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Scope of High-Frequency Time Keeping in Searches for Short-Period Gamma-Ray Sources

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Abstract. This paper presents a novel technique to derive the absolute time of occurrence of an event with an accuracy of < 200 μs by adapting the HF time synchronization technique to correct for the aging rate and the frequency drift of a temperature-controlled quartz frequency standard. The propagation delay suffered by the HF time signals has been estimated by monitoring the clock error with respect to time signals from five broadcast stations located at distances in the range 500–3700 km from Gulmarg. Using simulated data, we further show the viability of this technique in permitting periodicity searches on timescales of $\geqslant$ 5 milliseconds in cosmic gamma-ray data.

Key words: time keeping—gamma-ray sources—atmospheric Cerenkov technique

1. Introduction

The atmospheric Cerenkov technique (Jelly 1967; Weekes 1988) provides the only viable method of studying very high energy γ rays (10^{11}–10^{13} eV) from celestial objects, inspite of the constraint of a low duty cycle ($\leqslant$ 10 per cent) imposed on this technique by the need to operate on clear, moonless nights. However, the gray signals are quite weak in this energy range, corresponding to a flux of typically < 1 photon m^{-2} week^{-1}, and the sensitivity of most of the present generation γ-ray telescopes is such that long exposure spells, of upto a few months per source, are generally required to retrieve a d.c. signal with a good statistical significance. In addition, while searching for bursts of γ-ray emission, a supplementary stipulation, apart from good counting statistics, is to seek a near simultaneity of the cosmic event at two or more suitably separated geographical locations, which requires timing the event aboslute epoch to at least tens of milliseconds accuracy. Likewise, in case of periodic sources like pulsars and X-ray binary systems, the otherwise long signal recovery time can be substantially decreased by folding the event arrival times with the characteristic rotation/orbital period of the candidate source and performing a phase analysis (or a Rayleigh power test where the exact source period is unknown). Here the source emission appears as a significant enhancement in one or a few phase bins over the otherwise large albeit phase-uniform, cosmic-ray-produced background events. Such a data-folding operation again demands very accurate time keeping so as to prevent phase wandering and consequent smearing of the phase distribution of the signal photons. Quantitatively, the accuracy in time, Δt, needed to allow the folding of a dataset of duration t seconds, is related to the source period p by

$$\Delta t/t = (p/t)\Delta\phi \tag{1}$$

where $\Delta\phi$ is the desired width of the phase bin. Thus, for a generally preferred value $\Delta\phi = 0.1$, for example, the time accuracy required for a 120 day data sample is only ~ 1.6×10^{-4} s s^{-1} for a signal modulated at the 4.8 h orbital period of Cygnus X-3 but ~ 10^{-10} s s^{-1} for the suggested pulsar period of ~ 12.6 ms in this system (Chadwick *et al.* 1985).

A time accuracy of the order of ~ 10^{-10} ss^{-1} demands the use of atomic time standards but they are difficult to maintain and expensive to replace. The general practice, therefore, is to use temperature-controlled crystal oscillators as local frequency standards and to regularly correct for frequency drift and aging of the oscillator by slaving the clock to more accurate time-markers provided by satellite timing receivers (Putkovich 1981; Jain *et al.* 1981), TV synchronization systems (Kovacevic *et al.* 1981; Lake 1981) and high frequency time signals. The first two techniques are favoured by some g-ray astronomers (Ramana Murthy 1981; De Jager *et al.* 1988) as they are rather straightforward to implement and lead to a higher accuracy in absolute time ($\leqslant 30\mu$s). However, both the methods are comparatively expensive and suffer from the disadvantage of not being as universally available as the HF timing transmissions. As the HF transmission is generally received via the ionospheric F layer(s), the accompanying time markers are subject to two important uncertainties, undermining the precision of synchronization. One source of uncertainty is the short-term amplitude fading (Bhat *et al.* 1981a) which leads to a large second-to-second time jitter in the arrival of the time markers themselves. The second type of uncertainty is in the determination of propagation delay of the transmission between the transmitter and the receiver. This relatively long-term effect is a function of the user location, season, time of the day and the mode of propagation and sets the ultimate limit on the accuracy of the derived absolute time information.

