Frequency stability of the H-maser in Santa María

J. González-García
j.gonzalez@oan.es

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Revision history

Version	Date	Author	Updates
1.0	10-04-2020	J. González	First version

List of acronyms

TIM Time Interval Measurement

DPS Difference Per Second

TEF Time Error Function

DDS Direct Digital Synthesizer

AVAR Allan Variance

ADEV Allan Standard Deviation

OADEV Overlapping Allan Standard Deviation

Contents

1 Review of the measurement setup

The maser monitoring system is based on a Time Interval Measurement (TIM) of the elapsed time between two events: the rising edge of a 1 Hz TTL signal crossing over a specific threshold for two independent signals, one generated by the GPS receiver (1PPS_GPS) and a second one by the atomic clock at the station (1PPS_MASER). Traditionally, the former signal is connected to counters' channel A whereas the maser is connected to channel B[1]. A typical setup scheme is showed in figure1.

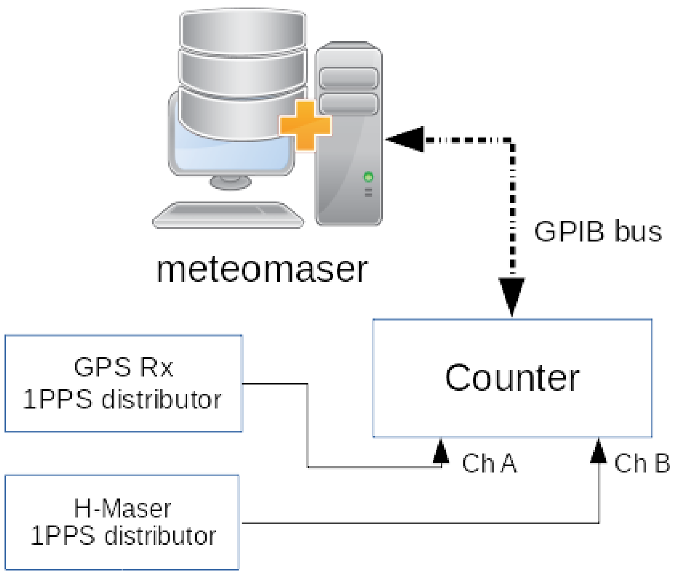

Figure 1: *Typical measurement setup.*

The measurement is configured to be triggered by channel A and stopped by the event on channel B so the counter is actually measuring the time offset between both signals. This is the value known as Difference Per Second (DPS). Whenever the frequency of the 1PPS_GPS signal is slightly higher than the 1PPS_MASER the signal on channel A ticks earlier than that at channel B and the difference is positive and near to 0. Otherwise the 1PPS_MASER would tick before, and the counter will show a reading that is near to 1 because it will have to wait almost a full period to stop the measurement. Nevertheless the monitoring software will convert this measurement in a negative value by subtracting 1 from the measurement.

Whenever the slope of the DPS over time is positive the signal starting the measurement have higher frequency. For this reason we call the measurement GPS-MASER, although there is still some controversy about this.

The DPS is measured every second, but only one sample is logged each ten minutes. The recorded data is stored in a MySQL database for further analysis. See [1] for more details.

[1]There is no convention across the VLBI community

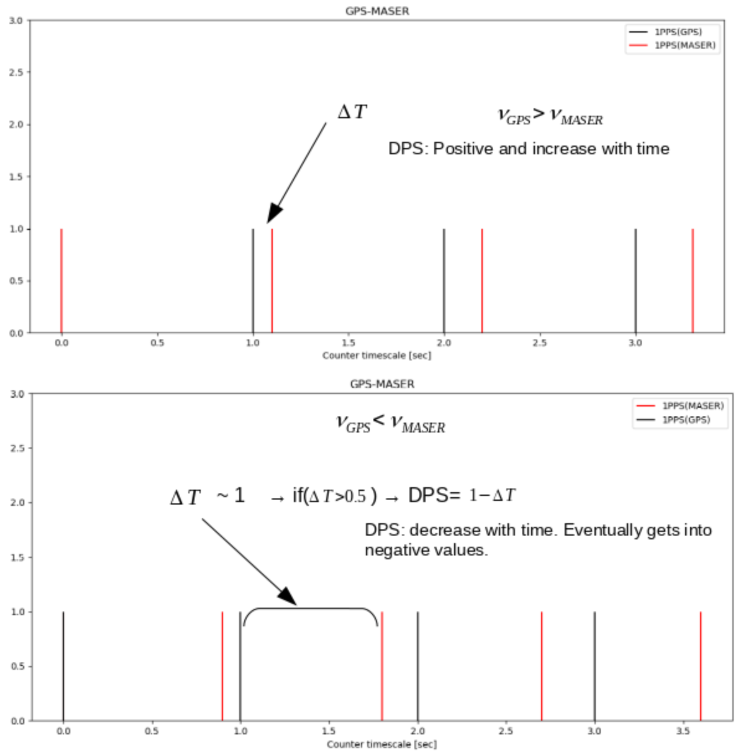

Figure 2: *Different DPS evolution with time.*

2 Visual inspection of the DPS data from 2020

The visual inspection of the DPS data from 2020 (figure 3) immediately shows that there was only one synchronization event on MJD = 58919 (11/03/2020). This is consistent with the expectations based on available information. The “GPS-maser” offset was 290.574 usec before the synchronization, and decreased to a value of 0.177 us after that. Typical phase samples using TIM have a strong linear dependency on time, like is the case here. This is caused by the frequency offset between the two oscillators. To study this, the first thing to do is to perform a linear regression over the data available, but before that, one would like to remove as jumps and gaps as possible. As noticed before, there is a clear jump which is determined to be 290.397 usec. Other data corruption effects, like small gaps might not be visible in a full snapshot if the spanned time is high or the phase drift very steep. For that kind of errors is better to use a prepocessing algorithms. In this study up to sixteen sample slips were found. Since most of them only affect to one sample, a simple interpolation by with Once the jump is removed we can try a linear fit over the full timeline (93.42 days).

As can be seen in figure 4, the data points perfectly adjust to a straight line with a slope of 3.33e-12 sec/sec. A new gap that was not visible in the previous plot has appeared at MJD=58861, it is even more evident because the fit is failing at that point. Analyzing the files it was discovered that more than 24 hours of data is missing between "2020-01-12 09:40:00" and "2020-01-13 16:00:00" (180 samples). Other than that, there are a few other samples missing, but not long time sequences. Figure 5 reflects a list of detected missing samples.

