Accurate on-line frequency calibration of a rubidium standard using INSAT STFS broadcast in differential mode

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The Standard Time and Frequency Signal (STFS) broadcast via INSAT has been used to provide on-line frequency calibration traceable to the National Physical Laboratory (NPL), New Delhi. The method consists of tracking the phase of the received STFS relative to the local frequency standard. The slope of this phase variation gives the frequency offset. The actual experimental data used in this study consist of those collected simultaneously at the ERTL(East), Calcutta and at NPL. Although, individual data have sinusoidal diurnal residual errors due to satellite position prediction inaccuracy, these are mostly common mode errors that cancel in the differential mode, leading to the present high accuracy of frequency calibration of the order of a few parts in $10^{-2}$ over a measurement period of few days.

1 Introduction

The Electronic Regional Test Laboratories (ERTL) under the STQC directorate of the Department of Electronics are mostly equipped with rubidium frequency standards as the inhouse reference relative to which they perform all the frequency calibrations. To establish traceability with the national standard at the National Physical Laboratory (NPL), New Delhi, these rubidium standards are transported to NPL for frequency calibration. The method of frequency calibration used at NPL consists of tracking the phase of the 5 MHz output of the rubidium device relative to the frequency standard at NPL for about 10 days. The slope of this variation then gives the frequency offset. While this calibration arrangement gives accurate results for both short term (~few minutes) and longer (~1 day), it suffers from some basic drawbacks. First, the rubidium clocks are transported to and from NPL in shutdown or cold condition. Thus, the frequency calibrations performed at NPL are not very strictly sustained during the transportation. Secondly, the overall duration of the whole process may turn out to be about one month during which time the ERTL has to do without its frequency standard. Keeping these limitations in mind it was proposed, in 1989, to use the Standard Time and Frequency Signal (STFS) broadcast via INSAT being transmitted by NPL. Primary advantage of this method is that it would provide an on-line calibration which would remove both the above mentioned limitations. Although the INSAT STFS has operated continuously since March, 1988, frequency calibration of ERTL rubidium clocks have been performed successfully only very recently. This is due to the problems encountered with the first generation STFS receiving equipment available in the market and the prototype decoders developed at NPL for this purpose. In the present paper, we present the first results of on-line frequency calibration of the rubidium standard at ERTL(East), Calcutta, using STFS.

In the subsequent sections are discussed the INSAT STFS broadcast, explaining in particular the differential STFS concept. The basic concepts of frequency calibration are then briefly reviewed. This is followed by the experimental results and discussion on possibilities for future improvements.

2 INSAT STFS broadcast

The coded STFS are being broadcast on one of the radio networking channels of INSAT since March 1988 (Ref. 1). This service can be received all over the Indian subcontinent and can provide a
time synchronization accuracy at about 10-20 μs level.

The STFS uplink to INSAT takes place from the Delhi earth station (DES) at Sikandrabad (UP) about 70 km east of Delhi. The channel has an uplink at 5899.675 MHz and a downlink at 2599.675 MHz. The RF bandwidth of the channel is 160 kHz and baseband STFS is frequency modulated on the carrier. The format of the time code which is currently operational is shown in Fig. 1. It consists of a regular train of packets of 5 kHz sinusoids occurring at 100 pps. The packet width is binary modulated in accordance with a code that carries the time of day and instantaneous satellite position information. The data transmission takes place at the rate of 1 byte per second and the entire message takes one minute to be transmitted. The transmitted time on STFS is derived from a cesium clock at DES which is kept synchronized to the NPL's atomic time scale through periodic portable clock trips.

