Vibration specifications for VLT instruments

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ABSTRACT

ESO invested enormous effort in developing and commissioning the VLT-Interferometer (VLT-I), a unique facility providing a spatial resolution equivalent to that of a 200m-telescope. Complementary to the regular VLT operations, latterly additional 230 nights per year were scheduled to execute scientific observations with large VLT-I baselines. But to the same degree as the VLT-I performance and stability were improving over the past years, likewise the vibration sensitivity of the optical system was increasing and stricter requirements on mechanical stability were necessary. As a consequence ESO started years ago an extensive program to identify and mitigate potential vibration issues. In the scope of this work, the mechanical vibrations induced by cryo-coolers, widely used in ESO's VLT instrumentation suite, were diagnosed as one of the major disturbance sources. In order to be able to better control their impact, the development of a more significant vibration specification for VLT instruments became essential.

In the course of preparing such a specification, we first followed an experimental approach where we installed a dedicated dummy instrument equipped with current ESO standard cryo-coolers in different VLT foci configurations and performed a comprehensive vibration measurement test campaign under real VLT/VLT-I operation conditions. All obtained vibration measurement data were spectral analyzed with respect to the actual VLT-I optical path length difference acceptance levels. This campaign gave valuable information about typical cryo-cooler induced vibration levels and their consequence for VLT-I operations. It also enabled the release if novel conform cryo-cooler instrument design and operation recommendations.

This paper describes the applied vibration measurement methodology on the basis of examples, the development and description of the significant VLT instrument vibration specification, and a proposal for a generic verification procedure for standalone instruments or sub-units prior final acceptance.

Keywords: ground-based instrumentation, VLT/VLT-I, cryo-cooler, cryogenics, vibration measurement, vibration specification

1. INTRODUCTION

Cryo-coolers were introduced at ESO more than two decades ago. They are mainly used to provide the required cryogenic temperature levels for infrared instruments and their highly sensitive detectors. Different types of these refrigerators are used for the present VLT instrumentation suite. Relevant puplications[1] describe their pro's and con's, especially regarding one of their main disadvantages, the non-negligible mechanical vibrations. It has been reported earlier[2] that nowadays extreme resolution and sensitivity capabilities of modern telescopes and instrumentation implicate significant susceptibilities against mechanical disturbances. Especially for the very sensitive VLT-Interferometer (VLT-I) even low level excited vibrations can be very critical or unacceptable. As a consequence ESO started some time ago an extensive vibration reduction project. Initial tasks involved were a comprehensive cooler survey, vibration test programs and implementation of alternative low-vibration cryo-coolers, but also the development of advanced passive and active vibration damping systems[2,3,4].

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The next project phase was comprising measurements and analyses of typical cryo-cooler vibrations at telescope system level. This phase implied two main parts, first the construction and commissioning of a dedicated VLT vibration dummy instrument (VLTDI), followed by a comprehensive vibration measurement campaign at the VLT, where the dummy instrument was installed in numerous Cassegrain-focus, Nasmyth-focus or Nasmyth-platform configurations at the 8m unit telescopes (UT), while measuring the optical path length difference (OPL) of the relevant telescope optical train as a function of a widespread VLTDI cryo-cooler operation parameter range. Therefore variations of cryo-cooler motor revolution; displacer movement direction in a sense being horizontal or vertical, respectively perpendicular or parallel to telescope altitude axis; operation of single or multiple (up to six in parallel) coolers in different radial and axial configurations; and either inclusively cold head anti-vibration damping systems or without (deactivated) were exercised. As a result of this experimental approach up-to-date instrument design and operation recommendations were launched in order to better control or avoid potential disturbance sources from the beginning[5].

The follow-up of the experimental phase was performed in the ESO HQ laboratories and had the goal to cross-calibrate the results of in total 153 different instrument configurations which were investigated at telescope system level with respect to the vibration sensitivity at instrument level. This translation is the key for generating a generally applicable instrument vibration specification. Critical analysis of all vibration measurement data with respect to current OPL limits required for a good VLT-I operation practice led to the first edition of such vibration specifications for VLT UT instruments. The description of the experimental approach, the measurement methodology and the deduction of the final specifications form the main part of the presented paper.

