiated.

Data Acquisition

The ground station equipment consists essentially of a radio receiver together with circuits for deriving from the station clock a range of comparison frequencies matching those of the satellite and a comparator for effecting the phase comparisons. All incoming signals from the satellite are affected by Doppler shifts. These effects are eliminated using a method of differencing in which a receiver generated oscillation is firstly phase locked to the incoming satellite reference frequency and then differenced from the incoming side tones. The difference frequencies obtained in this way reproduce at the station the phase of the satellite oscillator and consequently the dial reading of the satellite clock at the epoch of emission of the signal. These frequencies are then phase compared with the equivalent range of frequencies derived from the station clock. The reduction of measured phase differences to give directly the time difference between the satellite clock at the epoch of emission and the station clock at the epoch of reception is made by an on-line mini-computer linked to the phase comparator. The computer provides a visual display of the measure for each minute and also files the value on magnetic tape for subsequent analysis. From the orbital elements and the station coordinates in the same reference frame it is possible to predict instantaneous values of the satellite range. Pre-computed range values for each minute of the pass, expressed as propagation times of the radio signals over the calculated ranges, are available to the observer for each observation. By comparing these tabulated range values (T) with the measured or observed values (O) that are being obtained the observer can make an on-the-spot assessment of the quality of the reception and measurement.

Reduction of Observations

The measured difference between the clocks is composed of the true difference (i.e., difference in the clock dial readings) at the epoch of measurement and the travel time of the satellite signal. The travel time comprises both the propagation time and the equipment lags that can be measured in the laboratory. By correcting for the travel time the true difference between the clocks can be calculated. The propagation times (T values) supplied for use during an observation are computed up to several months in advance and consequently may only be of first order accuracy by the date of observation. More accurate T values, deduced from the Doppler tracking of the satellite about the date of observation, are used in the subsequent reductions. Neglecting errors of measurement and the equipment lags and assuming that the T value represents the correct propagation time, then the T-O value for any minute represents the time difference between the clocks at that instant. Furthermore, if the relative rate of the two clocks is zero the T-O values obtained for each minute of the pass should all be equal.

In tracking the satellite over a pass, clock comparisons are normally obtained for each minute in which the satellite altitude is greater than 5°. As a result both the length and the sector of the atmosphere traversed by the radio signals are continuously changing so that atmospheric inhomogeneities affect both signal velocity and wave refraction in a variable manner. In passes where high altitudes are attained the shorter atmospheric path gives more consistent results. Also, independent of the altitude attained, the best measures are obtained around the time of closest approach (TCA) of the satellite when both the range and the rate of change of range are minimum. Where the T values do not truly represent the orbital behaviour of the satellite, the source of the errors in T can be deduced from the nature of the variations in T-O around TCA when conditions approaching "steady state" exist in the experiment.

Figure 1 shows the measures obtained (O), the T values and data for various stages in the reduction of pass number 1144 in which the NTS-1 clock was compared with clocks at RGO and at NRL. The results for the two stations are quite independent but each set exhibits the salient features of the data obtained in a pass.

Figure 1 shows:

(a) T and O values for the minutes at which meaningful measures were obtained at the two stations

(b) T-O differences, plotted with a scale 500 times that of (a)

(c) T-O corrected by a linear term which has zero value at TCA.

As explained above, an essential condition for obtaining equal T-O values throughout a pass is that the relative rate of the two clocks being compared is zero. However, the satellite clock differs by about 49.2×10^{-10} from nominal while the departures of the caesium beam atomic clocks used in the two stations are only of the order 5×10^{-13}. The relatively very large rate of the satellite clock is reflected in the two sets of T-O values which, to first order, change by 0.3 usec min^{-1}. Because of its unique features the TCA is the fiducial reference time for which the adopted pass result is quoted and rate corrections are consequently applied to the results obtained at all other times throughout the pass to reduce all results to the epoch of TCA.

The rate is not required with great precision at this stage but, as may be seen in (b) and (c) of Figure 1, the adopted value has furnished corrections that have removed about 95% of the drift in T-O. Furthermore, although the final result is quoted for the epoch corresponding to TCA, it is clear that virtually all of the measures at both stations are within 1 usec of the values at TCA. For passes in which spurious measures are received at TCA, a T-O value for this epoch can be deduced from adjacent measures.

