Ultra low cost base station timing module

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Abstract— *An adaptive frequency stabilization approach is presented which enables a low cost single oven oscillator, having an absolute frequency stability variation over temperature of 4ppb/75C and ageing rate of 1ppb/day to meet the time synchronization requirements of WiMAX and CDMA base stations during 24 hour holdover operation. It is demonstrated that for typical temperature variations experienced within the base station the local base station clock can be maintained within 1 micro-second of universal time co-ordinates for holdover time frames in excess of 24 hours. The stabilization approach enables the oscillator frequency stability to be decreased by 10 times with respect to temperature and 20 times with respect to ageing relative to incumbent solutions. Such a result is world class and has immediate cost and size benefit to the timing module. It is demonstrated that the power consumption of the base station oscillator can be reduced from that required by a DOCXO of 9.6W to that of the OCXO at 3.5W under worst case warm up conditions. In addition the supply voltage can be dropped from 12 V to 5V removing the requirement for specialized power regulation systems. Reduction in the power supply requirements results in a reduction in the overall timing module footprint enabling migration of time base circuit from a stand alone module to its integration onto the radio modem card. System simulation, control loop algorithm implementation and hardware performance results are detailed demonstrating the working validity of the approach for next generation wireless base station timing modules.***

I. Base Station Time Syncronization Requirements

WiMAX and CDMA base transceiver stations are required to be time synchronous with respect to radio system time (RST). In code division multiple accesses (CDMA) time synchronization is used to provide a time offset between base stations that enables the mobile to carryout a soft hand off. In WiMAX time division duplex operation of the base stations requires synchronicity of transmission and reception in order to respect the minimum transmit receive time guard band specification.

Time synchronization of wireless base stations is commonly achieved through phase lock to a 1 pulse per second (1pps) signal from a satellite based time server, such as GPS (global positioning system). Base station synchronization requirements are specified with respect to the locked and holdover modes. In locked mode the 1pps time base of both WiMAX and CDMA base stations must have a time offset relative to RST no greater than +/-1us [1],[2].

Holdover mode is entered when the phase lock to the satellite time reference is interrupted. In holdover mode CDMA radio systems 1pps must not exceed +/-10µs time error over an 8 hour time period relative to RST [1]. WiMAX radio systems do not have a standardized time error but a number of +/-25us over an 8 hour period is an initial target.

The holdover specification drives the stability requirement of the base station timing module oscillator. The 1pps time error Δt relates to the stability of the oscillator Δf/fo and the time duration for which the stability errors is maintained through (1).

$$\frac{\Delta t}{T} = \frac{\Delta f}{fo} \tag{1}$$

Applying (1) to the CDMA time synchronization error of +/-10µs or the holdover duration of 8 hours leads to a maximum permissible static frequency error of the time base oscillator of +/-0.35ppb. In order to meet the stability specification over the 75^{o}C operating temperature of the timing module a double oven crystal oscillator is typically employed. As the frequency stability requirement becomes more stringent the cost, size and power consumption of the time base oscillator increase. It is possible to reverse this trend through the application of adaptive modeling of the base station clock oscillator during locked operation and then use of the resultant model during holdover to compensate for the oscillator frequency drift.

It is the focus of the present paper to demonstrate that a simple adaptive modeling approach based on the least squares fit can be used to compensate a single oven crystal controlled oscillator sufficiently to meet the 8 hour CDMA and WiMAX holdover specifications. It is further shown that by enabling single oven oscillator technology the physical size and power management of the resultant timing solution is reduced allowing integration of the resultant timing module onto the base station modem card resulting in significant cost saving.

Section II describes the timing module system. Section III details the digital control loop. In section IV the adaptive control algorithm is developed. Simulated performance for the control algorithm is presented in section V. Measured performance of the implemented module is presented in section VI. Section VII summarizes the performance and cost benefits of the resultant system.

