

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 subtracted 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  $\mu$ s. Via the satellite the frequencies of the time scales can be compared with an accuracy of  $2 \times 10^{-14}$ .

## 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

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

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

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  $\mu$ s 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  $t_r$  and  $r_s$  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

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

where  $\omega$  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	$\frac{2\omega A}{c}$ 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.

\*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  $\mu$ s from the long land path to Boulder. Via Loran C there are apparent changes of  $3 \times 10^{-13}$  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  $2 \times 10^{-14}$ .

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      Table II UTC(NRC)-UTC(USNO)=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

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	43966.67	6975
43708.80	4406	43847.79	5931	43969.62	6974
43709.79	4412	43850.77	5932	43972.64	7071
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		

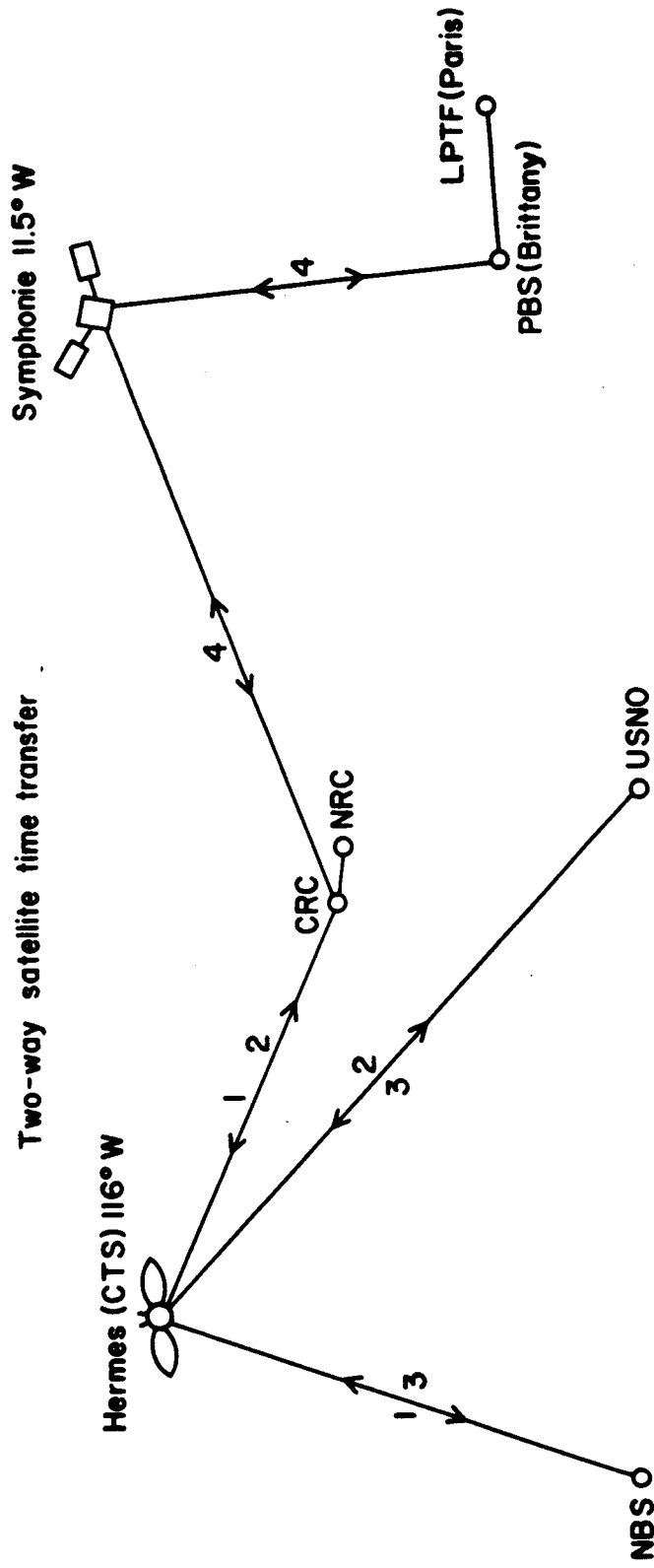


Figure 1. The Four Station, Two Satellite Network

Time transfer equation

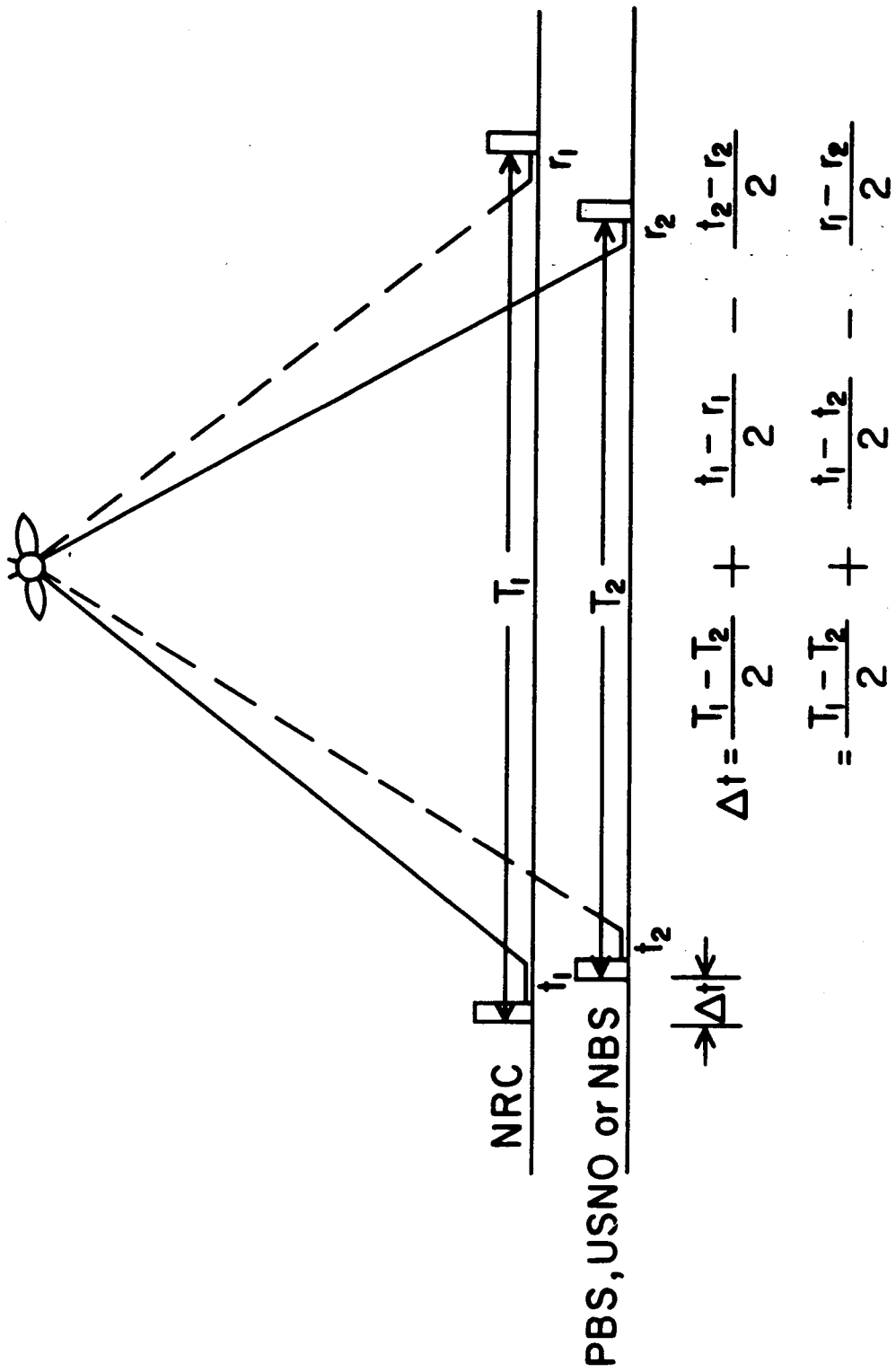
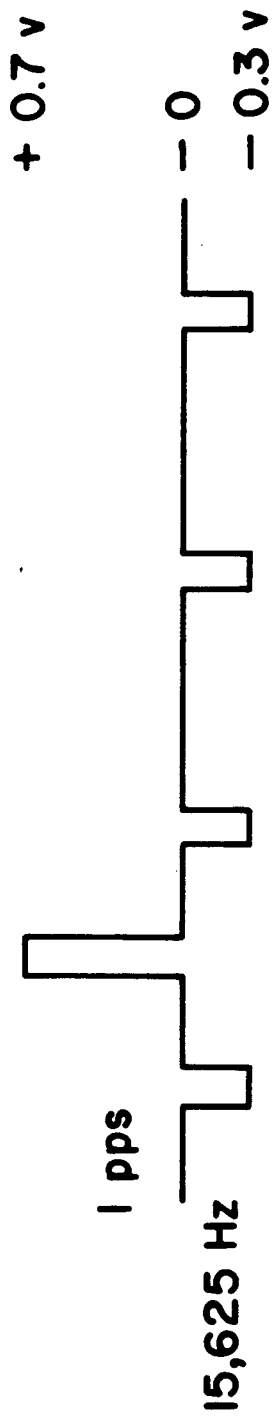


