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## *Aeolus high energy UV Laser wavelength measurement and frequency stability analysis*

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# Aeolus High Energy UV Laser wavelength measurement and frequency stability analysis.

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**Abstract**—The Aeolus mission is part of ESA’s Earth Explorer program. The goal of the mission is to determine the first global wind data set in near real time to improve numerical weather prediction models.

The only instrument on board Aeolus, Aladin, is a backscatter wind LIDAR in the ultraviolet (UV) frequency domain. Aeolus is a frequency limited mission, inasmuch as it relies on the measure of the backscattered signal frequency shift in order to deduce the wind velocity. As such the frequency stability of the LIDAR laser source is a key parameter for this mission.

In the following, the characterization of the laser frequency stability, reproducibility and agility in vacuum shall be reported and compared to the mission requirements.

**Index Terms**—High Energy, UV Laser, Frequency stability, reproducibility, agility, vacuum.

## I. INTRODUCTION

The Aladin backscatter wind lidar is set to work in the UV domain and more specifically at 355nm (tripled Nd:YAG). The Power Laser Head shall ensure emission, at end of life, of 80mJ. The PLH is composed of a Reference Laser Head (RLH, emitting at 1064nm) which is used to seed a Master Oscillator emitting 5-10mJ at this same wavelength. The Master Oscillator signal is then amplified (by a pre-amplifier and a power amplifier) to obtain more than 300mJ of infrared (IR) light, before frequency conversion. Second and Third Harmonic Generation yield, at laser output, pulses with an energy in excess of 110mJ, wavelength of 355nm, and pulse duration of the order of 20ns. These parameters are given at start of life, and have been verified for the Aladin nominal and redundant flight model of the laser.

The frequency stability, reproducibility and agility of the laser are essentially determined by the performances of the Reference Laser Head seeder and the Master Oscillator. Ideally, excess frequency noise coming from the seeded Master Oscillator should be minimal, but mechanical and thermal variations of the cavity length will impact frequency stability. The mechanical and thermal configuration of the MO shall, thus, be significant limiters of the laser frequency stability. The latter is conversely tributary to the mechanical and thermal environment of operation.

While amplification of the emitted pulses does not impact the wavelength stability, frequency conversion multiplies, by a factor three, the noise observed in the infrared domain.

In order to verify these hypotheses and the laser compliance, as it regards to its frequency characteristics, a wavemeter evaluation of the UV signal output was set-up during the endurance and the thermal vacuum qualification campaigns on the laser nominal flight model (FM-A). The measure in the UV domain was taken with a High Finesse laser calibrated wavemeter (WSU/10 prototype) which was graciously provided and put in place by Oliver Reitebuch, Benjamin Witschas and Christian Lemmerz from DLR. Independently, a measurement of the IR signal at the exit of the Master Oscillator, using beat note techniques, was run for part of the campaign. These data confirmed the expected behavior of the PLH (no impact from the amplification, and tripling of the noise level, due to THG). IR data were consistent with the UV frequency observation, but aren’t presented in the following.

Frequency stability data was acquired during two different tests: the Burn-in Test (BiT) and the Thermal Vacuum (TV) test. The duration of the TV test was roughly two weeks, during which the laser was at times switched off. The BiT test consisted of 5 weeks almost continuous operation. During the BiT the seeder was free running, while for the TV campaign it was frequency locked to its reference Fabry-Pérot resonator.

## II. EXPERIMENTAL SET-UP

The laser was placed in a thermal vacuum chamber. For the BiT temperature of the chamber was not controlled and remained at room temperature with daily variations. For the TV the chamber was set to perform qualification thermal excursions.

The laser UV output, coming from the chamber, was separated into different metrology channels by a holographic beam splitter. The second order of this Holographic Beam Splitter was coupled in a single mode, bow tie, polarisation maintaining small-core fibre. The fibre conveyed the UV light to the wavemeter on an adjacent table.