In the present communication, we show that, notwithstanding these uncertainties, it is feasible to adapt the HF time synchronization technique to adequately correct for the frequency drift and aging rate of a crystal oscillator over indefinitely long periods of time and also to derive absolute time information accurate to within 200 μs. Using simulated periodic data, we further demonstrate the viability of this simple and economical synchronization technique in permitting period searches down to the millisecond time-scale and thus allow to carry out γ–ray astronomy of a majority of short period sources from such good astronomical sites as may not fall within the range of timing satellites or the TV synchronization method.

2. Experimental details

High frequency timing transmissions broadcast at 10 and 15 MHz from ATA (New Delhi) and RWM (Moscow) have been regularly used over the years at Gulmarg, India, for a variety of scientific purposes (Bhat *et al.* 1980; Bhat 1982). The latest experiment to incorporate this synchronization facility is the Gulmarg γ-ray telescope (Koul *et al.* 1989) which has been recently commissioned to study point γ-ray sources at TeV energies (1 TeV = 10^{12} eV) through the atmospheric Cerenkov technique. The atmospheric Cerenkc events result from the optical Cerenkov light released in the terrestrial atmosphere. This generally follows the incidence at the top of atmosphere of a very high energy cosmic-ray particle but in < 1–2 per cent cases that of a γ–ray photon from a cosmic source (Kaul 1987). The telescope is provided with a temperature-controlled crystal clock to time the onset of each registered event with a resolution of 1 μs. The time synchronization circuit used at Gulmarg has been discussed in detail earlier (Bhat, Kaul & Yadav 1981b) and we only outline here the essential features. The reference time-markers are tapped from the audio-frequency section of a communication receiver and, after amplitude discrimination against extraneous noise, are suitably shaped to yield a TTL-compatible rectangular pulse with a rise-time of $\leqslant$ 100 μs and a frequency of 1 Hz. The markers derived thus, over periods of upto 10 minutes on a given day, are used to repeatedly interrogate the latches of the Gulmarg clock and the resulting timing data are stored on a personal computer to infer the clock error $\varepsilon(t)$ at the time of the synchronization.

Fig. 1 shows a typical frequency distribution of $\varepsilon(t)$ plotted as deviations from the sample mean error $\langle\varepsilon\rangle$ in units of the corresponding standard deviation σ. A total of 15 samples, each only ~ 10 minutes long and having typically ~ 100 events, are superposed to obtain a correct perspective of the nature of distribution. The appreciable dispersion of $\varepsilon(t)$, seen in Fig. 1, cannot be due to the frequency drift and aging of the local clock oscillator because of the limited duration of individual data samples (~ 10 minutes). On the contrary, its main cause is the short-term jitter in the arrival of reference time-markers themselves. As the distribution of the error is in reasonable accord with a Gaussian distribution, it presumably arises from random modulations, like fading, suffered by the HF transmission while propagating through

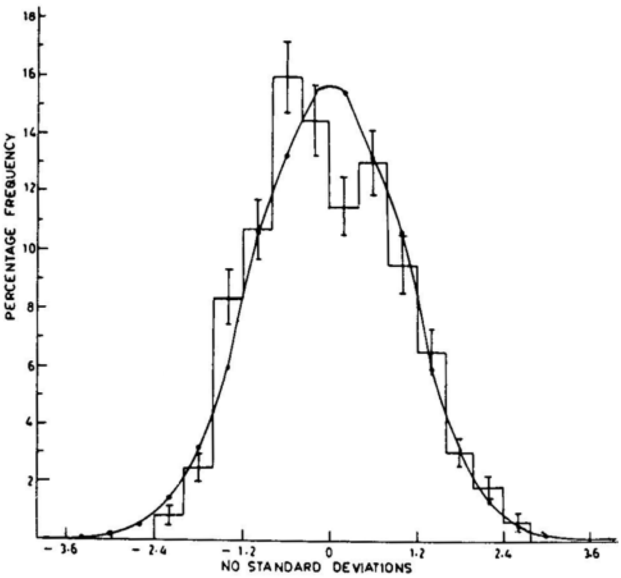

Figure 1. A typical frequency distribution of clock error plotted as deviations from the sample mean error. The histogram represents the observed distribution while the continuous curve shows the expected Gaussian fit to the observed distribution.

the ionosphere (Bhat *et al.* 1981a). The sample mean value is essentially free of this short-term jitter because of the symmetrical nature of the distribution and therefore represents the most probable value of the clock error at the time of synchronization.

