TWO-WAY TIME TRANSFER VIA GEOSTATIONARY SATELLITES NRC/NBS, NRC/USNO AND NBS/USNO VIA HERMES AND NRC/LPTF (FRANCE) VIA SYMPHONIE

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ABSTRACT

The two-way time transfer using the Hermes (CTS) satellite and the Symphonie satellite began in July, 1978. The Hermes experiment finished at the end of June 1979, and the Symphonie experiment will continue until the end of 1980. The N.R.C. uses terminals at the Communication Research Center about 25 miles from the N.R.C. laboratory, and the time transfer from N.R.C. to C.R.C. is made using line of sight TV reception with frequent checks by portable cesium or rubidium clocks. Initially the USNO used Goddard terminals, and the NBS a HEW terminal in Denver, and both relied primarily on portable clock synchronization. For the last eight months, Comsat terminals were used at the USNO and at NBS, so that no secondary time transfer was required. In France, the PBS Symphonie terminal is in Brittany, 300 miles from the Laboratoire de Temps et Fréquence (LPTF) at the Observatoire de Paris, and the time transfer to the terminal is made via the TV networks. The uncertainty in this latter link is about 20 ns, but for the other stations the uncertainty is 1 to 5 ns.

In most of the experiments, 1 pps pulses of the station atomic clocks were exchanged between the partners, and a cubic equation was fitted to the 1000 to 2000 second measurements. The equations were exchanged and substracted to obtain the time difference of the stations. The standard deviation in the fit of the equations varied, depending on conditions, from 1.5 ns to 16 ns. For the last month of the Hermes experiment a 1 MHz signal was used, giving a standard deviation of 0.18 ns.

The comparison of the time scales via satellite and via Loran-C (BIH Circular D) show clearly that some Loran-C links are very good, but that the NBS link varies by 1 μs. Via the satellite the frequencies of the time scales can be compared with an accuracy of 2 x 10^{-14}.

INTRODUCTION

A preliminary report on the two-way time transfer NRC/NBS and NRC/USNO via the Hermes (CTS) satellite was given at the PTTI meeting last year. The experiment finished at the end of June 1979, when the Hermes satellite was taken out of service, and this paper is the final report of the year's operation. The transfer NRC/LPTF (France) via the Symphonie satellite also began in July 1978, and is expected to continue until December 1980, but only the results of the first year will be presented for the purposes of comparison.

2. Satellite terminals

The NRC had the use of terminals at the Communication Research Centre in Ottawa, located about 25 miles from the NRC laboratory. The NRC rubidium clock and measuring equipment are housed at the 10 m Symphonie terminal. Initially for the Hermes experiment, the video signals were relayed via triax cables 1.5 miles to the 9 m Hermes terminal. After December 31, 1978 the signals were relayed an additional mile by cable with a 65 MHz carrier to a 2 m terminal, which operated until June 30, 1979. Time transfer from NRC to CRC was effected by line of sight TV reception calibrated periodically by portable clock transfers.

The USNO planned to operate using terminals at the Goddard Space Flight Center, but with various logistic and equipment problems, only one successful NRC/USNO transfer was possible. At the Wingspread Users Meeting, September 19, 1978 J. Kaiser suggested that portable 20 W 2.4 m Comsat terminals might be available, and one was installed at the USNO for transfers beginning November 14, 1978.

The Hermes satellite was a joint Canada/USA venture, with each country using the satellite on alternate days. The experiment was run on Canadian days up till December 31, 1978 after which time the Canadian allocation was dedicated to TV experiments. From January to June 1979, the experiment was run on USA days on time allocated to Comsat. The time transfers resumed on February 13, 1979 when the new CRC terminal was available and other arrangements were completed.

The NBS had the use of a HEW 200 W 3 m terminal on the top of a hospital in Denver from July 1978 to April 1979. Two portable Cs clocks were carried from NBS to Denver for each transfer, and TV transfer provided an additional check.

In April 1979, a second 2.4 m portable 20 W Comsat terminal was installed at the NBS laboratory at Boulder. The transfers NRC/Denver, NRC/Boulder and USNO/Denver, USNO/Boulder both agreed to 30 ns, so no correction for the change in terminal delays was made.

In France, the Symphonie terminal (PBS) at Pleumeur Bodou in Brittany is used for the NRC/LPTF (Laboratoire primaire de temps et fréquence) transfer. The PBS/LPTF (Paris) transfer is made via the French TV network with calibration by portable clocks. The precision in the PBS/LPTF link is about 20 ns, and the accuracy via the portable clock trips is about 100 ns.

The network described above is given in Figure 1.

3. Experimental procedures

In the two-way time transfer, the second clock 1 pps pulses are beamed to the geostationary satellite, and provide the start signal for the local counter. The counter is stopped by the pulse received from the other terminal via the satellite. If it is assumed that there is reciprocity in the satellite transponders and in the paths for the slightly different frequencies, then the time difference between the clocks and the two stations is given, as in Figure 2, by

$$\Delta t = \frac{T_1 - T_2}{2} + \frac{t_1 - r_1}{2} - \frac{t_2 - r_2}{2} \qquad (1)$$

$$= \frac{T_1 - T_2}{2} + \frac{t_1 - t_2}{2} - \frac{r_1 - r_2}{2} \qquad (2)$$

To date, the transmitter delays t_i and the receiver delays r_i have not been measured. However, if a simple transmitter t* and receiver r* are built to measure $t_1 + r^*$ and $t^* + r_1$ at station 1, and the same measuring equipment is carried to measure $t_2 + r^*$ and $t^* + r_2$ at the second station, then it is apparent from Equation 2 that $t_1 - t_2$ and $r_1 - r_2$ can be determined with high accuracy. These measurements will be made for the present CRC and PBS terminals.

The 1 pps video signal, shown in Figure 3, includes the normal horizontal sync pulses of the TV format to maintain proper levels in the TV video circuits. There is a disadvantage in the simple 1 pps format in that the rise time of about 200 ns makes the readings dependent on the trigger level of the counters. There are also variations if the S/N is low. Normally runs about 15 minutes were made, giving 900 readings. A cubic equation was then fitted to the measurements, and the two equations subtracted to remove the effects of satellite motion. The time difference between the station clocks was then calculated for a particular second, and the necessary transfers to the laboratory UTC scales included. The standard deviation in fitting the equation to the measurements varied from 1.5 ns to 16 ns depending on signal conditions.