The receiving set-up is shown schematically in Fig. 2. A chicken mesh antenna, 8 ft or larger in diameter, with a front end converter (FEC) mounted at its feed point, is used for this purpose. The FEC has to have a noise figure of 1.5 dB or better in order to have an acceptable signal to noise ratio. The received signal is mixed with a quartz controlled LO of 2545 MHz, converting it into an IF of 54.675 MHz which is then brought through a cable to a fixed frequency FM receiver. The demodulated output of this receiver is the coded 5 kHz STFS. The decoding of the STFS is performed using a decoder...
which is microprocessor controlled and totally automatic. The basic function of this decoder is to extract accurately the 1 pulse per second (pps), decode the time of day [in Indian Standard Time (IST)] and the current satellite position coordinates. A 1 pps so obtained is, however, delayed from the transmitted IST by an amount $T_p$ equal to the sum of the propagation delays over the 'transmitter-to-satellite' and the 'satellite-to-receiver' paths and a constant receiver delay. The co-ordinates of the transmitter and the receiver are fixed and supposedly known accurately. Thus, knowing the current satellite position from the signal data it is possible to compute $T_p$ exactly. This computation of $T_p$ is done by the microprocessor in the decoder in real time and this information is fed to a programmable delay generator which then corrects for the propagation delay. The output of the decoder is, thus, a corrected 1 pps which is synchronized to the transmitted IST to an accuracy of about 10-20 µs. It has been observed that 1 pps so obtained is very stable in the short term having jitter of less than 1 µs over 1-2 minutes. However, since the actual synchronization accuracy finally obtained is only ±10-20 µs, we have a built-in time interval counter in the decoder which has a least count of only 1 µs. This then limits the precision of the synchronization measurements.

The primary cause for inaccuracy in the received time through STFS is the satellite position prediction which is carried out in the following way. The data on satellite orbit information are received from the INSAT master control facility (MCF) at Hassan every 2-3 weeks. These data are then used as input to a prediction programme to generate hourly values of the satellite position for the next 25 days and loads the results into the STFS encoder at the transmitting station. The encoder interpolates between successive hourly values to transmit updated satellite position every minute along with the STFS.

Figure 3 illustrates typical results of time synchronization using STFS broadcast as already described. The data shown in Fig. 3 are residual time errors, i.e. the difference between the NPL atomic time scale and the STFS time received and corrected for propagation delay. As the cesium clock at DES is synchronized with the NPL time scale, residuals in Fig. 3 represent inaccuracy of the STFS technique. It can be seen very clearly that when new satellite orbital information was received from MCF, for example, on day 8792, the error is significantly reduced. With passage of time, however, the satellite position prediction error and consequently the inaccuracy increases. The next input of satellite orbital data on day 8811 again reduces the error.

The above level of accuracy of time synchronization is generally adequate for most of the present users of the STFS broadcast. However, there exist a few users such as the Radio Astronomy Group of TIFR, Bombay, who would require time synchronization accuracy approaching a µs or even better. For such users we use a concept termed differential mode STFS (Ref. 4). In its basic essentials the method is simple and has been utilized with good success in the field of time transfer as common-view GPS technique and passive TV technique via satellite. It consists of the following:

The STFS time transfer is carried out simultaneously at the given station and a reference station, such as NPL, and the residual errors recorded. As observed before in Fig. 3, the inaccuracy in the time transfer is not a random jitter of the received signal, but systematic error in the form of a slow diurnal. This diurnal variation is primarily a result of slight inaccuracy of the satellite orbit modelling which results in error in the computed propagation delay. The distance of the ground stations to the satellite is nearly 40000 km compared to a maximum of about 2000 km between any station in India. Thus the ray paths from any
two stations to the satellite subtend a small angle between them and most of the error is of common mode. On subtracting the residuals recorded at NPL from those at the given station most of this common mode inaccuracy can be cancelled out.

A simple theoretical expression for the differential STFS error between two stations A and B is given by

\[ \Delta T_A(DSTFS) = \Delta T_{pA} - \Delta T_{pB} \]

\[ = \Delta T_{pA} - \Delta T_{pB} = \frac{1}{c} (\hat{r}_A - \hat{r}_B) \cdot \Delta S \]

where, \( \hat{r}_A \) and \( \hat{r}_B \) are unit vectors along the ray paths from the satellite to the receiving station A and B, respectively. It has been shown by computer modelling that generally the differential error stays within 1 \( \mu \)s over any point in India.