During the period of monitoring of the clock error, the timing data are recorded in the above discussed manner on various days at around the same local time so as to keep to a minimum the effects on $\varepsilon(t)$ of possible longterm variations in the ionospheric conditions. Finally the sample mean error $\langle\varepsilon(t)\rangle$ is determined for each individual day alongwith the corresponding standard deviation.

3.1 *Correction for Oscillator Drift and Aging*

Fig. 2 displays the long-term behaviour of $\langle\varepsilon(t)\rangle$ during 2 different observation spells, viz., 1987 July-August and 1988 October-December, for a minimum of ~ 20 days during each period. The error bars attached to each data point represent the above-mentioned ± 1σ standard deviation values for the daily sample of $\varepsilon(t)$. We can represent $\varepsilon(t)$, the clock error at a given time t, by the following expression,

$$\varepsilon(t) = \varepsilon_0 + a\,t + 1/2\,bt^2. \tag{2}$$

Here e_0 is the initial clock time offset (but does not include correction for the propagation delay suffered by the reference time markers); $a = \Delta f/f$ *is* the frequency offset and *b,* the aging rate of the oscillator. The broken lines in Fig. 2 represent the best parabolic fits to the experimental data of the form given by Equation (2) and are obtained by the method of least squares. The excellent agreement observed with the expectation is reassuring and the resulting values of ε_0, a and b are listed in Table 1 for the two observation epochs alongwith the 1σ uncertainty limits in predicting $\varepsilon(t)$. Using these values of ε_0, a and $b,$ the clock error due to oscillator frequency drift and

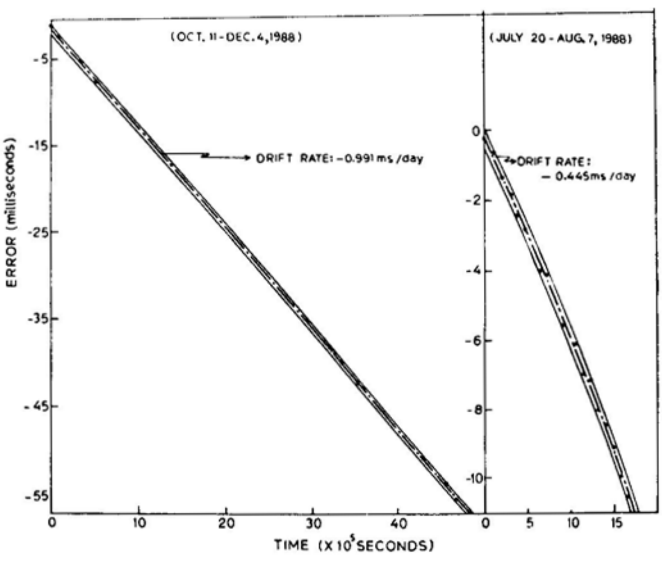

Figure 2. Long term behaviour of the clock error for the two different observation epochs. The ± 1σ error bands are also shown for both the fits.

Table 1. Initial offset, drift rate and aging rate.

Observation period	ε_0 μs	Drift rate a $\mu s\ s^{-1}$	Aging rate b $\mu s\ s^{-2}$
1987 July/Aug	-235.09	-0.5153×10^{-2}	-0.1153×10^{-8}
Standard deviation in $\varepsilon(t) = 167\ \mu s$			
1988 Oct/Nov	-1373.37	-0.1147×10^{-1}	-0.1099×10^{-10}
Standard deviation in $\varepsilon(t) = 215\ \mu s$			

aging rate can be computed and the time of registration of a Cerenkov event can be determined with a relative accuracy of $\pm$ 150 μs at any time during a given observation spell. It may be mentioned here that a study of the long-term behaviour of the clock-oscillator for six different epochs during the period extending from 1987 July to 1989 February, has shown a systematic variation in the drift rate with time. This is clearly seen in Fig. 3 in which we have plotted the drift rate as a function of the measurement epoch. It is observed that this variation in the drift rate, which essentially arises from the aging of the crystal oscillator, varies linearly with time as expected.