II. TIMING MODULE SYSTEM

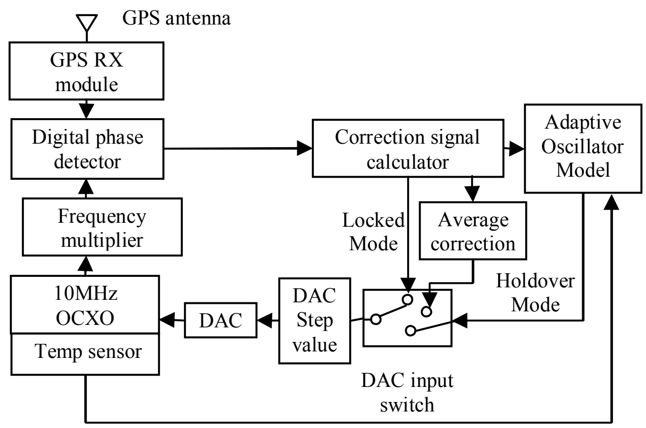

Figure 1. Block diagram of the Timing Module System

Fig. 1 illustrates the component parts of the base station timing module. A GPS receiver module provides a 1pps reference to the digital phase detector. The digital control loop which includes the phase detector, correction signal calculator and the adaptive oscillator model is resident on a field programmable gate array (FPGA) which contains an embedded processor. The digital phase detector uses an input clock generated from multiplication of the 10MHz reference oscillator to count between the rising edges of the 1pps signal from the GPS receiver module. A correction signal is calculated from the count value and applied to a digital to analog converter (DAC) to control the OCXO. The adaptive oscillator model is fed to the correction signal and the OCXO ambient temperature collected via a temperature sensor.

The key element of the timing module is the 10MHz crystal oscillator which is locked to the 1pps output of a GPS receiver module via the digital control loop. Table 1 compares the key performance parameters of the incumbent DOCXO and the single oven OCXO enabled by the control algorithm. An important benefit of the lower cost oscillator is that it enabled the power management for the oscillator to be cost and size reduced allowing the timing module to transition from a standalone module to being integrated onto the base station modem card.

TABLE I. INCUMBENT AND ENABLED OCXO TECHNOLOGY

Component parameter	***Incumbent DOCXO***	***Algorithm Enabled OCXO***
DC supply requirement	+12V	+5V
DC power consumption warm up	9.6W	3.5W
Peak to peak frequency stability over operational temperature ppb/75^{o}C	0.4ppb	4ppb
Ageing ppb/24hours	+/-0.05ppb	+/-1ppb
Dimension (L x W x H)/mm	50 x 50 x 38	25.4 x 25.4 x 12.7
Cost in volume 10K / USD	~$250	~$50

III. DIGITAL CONTROL LOOP

The correction signal generated by the control loop represents the frequency stability dependence of the OCXO on both the crystal ageing and temperature. It was found in the present work that the 8 hour holdover could be achieved by modeling just the OCXO frequency stability dependence on temperature. The crystal ageing rate decreases logarithmically with time leading to the error in the temperature based model due to ageing decreasing with time.

The digital control loop generates the OCXO frequency control signal by counting between edges of the GPS receiver 1pps. Count time resolution is achieved by frequency multiplication of the 10MHz OCXO output. If the OCXO has zero frequency drift then the digital phase detector outputs a count equal to the multiplied OCXO frequency +/- an error count, where the error count represent the GPS receiver noise. Typical GPS receivers introduce between 20 and 30ns rms jitter onto the 1pps edge. The underlying drift trend of the OCXO appears as a bias on the mean count value. The control loop uses a moving average filter to separate the OCXO drift trend from the RMS noise of the GPS receiver. The error count is multiplied by the digital phase detector resolution to generate the time error each second between the received GPS 1pps and the OCXO. The time error is integrated in the control loop code creating what is termed the cumulative time error (CTE).

$$CTE_k = CTE_{k-1} + \text{count time resolution x error count} \quad (2)$$

The correction signal used to control the OCXO results from a blending of the CTE and a moving average of the correction signal in accordance with (3).

$$\text{Correct} = \text{correct\_ref} - CTE_k/\text{damp} \quad (3)$$

The correct_ref term operates to provide an equilibrium point about which the CTE acts. In the initial closure of the control loop the damping factor , ‘damp’, is set to a value of 1, as a result there is no suppression of the GPS receiver noise. Once the absolute CTE has dropped below a threshold value the damping term is increased resulting in reduction of the RMS noise of the GPS receiver transferred to the correction signal.

The correction signal is applied to the OCXO using a DAC. The DAC resolution is the ratio of the control voltage range to the number of DAC steps. The correction signal is converted to a number of DAC steps using the OCXO tuning sensitivity, (Kvco), expressed in ppb/volt. Division of the correction signal by Kvco gives the voltage to be applied to the tuning port of the OCXO. Division of the tuning voltage by the DAC resolution provides the number of DAC steps which is converted to a binary control word to the control DAC. The resultant expression for calculation of the DAC steps is:

DAC_steps = round {(correction)/(Kvco*DAC_res)} (4)

Initially the Kvco of the OCXO is not known. Kvco is determined by the control loop prior to lock by applying a frequency step to the OCXO based on a nominal estimate for the Kvco. Based on the nominal Kvco the number of DAC steps is calculated and applied to the DAC. The control voltage resulting from the applied steps is calculated.