Figure 2. The Two-Way Satellite Time Transfer Equation



or

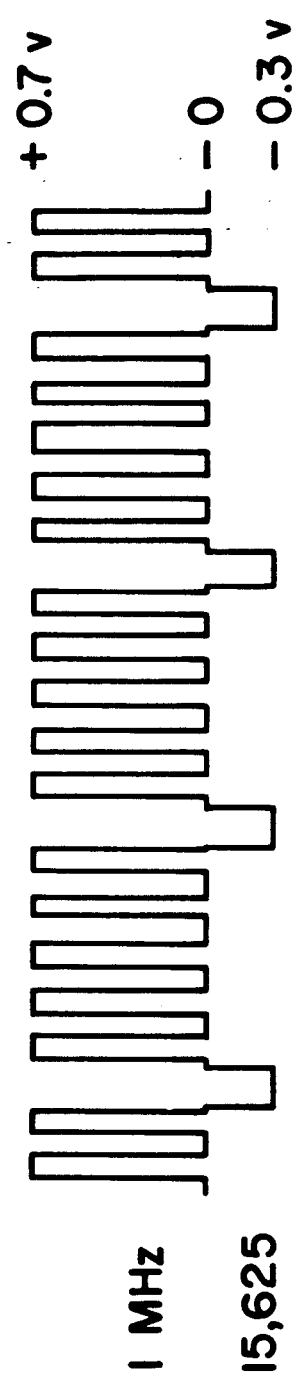
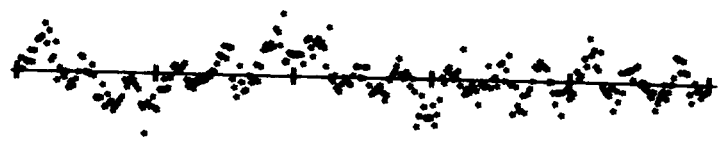


Figure 3. The 1 PPS and 1 MHz Video Format

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



1556001

1557001

1558001

1559001

1600001

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) = 7 ns. Trigger level is 0.25 VOLTS.  
 Y(t)(ns) = 6537709.67 - 5.1128137E+01\*t - 1.7761167E-03\*t<sup>2</sup> - 5.0445160E-08\*t<sup>3</sup>  
 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

