CLOCK SYNCHRONISATION EXPERIMENT IN INDIA USING SYMPHONIE SATELLITE

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ABSTRACT

A recent clock synchronisation experiment between the National Physical Laboratory (NPL), New Delhi and Space Applications Centre (SAC), Ahemedabad, in India via geostationary satellite symphonie-II, stationed at 49^{o} E longitude, is reported in this paper. As only one satellite transponder was available for this experiment, the two way transmission of the clock pulses was carried out by switching the transmit-receiver roles at the two stations at 5 minute intervals to achieve a nearly simultaneous two way transmission. Taking into account all the additional delays, the results demonstrated a clock-synchronisation accuracy of better than 0.5 microseconds. A crystal based portable clock flown aboard an aircraft confirmed this clock-synchronisation within a microsecond.

INTRODUCTION

The feasibility of precise clock synchronisation on an inter-continental basis has been demonstrated and looks attractive for time transfer on a global scale (See Somayajulu, 1977, for a recent review). These experiments carried over the past decade and a half have increased the precision of clock synchronisation. Currently a two-way transmission using a microwave transponder aboard a geostationary satellite is considered to provide the greatest precision in synchronisation of two remote clocks.

With the availability of the French-German geostationary satellite Symphonie-II to India for telecommunication experiments under a bilateral agreement an opportunity is provided for initiating clock synchronisation experiments in India. The satellite was parked over the equator above 49° E longitude in June 1977 add is expected to be located there for two years. Clock synchronisation experiments have been carried out from 17 to 30 April and 16th to 30 June, 1978 between National Physical Laboratory, New Delhi and Space Applications Centre, Ahmedabad via the Delhi and Ahmedabad earth stations. This report describes the details of these experiments and the results obtained.

DETAILS OF THE EXPERIMENTAL SET-UP

The symphonie satellite has two C-band transponders aboard of which one transponder was available for these experiments. The frequency for uplink transmission is 6347.5 MHz and is 4122.5 MHz for downlink reception. Both the Delhi (DES) and Ahmedabad (AES) earth stations are equipped with similar transmitting and receiving equipment. The relevant details are given in table-1.

Table 1. Details of Delhi andAhmedabad Earth Stations

	Delhi Earth Station	Ahmedabad Earth Station
Latitude (Geographic)	28° 36' 30"N	23° 1' 21.03"N
Longitude (Geographic)	77° 11' 0.0"E	72° 33' 52.48"
Height of the Antenna (above mean sea level)	240.7 m	74.2 m
Antenna Type & size	Parabolic dish Dia 10.7 metre	Parabolic dish Dia 14 metre
EIRP dbw (Max)	84.0	87.7
Transmit Freq.	6347.5 MHz	6347.5 MHz
Receive Freq.	4122.5 MHz	4122.5 MHz
IF Bandwidth	10 MHz	10 MHz
Modulation	FM	FM

A simplified block diagram of the experimental configuration at the two ground stations is shown in fig. 1. The C-band transponder on board the Symphonie satellite receives at a frequency of 6347.5 MHz and transmits at a frequency of 4122.5 MHz. The satellite transponder acts as a simple frequency translator without any signal processing. The bandwidth of the transponder is 90 MHz. The effective isotropic radiated power (EIRP) of the transponder is 29 dbw.

Each station in turn transmitted a continuous wave (CW) carrier that is deviated 240 KHz for a 30μs period of time. The rise time of the clock pulse is 50 ns. This deviation is caused by a 30μs clock pulse generated at a rate of 1 pps. The pulse shape is checked on an oscilloscope before starting the time measurement. The signal received from the remote station via the satellite is detected by the limiter/discriminator in the receiving system at the ground station. The leading edge of the discriminator output pulse stops the time-interval counter (HP Model 5245 or 5248 L/M) which is started by the local clock pulse. In effect, the counter measures the elapsed time between the start pulse of the local clock and the stop pulse from the remote clock. The counter readings are recorded with 10 samples centred on each minute and averaged. The duration of the experiments each day was 90 minutes. Each station transmitted for 5 minutes while the other received; immediately after 5 minutes the transmit-receive roles are switched for the next 5 minutes. This was repeated every 1/2 an hr. so that a maximum of 6 sets of samples are obtained each day. The time difference between the two clocks located at the ground stations is determined from these readings.