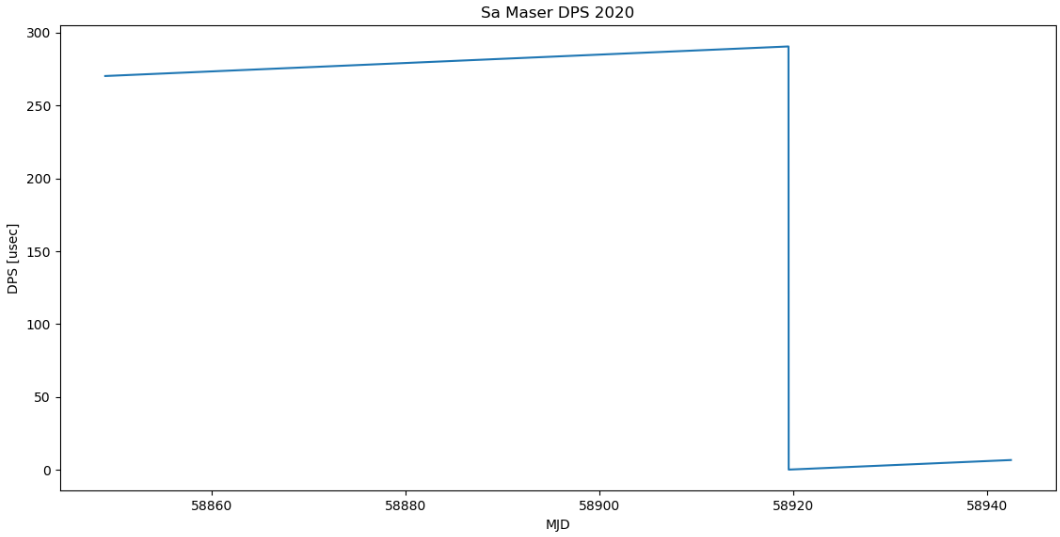

Figure 3: *Raw DPS data from 2020*

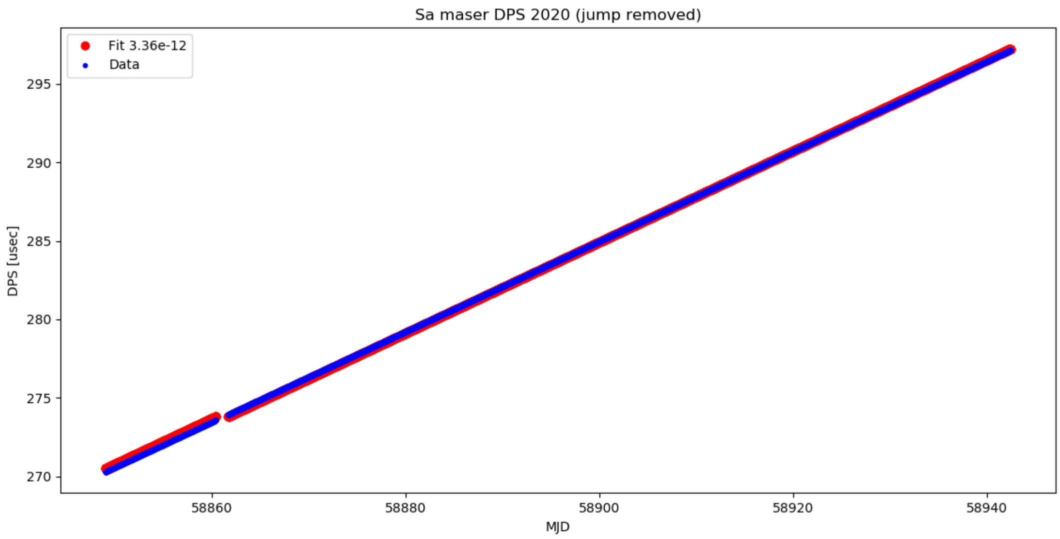

Figure 4: *Linear fit to the DPS data after removing the synchronization jump. Notice the gap near MJD=58860 that is now visible after changing the y domain range.*

```
Detected          missing          data          between:
[1642]    58860.4028    58861.6667    DeltaT    =    1820    [minutes]
[1771]    58862.5556    58862.5694    DeltaT    =    20    [minutes]
[2440]    58867.2083    58867.2222    DeltaT    =    20    [minutes]
[2646]    58868.6458    58868.6597    DeltaT    =    20    [minutes]
[4409]    58880.8958    58880.9097    DeltaT    =    20    [minutes]
[5076]    58885.5347    58885.5486    DeltaT    =    20    [minutes]
[7701]    58903.7708    58903.7847    DeltaT    =    20    [minutes]
[9818]    58918.4792    58918.4931    DeltaT    =    20    [minutes]
[9961]    58919.4792    58919.5    DeltaT    =    30    [minutes]
[10151]    58920.8125    58920.8264    DeltaT    =    20    [minutes]
[10159]    58920.875    58920.8958    DeltaT    =    30    [minutes]
[10698]    58924.6319    58924.6458    DeltaT    =    20    [minutes]
[10989]    58926.6597    58926.6736    DeltaT    =    20    [minutes]
[11106]    58927.4792    58927.4931    DeltaT    =    20    [minutes]
[12994]    58940.5972    58940.6111    DeltaT    =    20    [minutes]
```

Figure 5: *List of missing samples detected in the preprocessing.*

The sample slip case, where only one or two samples are missing, can be tricked by the artificial generation of data using k-neighbour averaging. Here a value of k=10 was used. A more complex problem is caused by long gaps in the time domain, because the introduction of artificial samples will conduct to some significant bias in the variance analysis, potentially conducting to wrong conclusions. Luckily, the only big gap in this data set is at the beginning so one can just discard all the data up to that point and still have a good amount of samples. This is the preferred approach because there is no biasing on the solution. For illustrative reasons, a second analysis will be showed in this report using the original data set with artificial samples introduced in the gap. The method for interpolation is another big question with no concrete solution and it is outside of the scope of this report. A linear fit was the chosen approach because it is simple and won't introduce any random component in the set. Looking at the raw data set the only visible effect (apart from gaps and jumps) in linear dependency of the DPS samples with time. This is the typical aspect of the TIM frequency stability analysis samples. The linear increment of time differences indicates that there is a frequency offset between the DUT and the reference. This is the "clock rate" value that is estimated by the correlator to maintain a zero-delay in the "fringe-stopping" stage. Typical clock rates within the IVS stations are in the order of 10^{-13}, with a few stations in the 10^{-12}. To correct the clock rate we need to tune the maser. Note that synchronization and syntonization are different concepts, since the former has no effect in correcting the frequency offset between two time scales in comparison. The T4Science EOFUS-C maser syntonization is explained in the OAN's technical document IT-OAN-2010-1 and in the User Manual.

3 Oscillator's phase noise model

A frequency source has a sine wave output signal given by:

$$v(t) = [V_o + \epsilon(t)]sin[2\pi\nu_o t + \phi(t)] \tag{1}$$

where

- V_o = nominal peak voltage
- $\epsilon(t)$ = amplitude deviation
- ν_o = nominal frequency
- $\phi(t)$ = phase deviations

For analysis of frequency stability we are concerned primarily with $\phi(t)$ term. The instantaneous frequency is the derivative of the total phase with time:

$$\nu(t) = \nu_o + \frac{1}{2\pi}\frac{d\phi(t)}{dt} \tag{2}$$

the fractional frequency error is defined as:

$$y(t) = \frac{\Delta f}{f} = \frac{\nu_o - \nu}{\nu_o} = -\frac{1}{2\pi\nu_o}\frac{d\phi(t)}{dt} = -\frac{dx(t)}{dt} \tag{3}$$

where x(t) is the Time Error Function (TEF). This the function that is being measured by the DPS values. It can be modelled as a two-order polynomial with the initial time offset T_o, the fractional frequency offset $\frac{\Delta\nu}{\nu}$, and the frequency drift D as coefficients, plus noise, a mean-zero process.

$$x(t) = T_o + \frac{\Delta\nu}{\nu}t + \frac{1}{2}Dt^2 + \sigma_x(t) \tag{4}$$

4 Frequency offset

In the previous sections we have seen that the long term time error is dominated by a linear drift, so let's ignore the quadratic term in (4) for now and assume that there is no time dependency on the frequency of our oscillators.

Consider the phase difference between two signals at slightly different frequencies separated by and initial phase offset given by:

$$\phi(t) = 2\pi\nu_o t - 2\pi(\nu_o + \Delta\nu)t + \phi_o = -2\pi\Delta\nu t + \phi_o \tag{5}$$

since we measure phase in time units, i.e., the TEF:

$$DPS = x(t) = \frac{\phi(t)}{2\pi}T_o = -\frac{\Delta\nu}{\nu_o}t + \frac{\phi_o}{2\pi}T_o \tag{6}$$

Clock rate is by definition the derivative of phase difference (in time) with time. Since we have assumed that there is no frequency dependency on time, we get to the same result as in (3).

$$\frac{\Delta\nu}{\nu_o} = -\frac{x(t)}{t} \tag{7}$$

The fractional frequency correction that we need to introduce in the atomic clock is just the 3.33e-12 sec/sec coefficient that we have obtained before. The next section deals with the technical detail on how to apply this correction.