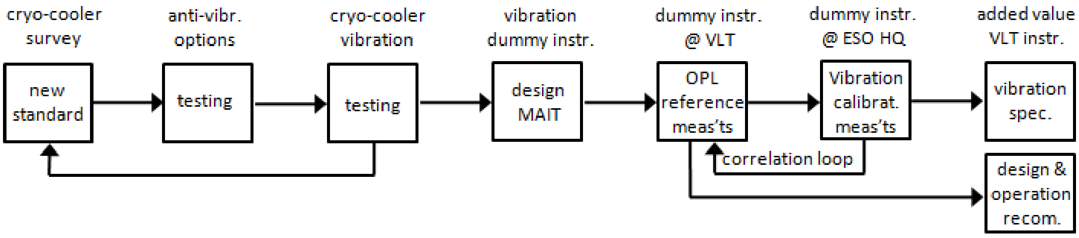

Figure 1: Schematic flow chart of major vibration reduction project phases

2. METHODOLOGY

The dedicated dummy instrument was installed consecutively in representative Cassegrain-focus, Nasmyth-focus or Nasmyth-platform configurations at UT-1 and -2. In total 153 different cases were exercised with variations in cryo-cooler motor revolution, displacer movement orientation, multiple or single cold head operation, with or without passive damping system. Vibrations were measured by use of the VLT vibration sensing system called 'Manhattan'. This system is based on a grid of accelerometers mounted at the VLT UT main mirrors M1, M2 and M3. Together with the individual acceleration spectra it provides also the optical path length difference (OPL) of each mirror and of the total optical system being relevant for VLT-I operations.

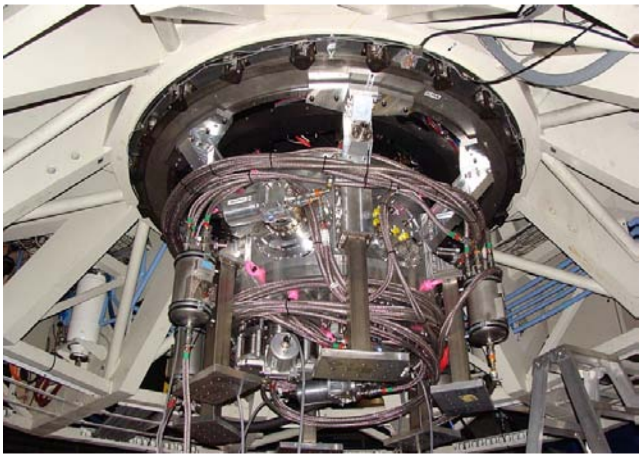

Figure 2: CAD of the 1000 kg VLT Dummy Instrument with six ESO standard cold heads in axial and radial arrangement (left); installed at the VLT 8m unit telescope Cassegrain focus rotator adaptor (right)

All cases were critically analyzed with respect to the current total OPL acceptance limits known from experience:

Total OPL >5Hz = 180nm
Total OPL >1Hz = 480nm

Exceeding these limits is criterion for exclusion of the corresponding configuration. Those cumulative signals being up to a frequency of 120Hz still below the limit were listed under novel instrument design and operation recommendations[5].