3.2 *Correction for Propagation Delay*

We note that, although using a portable atomic clock provides a more accurate and straightforward option for determining the propagation delay, it could not be done for the Gulmarg clock because of the non-availability of such a time standard. For this purpose we monitored the error of the Gulmarg clock on 4 consecutive days (1988 January 10–13), with respect to time-markers from ATA (New Delhi), RCH (Tashkent), RID (Irkutsk), BPM (China) and RWM (Moscow). These stations are situated at crow-flight distances of 650 km, 924 km, 3115 km, 3212 km and 3663 km respectively from Gulmarg. As in the normal course, the clock error with respect to each station was monitored ~ 100 times in quick succession (5–10 minutes each) and the sample mean errors with respect to individual stations determined. The time signals from BPM (China) could be monitored only on two days due to poor reception conditions.

As already explained, the errors contain contributions from initial offset, frequency drift and aging rate of oscillator as well as propagation delay. In order to separate the contribution to the clock error due to the local frequency standard, we find the difference between $\varepsilon(t)$ recorded on the last 3 days with respect to the corresponding error for January 10. These differences lead to a drift rate of $-\ 0.7722 \times 10^{-2}\ \mu s\ s^{-1}$, which is in excellent agreement with its value derived independently for RWM (Section 3.1) and is shown by the encircled point in Fig. 3. Using this value of the drift rate, the errors recorded on the different days from all the five stations have been corrected for frequency drift and contain contributions from initial offset and propagation delay alone. We now proceed to account for these two contributions in the following manner.

Assuming a mirror-type reflection of the HF time signals from a thin, single-layer ionosphere at an effective reflection height $h/2$, the propagation delay suffered by the

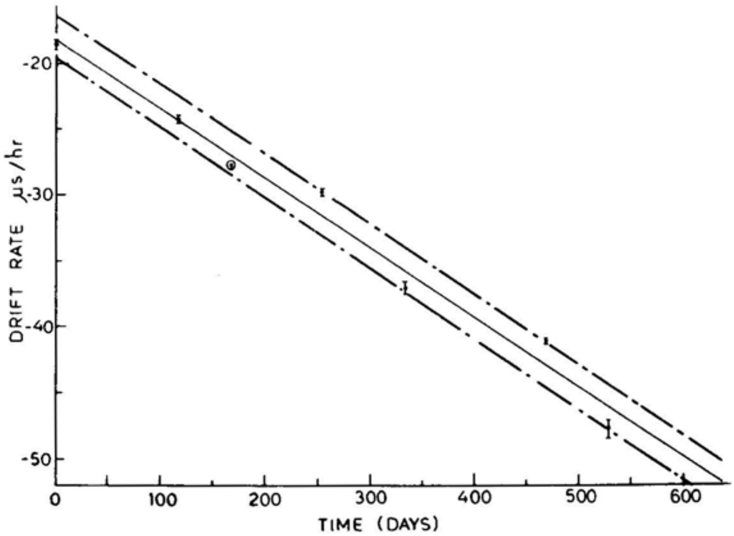

Figure 3. Variation of drift rate with time during the period 1987 July–1989 February. Note the $\pm$ 1σ error band for the straight line fitted to the data.

time-markers in reaching the Gulmarg clock from a transmitter separated by a crow-flight distance x_i is given by,

$$(T_i - t_0) = 1/c(x_i^2 + h^2)^{0.5} \tag{3}$$

where T_i is the total clock error expected and t_0, the initial clock offset. The term on the right-hand side represents the propagation delay expected on the basis of the above model and a one-hop propagation mode. If t_i is the experimentally observed error for the station at the distance x_i, we expect

$$\Sigma(T_i - t_i)^2 = \Sigma[t_0 + 1/c(x_i^2 + h^2)^{0.5}]^2 - t_i^2 \tag{4}$$

to be minimum if the experimental data conform to the hyperbolic fit represented by Equation (3).