The wavemeter requires an optical input energy of at least 0.02μJ to accurately gauge the wavelength. Injection into a

fibre being alignment sensitive, and the second order of the HBS being close to this limit, a small amount of data was not exploitable (less than 10%). The long durations of the tests allowed for statistically meaningful sets in spite of the above mentioned data losses.

### III. FREQUENCY STABILITY

#### A. Frequency stability indicators and significant timescales

When investigating the stability of oscillators and atomic clocks it was found that their phase noise did not consist of white noise, exclusively. White frequency noise and flicker frequency noise were also present. These noise forms become a challenge for traditional statistical tools such as standard deviation as the estimator will not converge. The noise is thus said to be divergent.

To solve this issue David Allan [1] proposed to introduce the 2-sample variance (hereunder), which for a purely white noise will be equivalent to the standard variance.

$$Avar = \sigma_y^2 = 1/(2\tau^2) \cdot Mean(X_{k+2} - 2 \cdot X_{k+1} + X_k) \quad (1)$$

For an observable  $X$  the Allan variance is defined as one half of the time average of the squares of the differences between successive readings of  $X$  over the sampling period  $\tau$ .

The Allan variance method can be used to determine the character of the underlying random processes that give rise to the data noise, and allows for conversion into frequency-domain measures of frequency stability (e.g. power spectral density) [2].

The short term frequency stability specification requires root mean square (RMS) variations of this parameter over 14s to remain below 7MHz. The 14s mark is chosen to ensure adequate signal to noise ratio of the measurement. Currently an Aladin observation is set to include 600shots (i.e. a 12s long acquisition)

If the data averaging over 14s for the instrument is not strongly dependent on the shot to shot atmospheric variability, then, in principle, the sampling period of interest for the frequency Allan variance would be 14s. Conversely, if the variability were very significant the standard deviation of the shot to shot frequency should be computed over 14s intervals. The mean value of as many reliable 14s long observations, as available, averaged would now represent a reasonable estimator for the specification.

The two definitions are not directly comparable. The Allan deviation over a sampling period of 14s being only sensitive to noise contributions over 14s, whereas the standard deviation for 14s long samples will be sensitive to noise contributors from shot to shot (0.02s) up to 14s. For completeness both estimators were computed.

The medium term frequency stability requires for the frequency over 1 week to remain below 60MHz. Alternatively the maximum expected thermal excursion of the laser (+0 to 2°C) must not result in above 60MHz frequency variations.

#### B. Laser frequency stability and seeder status

It is possible to qualitatively determine how the seeder status affects the frequency stability of the PLH, as the two tests for which we have acquired data were run in different

conditions. As previously mentioned, during BiT, the seeder was free running, whereas during TV the retroaction loop was closed locking the RLH frequency to its reference Fabry Pérot cavity.

For this qualitative analysis (shown in Figure 1) the variances (Allan and standard) were computed for increasing sampling times starting with 1s, and reaching a few ks. On the x-axis the sampling time, on the y-axis, in MHz, the variances. (Allan Variance for BiT cyan, Allan variance for TV blue, Variance for BiT magenta, Variance for TV red).

Another difference between the two tests was due to the thermal control of the thermal vacuum chamber baseplate, only present during TV. The presence of this thermal control adversely affected the vibrational environment of the laser (cf. low sample time behavior of TV test in Figure 1 and section III.C.)

On the other hand, this thermal regulation would have been beneficial to the long term (above 1000s) frequency stability, during the BiT. During this test the unlocked seeder frequency variations were correlated with the seeder thermal excursion, converted in frequency variations using RLH manufacturer provided conversion coefficients (cf. Figure 2). Taking into account a time constant, the temperature seen by the RLH is translated into a UV daily frequency variation. In Figure 2 the variations of the frequency with respect to its mean value (in MegaHertz) are shown as a function of time (days.)