The digital phase detector output is a measure of the frequency stability offset applied as a result of the Kvco calibration step. Since the applied tuning voltage and change in stability are now known Kvco can be accurately calculated and used in place of the initial estimate.

IV. ADAPTIVE CONTROL ALGORITHM

The OCXO frequency stability exhibits dependencies on crystal ageing and temperature.

The adaptive control algorithm operates in a training mode whilst the timing module is locked to the satellite timing signal. In training a straight line fit is applied to the temperature and correction signal data. A linear fit is possible because crystal oven constrains the crystal temperature variation to a small range about the turnover point of the crystal.

A linear equation is advantageous with regards to OCXO frequency prediction in that errors accumulate slowly over the holdover time as compared to higher order polynomials.

The correction signal contains the GPS receiver noise. Application of a least squares fit (LSF) [3], [4] is used to determine the coefficients of the straight line equation that optimally relates the temperature to the correction signal. The OCXO model equation to be fitted to the correction signal and temperature data is of the general form:

$$\mathbf{y_i} = \mathbf{a_2} \cdot \mathbf{x_i} + \mathbf{a_1} \quad , \tag{5}$$

Where the ‘i^{th}’ frequency stability readings of the OCXO are represented by:

$$\mathbf{y_i} = \frac{\Delta \mathbf{f}}{\mathbf{f_o}} \, , \tag{6}$$

and the ‘i^{th}’ temperature sensor reading is represented by:

$$\mathbf{x_i} = \mathbf{Temp_i} \tag{7}$$

The LSF algorithm operates to minimize the summation of the square of the residuals. The summation of the square of the residuals, ‘r_i’, is expressed as:

$$S = \sum_i \left(\frac{r_i}{\sigma_i} \right)^2 \tag{8}$$

The term ‘σ_i’ represents the standard deviation of the ‘i^{th}’ data point from the mean of the data set, mathematically expressed as:

$$\sigma_i = \bar{y} - y_i \tag{9}$$

Use of the standard deviation reduces the impact of outliers on the curve fit by decreasing the weighting on large residuals. It was found in this work that the data set size and consistent correction signal noise meant that equal weighting could be applied to all data without loss of model accuracy, consequently ‘σ_i’ was set to unity.

Substitution of (5) into (8) results in the following expression (10) for ‘S’ in terms of the required model coefficients, ‘a_1’ and ‘a_2’.

$$S = \sum_i \left(\frac{y_i - (a_1 + a_2 \cdot x_i)}{\sigma_i} \right)^2 \tag{10}$$

Setting the partial derivatives of (10) with respect to the coefficients ‘a_1’ and ‘a_2’ to zero results in (11) and (12).

$$\frac{\partial S}{\partial a_1} = 0 = \sum_i -2 \left(\frac{y_i - (a_1 + a_2 \cdot x_i)}{\sigma_i} \right) \tag{11}$$

$$\frac{\partial S}{\partial a_2} = 0 = \sum_i -2 \cdot x_i \left(\frac{y_i - (a_1 + a_2 \cdot x_i)}{\sigma_i} \right) \tag{12}$$

Letting,

$$S_1 = \sum_i \frac{1}{\sigma_i^2} \tag{13}$$

$$S_x = \sum_i \frac{x_i}{\sigma_i^2} \tag{14}$$

$$S_y = \sum_i \frac{y_i}{\sigma_i^2} \quad (15)$$

$$S_{xx} = \sum_i \frac{x_i^2}{\sigma_i^2} \quad (16)$$

$$S_{xy} = \sum_i \frac{x_i \cdot y_i}{\sigma_i^2} \quad (17)$$

$$\Delta = S_1 \cdot S_{xx} - S_x^2. \quad (18)$$

Expanding expressions (11) and (12) results in (19) and (20).

$$-2\sum_i \frac{y_i}{\sigma_i^2} + 2 \cdot a_1 \sum_i \frac{1}{\sigma_i^2} + 2 \cdot a_2 \sum_i \frac{x_i}{\sigma_i^2} = 0 \quad (19)$$

$$-2\sum_i \frac{x_i \cdot y_i}{\sigma_i^2} + 2 \cdot a_1 \sum_i \frac{x_i}{\sigma_i^2} + 2 \cdot a_2 \sum_i \frac{x_i^2}{\sigma_i^2} = 0 \quad (20)$$

Substitution of (13) to (18) into (19) and (20) results in the required expression (21) and (22) for the coefficients 'a_1' and 'a_2'.

$$a_1 = \left(S_y S_{xx} - S_{xy} S_x\right) / \Delta \quad (21)$$

$$a_2 = \left(S_1 S_{xy} - S_x S_y\right) / \Delta \quad (22)$$

The coefficient 'a_1' represents the linear fit constant and the coefficient 'a_2' represents the thermal sensitivity of the crystal resonance frequency.