For the month of June 1979, three modems built at NRC with the 1 MHz signal (Figure 3) were used at CRC, USNO and NBS. In the modem a crystal was locked to the incoming Doppler shifted 1 MHz wave train, and a wide band square wave was used to stop the counter. With these modems, a standard deviation below 0.2 ns was obtained.

In a later version of the modem, both 1 pps and 1 MHz signals are included, with the 1 pps at 0.7 volts and the 1 MHz at 0.3 volt level. The 1 pps is sent 0.5 μs in advance, and is used in the modem to open a gate to allow the first 1 MHz cycle following to trigger the counter. This gives the same output as a 1 pps signal, but with the precision of the 1 MHz signal. On a double hop to France and back, CRC/PBS/CRC, a standard deviation of 0.25 ns was obtained.

Figure 4 is a reproduction of the computer output at NRC for a five minute NRC/NBS time transfer on June 27, 1979 using the 1 MHz modem. The output includes a plot showing the fit of the cubic equation to the data, and a histogram with 1 ns resolution. After the switching transients at the beginning of the run all of the measurements are within 0.5 ns of the equation. The constant term should read 256537709.67, the first two digits having been suppressed for convenience in computation. The linear term, showing a path length change of 51 ns/sec, is typical, and emphasizes the need to subtract the results for the two stations for a particular second. The sawtooth evident in the plot is a beat between the transmitted 1 MHz and the Doppler shifted received 1 MHz. The interference was due to inadequate decoupling in the modem, which would have been corrected had the experiment continued. It does not affect our present results, but it does partially mask real variations of about 0.5 ns at the beginning of the run. It appears that the precision of the experiment is sufficient to observe ionospheric effects of the order of nanoseconds.

Experimental results

The results of the time transfer experiments are given in Table I (NRC/NBS), Table II (NRC/USNO), Table III (NBS/USNO) and Table IV (NRC/LPTF). On January 1, 1979 NBS added a steering correction of 20 ns/day. This has been subtracted in the second column of the NBS tables to provide continuity for plotting the two six-month periods.

The terminal delays t_i and r_i were not measured, and therefore there is an unknown offset or error in the satellite time transfer, which hopefully is constant. Portable clock results NRC/USNO showed the satellite value about 300 ns high. For the NRC/LPTF the satellite error is about 200 ns.

There is therefore a fortuitous cancellation of the terminal delays, but the errors and the uncertainty in the errors are such that some smaller fixed corrections to the tables were not made. One correction that must be applied in future high accuracy transfer is that for the Sagnac Effect.

This correction for measurements made with geostationary satellites in the rotating coordinate system of the earth is significant. The true time difference is given by

$$t\ (\text{East clock}) - t\ (\text{West clock}) = \Delta t\ (\text{measured}) - \frac{2\omega A}{c^2}$$

where ω is the angular velocity of the earth, and A is the projected area, on the equatorial plane, of the satellite and earth station network. The values* for the present experiment are given in Table V.

TABLE V

East	West	$\frac{2\omega A}{c^2}$ ns
USNO	NBS	75.5
NRC	NBS	67.6
NRC	USNO	-7.9
PBS	NRC	158.2

There is an interesting result for NRC/USNO, for while NRC is east of USNO, viewed from the satellite position it appears to be west.

The results of the Symphonie transfer to France are plotted in Figure 5. Transfers were made most working days until MJD 43913, and twice a week after that date. There was a break in the measurements during the eclipse period in the fall of 1978, and a shorter break following MJD 43913 when the antenna at CRC was changed.

There are occasional errors of about 200 ns which presumably arise from the time transfer to the laboratories, but the reason for these has not yet been identified.

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*David W Allan, NBS, private communication

In Figure 6 the results for the NRC/NBS, NRC/USNO and NBS/USNO transfers are plotted (with the 20 ns/day adjustment for the UTC (NBS) value after January 1, 1979). The scale of the figure is such that detailed comparisons of the time scales is not possible, but some general conclusions can be drawn.

First, a comparison of the satellite results with the Loran C values obtained from the BIH Circular D show that the Loran C NRC/USNO is very good for most of the year. Unfortunately the one Hermes result in July cannot be used, because at Goddard separate transmitting and receiving antennas were used and the terminal delay errors are likely to be much different than those of the duplex Comsat terminal. Therefore, there is no comparison with the portable clock measurements possible for this period.

The NRC/NBS Loran C results show, as expected, variations of about 1 μs from the long land path to Boulder. Via Loran C there are apparent changes of 3×10^{-13} in the relative frequencies of the time scales for periods of 3 to 4 months.

In the satellite results, there are two dates when changes were made in the NRC terminal. The first in January 1979 was to a different terminal at a different site, and there must be some vertical shift in the scales at that point. However, from the NRC/USNO Loran C measurements it does not appear to be large. The second in March was an obvious change of 120 ns in both NRC scales that did not appear for the NBS/USNO results. This was not explained, but the correction was added to all subsequent measurements.

The best results were obtained for NRC/NBS in 1978, when the main 9 m CRC terminal was used and a 200 W terminal in Denver. As was mentioned before, the 1 pps results are dependent on S/N and the quality of the received pulse. Over the last four months of 1978, when routines had been established, frequency comparison between the NRC and NBS scales was better than 2×10^{-14}.

The same accuracy was obtained for NRC/USNO for the month of June 1979, using the 1 MHz modem. Unfortunately, the two mid June measurements with NBS using 1 MHz were in error by about 40 ns. A wrong deviation setting on the terminal at Boulder resulted in a 2.2 volt rather than the proper 1 volt video signal being received by the partners and this caused phase distortion in the receiving stations. However, all ended well, and on the last day of the experiment, on June 27, 1979 a 2 ns closure was obtained for the three two-way transfers.

There was some difficulty in 1979 at CRC in maintaining a constant video delay in the complex and long transfer system. On days when there was an obvious CRC error, the points were ignored in drawing the curves.

Another "closure" experiment was carried out on April 9, 1979. The allocation on Hermes and Symphonie satellites was at the same time, and the video signals from NBS and from France were patched through the CRC terminal to effect an NBS/LPTF two-way transfer. Immediately before and after this transfer an NRC/NBS and NRC/LPTF transfer was made, and the sum of these agreed to 4 ns with NBS/LPTF result. This agreement was perhaps fortuitous because in using two satellites the near simultaneity of the normal two-way transfer is lost. A further experiment, in which the NRC/NBS and NRC/LPTF transfers were carried out at the same time, had to be abandoned because one of the counters at CRC was not sufficiently reliable.