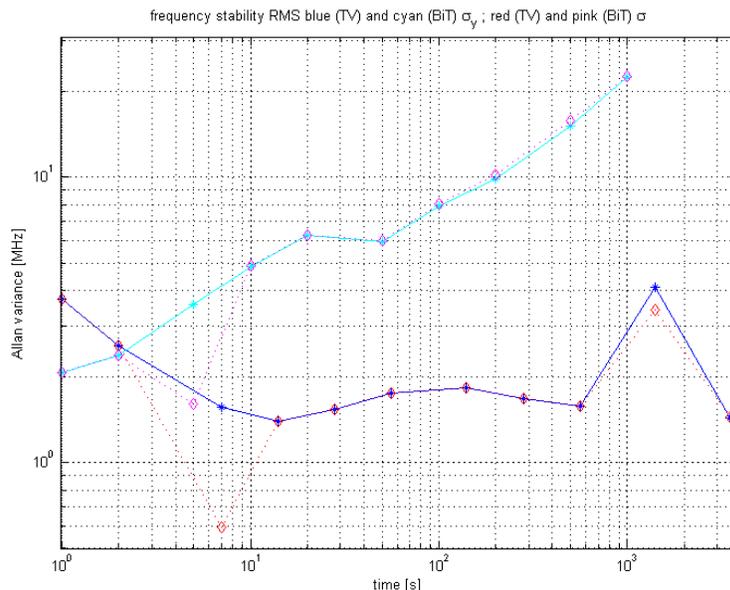


Figure 1 Variances for Burn-in (BiT) and Thermal Vacuum (TV) test.

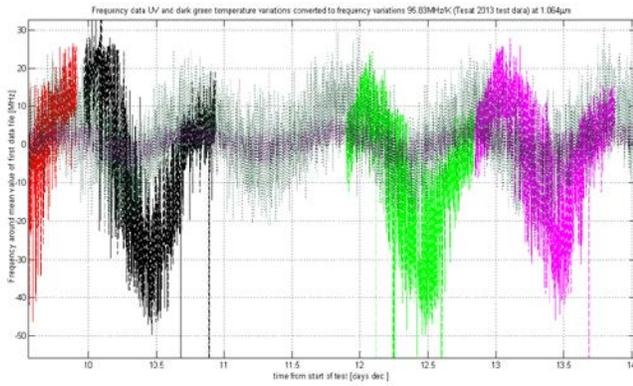


Figure 2 Frequency variation over time BiT and thermal variations of RLH converted to frequency.

Even so the unlocked seeder configuration is shown to be insufficient to meet the short term and the medium term requirements, as expected.

### C. Short-term frequency stability and vibrational environment

In the previous section a short term (/high frequency) sensitivity to vibrational environment could be deduced from the comparison between the chiller pump free BiT and the TV test.

At the end of the TV campaign an accelerometer was added to the experimental configuration to confirm this sensitivity. Since it was not possible to interrupt the vacuum during the ongoing test measurements, the accelerometer was positioned for a purely qualitative measurement on the door of the TVC. In any case, the vibrational environment of this test hardly represented the in-orbit condition. The frequency was then acquired over a few minutes in different vibrational configurations: one with the pumps (chiller and vacuum) on, one with only the vacuum pump on (BiT type vibrational environment,) and one with all pumps off. (The latter with a duration limited by the pressure increase in the chamber.)

In Figure 3 the different configurations Allan variances, and their corresponding vibrational root Mean Square spectra are shown. The spectra x-axis is expressed in frequency (Hz), while the  $\sigma_y$  is expressed as a function of time (s). The y-axis of the accelerometer read-out spectra are in  $V/\sqrt{\text{Hz}}$ , whereas the Allan variance is expressed as usual in MHz. To facilitate comparisons frequency labels were added to the x-axis of the Allan variance graph. The color code used is the same: pumps on configuration corresponds to red, vacuum pump on to green and pumps off to blue.

This comparison was, once more, purely qualitative, but serves as a convincing argument for frequency stability in-orbit being significantly better on the short term basis than specified, provided no resonances of the MO are excited by the platform.

### D. Medium-term frequency stability

As agreed with Airbus-DS, the TV test data was analysed in order to compute the long term frequency performances using the sensitivity test  $\pm 0.2^\circ\text{C}$  thermal cycle.