3 Frequency calibration

It is customary to characterize a high stability oscillator in terms of its relative frequency offset (or error), \( F \), which is defined as

\[ F = \frac{(f - f_0)}{f_0} = \frac{\Delta f}{f} \]

where, \( f \) is the frequency of the oscillator and \( f_0 \) is its nominal frequency. We note that \( F \) is a dimensionless quantity, being a ratio, and also that the \( F \) value for any frequency output obtained by multiplication, division, etc. of the base oscillator would be the same. In view of this basic definition, it is found to be convenient to determine the relative frequency offset of an oscillator by studying the 1 pps clock derived from it. If we use a time transfer technique, such as STFS, and monitor the clock drift \( \Delta t \) over a certain period of time \( T \), the average frequency offset of the oscillator is then given by

\[ \left| \frac{\Delta f}{f} \right| = \left| \frac{\Delta t}{T} \right| \]

One has to take proper care to determine the sign of the offset by noting the direction of the clock drift. A clock which gains time has a positive \( F \) and one that loses time has a negative \( F \) value. Gaining or losing time are scientifically ambiguous terms; so it is necessary to define the concepts of clock offset and drift. In algebraic notation we define the difference \( t_1 \) between a clock \( C \) and the reference clock, say NPL, at a certain time instant \( T \), as

\[ t_1 = C(T_1) - \text{NPL} \quad (T_1) \]

This expression implies that if a time interval counter is started with the 1 pps from \( C \) and stopped with 1 pps from NPL then the time interval reading is \( t_1 \). Further the drift of the clock \( C \) between times \( T_1 \) and \( T_2 \) \( (T_2>T_1) \) is \( \Delta t=(t_2-t_1) \). Depending on whether the drift \( \Delta t \) is positive or negative, (the clock \( C \) is gaining or losing time) it has a positive or negative frequency offset, respectively. The value of offset is the slope of the drift and is given by Eq.(2) with \( T=T_2-T_1 \).

4 Experimental results and discussion

The experiments on frequency calibration of the rubidium standard at ERTL(East) using STFS were carried out during 16-20 May 1994 in the preliminary phase and more extensively during 11-24 July 1994. The experimental set-ups both at ERTL and NPL were similar to that shown in Fig. 2. The rubidium standard at ERTL and the master cesium reference standard at NPL provided the local 1 pps clock time reference for the STFS decoder. The data were recorded automatically every 10 min on a serial printer.

Figures 4-6 show the observations during the preliminary phase. The x-axis is labelled in Mean Julian Days (MJD) which corresponds to the period indicated above. In Fig. 4 are shown the recordings at ERTL which were made only between 10 AM and 6 PM during this phase. What appear as large discontinuities in the slope in Fig. 4 are actually due to the fact that the residuals are parts of a sinusoidal variation as will be clear from an examination of the NPL data recorded simultaneously (shown in Fig. 5). An overall positive drift is, however, clearly visible over the whole period indicating a frequency offset. One can also see a few outliers in Fig. 4 which appear to be correlated with each other. These aberrations arise out of the receiver PLL going out of lock, once in a while, due to noise in the received signal. The lock hunting process in the receiver takes it preferentially to one side. Now, in this particular case, it is just a matter of chance that they appear correlated in Fig. 4. In Fig. 5 a small positive drift is also visible but it clearly due to the inaccuracy of the satellite position prediction.
modelling, as the clocks at DES, Sikandrabad and NPL are synchronized. Finally, in Fig. 6 we have invoked the differential STFS concept by subtracting the data in Fig. 5 from those in Fig. 4, thus eliminating most of the common mode error due to satellite position prediction inaccuracy. Barring a few outliers, all the data of ERTL(rubidium)-NPL, now fall close to a straight line indicating a linear positive drift. The slope of this drift is computed as $7.5 \pm 0.2 \times 10^{-11}$ which is the average frequency offset of the ERTL rubidium standard during this period.
Encouraged by this success, the experiment was repeated again during 11-24 July 1994. The observations for this phase are shown in Figs 7-9. For this period, the STFS monitoring at ERTL was essentially continuous and the diurnal sinusoids in Fig. 7 are very clearly apparent. Figure 8 illustrates the STFS monitoring at NPL showing again a small artificial drift, apart from gradually growing diurnal residual, due to inaccuracy in satellite position modelling. The actual drift of the rubidium clock, using differential STFS, is illustrated in Fig. 9. After recording data for one week at ERTL, during 11-18 July, they were sent to NPL by speedpost. Analysis of these data at NPL, as shown in the graph of Fig. 9 for this period between MJD 9544 and 9551, gave a frequency offset value of +6.3±0.15×10^{-11}. This
result was then communicated to ERTL. The fine frequency control of the rubidium clock was adjusted at 1600 on 20 July to reduce its frequency by this amount. The plot of Fig. 9 shows the effect of this adjustment for the subsequent period. The new value of frequency offset is now computed as $-0.3\pm0.1\times10^{-11}$. This offset was sufficiently small so that no further adjustment seemed necessary.

