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Comparative Analysis of OCXO Stability with reference to H-Maser for Frequency Stamping in VLBI Observations

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ABSTRACT: This report presents a comparative study on the stability of the OCXO (Oven Controlled Crystal Oscillator) with reference to H-Maser for frequency stamping in VLBI observations. Currently, GMRT utilises H-Maser for precise frequency stamping. Our goal is to integrate 15 m antenna at NCRA with GMRT for VLBI observations, using OCXO for frequency stamping at NCRA antenna.

KEYWORDS: OCXO, H-Maser, frequency stamping

1 INTRODUCTION

1.1 Background

Very Long Baseline Interferometry (VLBI) plays a vital role in achieving high-resolution observations by combining data from multiple radio telescopes spread across vast distances. A key requirement for the VLBI observations is the precise frequency stamping of the received signals. We need good clock performance for coherence and correlator synchronization. We require frequency stamping for several key reasons:

- **Phase Stability:** VLBI Observations relies on the precise measurement of the phase differences between signals received at different radio telescopes. Frequency stability ensures that the reference signal used to measure these phase differences remains consistent over time. Any instability in the frequency reference can lead to phase errors, which in turn degrade the quality of the interferometric data.
- **Signal Coherence:** Frequency instability can cause the signal to drift, leading to a loss of coherence. This loss of coherence can result in reduced signal-to-noise ratios and affect the accuracy of the final astronomical measurements.
- **Calibration and Data Processing:** Accurate calibration of the received signals against a stable frequency reference allows for the correction of various instrumental and atmospheric effects. Unstable frequencies can complicate this calibration process, leading to less accurate corrections and poorer quality final data.

1.2 Motivation

We aim to integrate the 15 m antenna at NCRA with the GMRT for VLBI observations. At the L-band (1000 MHz - 1420 MHz), the 80-km baseline between the GMRT and the 15 m antenna can achieve an angular resolution three times better than the full GMRT array.

Currently, the GMRT uses Hydrogen Masers (H-Masers) for frequency stamping. However, we are exploring the use of Oven Controlled Crystal Oscillators (OCXOs) at the 15 m NCRA antenna. OCXOs are known for their good short-term stability and are significantly more cost-effective compared to H-Masers. By assessing the feasibility of using OCXOs for frequency stamping, we hope to maintain high precision in VLBI observations while potentially reducing costs and simplifying maintenance.

Our goal is to determine if OCXOs can meet the stability requirements needed for VLBI, making them a viable alternative to H-Masers.

1.3 Objective

To assess the suitability of OCXO for this application, we conducted a comparative study to evaluate its stability with reference to the H-Maser. This study aims to address the following questions:

1. How much is the delay w.r.t frequency of OCXO?
2. How much is the delay w.r.t time of OCXO?
3. Verify Phase Closure for M1-M2-O1 combination.

2 DESIGN AND SET UP OF THE EXPERIMENT

2.1 Experimental Design

To test the stability of OCXO in comparison to H-Maser we designed an experiment utilizing two Reconfigurable Open Architecture Computing Hardware (ROACH) boards. An Analog-to-Digital Converter (ADC) operating at 300 MHz was used, and a signal with a bandwidth of 37.5 MHz was fed into the input of the ROACH boards. The H-Maser reference signal was connected to the clock input of ROACH0, while the OCXO reference signal was connected to the clock input of ROACH1.

A noise generator was employed to introduce noise into the system; which was then amplified using a power amplifier, to ensure that the ADC gets the sufficient noise power. The amplified noise passed through a series of filters: first a 100 MHz low pass filter, and then a 16 MHz low pass filter. The filtered noise was then transmitted to a 4-way splitter, which divided the input noise into four identical outputs, each with one-fourth of the original power.

These four noise outputs were labeled as two polarizations for each reference: Maser (M1, M2) and OCXO (O1, O2). Two of these outputs were fed into the inputs of ROACH0 (Maser reference), and the remaining two were fed into the inputs of ROACH1 (OCXO reference).

The GMRT Time and Frequency System (FTS) was used to generate the master time and frequency standards for the GMRT Receiver system, providing signals at 10 MHz, 1 pulse per second (pps), and 1 pulse per minute (ppm). This system was utilized to provide the 1 pps reference necessary to initiate data recording. The baseband raw voltages were recorded onto dual NVMEs installed in the recording machine.

2.2 Apparatus

ADC (Analog-to-Digital Converter), ROACH Boards, H-Maser, OCXO (Oven Controlled Crystal Oscillator), Noise Generator, Power Amplifier, Low Pass Filters (100MHz and 16MHz), 4-way power splitter, GMRT Time and Frequency System, Dual NVMEs.