5 Frequency syntonization

The T4Science EOFUS maser incorporates a programmable Direct Digital Synthesizer (DDS) in a phase-locked loop scheme that allows the user to compensate a frequency error in the signal coming out of the cavity (F_{out}). Modifying the frequency of this synthesizer (ν_{synt}), a relative frequency offset can be introduced in the output frequency. According to the maser's user manual, the output frequency of the maser at the front panel (5 MHz OCXO signal) is related to the synthesizer frequency under the lock condition, through the following relation:

$$\nu_o = \nu_{ocxo} = \frac{1}{284}(F_{out} - \nu_{synt}) \tag{8}$$

Since the OCXO frequency is a linear combination of the cavity frequency and the synthesizer, a relative output frequency offset produced by a synthesizer frequency step $\Delta\nu_{synt}$ is given by:

$$\frac{\Delta\nu_o}{\nu_o} = -\frac{\Delta\nu_{synth}}{284 \cdot \nu_o} = -\frac{\Delta\nu_{synth}}{1.42 \cdot 10^9} \tag{9}$$

According to the maser's User Manual, the synthesizer resolution (1 LSB) corresponds to a maser frequency resolution of:

$$dF_{mas} = \frac{5 \cdot 10^6}{2^{39}} = 9.09495 \cdot 10^{-6} Hz \tag{10}$$

The value for the main synthesizer frequency \$FM is stored in the first four bytes of a certain register. There is a reference value, \$FM0 that corresponds to the maser line frequency $F_{mas0} = 1420'405'571.00 Hz$ and allows the calculation of the current maser frequency through the equation:

$$F_{mas} = F_{mas0} + (\$FM - \$FM0) \cdot 9.09495 \cdot 10^{-6} \tag{11}$$

We are looking for the frequency offset:

$$F'_{mas} = F_{mas} + \frac{\Delta\nu}{\nu_o} \cdot F_{mas0} \tag{12}$$

substituting (11) in (12):

$$F_{mas0} + (\$FM - \$FM0) \cdot 9.09496 \cdot 10^{-6} + \frac{\Delta\nu}{\nu_o} \cdot F_{mas} = F_{mas0} + (\$FM' - \$FM0) \cdot 9.09496 \cdot 10^6 \tag{13}$$

and finally

$$\$FM' = \$FM + \frac{\Delta\nu}{9.09496 \cdot 10^6 \cdot \nu_o} \cdot F_{mas} \tag{14}$$

Equation (14) indicates that to get the new value for \$FM we need to read the current value of \$FM and calculate the actual output frequency. According to [3] (section 11.1) the relation between the offset in the output frequency and the offset in the synthesizer's frequency includes a sign swapping (equation 9), so the final formula for \$FM' is:

$$\$FM' = \$FM - \frac{\Delta\nu}{9.09496 \cdot 10^6 \cdot \nu_o} \cdot F_{mas} \tag{15}$$

Fortunately, the user does not need to care about all the previous details. There is a Python script written by P. de Vicente [2] that does all the calculations and communicate with the maser through the Python API *maser.py* under the maser's code directory */home/maser/maser/imaser37*. When executing the script, the user is asked to introduce the correction value, which is the measured slope in the DPS over time plot.

5.1 April 7th tuning

The figure 6 shows the console dialog for the correction performed on April 7th. The $FM register with the current synthesizer frequency is the first value in blue after the status parameters. The actual maser frequency is calculated with the decimal format of this value and returned in Hertz units. A discrepancy between the theoretical value and the number returned by the script has been detected. Doing the algebra in (11) the current value for the maser frequency obtained is 1420405751.7000928 Hz, so there is a difference of 1.4 Hz. At this level the discrepancy does not affect the $FM' calculation because there is a 10^7 factor and the $FM register only allows integers, but it could be a problem for higher frequency offsets.

```
raege@meteomaser:/home/maser/maser/imaser37$ ./correctMaser.py 3.36e-12
Connecting to the maser ...
Do you want to see all current parameters y/[n]) ? y

[27.534480000000002, 0.057387, 28.02268, 2.6068350000000002, 4.98032, 1.443222, 0.6507930000000001, 0.39194100000000004, 2.424906
, 6.943626, 8.193674, 8.667325, 10.903739, 10.830494, 12.578608000000001, 9.150742000000001, 11.445752, 40.00799, 0.223443, 23.00
364, 5.328703, 7.093546, 3.5347950000000004, 8.4249, 3.5347950000000004, 7.0818, 4.10172, 14.1918, 12.0554, 23, 9.762891999999999
, 4.991845, 24.903299999999998, 15.23535, -16.4073, 5.35122, 0, 8.43696, 18.126160000000002, 2, 1]

['63226438', 1420405750.2999072, 1663198264, 50, 192, 7, 199, 44, 50, 230, 7, 202, 16, 'N']

Current Frequency Synthesiser freq.: 63226438  (hex)
Current Maser frequency: 1420405750.299907  Hz
New Frequency Synthesiser freq. to apply: 63226645  (hex)
Do you want to apply this correction 3.36e-12 y/[n]) ? y
Applying the correction ...
  Frequency Synthesiser freq. after the correction: 63226645  (hex)
  Maser frequency after the correction: 1420405750.295132  Hz
raege@meteomaser:/home/maser/maser/imaser37$ █
```

Figure 6: *Screeshot of the console dialog during the first syntonization attempt.*

According to the usage instructions of the correction script in [2], the fractional frequency as the slope of DPS versus time must be given as the parameter in the command line execution. Therefore the software needs as input the fractional frequency correction. The document alerts the reader to check if the correction was applied in the right direction. Since the drift is so small (0.25 usec/day), a few days later the offset was checked again, finding that it was almost exactly twice the previous value (see figure 7). So the correction was added with the wrong sign.

Inside the code of *correctMaser.py* there is a call to the *computeFrequencyCorrection()* function (line 47) defined in the *maser.py* library. This routine is used to compute the $FM' value (line 344). The formulae used is (14) whereas the author believes (15) should be used, if the script receives the frequency correction.

5.2 April 11th tuning

After confirming the sign swapping, a second syntonization was done on April 11th. The console dialogue is shown in figure 8. This time the correction was successful and the offset was removed.

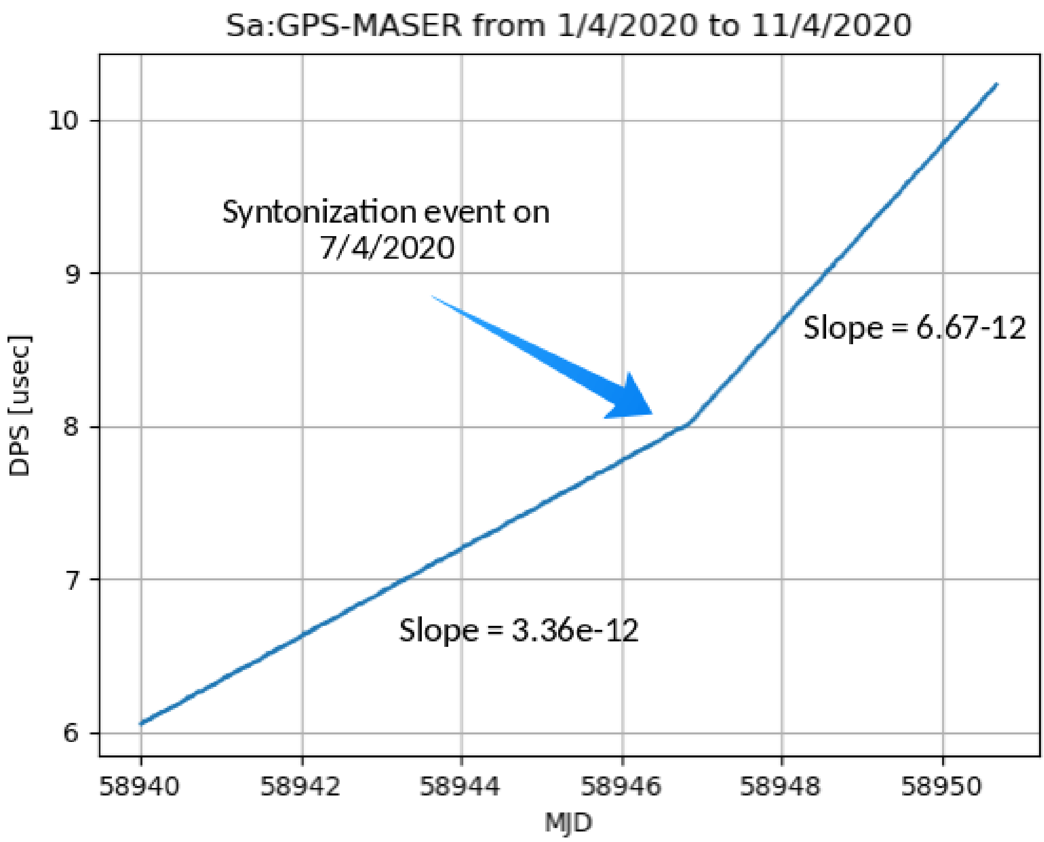

Figure 7: *DPS evolution before and after the first syntonization attempt.*

```
raege@meteomaser:/home/maser/maser/imaser37$ ./correctMaser.py -6.67e-12
Connecting to the maser ...
Do you want to see all current parameters y/[n]) ? n
Current Frequency Synthesiser freq.: 63226645  (hex)
Current Maser frequency: 1420405750.295132  Hz
New Frequency Synthesiser freq. to apply: 63226233  (hex)
Do you want to apply this correction -6.67e-12 y/[n]) ? y
Applying the correction ...
  Frequency Synthesiser freq. after the correction: 63226233  (hex)
  Maser frequency after the correction: 1420405750.304609  Hz
raege@meteomaser:/home/maser/maser/imaser37$
```