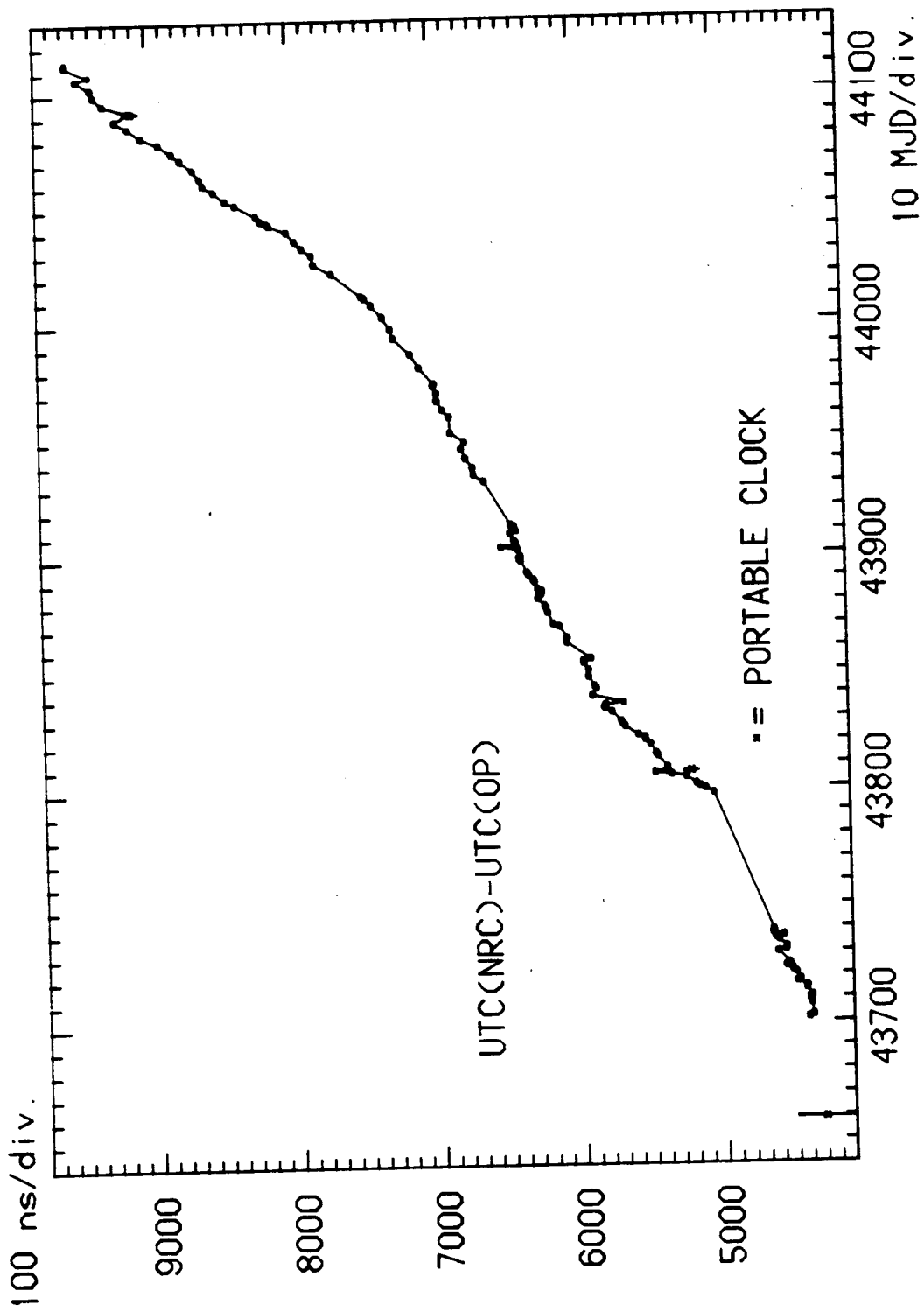


Figure 5. The Difference in the NRC and OP (or LPTF) Time Scales Via the Symphonie Satellite