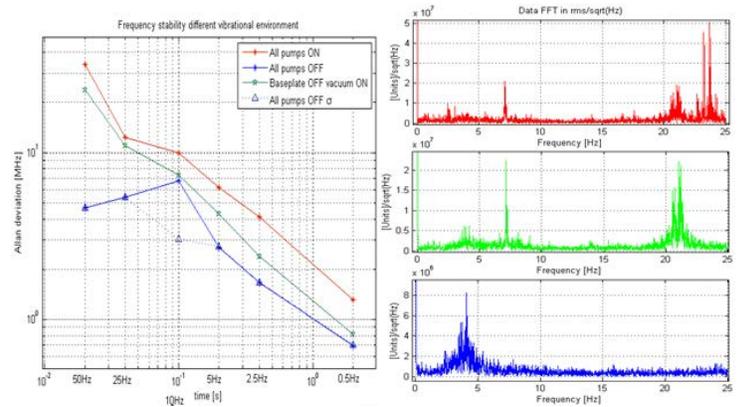


Figure 3 Allan variance and corresponding vibrational spectra for different seismic environments.

Inasmuch as this cycle exceeds the expected thermal variations over one week operation in orbit (i.e. from 0 to  $0.2^\circ\text{C}$ ), the laser behavior on the long term can be extrapolated from the sensitivity tests performed during the TV campaign. (Thermal gradients will be the driving parameter for frequency stability over longer timescales.)

In order to consider only the long term effects, Airbus-DS has specified that the data should be averaged over 7s in order to get rid of the high frequency contributions.

Four sensitivity tests under vacuum conditions were available for analysis. One at ambient temperature, one with the laser interface at  $+35^\circ\text{C}$  and two at  $-2.5^\circ\text{C}$ .

If we take into account all of these cycles, it can be observed that the absolute frequency peak to valley variations remain below 25MHz (cf. Figure 4 hereunder). In this figure, the black curve represents the frequency absolute variation over time (hours) in MHz with respect to the mean value during the ambient cycle. The red curve represents the frequency variations during the hot plateau using the same reference value, and the blue curves represent the frequency variations during the cycles on the cold plateau.

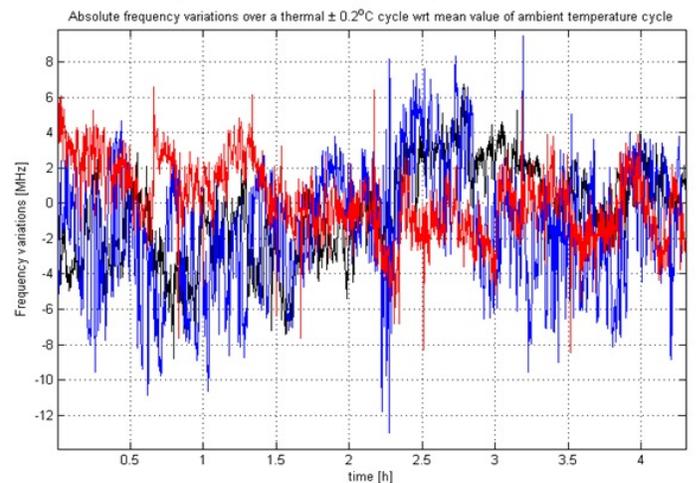


Figure 4 Absolute frequency variations during thermal cycle wrt. ambient T cycle mean value.

The maximum value reached (during cold plateau cycle) with respect to the ambient temperature absolute frequency is +9.51MHz. The minimum value reached (always for a cold plateau cycle) is -13.02MHz below the ambient temperature mean frequency. The maximum deviation is therefore  $\pm 13$ MHz taking into account all different cycles executed for all different thermal conditions (cold plateau, hot plateau and ambient). This is well within specification. Furthermore, this pessimistic estimate is also taking into account the reproducibility contribution as the laser was switched off (non-operational thermal cycle) between the different thermal sensitivity cycles. Within one single cycle the peak-to-valley variations are below 24MHz for all thermal conditions.