Near the end of the experimental period Comsat laboratory installed two PSK modems, which had been modified for time transfer, at the USNO and NBS terminals. This system demonstrated a higher efficiency in the time transfer, and achieved a sigma of 17.5 ns on a link of 100 kHz bandwidth.

The final comparison of the four time scales is given in Figure 7. In this figure the intercepts and slopes have all been altered to permit an expansion of the scale. Any factor that is common to the three curves arises from the NRC scale, and other individual changes can be determined by using the other two scales as controls.

Conclusions

There is no doubt that these long term experiments have shown the advantages of the two-way satellite time transfer. Our efforts must now be applied to the development of an economical operational system using commercial satellites.

Acknowledgements

We must acknowledge that we have had a great deal of assistance in these experiments. The Canadian Department of Communications has been most helpful in arranging the participation of NRC in both the Symphonie and Hermes experiments, and the staff of the Communications Research Center has given us excellent support with their terminal facilities. The joint French and German Secretariats have been generous in allocation of time on the Symphonie satellite,

and the PBS staff very cooperative. The CTS program office of NASA formalized the arrangements for NBS and USNO participation. The use of the Denver terminal of the Department of Health Education and Welfare for the first nine months of the Hermes experiment provided some of the best NRC/NBS results.

Table I UTC(NRC)-UTC(NBS)=dt ns

MJD	dt	dt*
43717.83	2706	
43724.83	2674	
43731.85	2639	
43738.83	2643	
43759.84	2566	
43766.83	2558	
43773.84	2598	
43780.84	2684	
43786.83	2720	
43800.83	2891	
43807.83	2975	
43814.88	3009	
43821.88	3058	
43828.88	3087	
43842.88	3195	
43849.88	3233	
43856.88	3290	
43863.87	3322	
43870.87	3367	
43931.64	4938	3765
43952.68	5609	4015
43965.81	5990	4134
43972.61	6245	4253
43986.61	6566	4294
44002.60	7177	4585
44007.63	7265	4572
44028.73	7957	4842
44035.86	8126	4869
44044.67	8382	4949
44051.67	8642	5069

Table II UTC(NRC)-UTC(USNO)=dt ns

MJD	dt
43826.71	4938
43833.71	5033
43840.72	5053
43847.71	5129
43854.71	5191
43863.89	5207
43917.61	5363
43931.59	5420
43952.63	5474
43965.78	5548
43972.58	5574
43986.59	5586
43993.64	5710
44007.60	5690
44028.76	5911
44035.80	5939
44044.60	5987
44051.58	6053

Table III UTC(NBS)-UTC(USNO)=dt ns

MJD	dt	dt*
43917.65	989 (Denver)	1882
43938.64	354 "	1667
43945.63	44 "	1496
43952.70	- 123 "	1471
43965.83	- 436 "	1421
43972.66	- 613 "	1380
43986.68	- 998 "	1276
44002.63	-1477 "	1176
44002.64	-1446 (Boulder)	1146
44007.56	-1578 "	1113
44014.87	-1690 "	1142
44028.78	-2007 "	1106
44044.61	-2355 "	1077
44051.63	-2586 "	986

For dt*, the -20 ns/day change in UTC(NBS) frequency on January 1, 1979 (MJD 43874) has been removed to maintain consistency with the 1978 data. The dt* values are plotted in Figures 6 and 7.

: TABLE IV UTC(NRC)-UTC(LPTF) = dT

MJD	dT		MJD	dT		MJD	dT
43701.80	4419		43839.78	5906		43959.64	6889
43702.81	4387		43842.75	5879		43962.66	6937
43707.80	4401		43843.75	5890		43966.60	6975
43708.80	4406		43847.79	5931		43969.62	6974
43709.79	4412		43850.77	5932		43972.64	7001
43710.80	4395		43853.77	5964		43973.60	6992
43713.81	4430		43854.80	5963		43980.60	7097
43714.80	4428		43855.80	5912		43986.64	7158
43716.80	4498		43862.70	6082		43993.59	7276
43717.80	4477		43863.76	6086		43997.56	7296
43720.80	4505		43864.76	6076		44002.56	7351
43721.80	4527		43869.71	6130		44007.64	7426
43722.80	4533		43870.76	6175		44010.65	7474
43723.80	4575		43875.69	6213		44011.63	7496
43724.80	4549		43877.76	6223		44021.62	7704
43729.80	4631		43878.69	6232		44025.61	7829
43730.79	4573		43881.76	6280		44029.60	7843
43731.80	4570		43882.69	6274		44032.62	7912
43734.80	4622		43883.69	6254		44035.62	7963
43735.80	4645		43884.75	6250		44039.60	8018
43736.79	4589		43885.76	6281		44042.64	8142
43737.79	4665		43888.76	6303		44043.54	8162
43738.80	4658		43889.69	6313		44044.56	8200
43797.76	5064		43891.75	6343		44046.62	8231
43799.71	5120		43892.75	6354		44051.60	8378
43800.76	5156		43897.66	6396		44053.61	8448
43801.75	5183		43898.62	6410		44057.60	8528
43804.75	5253		43899.62	6399		44060.62	8604
43805.67	5357		43902.62	6415		44063.62	8624
43806.67	5473		43903.66	6537		44067.61	8674
43807.77	5384		43904.66	6431		44071.60	8760
43808.77	5386		43905.60	6429		44074.60	8821
43813.70	5454		43906.60	6444		44078.61	8912
43814.76	5465		43909.61	6471		44081.61	9036
43818.75	5504		43910.66	6428		44085.60	9129
43820.70	5539		43911.66	6452		44088.62	9221
43821.75	5538		43912.61	6440		44092.60	9120
43822.74	5590		43913.62	6467		44095.62	9304
43826.70	5683		43931.66	6650		44099.61	9371
43827.70	5696		43934.66	6724		44102.61	9391
43828.75	5706		43937.66	6729		44106.60	9493
43832.73	5772		43941.66	6779		44108.62	9407
43834.70	5823		43945.64	6808		44113.81	9571
43835.74	5814		43948.66	6784			
43836.75	5687		43952.64	6881			