SYNCHRONISATION OF DES ATOMIC CLOCK WITH MASTER CLOCK

The National Physical Laboratory (NPL), New Delhi, maintains the national time standard through a cesium clock HP Model 5061 A with option 004. NPL also transmits time signals derived from the standard clock on ATA-transmissions at carrier frequencies of 5, 10 and 15 MHz. Another cesium clock type HP 5061 A with option 004 was located at the Delhi Earth Station and was kept in synchronization with the master clock by the following methods:

i) Via tracking of ATA broadcast

From the ATA-time transmissions received at DES 1 PPs pulses are generated by zero-crossing detection technique. The delay between these pulses and the 1 pps pulses from the Cesium Clock located at DES is measured by the time interval counter; from this delay measurement and computing the (ground wave) propagation delay between ATA (Greater Kailash, New Delhi) and DES, the DES cesium clock is adjusted for synchronism with the Master Clock within 50 μs.

(ii) Via Portable Clock

A 1 pps pulse is generated from the 100 KHz output of HP 105B type crystal oscillator. This 1 sec pulse is autosynchronised with the Master Cesium Clock. The synchronised crystal clock is immediately transported to DES where it is then used to synchronise the DES cesium clock to about 0.1 μs. The history of the crystal is well known before. At the end of each experimental period, the cesium clock at DES was transported to ATA for direct comparison with the master clock. The offset measured was consistent with that determinted by the portable crystal clock to within 0.1 μs.

Before the start of the experiments the AES atomic clock is synchronised to the Master Clock to within 1 ms using the ATA-transmissions received at Ahmedabad.

FACTORS AFFECTING THE PRECISION AND ACCURACY OF CLOCK SYNCHRONISATION

(a) Precision of Synchronisation

The precision of clock synchronisation, i.e., the minimum absolute time difference to which two Clocks could be synchronised, is determined essentially by the signal-to-noise power ratio at the receiver output which provides the stop pulse to the time interval counter and the counter error, the latter being taken as $\pm$ 1 digit. The finite signal-to-noise ratio causes a jitter of the leading edge of the clock pulse, thus causing an error in the measurement. The r.m.s. jitter in the arrival time of the clock pulse is given by

$$\delta t_{rms\ jitter} = \frac{tr}{(2^{S/N})^{1/2}} \qquad \text{.........(1)}$$

where tr is duration of the clock pulse and S/N is the signal-to-noise power ratio. In our case tr is 30 μs. The stated S/N ratio for both DES and AEA is 50 db min. Using these values, from equ. (1) we obtain an estimate of rms jitter as 67 ns.

The combination of the rms jitter and the inherent counter error will show up as random fluctuations of the counter output superposed on any systematic drift due to factors to be described in the next section. Thus the standard deviation of the counter reading is a measure of the precision of synchronisation.

(b) Accuracy of Clock Synchronisation

The accuracy of the clock offset measurement or synchronisation depends on the extent to which signal delays introduced in the total system are known or accounted for. The total signal delay time comprises the time delay introduced by the intervening electronic equipment, i.e., the transmitting equipment at the earth station, the satellite transponder, and the receiving equipment at the other ground station, the delay in the ionosphere and the troposphere, and the free space path delay between the ground station and the satellite. Thus contributing factors for the total signal-delay error budget are:

(i) Ionospheric and tropospheric delay errors

(ii) Satellite position error

(iii) Equipment delay errors

The signal delay is defined as the time required for an identifiable point in the signal waveform from entering the transmitting equipment to its reappearance at the output of the receiver. In the present case it is the 50% value of the leading edge of the 1 pps pulse.