Figure 8: *Screenshot of the console dialog during the second syntonization attempt.*

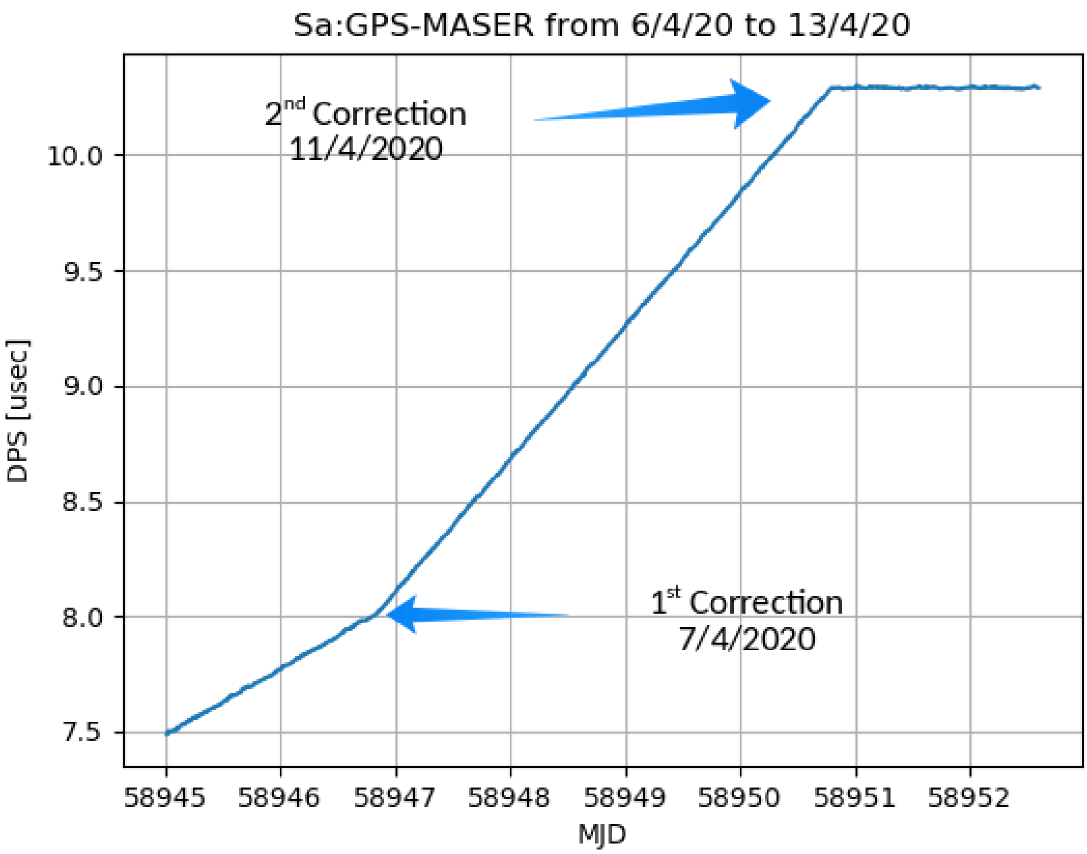

Figure 9: *The two syntonization events in the DPS plot.*

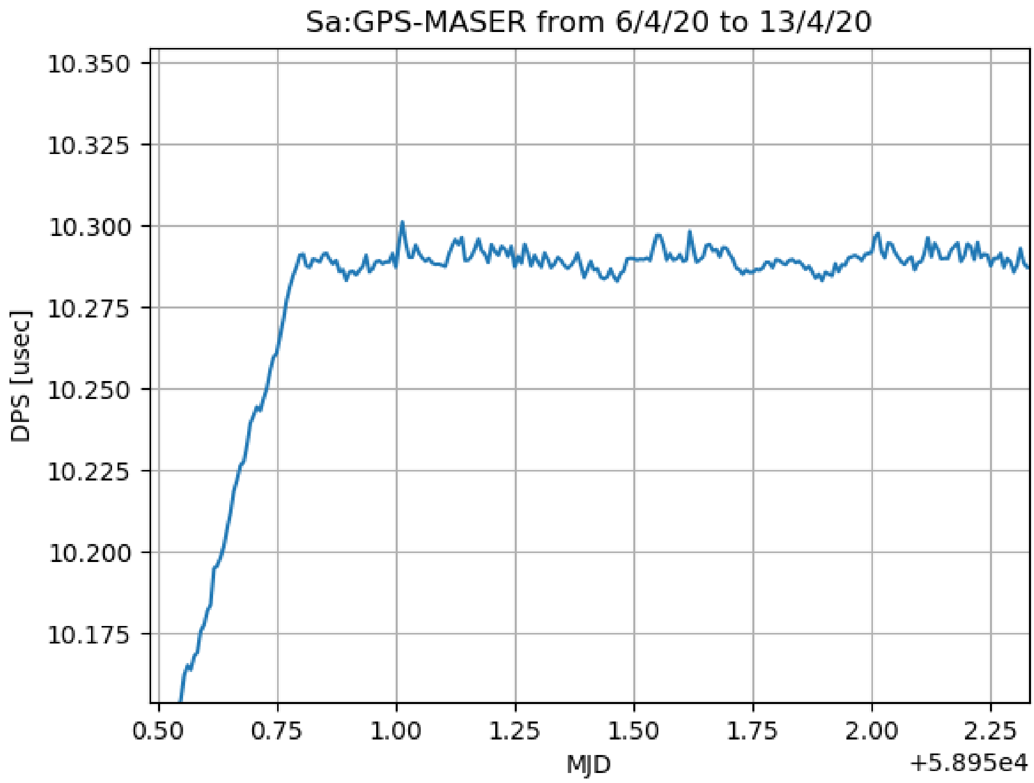

Figure 10: *Syntonization on April 11th removed the frequency offset. Without the linear term, the noise becomes more evident.*

6 Frequency stability

The most common tool to study frequency stability in oscillators is the Allan Variance (AVAR). This statistical estimator is mean to characterize the random frequency fluctuations to the exclusion of all systematic effects in any stochastic processes, avoiding the problem of no convergence that affects the typical dispersion estimators in stochastic processes . The AVAR is therefore unresponsive to the linear term of the phase difference measurements, but not to the higher order deterministic components like the frequency drift. The Allan variance is defined as:

$$\sigma_y^2 = \frac{1}{2} E\{(y_{k+1} - y_k)^2\} \tag{16}$$

where y_k is the k-th sample of the fractional frequency increment in the period τ. Considering ν_o as the oscillator nominal frequency:

$$y_k = \frac{\nu_k[Hz] - \nu_o[Hz]}{\nu_o[Hz]} \tag{17}$$

y_k can also be computed from phase $\phi(t)$ [rad] or time error function samples x(t) if these quantities are measured instead of the average frequency over tau.

$$y_k = \frac{1}{\tau} \int_{t_o+(k-1)\tau}^{t_o+k\tau} y(t)dt = \frac{1}{\tau}[x(t_o + k\tau) - x(t_o + (k-1)\tau)] \tag{18}$$

Both the time error function x(t) [s] and the phase noise process $\phi(t)$ [rad] are defined as the integral of the instantaneous frequency process y(t). Only units are different.

$$x(t) = \frac{\phi(t)}{2\pi\nu_o} = \int_0^{t_o} y(t)dt \tag{19}$$

The Allan Standard Deviation (ADEV) is defined as the square root of the AVAR, and it is one of the ITU recommendations for frequency stability specifications in oscillators (ITU-R TF.538-4).

We have computed the ADEV with the available data. It must be noticed that this is not the Allan deviation for the DUT itself but for the reference + DUT combination since we are using a so called *Transfer Standard*, the GPS timescale. The $1/2$ factor in (16) accounts for the case when two similar clocks are used for comparison, which is not exactly the case here. Nevertheless, GPS timescale is considered to be a good reference for long integration times. Since the phase noise of the GPS receiver is several orders of magnitude bigger than those of the maser due to the proper radio signal propagation in free space, for small integration times the plot will be dominated by this white noise, whereas as τ increases the maser frequency variance would become dominant as we approach the long term stability of the GPS timescale. From our experience, typical Allan deviation curves for a GPS receiver and a H-maser typically meets at the level of 10^{-14} at $\tau = 10^6$ seconds, after the maser has reached its noise floor (FM flicker noise).