TABLE 1

Inter-Observatory Clock Comparisons via TIMATION III

Date 1975 July	RGO Data TCA h m	RGO Data T–O µs	NRL Data TCA h m	NRL Data T–O µs	NTS1 Data Rate µs/min	NTS1 Data Correction µs	NRL minus RGO
2.5	12 13	+5977.10	12 44	+2955.75	–.2969	– 9.20	+3012.15
3.5	11 43	+5559.45	12 13	+2538.40	–.2961	– 8.88	+3012.17
4.5	11 12	+5142.30	11 47	+2119.90	–.2957	–10.35	+3012.05
7.4	09 39	+3891.30	10 23	+ 866.35	–.2959	–13.02	+3011.93
8.4	09 10	+3474.05	09 55	+ 448.76	–.2948	–13.27	+3012.02
9.4	08 41	+4228.60	09 27	+1203.04	–.2953	–13.58	+3011.98
11.4	07 41	+3398.13	08 31	+ 371.24	–.2946	–14.73	+3012.16
15.5	12 35	+1612.35	13 00	–1407.19	–.2950	– 7.37	+3012.17
16.5	12 04	+1196.59	12 31	–1823.80	–.2958	– 7.99	+3012.40
17.5	11 31	+ 781.29	12 02	–2240.25	–.2957	– 9.17	+3012.37
21.4	09 30	– 885.30	10 09	–3909.13	–.2956	–11.53	+3012.30
22.4	09 00	–1302.04	09 41	– 326.50	–.2963	–12.15	– 987.69
23.4	08 31	–1719.95	09 11	– 744.72	–.2969	–12.47	– 987.70
24.1	01 24	–2019.74	02 21	–1049.03	–.2974	–16.95	– 987.66
25.1	00 55	–3790.87	01 52	+ 179.67	–.2960	–16.87	–3987.41

TABLE 2

Clock Comparisons by TIMATION III and LORAN-C (microseconds)

Date 1975 July	NRL minus RGO	Difference in Receiver Lags	NRL minus RGO	UTC minus NRL	UTC minus RGO (TIMATION)	UTC minus RGO (LORAN-C)	Method Differences
2.5	12.15	-8.90	3.25	-19.18	-15.93	-16.4	+0.5
3.5	12.17	-8.90	3.27	-19.27	-16.00	-16.3	+0.3
4.5	12.05	-8.90	3.15	-19.33	-16.18	-16.3	+0.1
7.4	11.93	-8.90	3.03	-19.52	-16.49	-16.8	+0.3
8.4	12.02	-8.90	3.12	-19.58	-16.46	-16.6	+0.1
9.4	11.98	-8.90	3.08	-19.65	-16.57	-16.7	+0.1
11.4	12.16	-8.90	3.26	-19.77	-16.51	-16.6	+0.1
15.5	12.17	-8.90	3.27	-20.00	-16.73	-16.7	0.0
16.5	12.40	-8.90	3.50	-20.06	-16.56	-16.9	+0.3
17.5	12.37	-8.90	3.47	-20.12	-16.65	-16.7	+0.1
21.4	12.30	-8.90	3.40	-20.34	-16.94	-17.3	+0.4
22.4	12.31	-8.90	3.41	-20.40	-16.99	-17.4	+0.4
23.4	12.30	-8.90	3.40	-20.46	-17.06	-17.6	+0.5
24.1	12.34	-8.90	3.44	-20.50	-17.06	-17.5	+0.4
25.1	12.59	-8.90	3.69	-20.56	-16.87	-17.6	+0.7

Comparisons of RGO and NRL Clocks

It is evident that independent comparisons of clocks at two stations with the satellite clock can be used to determine differences between the clocks at the two ground stations. Similar equipment was used at RGO and at NRL, that at RGO being loaned by NRL for the duration of the experiment. In order to minimise effects of the large rate of the NTS-1 clock the results discussed here are based only on passes during which simultaneous measures were made at both stations.

At satellite rising or setting, the great circle distance of the sub-satellite point from an observing station is 72° so the circle with this radius and centred on the station may be taken as the effective horizon of the satellite. The surface area common to two such circles with their centres separated by 57° (the Herstmonceux-Washington great circle distance) thus represents the common effective horizon of NRL and RGO. Due to the configuration of the stations and the satellite orbit, in a common pass TCA at the RGO generally occurs half to one hour before TCA at NRL. An ideal pass in which zenith transit of the two stations occurs is impossible and indeed high altitude passes that are equally high at the two stations are exceedingly rare. Figure 2 shows the subsatellite tracks of the common passes discussed in this paper and also the two points on each track that mark the TCA for each station. The 5-digit numbers in the figure denote the date of the pass (1975 day number).