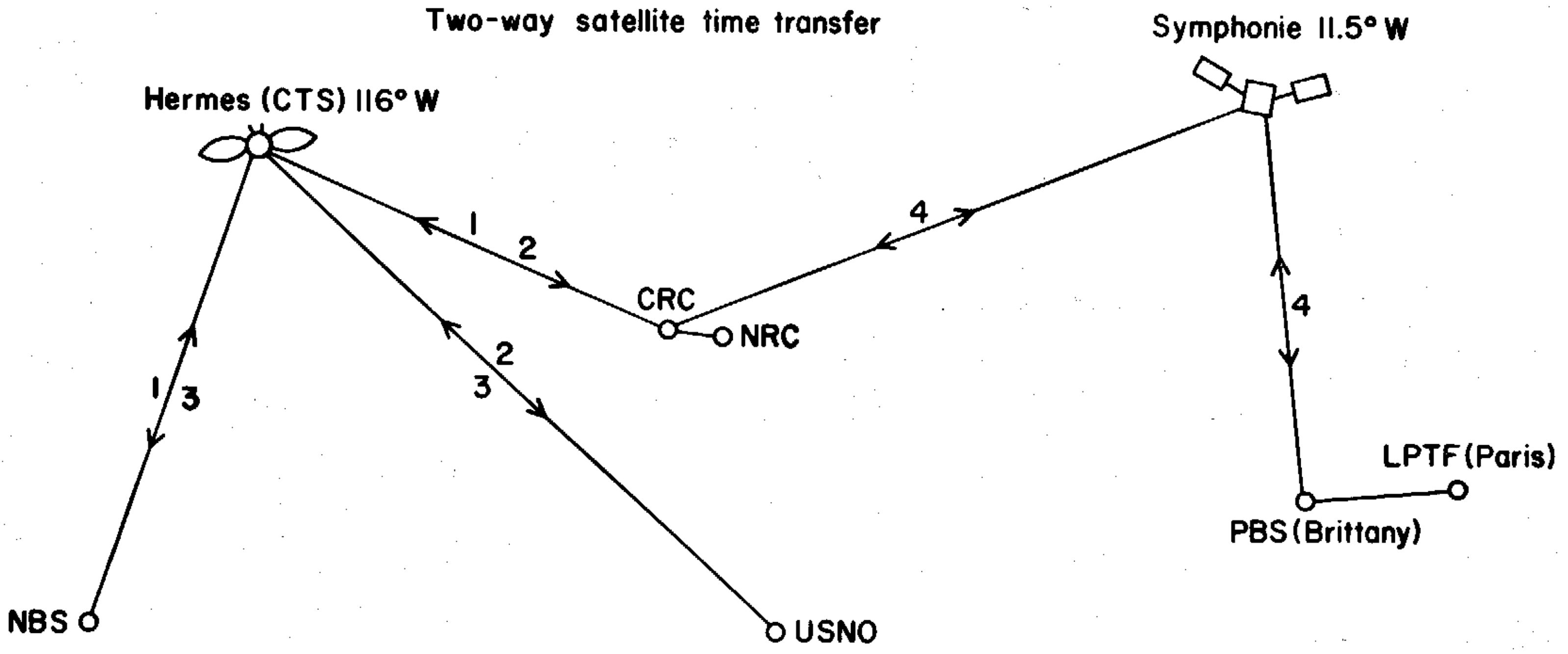
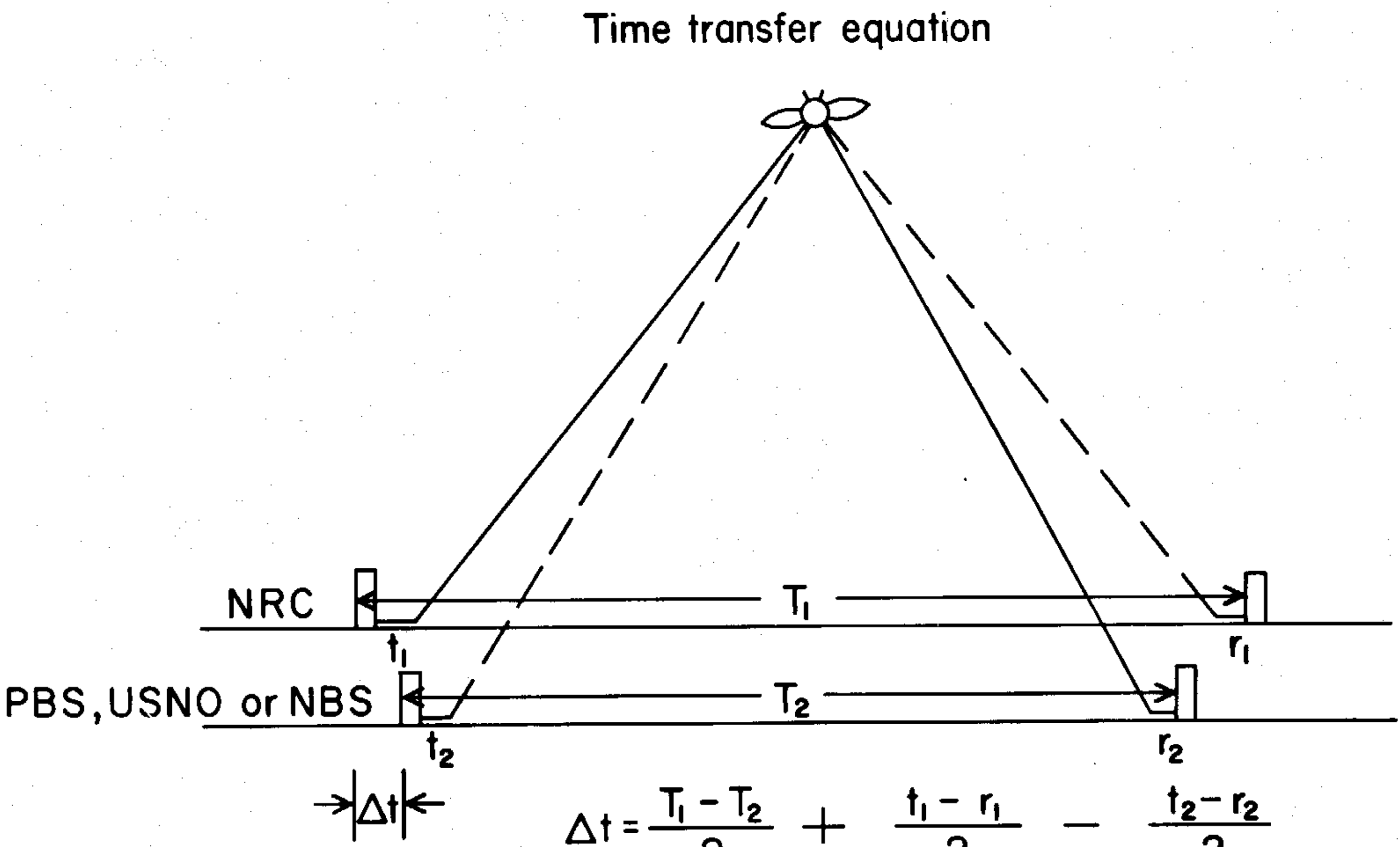