i) Ionospheric and tropospheric errors

In the earth's ionosphere and the troposphere the signal delay is equal to the group delay i.e., the signal energy propagates with the appropriate group velocity. The group delay in the ionosphere is essentially proportional to the total electron content which has a diurnal variation, also a day-to-day variability and is a function of frequency. As the additional ionospheric delay is frequency dependent, an error in a two-way method will be caused by the inequality of the propagation time for two directions of the path. In high frequency approximation, the ionosphere delay 'd' is

$$d = \frac{40.3}{c f^2} \int_{Path} N_e \, ds = \frac{40.3}{c f^2} N \quad \text{- - - -} \quad (2)$$

where

c : light velocity

f : frequency in Hz

Ne: election density per meter cube

N : total election content along the path

using eqns. (2), the error due to the ionospheric effect, E_I, for the up-link of 6 GHz and the down-link of 4GHz is given by

$$E_I = \frac{1}{2} (d_{DA} - d_{AD}) - 2.33 \times 10^{-27} (N_D - N_A) \quad \ldots(3)$$

where N_D , N_A are the total election contents (e^1/m^2) along the path from satellite to the DES & AES respectively and d_{DA} and d_{DA} are the delay from DES to satellite and to AES and from AES to satellite and DES respectively.

On the other hand the troposphere group delay is practically independent of frequency and is insignificant for elevation angles greater than 15° (In the present case the elevation angle is 45°). At the C-band microwave frequencies, treating the velocity propagation as essentially the velocity of light (2.9979×10^8 m/s), from earth station antenna to the satellite introduces an error of less than 5 ns in the group delay computation.

In the present experiment a two-way transmission is used. Although it is not strictly simultaneous, it is nearly simultaneous in the sense that the transmit-receive roles of the two stations are alternatevely switched after a 5-minute interval. During this time the ionospheric and tropospheric conditions are practically unchanged and therefore the propagation delay drops out in the final computation of the clock offset. The contribution due to any satellite motion is discussed in the next section. An explicit assumption involved is that the electromagnetic path between DES and AES is reciprocal. This assumption is not strictly valid because the uplink and downlink frequencies differ by 2 GHz. However, the differences in the path reciprocity are negligible at the C-band frequencies, amounting to less than 1ns.

ii) Satellite Position Errors

Symphonie satellite is not in an absolutely synchronous orbit. The motion of the satellite during the period of tests produces a steady and systematic change of the apparent time delay that is measured. The DES and AES transmit-receive roles are switched alternately for 5 minutes. During the period of measurements the satellite drift error is less than 1μs over the one minute interval for which time delay is measured. In any case, this systematic drift is taken into account by least square fit on a computer of the piecewise observations.

The error in the position of the ground stations does not exceed 1m and is hence inconsequential.

iii) Equipment Delay error

The time signals experience additional delay in passing through the electronic equipment in the transmit-receive chain, viz., the transmitting and receiving equipment at each ground station and the satellite transponder. In the present case the satellite transponder operating in the C-band uses very wide bandwidths (90 MHz); moreover the satellite transponder essentially operates in a translational mode and hence the delay in the satellite transponder is negligible.

The major error contribution comes from the equipment delay at the ground stations. The various equipment delay contributions may be itemized as follows:

i) The time delay in the modulation circuits and the transmitter Chain at each station (δt_1, δt_2);

ii) The time delay due to the finite length of transmission line/waveguide to the transmitting antenna feedpoint (δta_1, δta_2);

iii) The time delay from the receiving antenna feed point to the parameteric amplifier input and the delay due to the transmission line/waveguide from the parametric amplifier output to the main ground station (δra_1, δra_2)

iv) The time delays in the demodulation and output circuits (δr_1, δr_2).

As mentioned earlier, any uncertainty in the time delay measurement will appear as bias in the clock offset measurement while any variability in the delays limits the accuracy.

At each earth station before the start of the experiment each day, the equipment delay was measured as part of the calibration procedure, by internal looping. A sample of the transmitter output is downconverted to the receiver frequency using a broadband mixer whihh contributed an insignificant amount of delay. The measured signal delay at DES was $1.28\mu s$ and for AES it was $2.8\mu s$ This AES delay included an extralength of 57m to the down converter which introduced an extra time delay of $0.57\mu s$ in the loop delay. Thus the time delay in the electronic equipment in the AES internal loop is $2.23\mu s$. The variation in the delay was less than $0.1\mu s$.