Figure 2 also shows the area surrounding each station within which the satellite altitude exceeds 60°. Of the 15 passes discussed, TCA at NRL for 14 were within this area while in the RGO high altitude area TCA occurred only 5 times. No doubt as the period of the experiment is extended this inequality will diminish. Also, although the reception equipment in use at the RGO functioned satisfactorily, there are grounds for believing that it is marginally inferior to the equipment in use at NRL. The differences in altitude and equipment may explain why the reception efficiency at the RGO, i.e. the ratio of measures secured to the number that might have been obtained, was about 75% of that achieved at NRL. There is, however, no significant difference in the overall accuracy of the two stations over the period discussed.

Results

The measures made at the two stations and the deduced differences between the stations' clocks are summarised in Table 1. The tabulated T-O values represent clock differences, in the sense satellite <u>minus</u> station clock, at TCA for both stations. A correction for the rate of NTS-1 is applied to the RGO measures to reduce them to the epoch of TCA for NRL. Because differences in TCAs for the two stations are of the order 50 minutes, the rate of NTS-1 is required with an accuracy of better than 0.002 μsecs min^{-1} (equivalent to 3×10^{-11}) to achieve 0.1 μsec precision in the station differences which are tabulated in the final column. The true station difference only amounts to a few microseconds; the values given in the table are much larger due to the presence in the data of integer milliseconds that are included in the software for convenience in data handling.

Loran-C receivers at the RGO furnish a daily measure of the departure of the station clock from the UTC system of the US Naval Observatory and even more refined comparisons with this system are carried out at NRL. The quality of the RGO-NRL link via TIMATION may be assessed by comparing it with that achieved through Loran-C on the same dates. The comparisons are set out in Table 2 in which the first data column is the final column of Table 1, with integer milliseconds removed. It should perhaps be stressed that in the table the time system designated RGO is that of the station clock (CsJ) used in the satellite comparisons and not the UTC system of the RGO which is based on all the observatory clocks. As mentioned above, the UTC system employed here is that of the USNO. The comparisons indicate that; (i) there is a systematic difference of 0.3 μsec between the two methods and (ii) the methods are of the same order of accuracy. Assuming, as the data suggest, that UTC-RGO changes linearly over the period, the departures of the two sets about a line with slope 0.05 μsec day^{-1} have been calculated. The dispersion is shown in Figure 3 in which it may be seen that in the small sample available the TIMATION results are more consistent, with a standard deviation of ± 0.13 μsec as against ± 0.17 for Loran-C.

The results may be seen as a success for the time transfer experiment with TIMATION because the accuracy is already of the same order as Loran-C and the coverage is virtually world wide. The comparison accuracy at a single station is of the order ± 0.01 μsec; the disproportionate loss in accuracy in inter-station comparisons may be attributed to the critical dependence upon precise evaluation of the rate - and also upon the stability of the rate - of the NTS-1 clock. This limitation would hardly exist if the satellite was furnished with an atomic clock.

The continuation of the comparisons of the Timation and Loran-C links between the USA and UK should thus prove of great value and it is perhaps permissible to express appreciation of the willing co-operation of NRL and the USNO. It is already evident that, as the system is extended and used by ground stations world wide, the degree of timing precision that can now be achieved fully justifies the decision to incorporate a caesium clock in NTS-2.

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2. Proceedings PTTI Strategic Planning Meeting, Volume 1, page 108. 1970.

3. R L Easton, P Morgan and H M Smith IEEE trans: Instrumentation & Measurement, p 525, Volume IM-23, No. 4. December 1974.