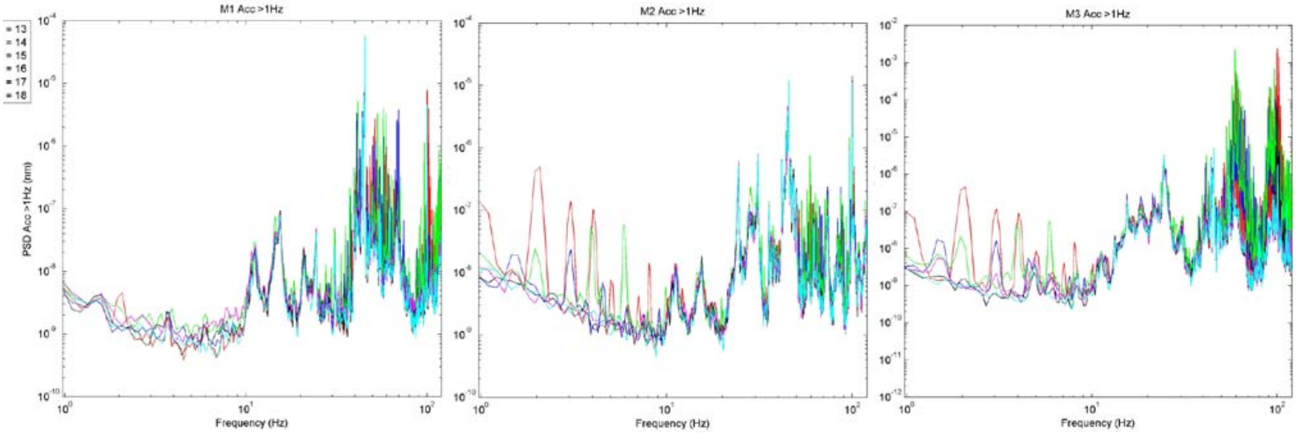

Figure 3: Typical vibration spectra of six different Cassegrain-focus instrument configurations (CF_13 – 18) as measured for the relevant telescope mirrors M1, M2 and M3. PSD is given in g^2/Hz over the frequency range of interest.

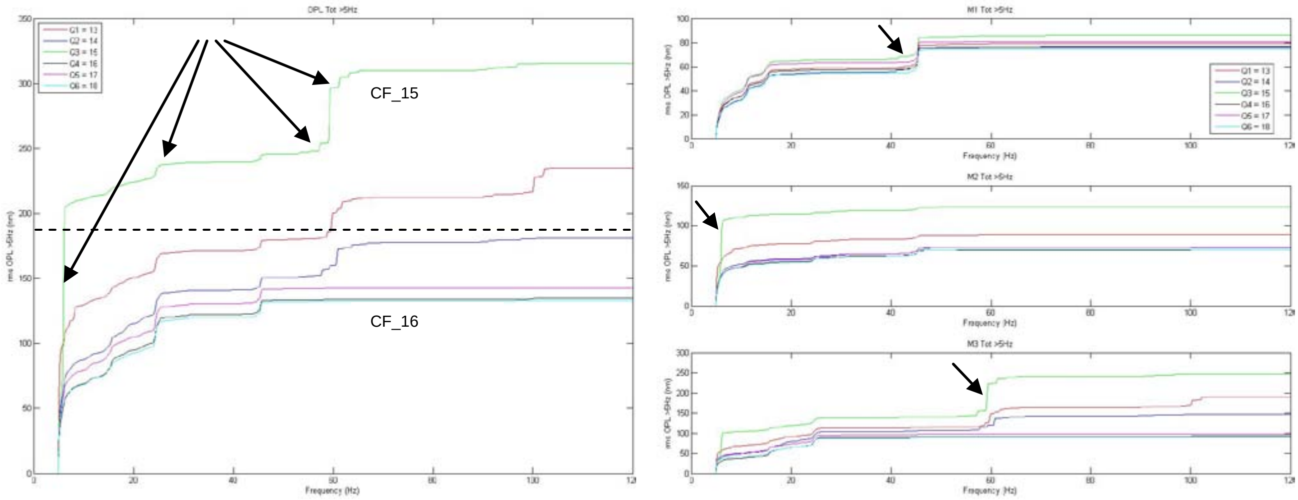

Figure 4: Six Cassegrain-focus configurations CF_13 - 18: Cumulative OPL >5Hz in nm; VLT UT total optical system (left) and individual mirrors M1, M2, M3 (right). The total acceptable OPL limit is indicated as dotted line. Noticeable signal steps are marked. For example: total OPL @120Hz of CF_15 = 320nm; total OPL @120Hz of CF_16 = 130nm. Note: the total OPL of the telescope background (all cryo-coolers off) was measured to be around 130nm.