Using a base value of $h/2$ = 200 km for the effective reflection height, we have altered it progressively in small steps and used a successive approximation method to minimize the above expression for each of the five stations for which we have data. This leads to the most probable value of 228 km for the effective height of the reflection layer and – 5694.5 μs for the initial clock offset for the period 1988 January 10–13. Using this value for t_0, the propagation delay (T_i – t_0) for the five stations can be determined. The resulting values of the propagation delay (Table 2) are plotted as a function of receiver-transmitter distance x_i in Fig. 4 alongwith the best hyperbolic fit to the data. The scatter in the plotted values on a day-to-day basis sets the ultimate limit on predicting accurately the propagation delay for a given transmission. In our case, it is found to vary between 64.3 μs and 451.5 μs. The scatter observed for RWM (Moscow) has a low value of only 96.7 μs which is due to the distinctly better quality of reception of these time signals at Gulmarg.

We note that the propagation delay values obtained here closely match with earlier predictions (Morgan 1959) for a one-hop propagation mode. This means that other

Table 2. Propagation delay as a function of transmitter distance.

Date	Observed propagation delay $(T_i - t_0)\ \mu s$				
1988 January	ATA 651 km	RCH 924 km	RID 3115 km	BPM 3212 km	RWM 3663 km
10	2631.1	3098.3	11032.5	—	12123.8
11	2853.4	3011.6	10840.0	10958.6	12185.5
12	2898.1	3127.7	10488.3	—	12365.2
13	3264.9	2968.5	10507.6	10935.5	12135.7
Mean	2911.9	3051.3	10717.1	10947.1	12202.5
σ	$\pm$227.6	$\pm$64.3	$\pm$229.6	$\pm$16.8	$\pm$96.7
Expected propagation delay (μs)	2649.7	3436.5	10493.5	10814.9	12303.1

Value for t_0 is –5694.484 μs.

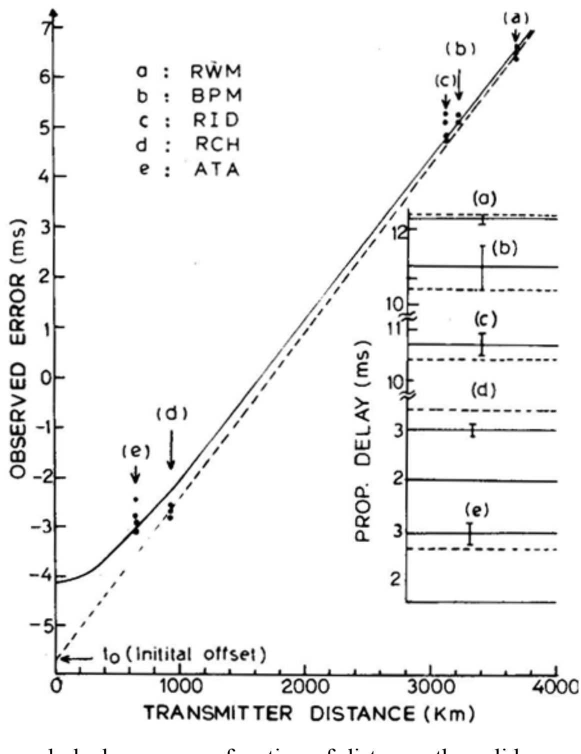

Figure 4. The observed clock error as a function of distance; the solid curve represents the best hyperbolic fit to the errors and the dotted line is the asymptote to the hyperbola meeting the ordinate at the value of initial time off-set in the clock. Inset shows the observed (full line) and the expected (broken line) propagation delays for each station.

users may directly refer to Morgan's charts for estimating propagation delay for their transmitter-receiver distances. The maximum uncertainty in this estimate can be upto 500 μs on account of the need to guess a proper value for the reflection height. However, the corresponding uncertainty in the case of Gulmarg clock, with appropriate corrections for frequency drift, aging rate and propagation delay as described above, turns out to be only ~ 180 μs.