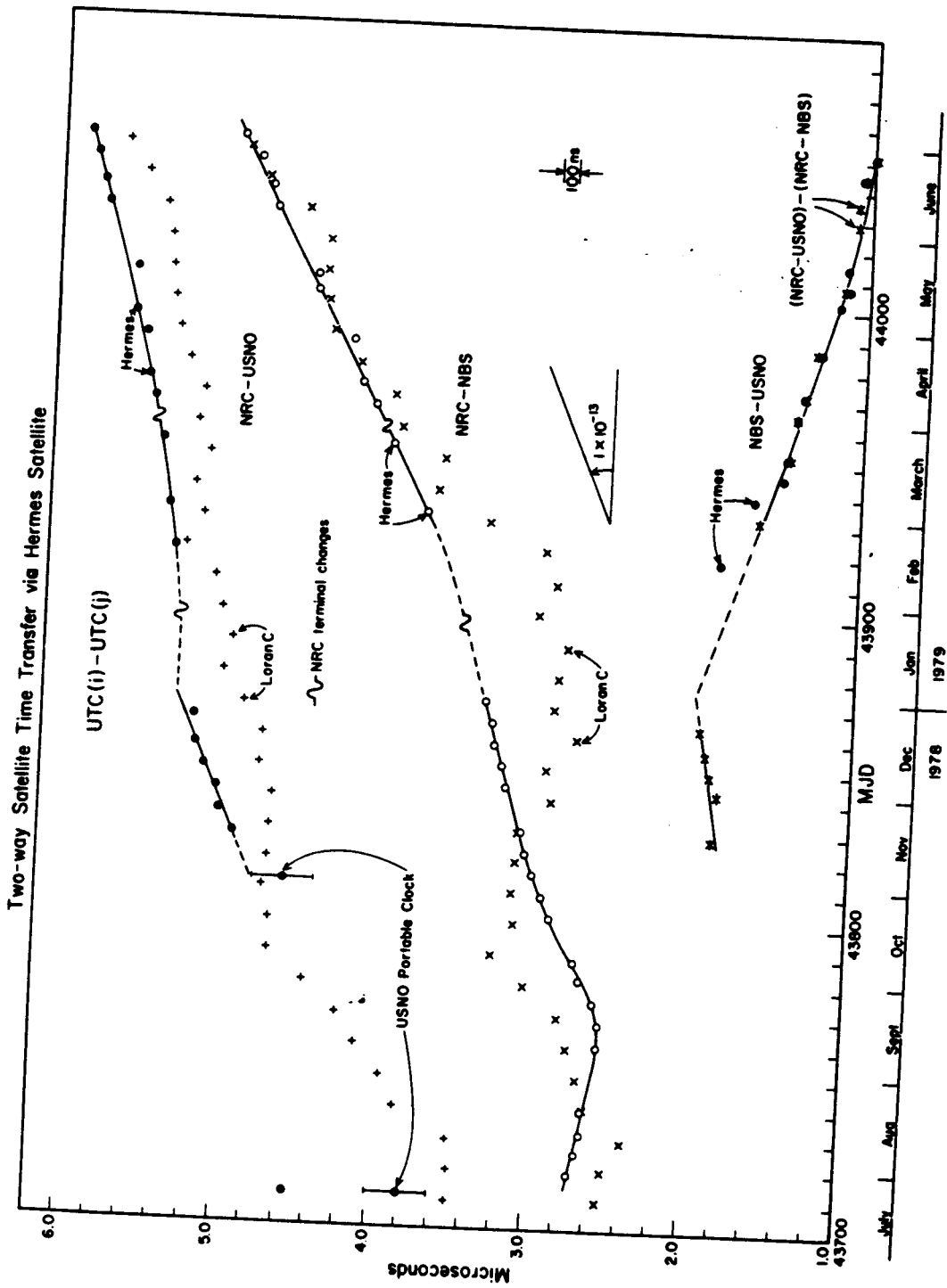


Figure 6. The Differences Between the NRC, NBS and USNO Time Scales Via the Hermes Satellite