Figure 1. The Four Station, Two Satellite Network



$$\Delta t = \frac{T_1 - T_2}{2} + \frac{t_1 - r_1}{2} - \frac{t_2 - r_2}{2}$$

$$= \frac{T_1 - T_2}{2} + \frac{t_1 - t_2}{2} - \frac{r_1 - r_2}{2}$$

Figure 2. The Two-Way Satellite Time Transfer Equation

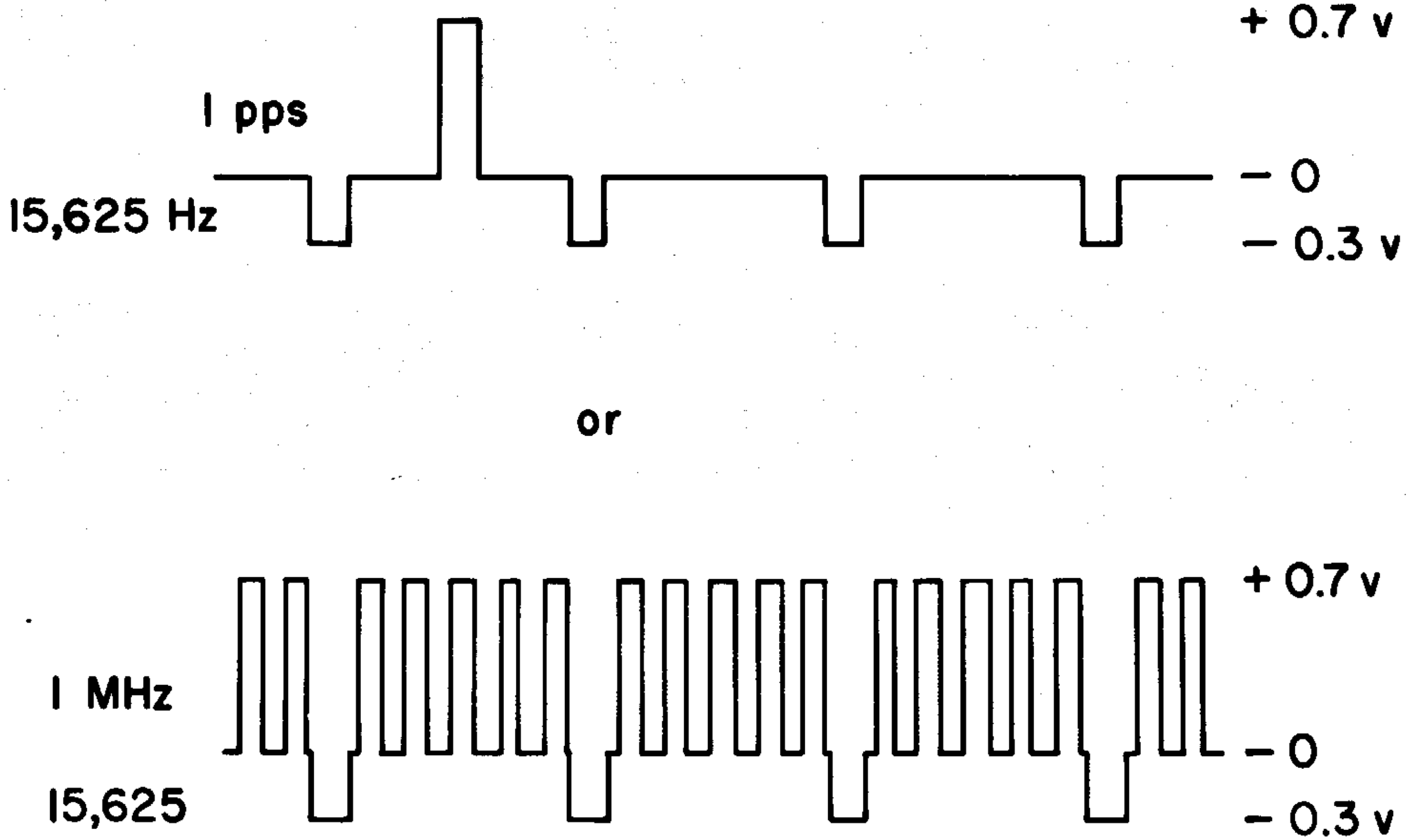


Figure 3. The 1 PPS and 1 MHz Video Format

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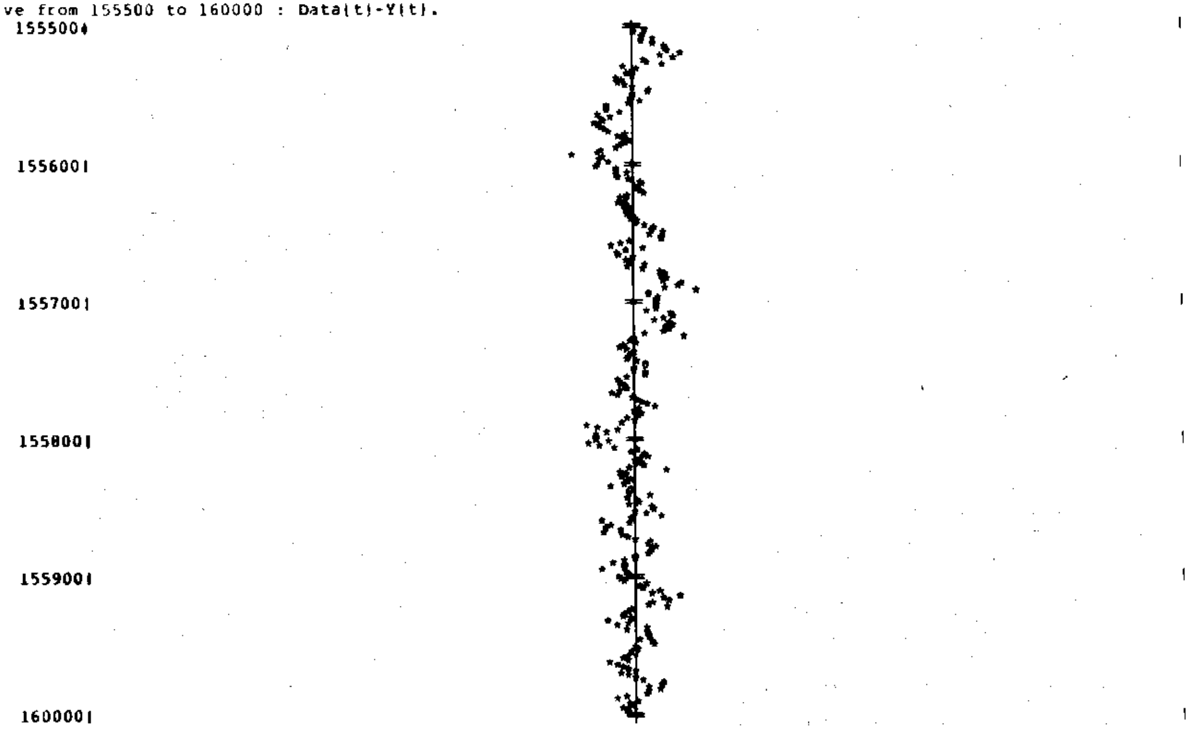
The file is BOU178153935
Scale is  1 ns per inch, from -5  to  5
Curve from 155500 to 160000 : Data(t)-Y(t).
```



```
Histogram : scale =  3:1,computed from 155500 to 160000
 AT >24 :      1 |
 AT   1 :      1 |
 AT   0 :    297 |***************************************************************************************************
 AT  -1 :      1 |
 AT<-24 :      1 |