In the determination of the clock offset, the equipment time delay that enters the picture is the difference between transmitter time delay at DES plus the receiver time delay at AES and the transmitter time delay at AES add the receiver time delay at DES. Since the transmitter and receiver time delays at each station could not be measured separately, it was assumed that the total internal loop delay is equally divided between the transmitter and the receiver. Thus the net difference of the delays considered above is taken to be zero. This assumption introduces an unresolved bias of $\pm 1.0\mu s$.

The time delays introduced due to finite transmission line/ waveguide lengths at DES add AES are:

$$\delta t_1+\delta r_1 = 1.28\mu s. \qquad \delta ta_1=0.175\mu s \qquad \delta ra_1=0.2\mu s$$

$$\delta t_2+\delta r_2 = 2.8\mu s. \qquad \delta ta_2=0.364\mu s \qquad \delta ra_2=0.35\mu s$$

RESULTS

Measurements of the total time delay were made on 21 days during the two test periods in April and June 1978. Each day a maximum of 6 sets of measurements each consisting of at least 50 observations-10 centred on each minute during the 5 minute interval - have been accummulated. These data are used to determine the AES clock offset with respect to the DES clock and hence with respect to the NPL Master clock. Also because the two test periods are separated by about 6 weeks with the clock running, an opportunity is provided to determine the systematic or long - term drift rate of the AES clock with respect to the master clock.

The clock error or offset is defined as follows: (Ramasastri et al)

Clock offset (E) = Master clock time (NPL) - User Clock Time. If the user clock lags behind the Master clock E is positive and is negative if the user clock is ahead or the master clock.

The clock offset is computed as follows. Referring to fig.2

Let τ_1 be the apparent time delay measured at AES with DES transmitting.

τ_2 be the apparent time delay measured at DES with AES transmitting.

τ_{t_1}, τ_{t_2} be the equipment delays in the DES transmit chain and receive chain respectively ($\tau_{t_1} = \delta t_1 + \delta ta_1$; $\tau_{r_1} = \delta r_1 + \delta ra_1$)

τ_{t_2}, τ_{r_2} be the equipment delay in AES transmit and receive chain respectively ($\tau_{t_2} = \delta t_2 + \delta ta_2$; $\tau_{r_2} = \delta r_2 + \delta ra_2$)

The clock offset then is given by

Clock offset E = $\frac{1}{2}\left[(\tau_1 - \tau_2) - \left\{(\tau_{t_1} + \tau_{r_2}) - (\tau_{t_2} + \tau_{r_1})\right\}\right]$

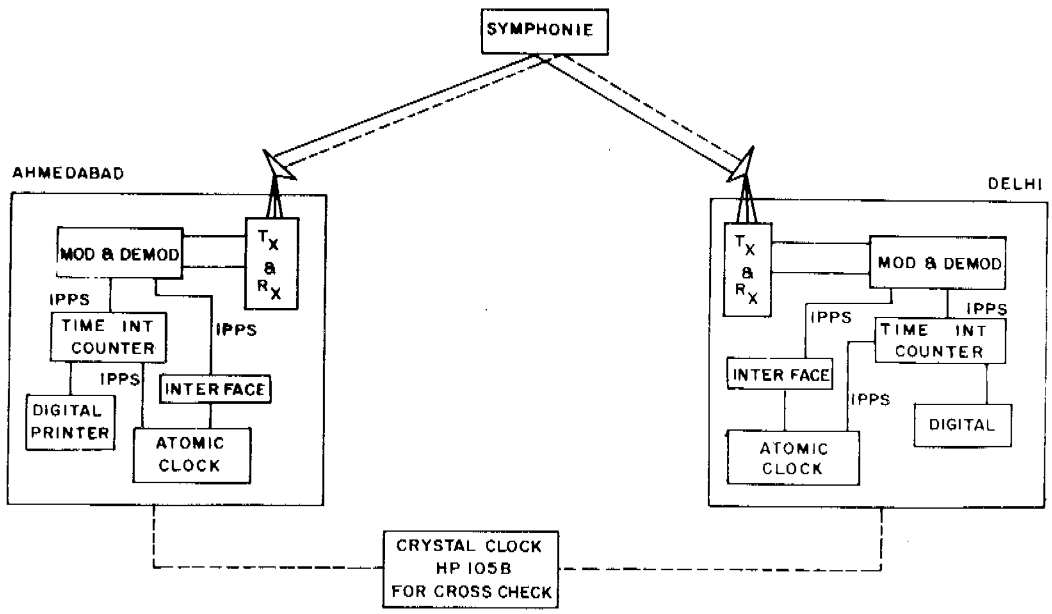
$= \frac{1}{2}\left[\Delta\tau - \delta\tau\right]$ where $\Delta\tau = \tau_1 - \tau_2$ and $\delta\tau = \left[(\tau_{t_1} + \tau_{r_2}) - (\tau_{t_2} + \tau_{r_1})\right]$