4. Application to short-period source searches

In a search for periodic signals from potential γ-ray sources, several different statistical techniques, including phasogram analysis, Rayleigh power analysis, Z_n^2 test and Protheroe statistic have been employed. Among all these methods the phase histogram technique, involving binning of timing data into various phase bins associated with a source of given period, is more popular. This method is, therefore, used here to illustrate that for an absolute time accuracy of ~ 180 ps possible by slaving the Gulmarg clock to RWM (Moscow) it should be feasible to limit phase uncertainty to within 10 per cent of period or, equivalently, to within 1 bin in the customary 10-bin phasogram, even while dealing with sources with periods down to a few ms. We carried out a simple simulation study to verify this inference. A selection of ~ 1057 RWM timing pulses, out of a total of 4000 markers received between 1988 March 24–April 29, were randomly picked to mimic events from a cosmic source whose period remains essentially unchanged over indefinitely long periods. In view of the known large

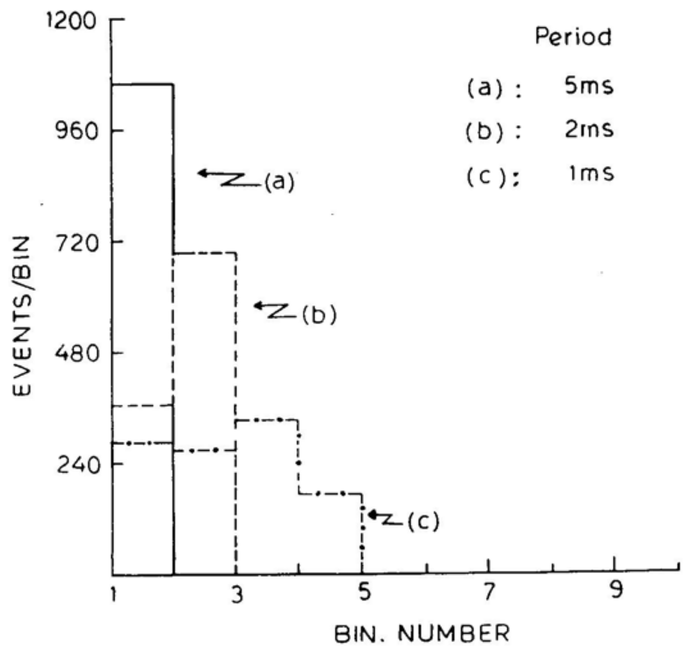

Figure 5. Phasograms derived from the simulated data. The three phase-histograms refer to representative trial periods of 5 ms (a), 2 ms (b) and 1 ms (c) respectively. For trial periods > 5 ms, the phase-histogram is expected to be identical to that shown in (a).

Second-to-second jitter that these markers can suffer in the ionosphere (unlike periodic events of cosmic origin), the selection was made randomly out of those markers for which the predicted clock error ε was within ± 150 μs of the corresponding sample mean value ⟨ε⟩. This is comparable with the error in predicting the absolute event time using RWM and will thus enable to give a realistic measure of phase smearing in our case. The times of registration of these selected events were duly corrected for. the clock error by using appropriate values for ε_0, *a* and *b* for the period 1988 March 24–April 29, and also for the propagation delay by referring to Table 2. The resulting time series was subjected to a phasogram analysis by using the relation

$$\phi(t) \sim (t - t_0)/p \quad (5)$$

where $\phi(t)$ is the phase of the event registered at the absolute time *t* as obtained above, t_0 is the time of arrival of the first event used in the analysis and *p* is the desired trial period. As the time-markers involve a basic period of 1 s, submultiple values of this period were assigned to *p* and 10-bin phasograms derived every time. Fig. 5 shows a selection of the resulting phasograms. For all periods down to 5 ms, all the events are found to line up in the same phase bin and, as expected, no phase-wandering is noticed. On the contrary, for trial periods p = 2 ms and 1 ms, the events are found to be distributed in two and four adjacent bins of a 10-bin phasogram respectively, which is indeed due to a residual error of ~ 200 μs in predicting absolute time. This simulation study thus clearly demonstrates that period searches down to 5 ms can be reliably made using the HF technique without running the risk of any phase smearing.

5. Conclusions

HF time synchronization technique offers a simple and economical way of predicting absolute time to an accuracy of ~ 200 μs over data-collection 'seasons' of at least a few months duration. This makes the method viable for conducting period searches in γ-ray and other astronomies for most species of candidate sources, including a majority of millisecond pulsars.

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