After completing the OPL data analysis with categorizing recommendable respectively avoidable VLT UT instrument configurations, the next step was to translate these findings into measureable quantities on instrument level. First of all it was essential to develop a mobile acceleration measurement set-up to be able to verify any instrument’s vibration level location-independently. This requires a comparable, quasi stand-alone and all-purpose instrument mounting which is universally fitting all potential instrument types. The most suitable solution was used suspending the instrument like a simplified pendulum with particularly one fixation at a massive ceiling structure or at the hook of a heavy duty laboratory crane. The VLT Dummy Instrument was arranged this way in the ESO HQ laboratories and all earlier 153 VLT foci configurations were simulated, each with the same operating parameters and representative orientations. Accelerations were measured on instrument level using a 3-axis accelerometer block with appropriate data acquisition system.

The newfound acceleration spectra were individually analyzed regarding their correlations with the OPL spectra. A step function in the OPL curve provides an indication of significant disturbance at the given frequency. In a comprehensive survey all obtained acceleration spectra were inspected to identify corresponding impacts. Accordingly a spectral envelope was converged, considering all such spectral events, as criterion for distinguishing admissible and inadmissible instrument vibration levels.

Using Gifford-McMahon-type cryo-coolers is adding some more complications in defining simple criteria. Their displacers typically oscillate at low frequencies (0.5 – 3Hz) and this is usually creating a series of corresponding signal spikes at the according first frequency and the subsequent harmonics. We found that not only the amplitude of the spectrums fundamental signal matters, but also the amplitude of those spikes. Consequently two criteria had to be defined, the so-called acceptance level for fundamental signal and the acceptance level for spikes. To be consistent with the final vibration specification none of the 3-dimensional signals must exceed these levels. We also found that cryo-cooler instruments are having different impact on each of the three VLT UT foci, which was finally resulting in three individual vibration specifications.

3. EXEMPLARY RESULTS

In this section some exemplary results from the cross-calibration measurements are presented. The acceleration spectra were measured at instrument level. Frequency range of main interest is 1 – 120Hz. Amplitude axes are given in acceleration (left ordinate) as well as in force (right ordinate), both in dB units. Definitions and nomenclature concerning these units and their correlations are presented in the next section. The converged envelope for defining the acceptance level for fundamental signal is displayed as coarse dashed line respectively as fine dashed line for the level for spikes. Each of the spectra is composed of three curves, one for each space direction X, Y, Z; plus the background vibration level received with all coolers shut off which is indicated as the yellow lower curve.

3.1 Cassegrain-focus configuration

The following figure shows as an example the unacceptable Cassegrain-focus instrument configuration CF_15. Measured 3-axis fundamental signals are exceeding the coarse dashed line at 7Hz; 35Hz; 40-50Hz and around 100Hz. In addition a spike at 2Hz caused by the first cryo-cooler excitation frequency is exceeding the fine dashed line. Correlations of these impacts can be found in the OPL measurement of figure 3. An ideal example for an acceptable Cassegrain-focus instrument configuration is shown at the right side of figure 4. In CF_16 the measured 3-axis fundamental signals and all equidistant 1Hz spikes are below the respective acceptance levels. This confirms the extremely low OPL values found for this configuration, see figure 3.