If the equipment delay in each transmit - receive circuits is the same $\delta\tau$ is zero. However for reasons outlined in Section 4 (iii) an unresolved bias of $\pm$ 1.0μs exists.

Thus Clock offset $= \frac{\Delta\tau}{2} \pm 1.0\mu s$

As mentioned earlier, during test period each day 6 sets of observations of 5 minute duration are obtained at each station. Each sample consists of 10 observations centred on the minute. In order to take care of the systematic drift due to satellite motion, the piece-wise samples are processed on computer using a least squares fit for both the stations (Fig. 3,4). From these curves the average clock offset for each day is measured.

The corresponding standard deviation is also computed. Un-



BLOCK DIAGRAM OF TIME COMPARISION EXPERIMENT

FIG. 1

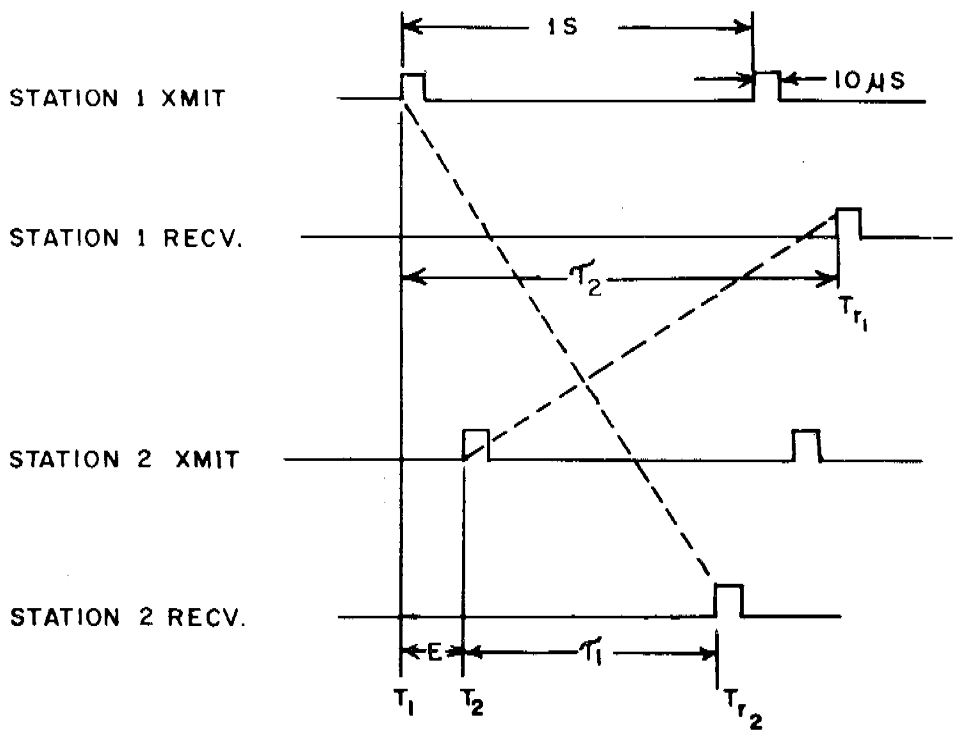


Fig. 2 TIMING DIAGRAM.