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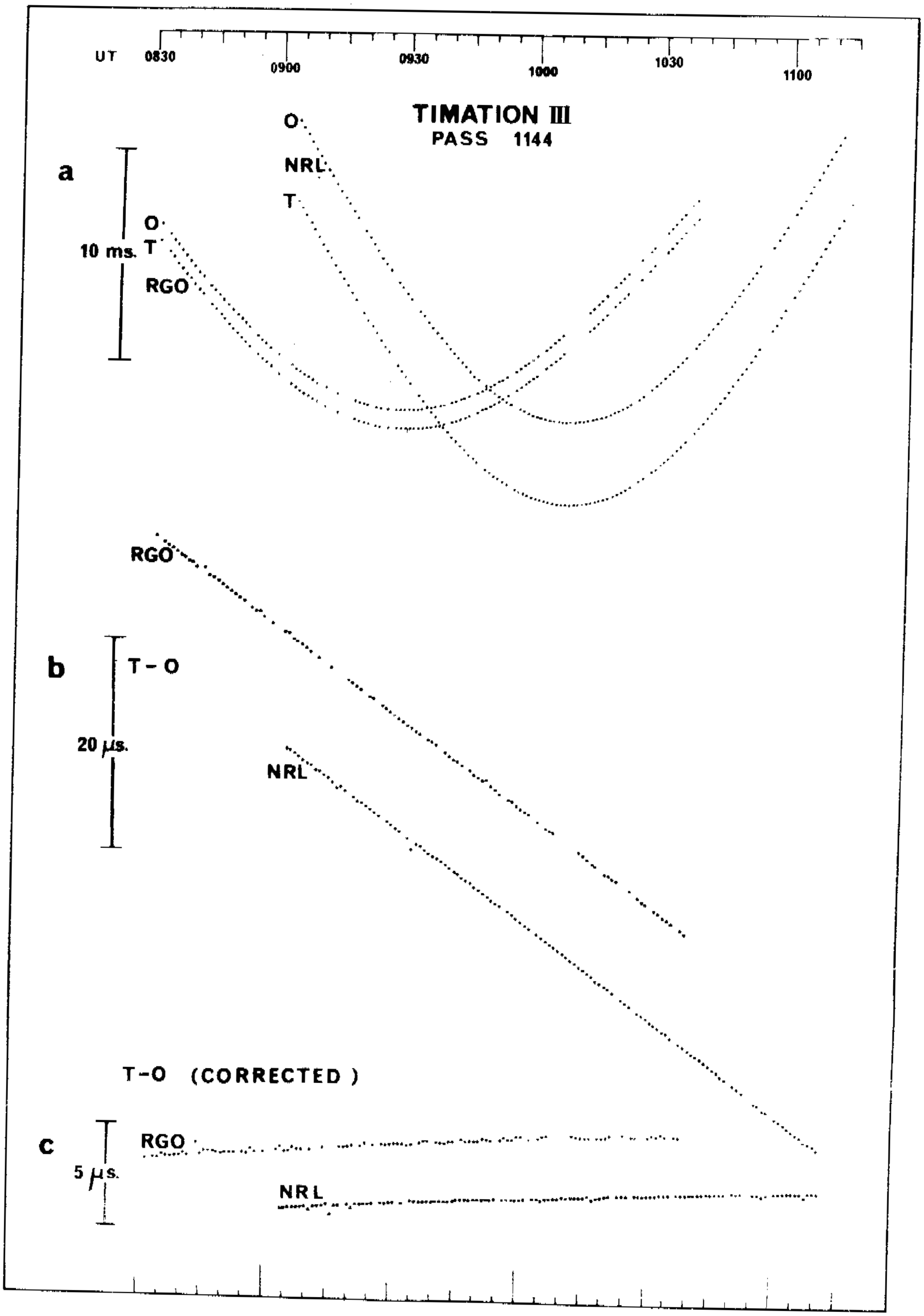