The file is BOU178153935: from 153938 to 161001
Origin is 160000.
 UTC(NRC)-UTC(CRC)=? ns. Trigger level is 0.25 VOLTS.
 Y(t)(ns) =    6537709.67 -5.1128137E+01*t -1.7761167E-03*t2 -5.0445160E-08*t3
Calculation includes 155502/155955
 Std dev =        0.19 ns ( window =      2000 ns ).
     0 pts rejected on a total of   294.
```

Figure 4. The Fit of a Cubic Equation to the Data at NRC for 1 MHz Modulation on June 27, 1979

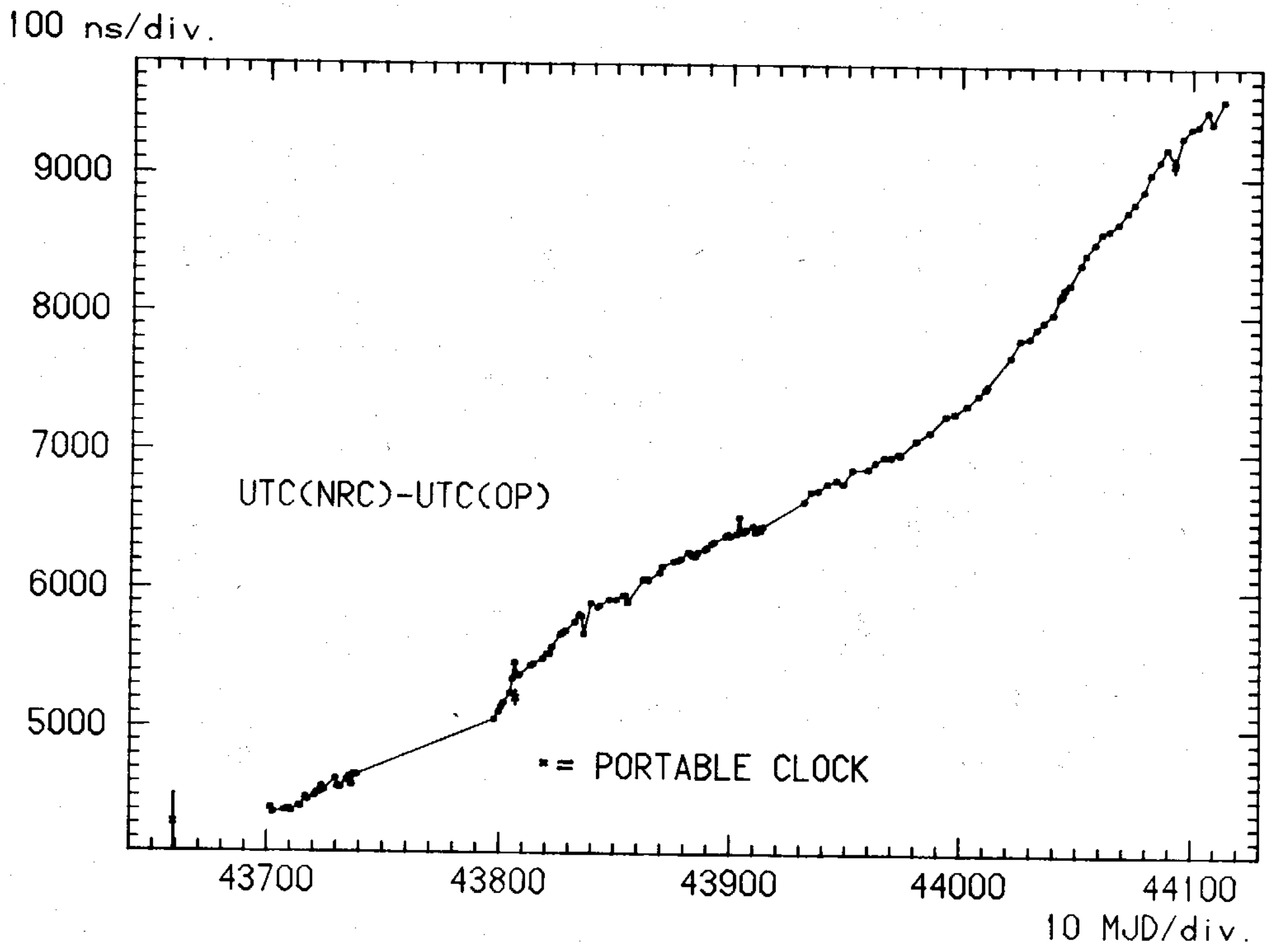


Figure 5. The Difference in the NRC and OP (or LPTF) Time Scales Via the Symphonie Satellite

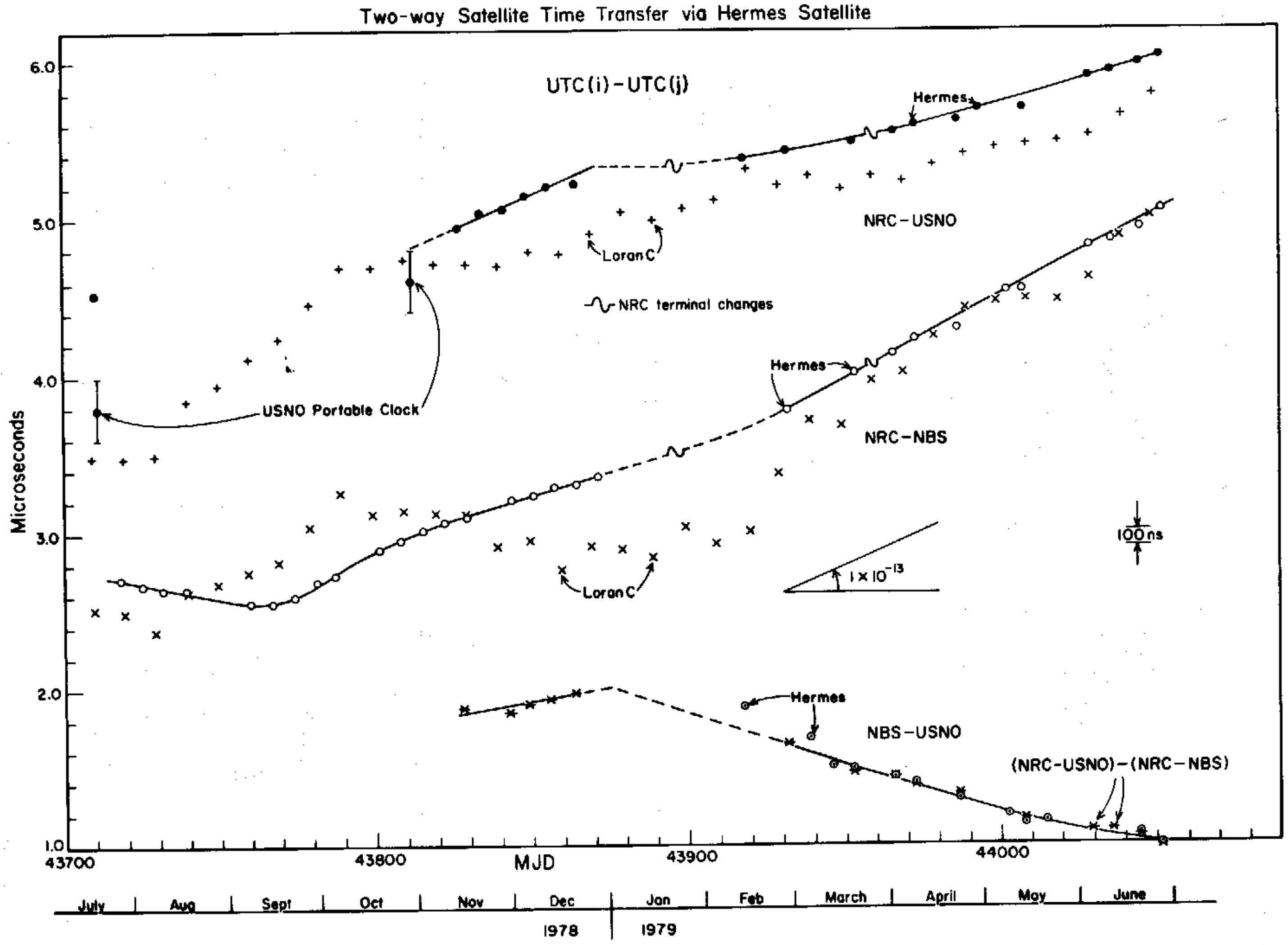


Figure 6. The Differences Between the NRC, NBS and USNO Time Scales Via the Hermes Satellite

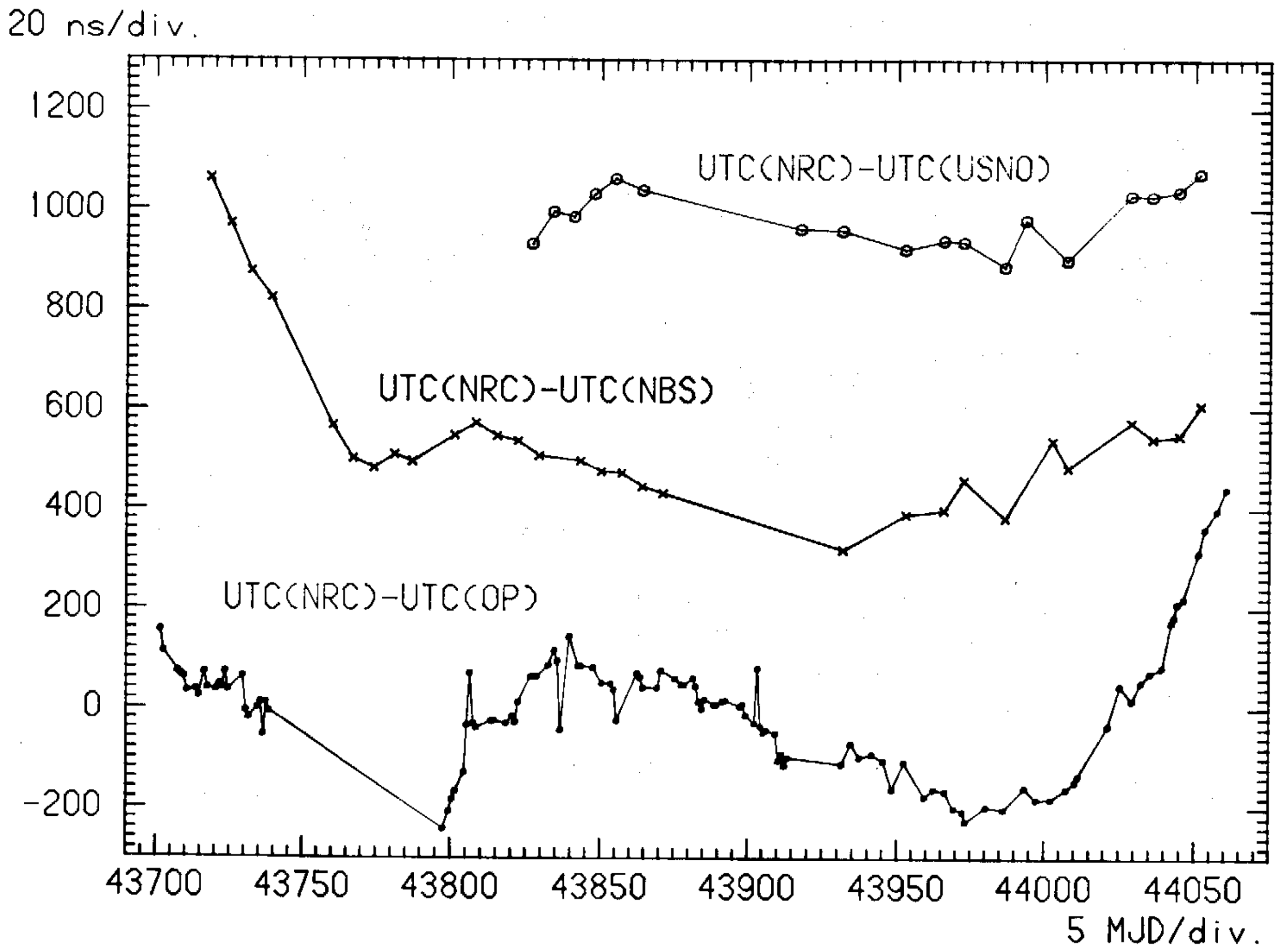


Figure 7. The USNO, NBS and OP Time Scales Compared to that of NRC. The Intercepts and Slopes have been Altered to Permit an Expanded Scale.

QUESTIONS AND ANSWERS

MR. CHI:

Are there any questions?

DR. COSTAIN:

Are there any answers?

MR. CHI:

Would you please use the microphone and identify yourself for the sake of recording?

MR. LAUREN RUEGER, The Johns Hopkins University, Applied Physics Laboratory

With all those precision measurements, what kind of a standard were you using out at the stations because we see in time order scatter a nanosecond kind of a variation in cesium standards?

DR. COSTAIN:

There was an HP Rubidium at the CRC site.

MR. RUEGER:

Okay. What about the standardization of the point on the pulses that you used for determining the epoch of a measurement? We have been hearing for a while that people use different places on these rise times and different rise time pulses and characterization. Have you some kind of standardization for this purpose?

DR. COSTAIN:

We try to operate at a quarter of a volt trigger level on the standard one volt pulses or .7 volt pulses. But of course with the one PPS it is very sensitive in fact to the quality of the received signal and the trigger level and somebody comes by and changes the trigger level from time to time. This is why we prefer the one megahertz. When you have got a wideband square wave it doesn't make much difference where the trigger is set.