The crystal oscillator ageing was specified by the manufacturer to be 1ppb per day. Assuming a linear ageing rate described by the equation:

$$\left(\frac{\Delta f}{f_o}\right)_{age} = m_{age} \cdot t \quad (23)$$

Where m_{age} is the frequency stability change per second of $1.157\text{x}10^{-5}$ppb/sec. Integration of (23) with respect to time gives the required expression for the cumulative time error (24) in terms of the ageing rate and holdover time.

$$CTE = \frac{1}{2} m_{age} \cdot t^2 \quad (24)$$

Substitution of the OCXO ageing rate, $1.157\text{x}10^{-5}$ppb/sec, and the 8 hour holdover time into (24) results in a cumulative time error of 4.8us Fig.2. illustrates the relationship between the ageing frequency drift rate and the CTE.

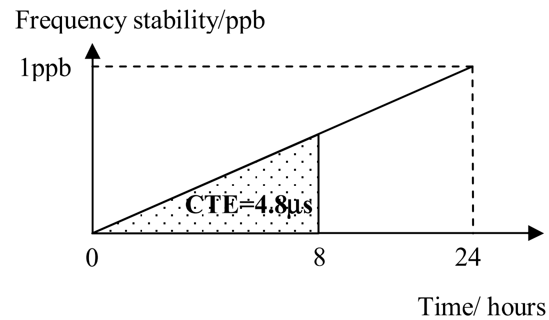

Fig. 2 Calculation of timing error resulting from idealized oscillator ageing rate of 1ppb/day.

The CTE calculated for the ageing process fell well within the WiMAX target specification of 25us in 8 hours and also within the CDMA holdover specification of 10 microseconds in 8 hours, consequently an ageing model was not implemented in the control algorithm.

A flow diagram depicting the operation of the adaptive control algorithm is illustrated in Fig.3. The buffers which store the values of the running sums (13) to (17) required for calculation of the least squares fit are periodically initialized to zero to prevent numerical overflow errors. The LSF algorithm is considered to have converged to a sufficiently accurate level for holdover when a predetermined change in ambient temperature is met. In addition to the ambient temperature range requirement the extracted 'a_2' coefficient must fall within a preset range. Once both the aforementioned conditions are met the solution is considered valid for use during holdover. In the event that holdover is entered the most recently calculated model coefficients are used.

The control algorithm detailed in the current paper is protected by US patents 6,711,230 and 7,015,762.