2.3 Procedure

1. **Signal Preparation:** The experiment began by feeding a 37.5 MHz bandwidth signal into the input of the ROACH boards. An ADC operating at 300 MHz was used to process this signal.
2. **Clock Reference Setup:** The H-Maser reference signal was connected to the clock input of ROACH0, while the OCXO reference signal was connected to the clock input of ROACH1.
3. **Noise Introduction:** A noise generator introduced noise into the system. This noise was amplified using a power amplifier to ensure sufficient power levels.
4. **Noise Filtering:** The amplified noise was passed through a 100 MHz low pass filter followed by a 16 MHz low pass filter to refine the noise signal.
5. **Signal Splitting:** The filtered noise was transmitted to a 4-way power splitter, dividing it into four identical noise outputs. Each output had one-fourth of the power of the original noise signal.
6. **Labeling and Distribution:** The four noise outputs were labeled as two polarizations for each reference: Maser (M1, M2) and OCXO (O1, O2). Two of these outputs (M1, M2) were fed into the inputs of ROACH0 (Maser reference), and the other two (O1, O2) were fed into the inputs of ROACH1 (OCXO reference).
7. **Time Synchronization:** The GMRT Time and Frequency System provided the 1 pps reference signal to initiate data recording, ensuring synchronization across the system.
8. **Data Recording:** The baseband raw voltages were recorded onto dual NVMEs installed in the recording machine.

3 DATA ANALYSIS

The raw data recorded was loaded into the environment as a NumPy array. Given the two-hour duration of data collection, with data points recorded every second, a total of 7200 data points were obtained.

- Time Array: A time array was generated to represent the time in hours for each data point. This array facilitated the temporal analysis of the recorded data.
- Frequency Array: A frequency array was created to represent the frequency components of the data. This was achieved using the `np.fft.rfftfreq` function, which generates an array of sample frequencies based on the data length and the sampling rate.
- Correlation: The next step involved processing two files simultaneously. Fast Fourier Transform (FFT) was performed on the data at every second across the two-hour duration for both files. The cross-power spectrum was computed by multiplying the FFT of the first file with the complex conjugate of the FFT of the second file. This computation was averaged over all samples and stored in a new NumPy array. The combinations used are : M1-O1, M2-O2, M1-M2, O1-O2, M2-O1.
- Phase Correction: The initial phase offset was corrected by multiplying with the complex exponential of the negative initial phase.
- Plots: The processed data was plotted to visualize the results. The graphs of Amplitude vs Frequency and Phase vs Channel have been plotted for all the combinations.

4 QUANTITIES ANALYSED

4.1 Delay Rate with Time

From the plot of Phase, the delay at each 1-second timestamp is calculated within the channel range of $750 - 1250$. These delays are then plotted against time to obtain the Delay vs Time function. The slope of this plot reveals how the delay varies over time. The graph is plotted for the combinations: M1-O1 and M2-O2. Below are the plots for the mentioned combinations.

4.2 Delay wrt Frequency

From the plot of Phase, the delay at each channel is calculated for the first 4500 seconds of observation $\sim 1.5hrs$. These delays are then plotted with frequency to obtain the Delay vs Frequency Funtion. The slope of this plots reveals how the delay varies over frequency. The graph is plotted for the combinations: M1-O1 and M2-O2. Below are the plots for the mentioned combinations.

4.3 Phase Closure

Phase closure is the property where the sum of the phases around a closed loop of three (or more) baselines is zero (or a constant value), modulo 2π. This property is derived from the fact that phase errors due to instrumental and atmospheric effects are largely canceled out when considering the phase differences around a closed triangle of baselines. To ensure the accuracy of our calculations, we verified the phase closure property for the combination of M1-M2-O1 at $9\ MHz$ and $1000\ MHz$.

5 FINDINGS

5.1 Results

The results are based on comparing Maser with respect to OXCO. We found the following results from the quantities analysed:

1. Delay Rate with Time:

   M1-O1: $-1.668 \times 10^{-08} \pm 3.544 \times 10^{-11} \quad seconds/hour$

   M2-O2: $-1.668 \times 10^{-08} \pm 3.542 \times 10^{-11} \quad seconds/hour$

2. Delay wrt Frequency:

   M1-O1: $-3.697 \times 10^{-06} \pm 5.195 \times 10^{-10} \quad Hz/MHz$

   M2-O2: $-3.699 \times 10^{-06} \pm 7.277 \times 10^{-10} \quad Hz/MHz$

5.2 Discussion

Our analysis reveals that the OCXO exhibits a drift relative to the H-Maser at a rate of approximately $17\ ns/hr$. Additionally, with respect to frequency, the OCXO drifts at a rate of approximately $3.7\ \mu Hz/MHz$. This drift must be accounted for in real VLBI observations to ensure the accuracy and reliability of the frequency stamping.

Beyond the drift rates, we observed notable trends in the phase versus time plots when looked at individual channel. We focused on the 900th, 1000th, and 1100th channels and found that the phase follows a consistent trend over time. The trend is observed before and after the inital phase correction. We suspect this trend is likely due to ADC quantization effects and floating point precision limitations. However, the variations are at the order of $1/100th$ of degree. We can safely neglect these variations. The plots are shown below.

Furthermore, our results show a noticeable phase at t=0 for both the Maser (M1-M2) and OCXO (O1-O2) combinations. For M1-M2, phase is $-36.56°$ at $10\ MHz$. For O1-O2, phase is $-37.63°$ at $10\ MHz$. We attribute this initial phase difference to variations in the cable lengths used in the experimental setup.

Additionally, we noticed an abrupt change in the delay vs. time plot between $1hr\ 24min$ and $1hr\ 36min$. The cause of this anomaly is unclear, and we are uncertain about its significance and the reasons behind its occurrence.

6 CONCLUSION

The OCXO demonstrates potential as a viable alternative to the H-Maser for frequency stamping in VLBI observations. While it does exhibit some drift and minor phase variations, these can be managed with proper calibration and correction techniques.

References

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