#### IV. ABSOLUTE WAVELENGTH AND REPRODUCIBILITY

The laser central wavelength value in vacuum, must remain in the spectral range for which the coatings were produced and ensure that the radial wind speed ( $v_r$ ) can be retrieved from the frequency shift  $\Delta f = 2 \cdot v_r / \lambda$ . The central frequency value in vacuum must be  $354.8\text{nm} \pm 0.03\text{nm}$ .

Reproducibility is defined as the frequency difference between the absolute frequency of the laser at two different times with respect to the mean frequency/wavelength value. Reproducibility of the wavelength/frequency after a switch off is requested to remain below 30pm. After a frequency change (calibration ramp) but no switch off a reproducibility of 25MHz is specified.

If we take into account the wavelength values in all possible thermal conditions during the TV (using the cycles described in the previous section,) we can observe that the wavelength is 17.331pm away from the nominal value of 354.8nm, and thus well within the  $\pm 30$ pm acceptable offset for the central wavelength.

Wavelength deviations over the different thermal cycles (with a switch off) are of the order of  $\pm 5$ fm (i.e. 11MHz) and therefore easily compatible with both reproducibility requirements.

Using the BiT campaign it is possible to obtain a reproducibility estimate taking into account transportation of the laser and internal inspection and realignment. (The latter operation was needed to palliate for a misalignment whose root cause may have been a mechanical settling in vacuum). Between campaigns the reproducibility is still within a few pm (2.5pm maximum deviation) which is compliant with the specified maximum repeatability variation of 30pm. Using the two campaigns we obtain for the central wavelength:  $354.8\text{nm} + 18.531\text{pm} \pm 1.3\text{pm}$ .

#### V. LASER FREQUENCY AGILITY (INSTRUMENTAL CALIBRATION SET-UPS)

To allow for calibration of the instrument in flight the laser is expected to be able to emit a series of frequency steps permitting to determine the instrumental response to different frequency shifts/ wind velocity. The results of the response measurements during the frequency ramps are used to determine the transfer functions of the Mie and Rayleigh channel, as well as to tune the nominal transmitter frequency to

the centre of the Mie channels useful spectral range, and to centre the crossing point of the Rayleigh channel accordingly. While the broader range of the spectral transfer function is scanned with scheme 1 (steps of 250 MHz), the fine adjustment and characterisation is based on scans with steps of 25MHz (scheme 2).

Both scheme 1 and scheme 2 require for the laser to demonstrate agility of the order of the GHz.

- Scheme: 1 From -5GHz to +5GHz, with regard to the chosen central frequency. Typical operation is to change one frequency per 12s or overall duration of 8 minutes. Forty 250MHz steps over range. Noise of frequency offset (wrt specified frequency for step) below 10MHz over ramp.
- Scheme 2: From -0.75GHz to +0.75GHz, with regard to the central frequency. Typical operation is to change frequency every 24s or a typical duration of 24 minutes. Sixty 25MHz steps over range. Laser must lock on the next frequency in under 320ms (16shots). Noise of frequency offset (wrt specified frequency for step) below 1MHz over ramp. Slow drift of ramp wrt theoretical slope lower than 1.7MHz RMS ( $1\sigma$ ).

Taking into account the wavemeter error (2MHz) and the laser frequency noise shown in the previous paragraph it is clear that the error on both frequency offset noise and slow drift for the scheme 2 will be higher than the specified value. In the vacuum set-up these two requirements can only be verified within error.