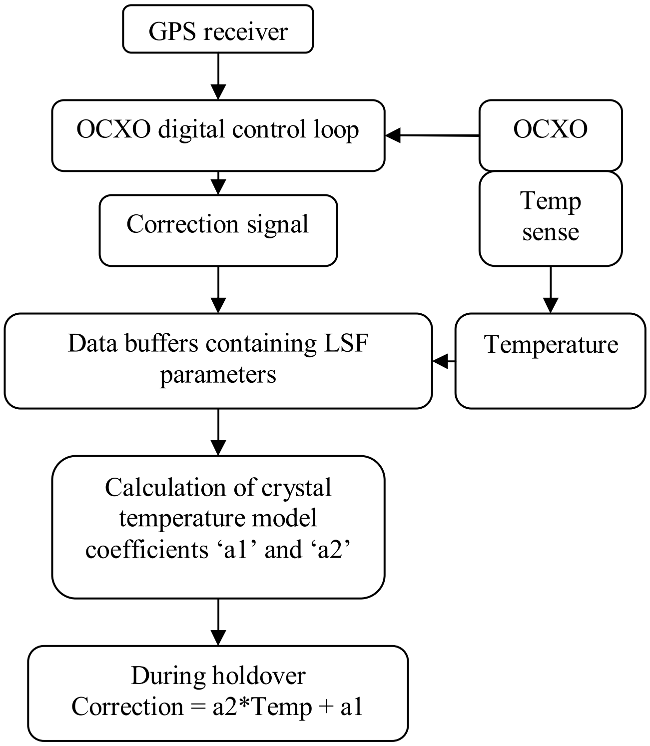

Fig.3 Flow diagram for adaptive control algorithm

V. Simulation of Control Algorithm

In order to confirm correct operation of the algorithm a software test platform was developed. The test platform contained an idealized model for the OCXO containing a linear frequency dependence on temperature and linear frequency dependence on ageing. The ageing and temperature rates were selected based on manufacturers’ data for the selected OCXO of 4ppb/ 75C and 1ppb per day respectively. The software test bed was designed to be toggled between locked and holdover modes to enable the least squares fit algorithm to train and then correct the oscillator model. A second oscillator model was run in parallel with the first to demonstrate the impact of not using the control algorithm during the holdover. Integration of the frequency stability of the corrected and uncorrected OCXO frequency stability enabled the cumulative time error to be plotted in both cases.

An estimate of the thermal environment internal to the modem card was incorporated as a test vector into the simulation test bed and is graphed in Fig. 4.

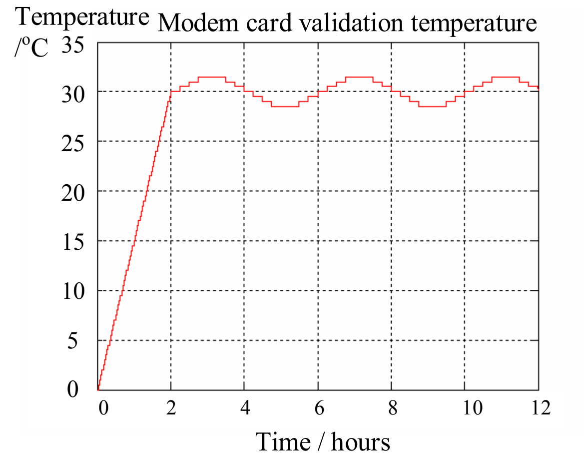

Fig. 4 Estimated temperature profile experienced in modem card as a result of cooling fan cycling

The graph of Fig. 5 shows the simulated least squares fit of the temperature model to the correction signal data. The solid line passing through the data points is the least squares fit.

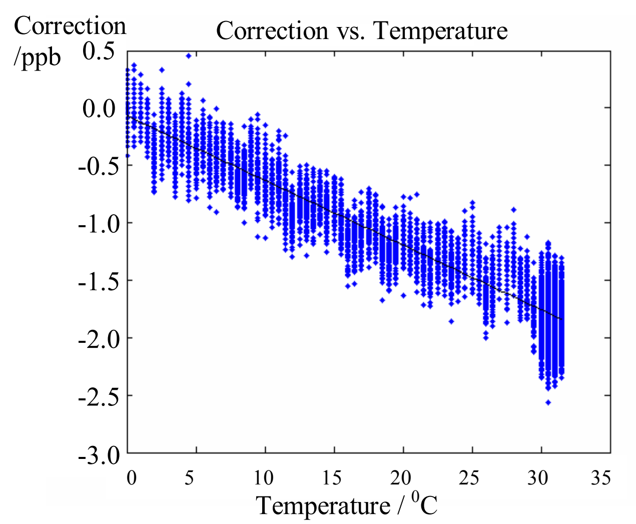

Fig.5 LSF to data solid line passing through the data points

Fig. 6 is a graph of the simulated CTE resulting from the holdover in the case of the corrected and uncorrected oscillator models.

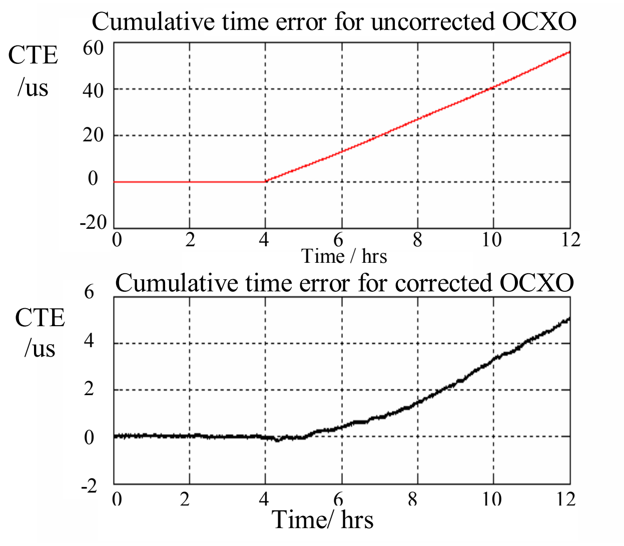

Fig. 6 CTE for corrected and uncorrected OCXO during locked and holdover mode. Holdover initiated at 4 hours.