The only thing is, is you have to make sure, and we did, that the megahertz is synchronized with your 1 PPS.

MR. RUEGER:

Does everybody in your network use exactly the same characteristics in this respect?

DR. COSTAIN:

We endeavored to. That was the main thing. The video treatment in the terminals was not always the same.

MR. CHI:

I would like to ask you one question if I may, and that is what is the variation of the corrections throughout the time of measurement? Is that variation large or fairly constant?

DR. COSTAIN:

It is a bit difficult to tell with the type of experiment we were running, I mean, and you were fitting a cubic equation and can cover a lot of faults. But I think we could see real variations of the order of nanoseconds.

I was going to say that my endeavor is, if I can persuade our authorities to get two terminals for Ottawa, to do a two-way time transfer to ourselves, eliminate clock errors and make a definitive evaluation of this statellite system.

DR. LESCHIUTTA:

Can you please tell us something about what techniques you are proposing to use in order to calibrate the ground stations? Calibrate the delay of the ground station?

DR. COSTAIN:

Yes. I should elaborate. While it is intentionally what we intend to do with Symphonie, first make a small transmitter, a little gun diode, that you use to measure the artificial transmit/receiver loop, then carry that to the next station and make exactly the same measurement and subtract it. I think that can be done to one or two nanosecond precision.

And the same with the transmitter. You build a small receiver and you carry that receiver, cables and everything and make the identical measurement at the other station. And it is the difference in those measurements that you want to know.