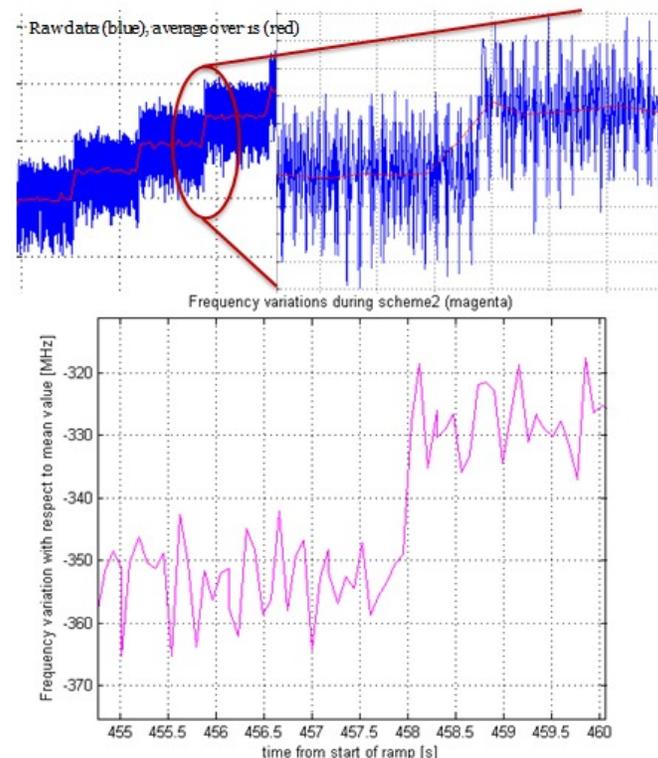


Figure 5 Scheme 2 transition, no lock loss.

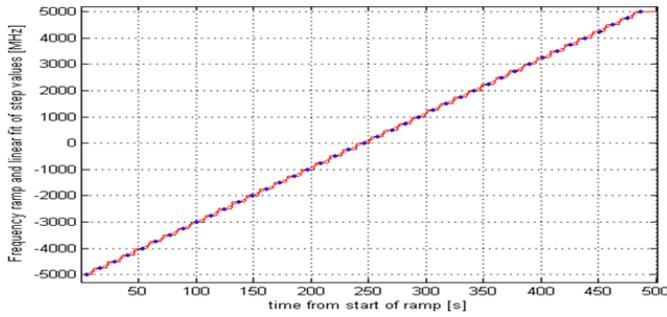


Figure 6 Scheme 1 frequency ramp over time.

Frequency variations of the laser can be accomplished without any loss of lock (for the 25MHz steps) during scheme 2. This is not always true for the scheme 1 where the larger steps can occasionally induce unlocking of the RLH. Lock is reacquired within 2-4 shots, this would therefore still be within the specification applied to scheme 2.

The time needed to reach the higher frequency, during scheme 2, is of the order of  $360\text{ms} \pm 160\text{ms}$  which corresponds to an excellent tuning range of  $4.16\text{GHz}/\text{min}$ . The determination of the transition time for the scheme 2 (as can be seen from Figure 5) is, however, perturbed by the noisy vibrational environment, which gives shot to shot noise comparable to the step height. Averaging over time (1s, red curve) the MHz scale frequency offset value allows to obtain a clear ramp, but does not allow for determination of the transition time. A sliding average over 4 pulses (0.08s), magenta curve, allows for the former rough determination.

For scheme 1, the ramp (cf. Figure 6) shows a frequency noise  $\sigma(\Delta f_i) = 3.3\text{MHz} \pm 1.6\text{MHz}$ , which is below the specified 10MHz limit.

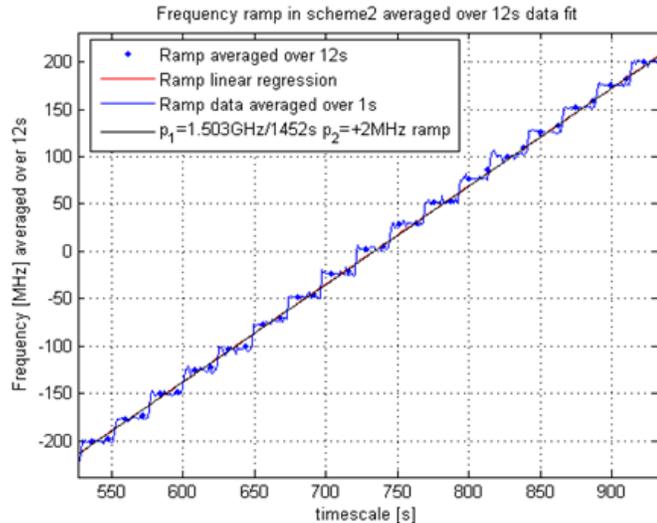


Figure 7 Scheme 2 frequency ramp detail, timescale in (s), Frequency variation wrt to central frequency in MHz, and determination of the best slope.