The initial ADEV estimation (figure 11) gave shocking results, with levels one order of magnitude greater than those expected for atomic clocks. In view of this results, a more detailed

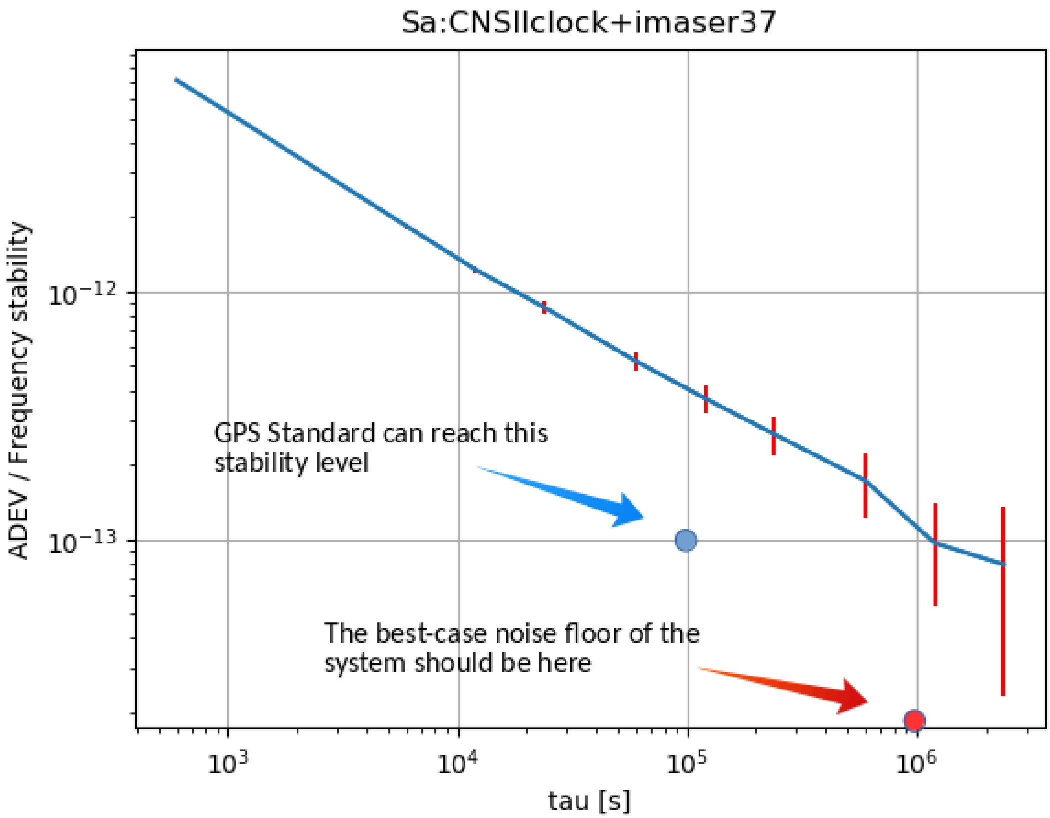

Figure 11: *ADEV plot for the EFOS C maser at Santa María.*

inspection of the data was made, and finally the gap between the 12th and 13th of January was discovered.

The confidence level (1σ) of the ADEV estimate can be roughly calculated as $\frac{1}{\sqrt{M}}100\%$ where M is the number of fractional frequency samples used in the calculation for any specific integration time. Since our data spans for about 92 days, the confidence level at $\tau = 10^6$ is $\approx 40\%$, too bad to be trusted.

A variation of the ADEV that is more used is the Overlapping Allan Standard Deviation (OADEV). By using a moving window that overlaps by n samples with the previous calculation more fractional frequency samples can be obtained thus reducing the uncertainty. The overlapping Allan variance for time samples is defined as:

$$\sigma_y^2(n\tau_o, N) = \frac{1}{2n^2\tau_o^2(N-2n)} \sum_{i=o}^{N-2n-1} (x_{i+2n} - 2x_{i+n} + x_i)^2 \tag{20}$$

The following figure helps to illustrate the difference between both methods.

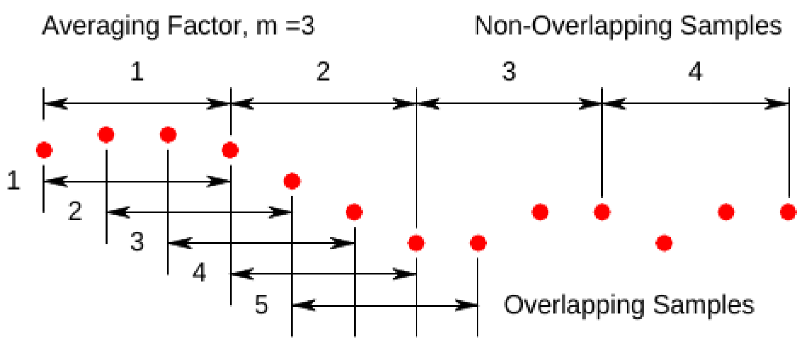

Figure 12: *OADEV versus OADEV sample pool.*

With this method the confidence level for long τ is considerably higher.

In the preprocessing stage we have discovered a big gap in the data set. Two different approaches to cope with this issue were presented there, data reduction or sample interpolation. Following, the results of the OADEV analysis for this two methods are presented.

6.1 Data reduction

This scenario only uses samples from "2020-01-13 16:00:00" towards the end, so we are loosing 15% of the full data. Recommendations for frequency stability analysis ([4]) also include the removal of systematics in the data, specially the frequency drift (quadratic term in (3) because the Allan variance does not converge for high taus when the drift is present. The first data point is at position 1643 in the original data array. The linear regression shows the expected slope and removing the frequency offset we can see a quadratic curve, which is typical of the frequency drift term.

If we apply a quadratic regression to the DPS residuals, only the random components are left. Notice that over a full smooth variation, a sort of discontinuity is visible around

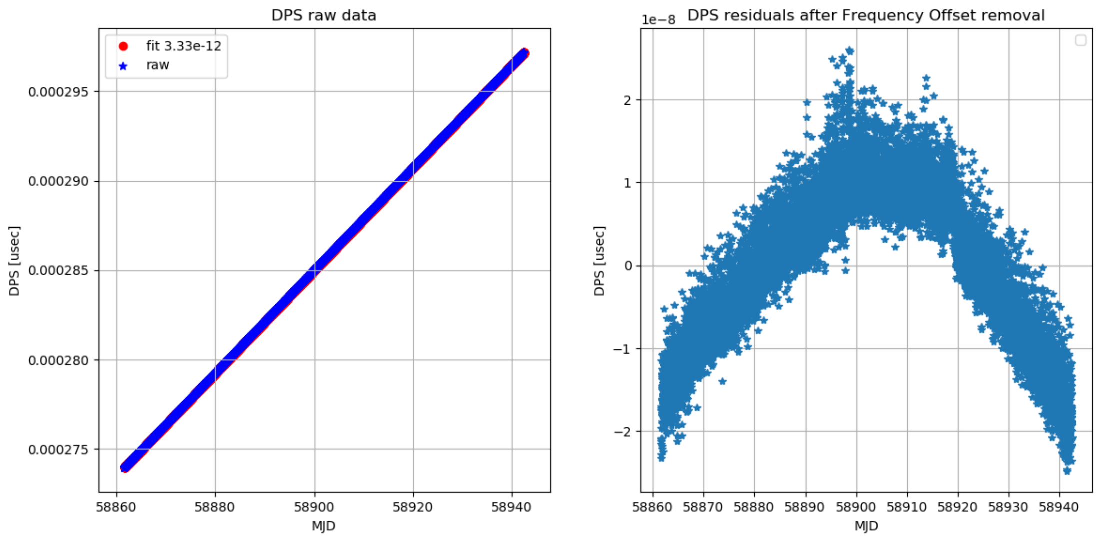

Figure 13: *Linear regression for reduced data set.*

MJD=58920. Probably this is produced by the jump correction, which wasn't perfect. For long term frequency analysis is preferable not to have synchronization events in the data.