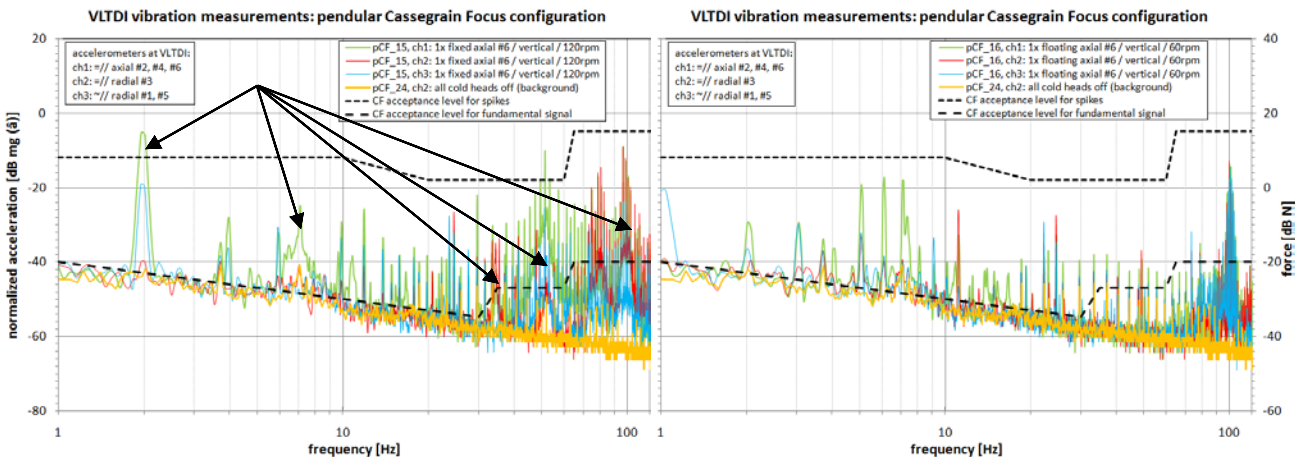

Figure 5: Left: CF_15 as an example for unacceptable Cassegrain-focus instrument configurations. Marked exceeding to be compared with figure 3.
Right: CF_16 as an example for acceptable Cassegrain-focus instrument configurations. No exceeding found as confirmed by figure 3.

3.2 Nasmyth focus configuration

The next figure is showing an example for Nasmyth-focus instrument configurations where total the OPL was exceeding the limits (NF_09). Exceeding were found around the first cryo-cooler frequency of 2.5Hz; at 5Hz; at 22.5Hz (the 8th harmonics of 2.5Hz) and between 40-50Hz. In comparison the other example (NF_75) is consistent with the acceptance levels.

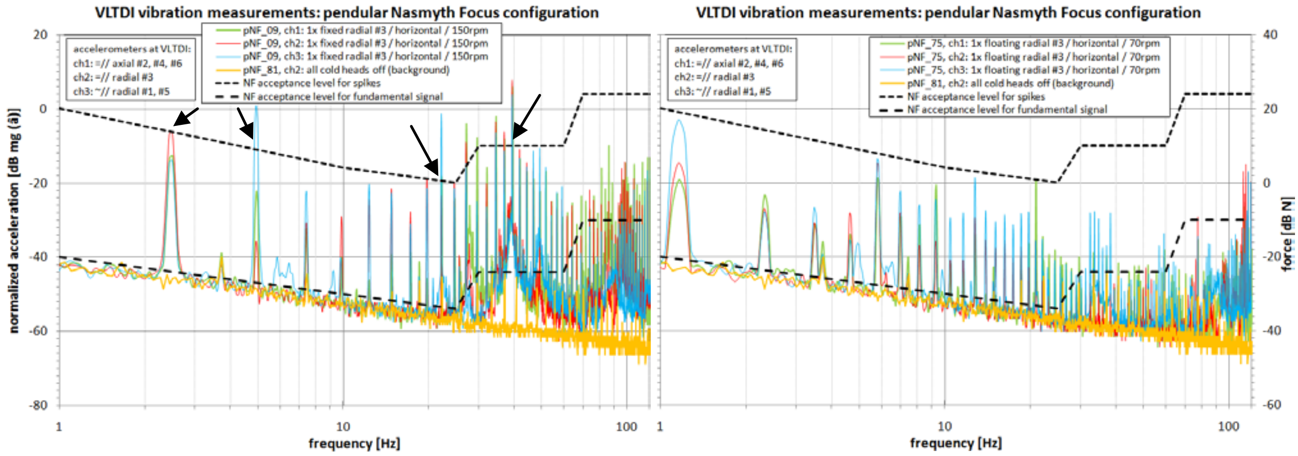

Figure 6: Left: NF_09 example as an example for an unacceptable Nasmyth-focus instrument configuration. Right: NF_75 as an example for an acceptable Nasmyth-focus instrument configuration.