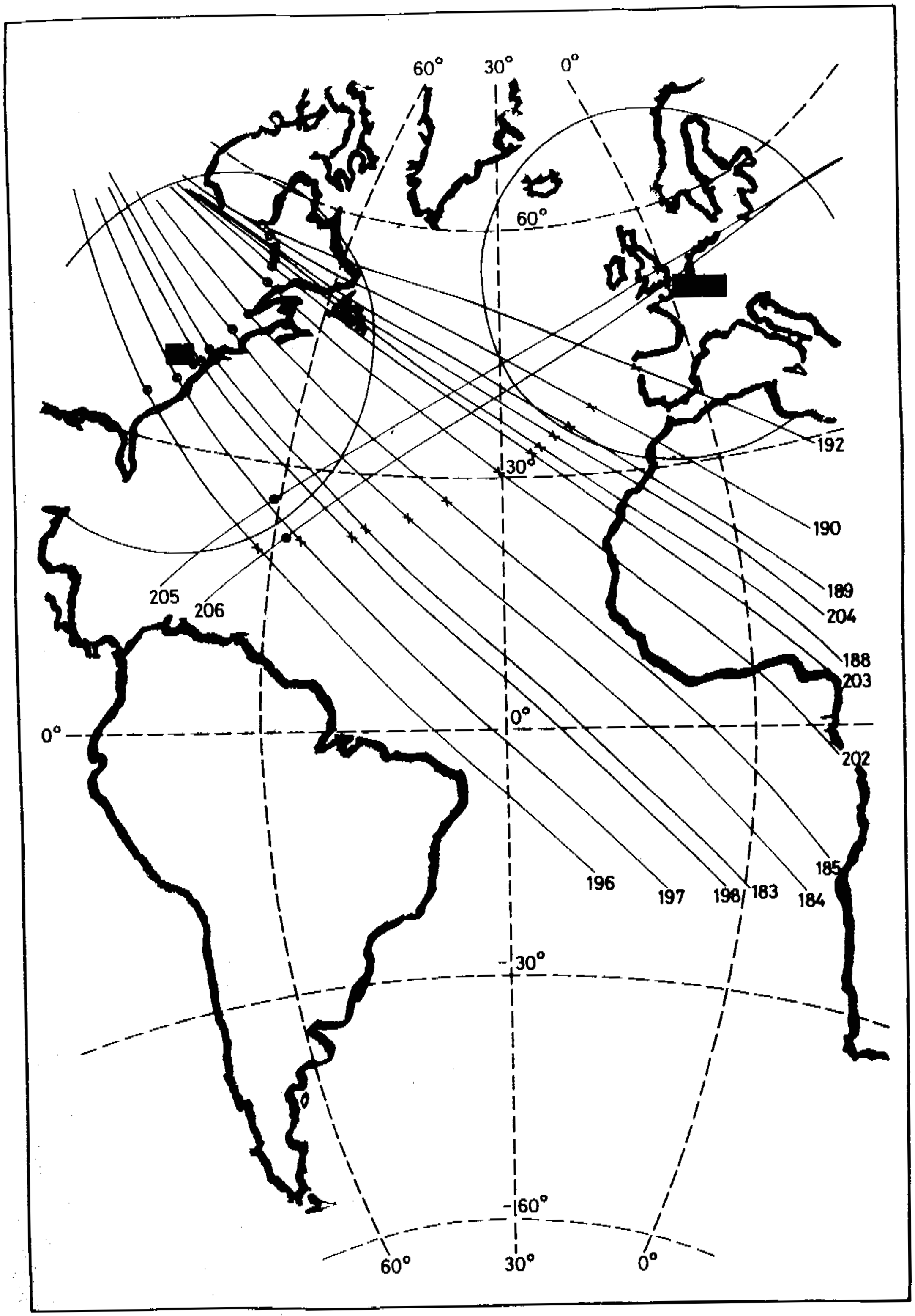
Figure 1. For explanation see opposite.