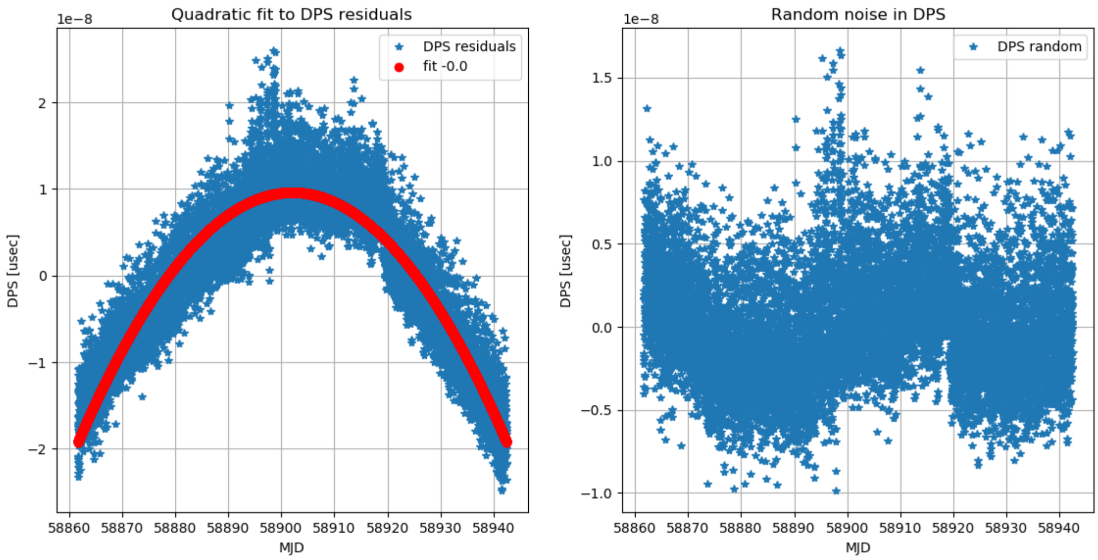

Figure 14: *Quadratic regression to residuals of the reduced data set.*

In the OADEV plot we have included three traces. The blue (raw data) and orange (linear regression residuals) reach the noise floor at $\tau \approx 10^6$ because the drift was not removed, whereas the variance of only the random component continue to decrease. It must be taken into consideration that this set only contains 79 days of data, and for integration times $\tau \approx 10^6$ there are only 6 fractional frequency samples completely independent.

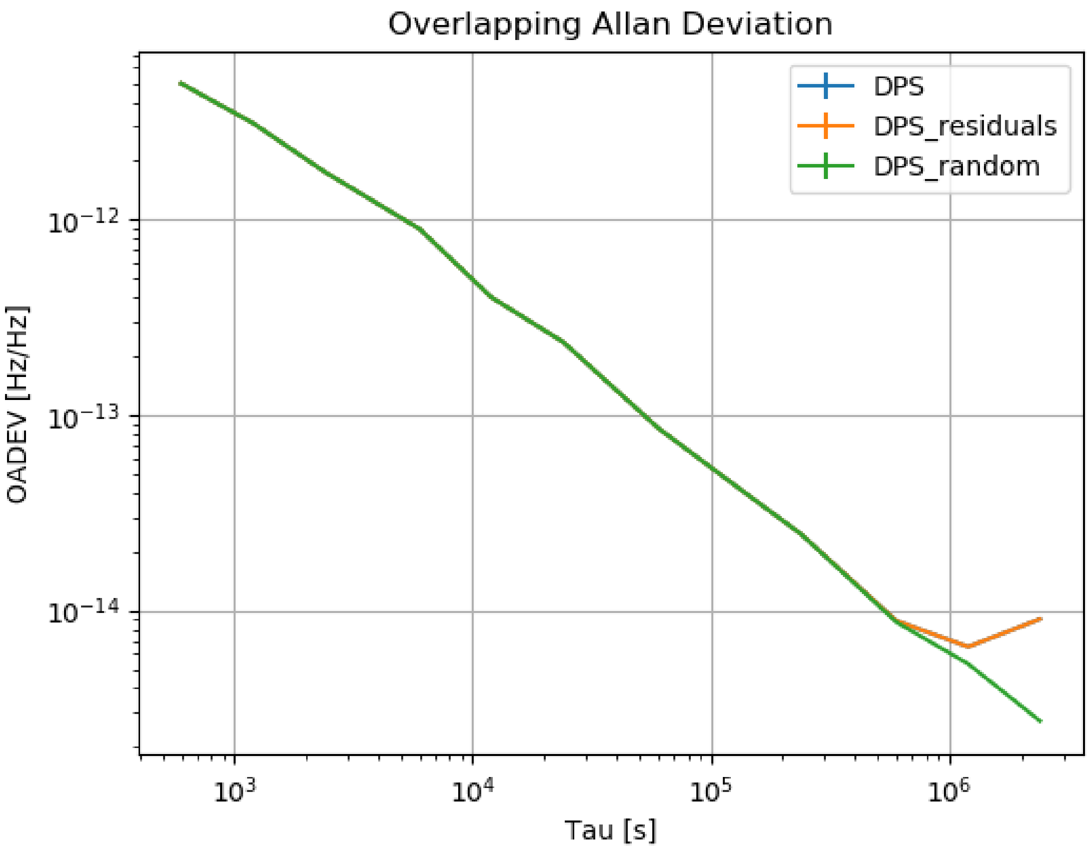

Figure 15: *OADEV for reduced data set.*

6.2 Linear interpolation

The OADEV results for the modified data set through linear interpolation inside the gap are included in the comparison plot (figure 18). Both methods show a good level of agreement, although there are some minimal differences. When the drift is present the reduced data set increase faster after reaching the noise floor (it could be a consequence of having less samples). On the other hand, without any deterministic effect, the reduced data decrease below the other set. We think this is because the quadratic regression is less accurate in the latter because of the linear interpolation. Note that the noise component in figure 17 show two discontinuities, the synchronization jump and the gap.

7 Maser status parameters

The monitoring system keeps a record of the parameters status in a database that is updated once per hour. All the monitoring parameters (see Table in section 12 from the user manual) have been reviewed and confirmed that are inside their nominal range. No alarm conditions were detected. The following plots were selected to be included in this report because they correspond to the most important parameters in the proper performance of the atomic clock. All the plots have a colorbar that indicates the nominal range (green) and alarm condition (red).