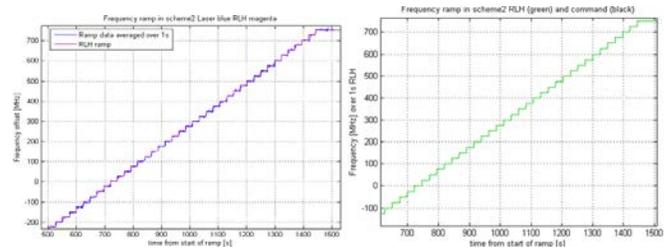


Figure 8 Frequency variations [MHz] over time [s], during ramps (details) PLH (blue), RLH (magenta left and green right), and command (black). PLH, RLH and command are superimposed.

For scheme 2, as already observed, the noise on each frequency plateau is very high compared to the requirement. Several MHz of noise to be compared to an offset variation  $\sigma(\Delta f_i)$  to be verified below 1MHz.  $\sigma(\Delta f_i) = 2\text{MHz} \pm 3\text{MHz}$ . The air measurement of this value (with no pumps perturbing the PLH) gave a value for this offset of the order of 0.6MHz over the 24minutes ramp.

The slow drift verification allows for averaging of the ramp values over 12s (diamond shaped points in Figure 7).

The fit of the average frequency values at the centre of each step weighted by the uncertainty for each step frequency allow for determination of the the best linear regression parameters. With 95% confidence bounds the following linear regression coefficients are obtained ( $f_{fit} = p_1 \cdot t + p_2$  and y-axis zero is the central frequency and the origin of the timescale is the start of the ramp):

$$p_1 = (1.035 \pm 0.002) \text{ MHz/s}$$

$$p_2 = (-757 \pm 2) \text{ MHz}$$

The linear coefficient is lower than the expected value of  $1.042\text{MHz/s}$  ( $1.5\text{GHz}$  ramp over 24minutes). Verification of the RLH emitted frequency and input command frequency (Figure 8) show that the laser followed the set ramp. This slope error can therefore be corrected. Without correcting for slope error the slow drift would be of the order of  $14\text{MHz} \pm 3\text{MHz}$  while applying this legitimate correction a value of  $0.7\text{MHz} \pm 3\text{MHz}$  is obtained. Uncertainty is given by the 2MHz of the wavemeter or alternatively by the fit uncertainty  $\pm 0.002 \text{ MHz/s}$  or, over 1440s (24 minutes), 3MHz.

## VI. CONCLUSIONS

Central wavelength value and reproducibility has been demonstrated in vacuum.

The short term frequency stability has also been successfully demonstrated. As long as the reference laser is frequency locked on its ULE cavity and correctly seeding the MO, RMS noise below 7MHz is reached. If the PLH is situated in a mechanically quiet environment the RMS noise (still taking into account the shot to shot contributions) can be inferred to be below 4MHz, but may depend on vibrational spectra.

The long term frequency stability has also been successfully demonstrated to be significantly better, over a weekly thermal cycle of the interface, than specified 60MHz limit. The worst case scenario for the peak to valley frequency variation being 24MHz.

The laser agility has been shown to answer to requirement with a tuning range of 4.16GHz/min. The calibration schemes have been demonstrated, as far as the set-up allowed for, to answer to expectations. In air verification on the heterodyne beat note of the MO output with the RLH itself has allowed for confirmation of the in vacuum obtained values.

#### ACKNOWLEDGMENT

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