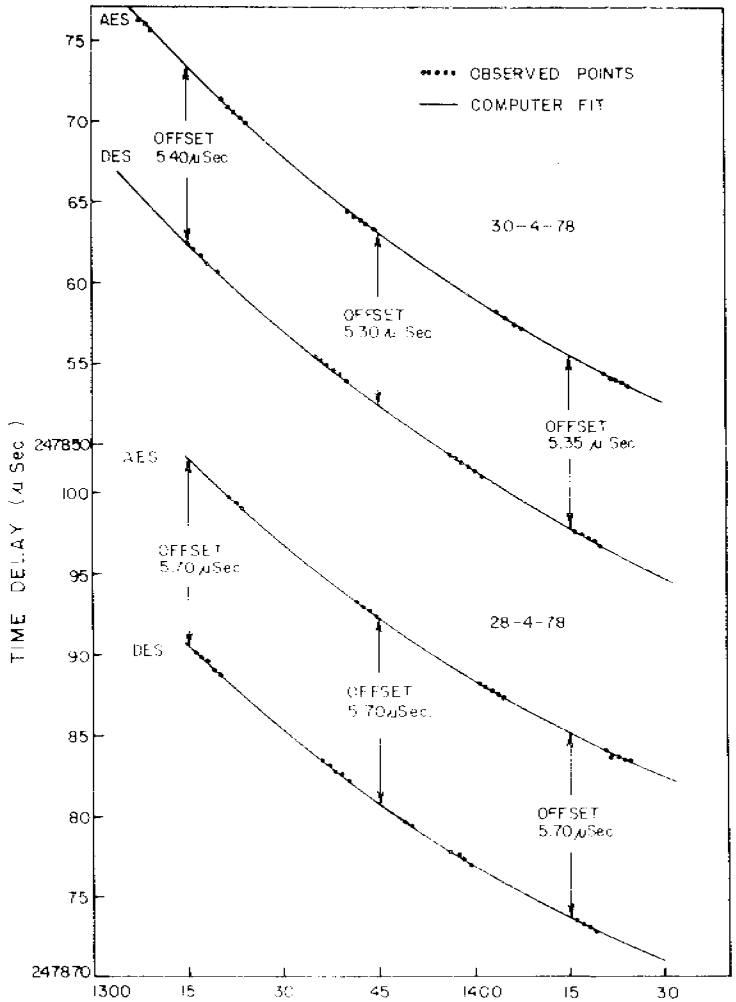


Fig 3

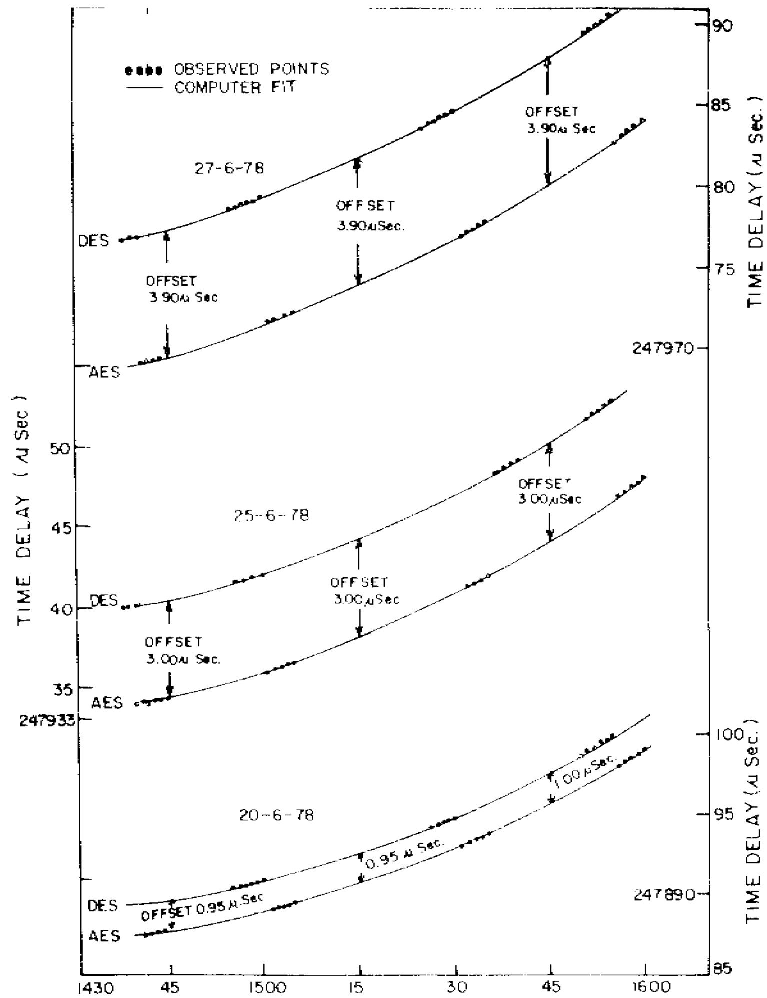


Fig. 4

Off-set between the clocks determined through computer fit in the observed time-delay points.