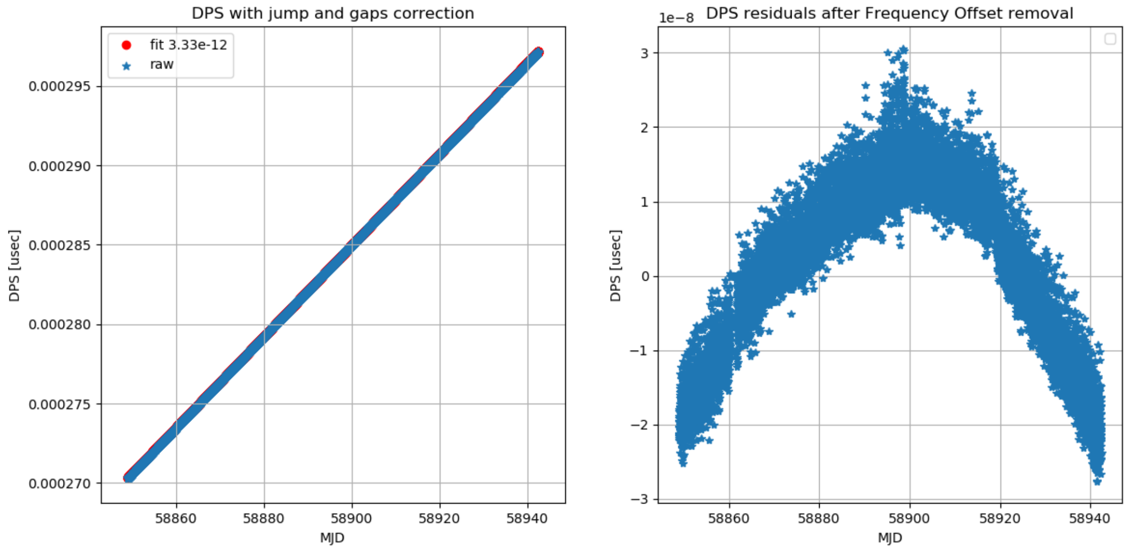

Figure 16: *Linear regression for interpolated data set.*

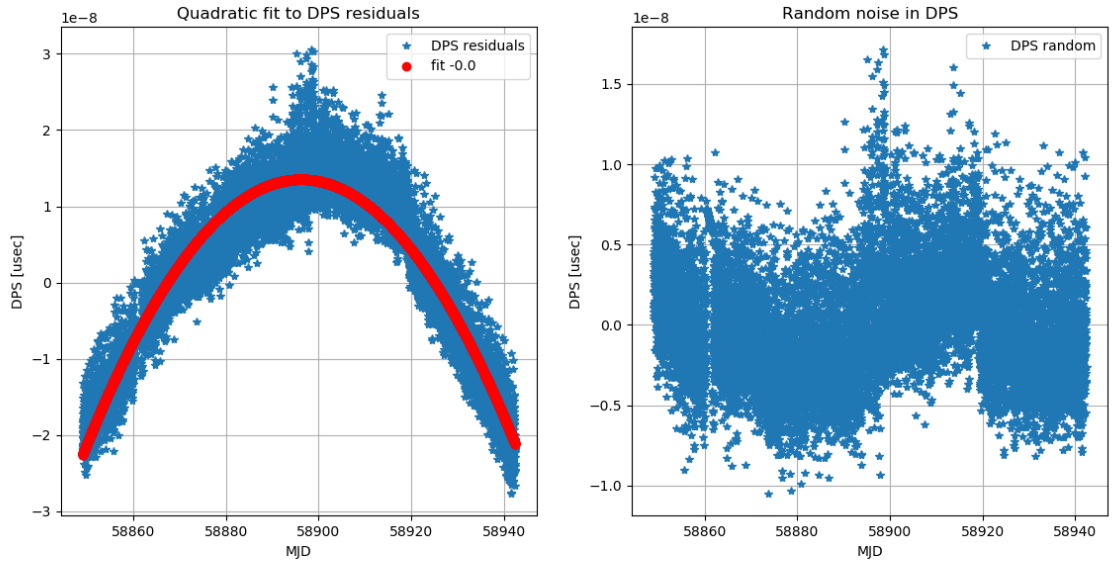

Figure 17: *Quadratic regression to residuals of the interpolated data set.*

In the colorbar it is also indicated the last stored value.

7.1 Power (mains and batteries)

During nominal operation the maser is powered in parallel by the AC line (channel B) and the UPS (batteries) (channel A). DC voltage from the AC line in adjusted to be slightly larger than the UPS line, so the system drains current from the site's main AC line.

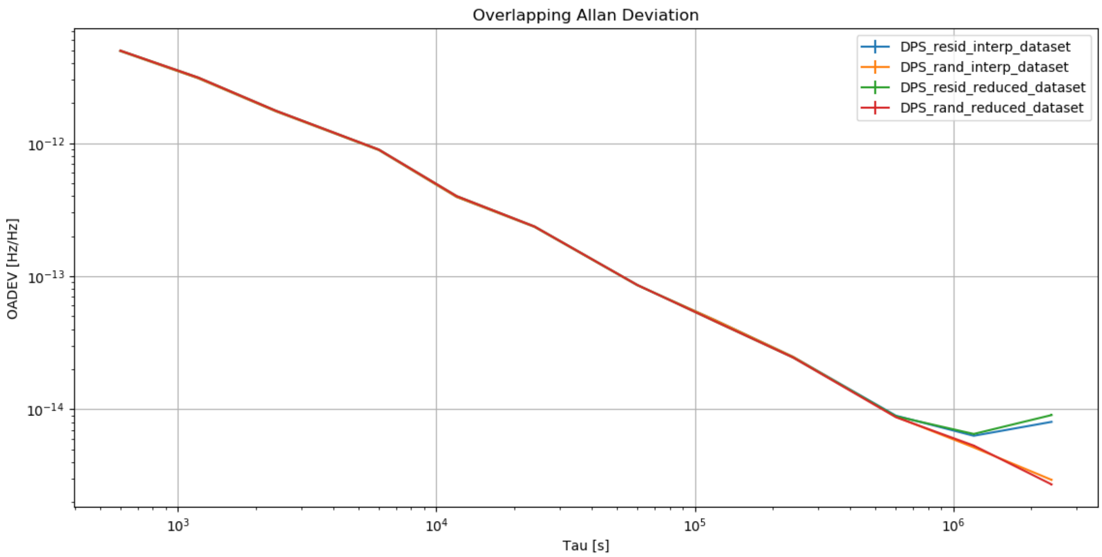

Figure 18: *OADEV comparison for two different approaches to handle data with gaps.*

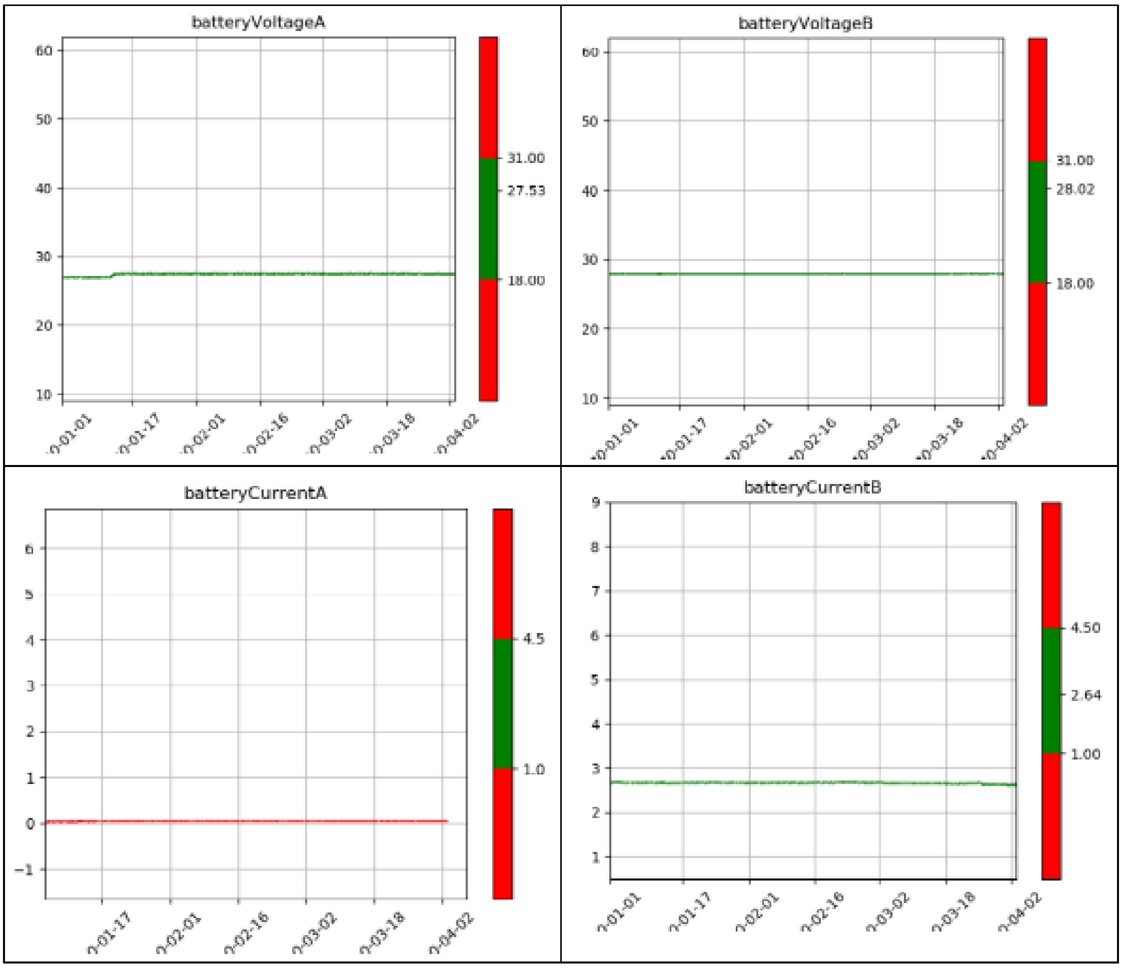

Figure 19: *Power supply monitoring parameters.*

7.2 Molecular Hydrogen flux

The molecular hydrogen flux filling the dissociatior is controlled by a current that heats a Nickel valve and measured using a Pirani sensor. The measured value is monitored as "hydrogenPressureMeas", and the setting point is "hydrogenPressureSet". The current is "purifierCurrent".