The simulation results indicated that the algorithm would meet the original target specification of +/-25µs in 8 hours as required by WiMAX and +/-10µs over 8 hours as required by CDMA without requirement to correct for the ageing drift of the oscillator. The results also showed that the algorithm provided a 10 fold improvement in the timing error over the uncorrected oscillator.

VI. Measured Timing Module Performance

The timing module was integrated onto the radio modem card. The even second output from the timing module was measured against a GPS referenced 1pps. The measurement setup is detailed in Fig.7.

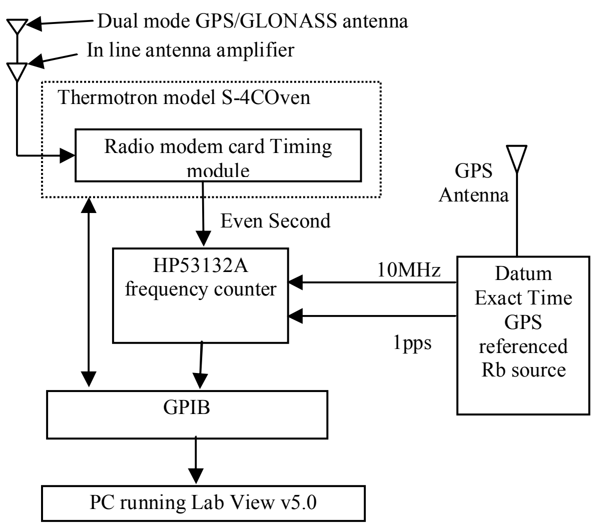

Fig. 7 Radio modem timing module measurement set up.

The cumulative time error of the timing module was measured against a GPS locked 1pps reference. In order to exercise both locked and holdover modes the GPS derived 1pps signal was disabled through software command. The typical modem card temperature profile was employed. The cumulative time error measured for the timing module is graphed in Fig.8.

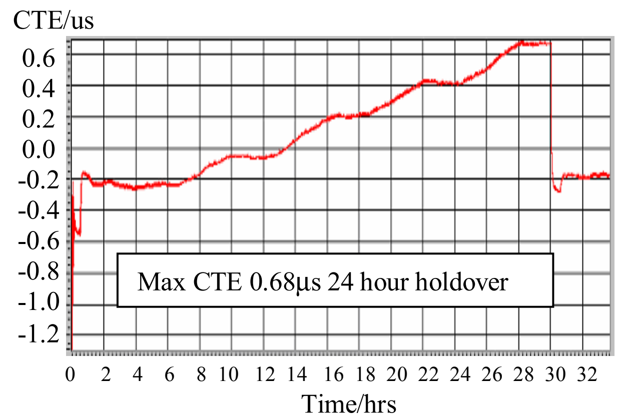

Fig. 8 Measured CTE for timing module integrated onto radio modem card. Holdover initiated at 6 hours.

The measured CTE for the module was 0.68us with respect to GPS time over a 24 hour period indicating the effectiveness of the LSF adaptive algorithm.

VII. Conclusions

It has been demonstrated that the frequency stability of a low cost single oven crystal oscillator can be accurately modeled using a standard least squares fit algorithm. The model accuracy has been shown sufficient to maintain the oscillator within 0.68us of GPS time for the duration of a 24 hour holdover period whilst experiencing a temperature fluctuation typical of the radio modem card under fan cooling. The cost benefit of the approach arises both from the lower cost of the crystal oscillator and also the lower cost of the power regulation circuitry.

Aknowledgments

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References

[1] "Recommended Minimum Performance Standards for cdma 2000 Spread Spectrum Base Stations,"3GPP2 Standard C.S0010-C, release C, version 2, release data February 24, 2006.

[2] IEEE Std 802.16e-2005, IEEE Standard for Local and Metropolitan Area Networks, Part16: Air Interface for Fixed Broadband Wireless Access Systems, Amendment 2: Physical and Medium Access Control Layers for Combined Fixed and Mobile Operations in Licensed Bands, and Corrigendum 1.

[3] "Numerical Recipes in C: The Art of Scientific Computing," Cambridge University Press, pp657-661

[4] J.M.Powers, "Method of Least Squares,"University of Notre Dame, February 2003, unpublished.