TABLE II a

Date	Time	Average $\Delta T/2$ (μs)	$\sigma(\Delta T/2)$	σ for fitted curves DES	AES	Counter resolution	Remarks
21.4.78	1300-1430	18.03	--	--	--	100 n Sec.	AES clock reset
22.4.78	-do-	18.10	--	--	--	100 n Sec.	--
27.4.78	-do-	7.75	--	--	--	100 n Sec.	AES clock reset
28.4.78	-do-	5.72	.034	.010	.020	100 n	--
29.4.78	-do-	5.58	.035	.016	.011	100 n Sec	-- --
30.4.78	-do-	5.35	.042	.021	.011	100 n Sec.	--

Average AES Clock Drift = .12 μSec/day

fortunately at DES the time interval counter used has only a 100 ns resolution. However a 10 ns resolution counter was used on 11 days during the tests and the standard deviation computed from these observations is taken to be representative of the capabilities of the experimental system.

The results of the measurements are summarised in table II a,b. It is concluded that the clock synchronisation is possible to a precision of .17μs using a 100 ns resolution time interval counter and to a precision of .08μs with 10ns resolution counter. The accuracy of synchronisation, taking into account all the possible delays, is about 0.5μs, with a bias of $\pm$ 1μs which is probably an overestimate.

In order to determine the drift rate of the AES clock with respect to DES clock and hence with respect to the NPL master clock, the results are plotted in Fig. 5. During the April tests the AES clock offset was + ve and it was drifting at a rate of .12μ per day up to June 16. On June 17th

TABLE II b

Date	Time	Average $\Delta T/2$ s	$\sigma(\Delta T/2)$	σ for fitted curves DES	AES	Counter resolution 100ns	Remarks
16.6.78	1430-1600	+11.21	.12	.020	.012	100n Sec.	Clock
18.6.78	-do-	.03	-	-	-	10n Sec.	Clock reset
19.6.78	-do-	-0.38	.076	.077	.014	-do-	
20.6.78	-do-	-0.95	.013	.008	.004	-do-	
21.6.78	-do-	-1.38	.288	.018	.001	Resolution 100 n Sec.	
23.6.78	-do-	-2.32	.023	.01	.002	Resolution 10 n Sec.	
24.6.78	-do-	-2.64	.097	.001	.058	-do-	
25.6.78	-do-	-3.05	.010	.005	.001	-do-	
26.6.78	-do-	-3.46	.010	.007	.008	-do-	
27.6.78	-do-	-3.92	.007	.004	.005	-do-	
28.6.78	-do-	-4.23	.076	.006	.002	-do-	
29.6.78	-do-	(-5.39)	-	-	-	-do-	Clock reset
30.6.78	-do-	(-3.49)	-	-	-	-do-	-do-