Figure 2. Subsatellite positions corresponding to TCA at NRL (o) and at RGO (x). For explanation see opposite.

Figure 3. Scatter in comparisons between RGO and UTC (USNO).


UT
0830
0900
0930
1000
1030
1100
TIMATION III
PASS 1144
a
10 ms.
O
NRL
T
O
T
RGO
b
T - O
20 μs.
RGO
NRL
T-O (CORRECTED)
c
5 μs.
RGO
NRL


60°
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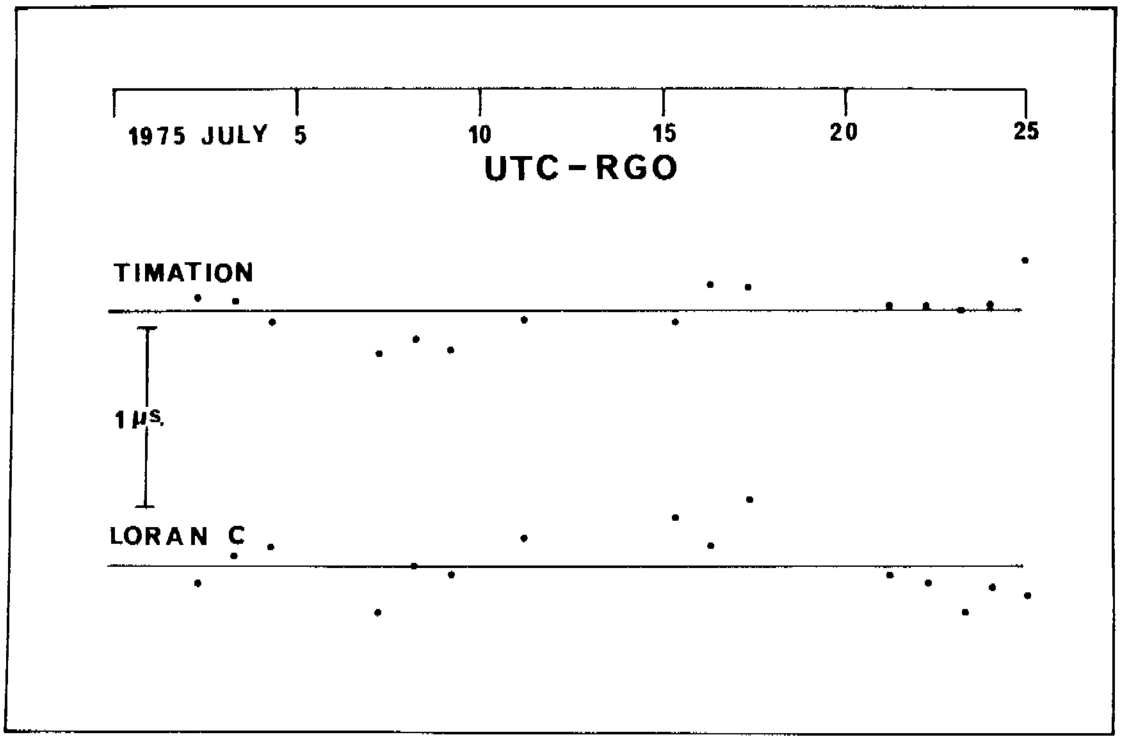
1975 JULY
5
10
15
20
25
UTC - RGO
TIMATION
1 μs.
LORAN C

QUESTION AND ANSWER PERIOD

MR. LUCK:

John Luck, National Mapping, Australia.

I have been out of Australia since before this latest series of experiments was conducted. This is my first view of the results, and I am quite delighted and I would like to join with Mr. Smith in thanking Dr. Winkler, Roger Easton and all the others in coming to Australia in particular and the other places. I cannot express how grateful we really are.

Referring to your slide showing the Australian and Japanese results against USNO, the results seem to have two lines on them. Is this just random scatter or do you suspect something more systematic there?

MR. SMITH:

Well, thank you for your very kind remarks and certainly I join with you in expressing thanks to those who were responsible for this. I do congratulate you on the excellent results which have been obtained.

But, with regard to your specific question, I think I am at a point where I call upon one of the NRL representatives. Whether he will feel disposed to make any comment at this stage, I don't know. You will appreciate that some of the travelers have only just returned. These graphs have only just been produced and they really haven't had a lot of time to think about answers to all the questions which I know they are asking themselves. But, would someone from NRL like to comment and say whether we do, in fact, have some systematic difference in the Australian results?

MR. LYNCH:

Don Lynch, Naval Research Lab.

I was fortunate enough to go on this trip. In regard to John's question, this is true. These represent passes at different times of day and there is a combination of reasons for why there is this spread. There is a small amount due to residual ionospheric effect at different times of day. I think in this case, although, we haven't gone into the final analysis, I think you will find that this is primarily due to the different geometry. That is, we are looking at the satellite on a different part of the orbit.

There is a preliminary analysis we have been using, predicting the position of the satellite, which is several weeks old. Now, what we intend to try to do in removing or examining this further, is to update our position of the satellite, using newer data for tracking purposes, re-evaluate the position of the satellite and see if this doesn't remove part of this error. But, I think it is primarily due to these two effects, the geometry due to the old trajectory and the ionospheric effect.

DR. HELLWIG:

You refer to the importance of the performance of the satellite clock; what kind of clock was really used on NTS-1 for these experiments?

MR. LYNCH:

The clock that was used in the satellite during the time period of these experiments was the quartz clock.

DR. HELLWIG:

I would like to ask why wasn't the rubidium used?

MR. LYNCH:

We were using the quartz during this period. We had been evaluating the behavior of the quartz and we had a little more history on it. The other thing is that we did experience, in using the rubidium clock, some unlocking of the rubidium and discontinuity and we thought, probably, during this experiment we would be better off using the quartz even though it might be less stable. But, we had limited time to perform this experiment and we wanted to use something that we thought was probably going to hold in and not unlock on us, although we had no way of knowing whether or not the rubidium would have stayed in, had we tried it.