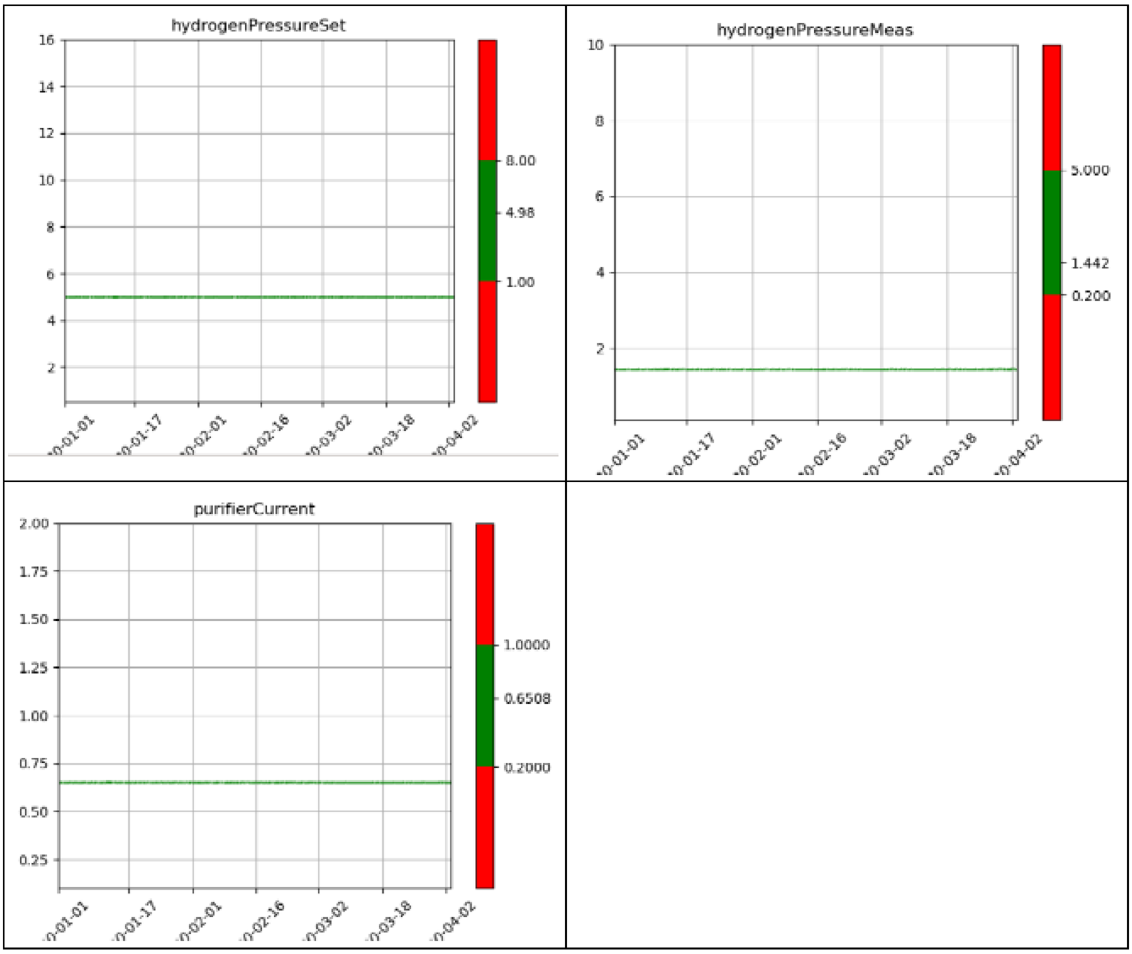

Figure 20: *Molecular H flux monitoring parameters.*

7.3 Ambient temperature and magnetic field

Ambient temperature and external magnetic fields have an impact on the maser frequency stability and phase noise. **To obtain a good phase noise the ambient temperature should be kept within +- 0.1 degrees Celsius, this needs to be supervised**. The voltage of the solenoid that keeps the controlled C-field is constant and that is fine.

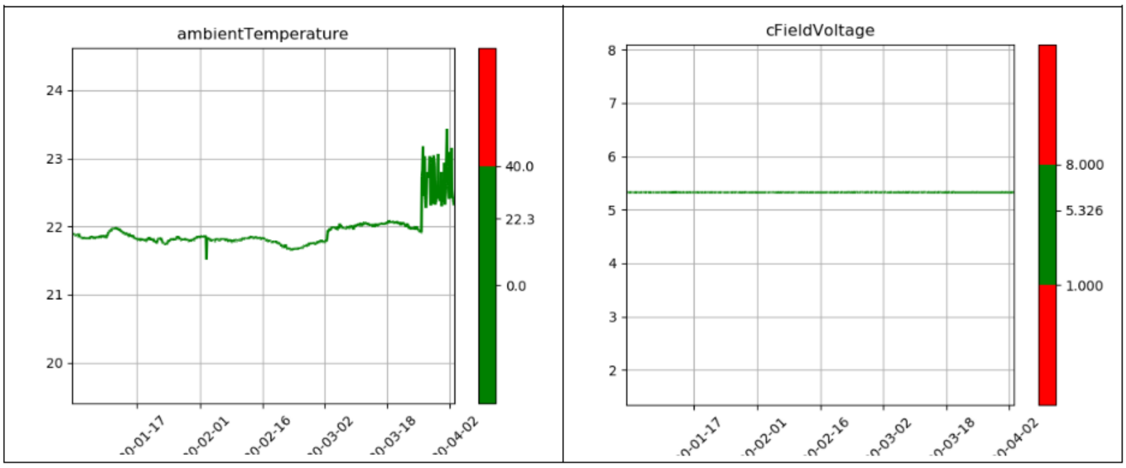

Figure 21: *Ambient temperature and magnetic field monitoring parameters.*

7.4 Hydrogen storage

Hydrogen storage pressure level is in relatively low level, **it is recommended to contact T4Science in case a recharge is necessary.**

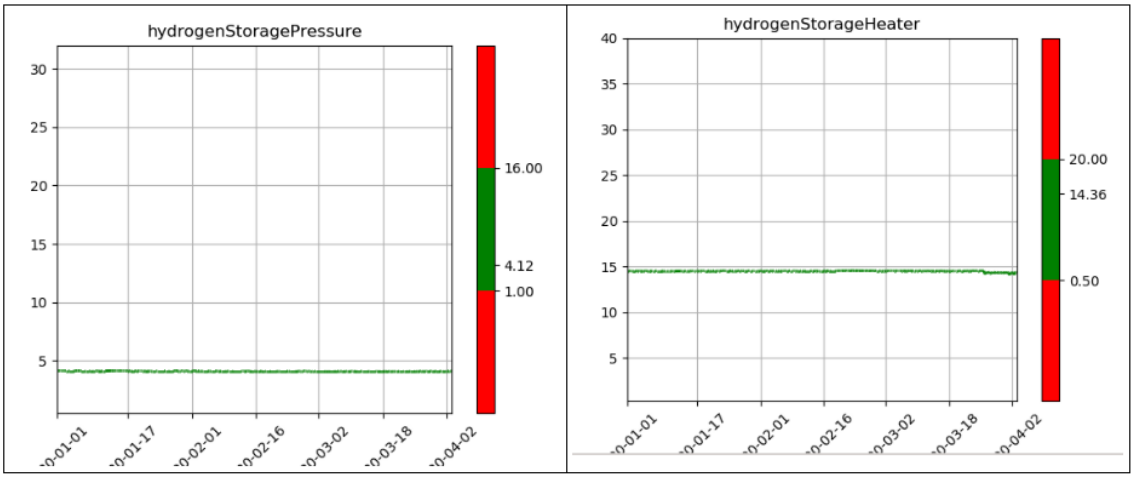

Figure 22: *H storage monitoring parameters.*

8 Conclusions

The following conclusions are presented in this report:

- A relative frequency error of -3.3310^{-12} Hz/Hz has been detected and corrected.
- The frequency stability analysis using the Allan Variance is satisfactory, and it has been proved that the Hydrogen maser RAEGE station at Santa María is performing within the

expected levels. From this point of view, it can be said that it is perfectly suitable for VLBI observations [5].

- Maser's status parameters have been reviewed. There is no evidence of any dangerous situation but it is recommended to contact T4Science to check the reserve levels of molecular hydrogen.

It is advisable to check the condition of the battery system. The user manual should be consulted for this.

References

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[3] T4Science. "Installation Operation and Maintenance User Manual", T4Science 2010

[4] W.J. Riley. "Handbook of Frequency Stability Analysis", NIST 2008

[5] T. Clark, R. Hambly. "Timing for VLBI", oral presentation, IVS Technical Operations Workshop 2009.