Average AES Clock Drift = .43 μSec./day

the AES clock stopped. After recommissioning the AES clock,

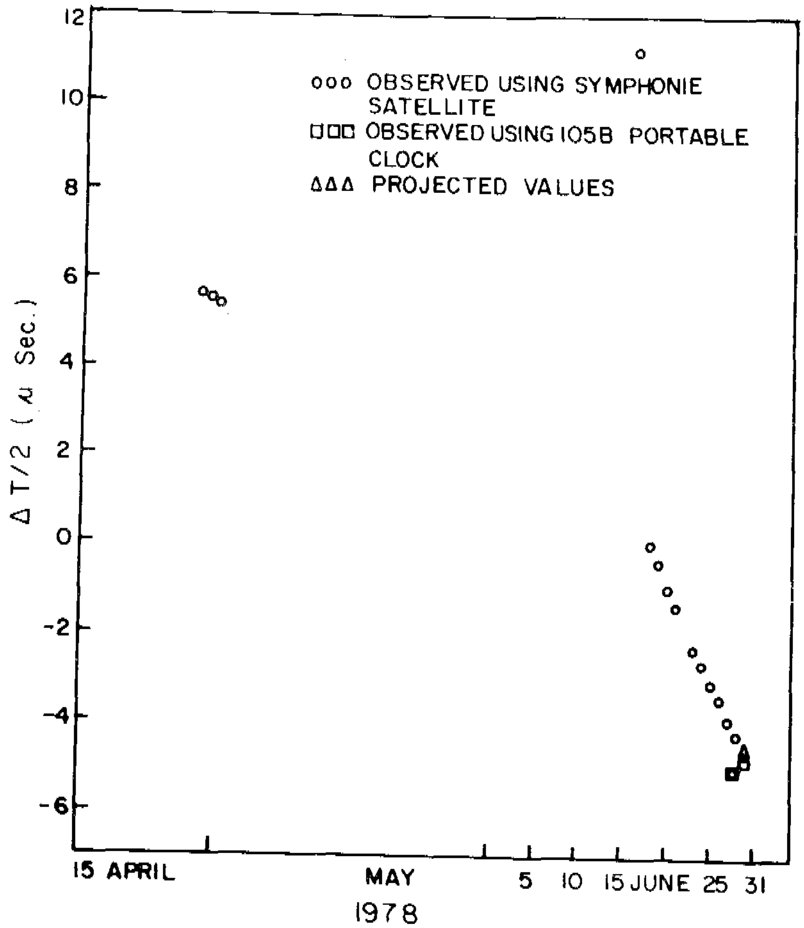


Fig. 5

Drift rate of AES clock w.r.t. DES clock

and after stabilisation it was synchronised with respect to DES clock and the offset was ± ve. During the rest of the June test period the apparent drift rate of the AES clock with respect to the DES clock was 0.5μs per day. This apparently different drift rates reconciled as follows. The DES clock has a drift rate opposite to that of AES with respect to the NPL master clock. When the AES clock offset (with respect to DES) was + ve, the apparent drift rate is smaller because the two clocks were drifting in the same direction. When the offset became - ve, the clocks were drifting in opposite directions and hence the apparent drift rate is the sum of the drift rates of the two clocks and hence is apparently much larger than during April test. The drifts of the AES and DES clocks are plotted in the same figure which establishes a uniform drift rate of the AES clock with respect to the NPL, Master Clock

Check of the Consistency of Clock Synchronisation with portable clock

The heart of the portable clock is a crystal oscillator model HP 105B. This oscillator output has been used to derive second pulses. The arrangement is also there to autosynchronise the epoch of the second pulses within a fraction of microsecond with respect to that of a cesium clock second pulses. The drift rate of the crystal clock has been studied very critically for better prediction of the clock epoch.

Before flying the clock, it is auto-synchronised with master cesium at ATA to within 0.4 microsecond and the time difference is noted in time interval counter HP 5248L. The clock is then flown to Ahmedabad by a commercial aeroplane and the AES cesium clock was directly compared with this portable clock, after about four hours time of its auto synchronisation with ATA cesium in Delhi. At Ahmedabad the offset between ATA and AES clock was found to be 1.95 μsecond with drift prediction uncertainties of $\pm$ .25μsecond (at that time according to symphonie experiment offset was 1.15μs). In the return flight the portable clock was autosynchronised with AES cesium and after roughly four hours the portable clock was again compared with ATA cesium and the offset was found to be 1.5μs (at that time the projected values of symphonie experiment was 1.32 μs).

Thus the flying clock experiment confirms the consistency of the clock synchronisation experiment via symphonie satellite to an accuracy of $\pm$ 0.25 μs.

On 28th June the difference between the flying clock experiment and the Symphonie experiment was found to be 0.8 μs which is well within the uncertainty in symphonie experiment. However, on the second day (29th June) this difference was 0.18μs. Though both these values are within the limit of uncertainty of symphonie experiment but thedifference of 0.62 μs on consecutive two days observations may be due to some uncertainty in behaviour of crystal due to jerks while flying.

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