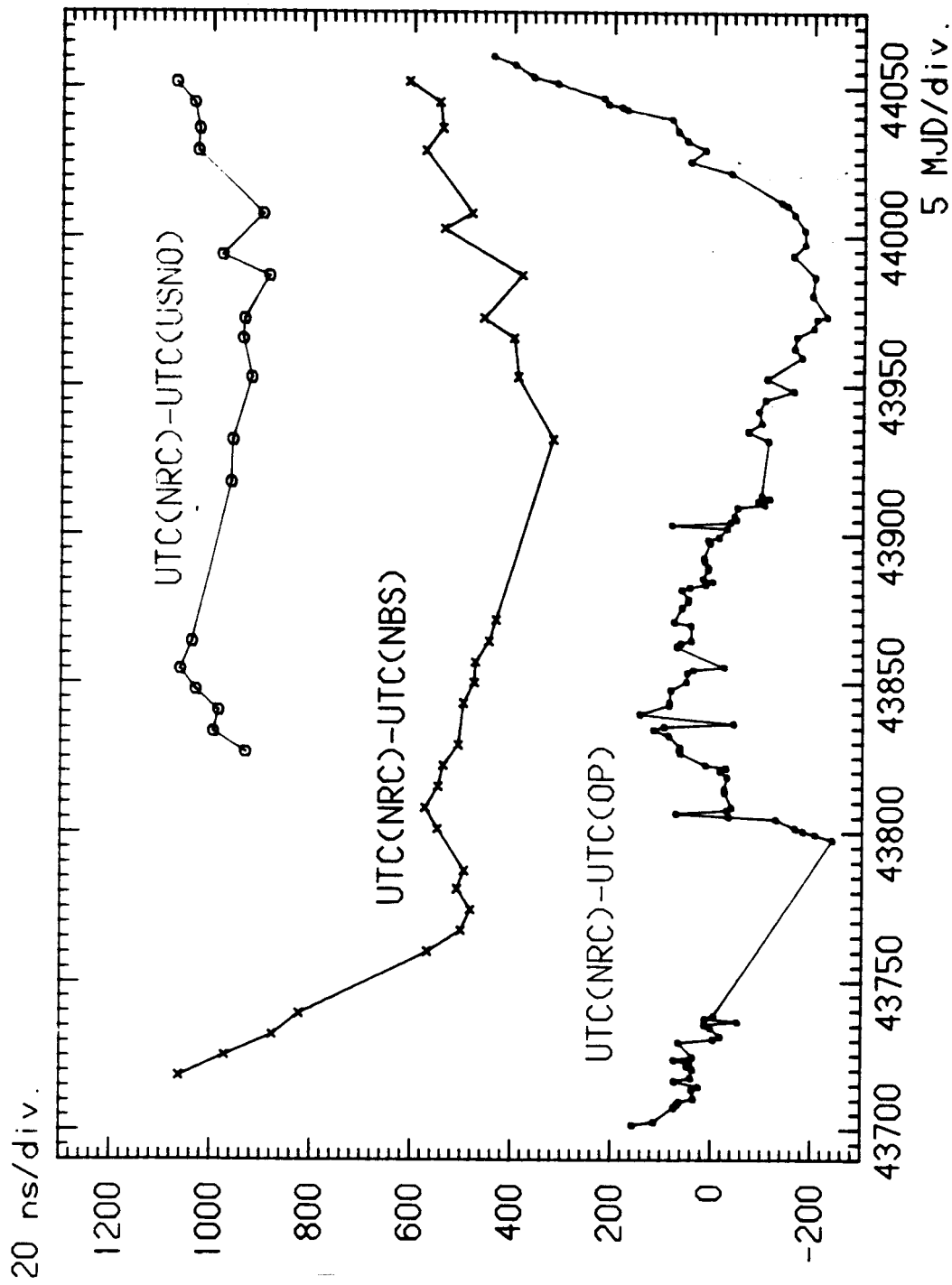


Figure 7. The USNO, NBS and OP Time Scales Compared to that of NRC. The Intercepts and Slopes have been Altered to Permit an Expanded Scale.