It is very difficult, I think, to measure precisely and separately the transmitter delay and the receiver delay at a station. If we can make the difference measurements between the two stations, then I think it can be much more accurate.

MR. PLEASURE:

Would you please comment on the technique suggested by Professor Cohen of the University of Pennsylvania in an article in "Physical Review Letters" where he has geostationary satellites communicating with one another and with ground stations and using that to calculate Einstein. Were you aware of that?

DR. COSTAIN:

I think I did read the paper. I don't know that any further verification to my knowledge is needed in relativity theory to the accuracy that we can make the measurements. You must, of course, take into account a rotating coordinate frame--

MR. PLEASURE:

But he could not do that accurately. He has an approximation that he would like to have measured.

DR. COSTAIN:

Well, if we can achieve nanosecond accuracy, this would be one percent verification on this SAGNAC effect. I would say that my objective is not that; my objective is a cheap commercial network. It is an interesting thing, but it costs money to mount a more elaborate satellite to satellite and we are at the moment searching for a way to make our communication network economical. And I think one of the things we have going for us is that I think the communications networks will need sub-microsecond times in their systems in the very near future.

DR. SERENE:

Are you planning to compare your result using the LASSO system, in the area of 1 nanosecond?

DR. COSTAIN:

The inquiries that we have made that we do not have access to a telescope for the two-way, and I am not sure, in fact, whether I would have the money or manpower for the one-way from Ottawa. We are suffering a bit from retirements and it is going to be a bit complex in the next two years. We might know certainly before the experiment is finished. We might hope to be able to participate. At the moment, I cannot do so.