Certain features of the Differential STFS frequency calibration process described so far need to be elaborated. We must remember that the received STFS is also a standard frequency traceable
to NPL. Therefore, if one measures the drift of say (ERTL–STFS), then its rate should yield the value of frequency offset of the ERTL rubidium standard. The difficulty, however, lies in the fact that there are sinusoidal diurnal oscillations and, sometimes, a small drift in the clock offset (ERTL–NPL) which are artificially introduced due to inaccuracy in the satellite orbit modelling. One way to get rid of this difficulty is to take a period spanning several days so that one could fit a line through the middle of the sinusoids. This would necessitate the assumption that the frequency of the standard is constant over this period. While this is a good assumption for a high quality atomic standard, such as a rubidium or a cesium as shown in Fig. 9, it may not hold good for a crystal oscillator. Also, if the observations are not continuous but are in short segments during different times of the day, it may become difficult to fit an average line. The above difficulty is overcome by using the differential STFS concept. It is then possible to determine accurately the frequency offset even over short durations. Typical value of residual r.m.s. jitter in the differential mode with the present system hardware is about 0.5 μs. This would yield a frequency determination uncertainty of \( \approx 0.3 \times 10^{-11} \) over a one-day measurement.

A typical illustration of the nature of frequency variation of a high quality crystal oscillator is shown in Fig. 10. This is an HP crystal oscillator, belonging to Indian Telephone Industries (ITI), Naini, that was calibrated at NPL using the differential STFS. One clearly observes the irregular frequency changes during MJD 9361-63 and again around 9368. These could be due to temperature frequency changes of the environment. The outliers, seemingly bunching on one side, are explained as before due to loss of lock in the decoder PLL.

5 Summary and conclusions
In this paper the INSAT STFS broadcast by NPL and its use for accurate frequency calibration of high stability oscillators have been described. The most advantageous feature of this technique is that it can be performed on line. It has been demonstrated that by using the STFS broadcast in the differential mode it is possible to get a calibration uncertainty of a few parts in \( 10^{12} \) over a measurement period of 1-2 days. We have also performed on-line calibration of the rubidium frequency standard at ERTL(East), Calcutta, for the first time using this technique. As a result of determining the frequency offset accurately it has also been possible to set the rubidium standard frequency very close to that of NPL. This technique has also been shown to be useful for studying frequency variations of crystal oscillators.
As has been mentioned in the previous section, the r.m.s. jitter in the data is ~0.5 μs. This is not due to the actual jitter in the received signal but due to an inherent limitation of the system hardware—namely, that the built-in time interval counter has a least count of 1 μs. The resolution of the time interval counter is proposed to be improved in future to further improve the frequency calibration accuracy.

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