3.3 Nasmyth-platform configuration

The acceptance level for spikes is different for instrument configurations having horizontal or vertical mounted cold heads. The difference is either with or without at specific notch around 10.8Hz. It turned out that exceeding in this particular frequency range is critically influencing the total system OPL. The next figure is showing an example with an exceeding spike at 10.8Hz caused by the 4th harmonic of the first frequency (2.17Hz). The second example is taken from a measurement where the cryo-cooler was operated at a slightly different frequency (2Hz). Spikes at 4th and 5th harmonics (10Hz and 12Hz) did not degrade the total OPL.

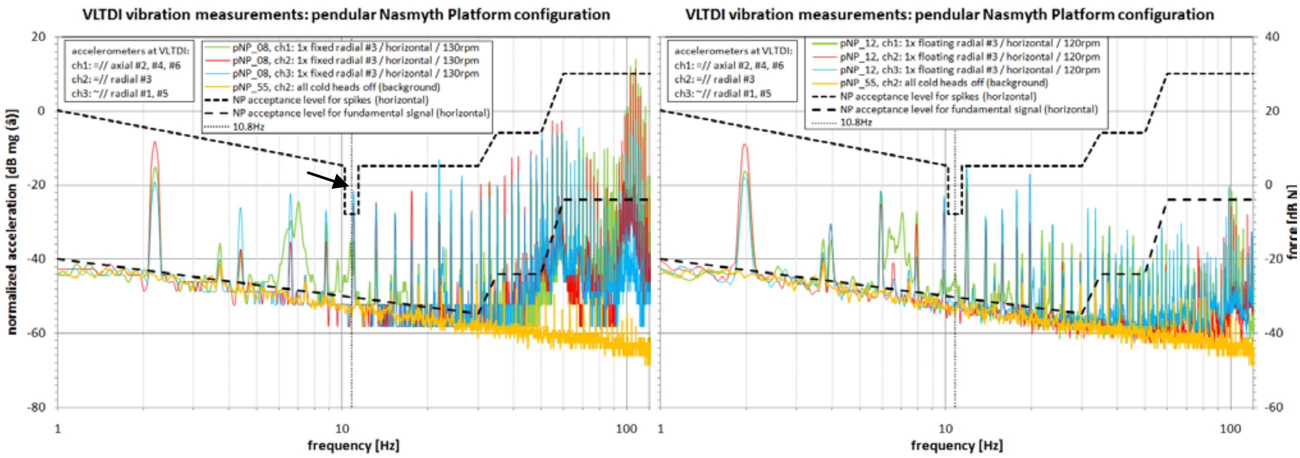

Figure 7: Left: NP_08 as an example for an unacceptable Nasmyth-platform instrument with horizontal cold head configuration. Right: NP_12 as an example for an acceptable Nasmyth-focus instrument configuration.

4. VLT VIBRATION SPECIFICATION FOR UT INSTRUMENTS

One important aspect of such a specification is applicability and verifiability. A lot of effort was put in development of a practical measurement set-up and in the definition of an applicable procedure to receive valid and comparable results. The following nine criteria are regarded as essential to fulfill ESO's VLT UT cryo-cooler instrument vibration specification:

1. Basis for comparison is an independent measurement approach (independent from other hardware or other parasitic perturbations) in form of a so-called pendular instrument set-up: e.g. instrument to be suspended by means of one single non-elastic sling at a laboratory crane (crane load capacity >5x instrument mass), or at a similar massive structure. It has to be ensured that the verified instrument is potentially free oscillating in all non-constrained degrees of freedom. For this simplified pendulum the rope length L has to be chosen so that the eigenfrequency f is below 0.5Hz. For example:

   $f = (1 / 2\pi) * \sqrt{(g / L)}$ with $g = 9.81\ m/s^2$, $L \approx 2.5\ m$

   $f \approx 1 / \pi \approx 0.3\ Hz$

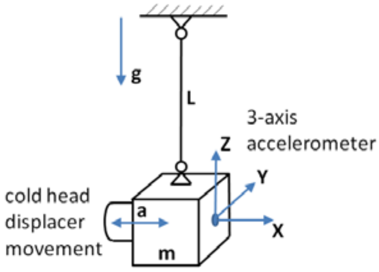

Figure 8: Schematic pendulum set-up for independent instrument vibration verification

2. Instrument orientation has to be chosen to be best representative for the expected VLT focus configuration.

3. Accelerometer system to be installed at rigid massive instrument structure measuring simultaneously in three orthogonal space directions X, Y, Z. One of them must be parallel to the main excitement axis, which is for example given by the main cryo-cooler displacer movement axis.

4. Acceleration measurement with cryo-coolers in nominal operation and with all coolers shut down for reference (background).

5. Generation of meaningful acceleration amplitude spectra in the frequency range of 1-120Hz for all three measurement channels. For log-log plots the engineering units are dB mg (1 milli g = $9.81 * 10^{-3}\ m/s^2$) for the field amplitude and Hz (1/s) for the frequency axis. In this context acceleration spectral density (ASD in g^2/Hz) is not considered, but corresponding data could be transferred to acceleration and vice versa using the formula $ASD = a^2 / 2\Delta f$.

6. When taking accelerations into account the field amplitude has to be normalized by the mass correction factor (k = m [kg] / 1000kg). The unit of normalized acceleration is [dB mg (â)] (see section 4.1). When taking forces into account, estimations as described in section 4.2 may be applied to derive equivalent values in Newton (respectively dB N).

7. The measured fundamental signal must not exceed the defined 'acceptance level for fundamental signal'. Compare all signals versus background and subtract system glitches where applicable.

8. None of the spikes caused by the cryo-cooler must exceed the defined 'acceptance level for spikes'. Compare all signals versus background and subtract system glitches where applicable.

9. If one or more of the criteria no.1 – 8 are not fulfilled the instrument is not qualified.

4.1 Nomenclature for acceleration

In our nomenclature the measured acceleration field amplitudes are presented in the logarithmic unit dB mg (1 milli g = $9.81 * 10^{-3}$ m/s^2) with the following correlations:

20 dB mg	≡ 10 mg
0 dB mg	≡ 1 mg
-20 dB mg	≡ 0.1 mg
-40 dB mg	≡ 0.01 mg = 10 µg
-60 dB mg	≡ 0.001 mg = 1 µg
-80 dB mg	≡ 0.0001 mg = 0.1 µg

The ordinate axes of the presented spectra aim for universally valid and comparable values. Therefore the measured acceleration (a) has to be normalized with respect to the reference mass (M), which was for all tests performed with the VLTDI 1000 kg. To create normalized acceleration (â) the measured amplitude (a) has to be multiplied by the mass correction factor (k).

$\hat{a} = a * k$

$\hat{a}$	normalized acceleration
a	measured acceleration
k	mass correction factor

The mass correction factor (k) accounts for the verified instrument mass (m) with respect to defined reference mass (M).

$k = m\ [kg] / M$

m	mass of verified instrument in kg
M	reference mass = 1000 kg

$\boldsymbol{k = m\ [kg] / 1000\ kg}$

For the measurements with the VLTDI the k-factor equals 1.

The unit of normalized acceleration is [dB mg (â)]. It is assigned to the first ordinate axis.

The second ordinate axis is assigned to force; the unit is [dB N].

4.2 Nomenclature for force

The generated force (F) can be derived from the measured acceleration (a) and from the known moving mass, which is in this case the verified instrument mass (m).

$F = m\ a$

F	disturbance force in N
a	measured acceleration in g
m	mass of verified instrument in kg

During calibration measurements the total moving mass of the VLTDI was:

$m = 10^3$ kg (mass of VLTDI cryo-vacuum instrument = 1 ton)

0dB mg acceleration amplitude means for example:

0dB mg: 1 mg = $9.81 * 10^{-3}$ m/s^2

$F = 10^3\ kg * 9.81 * 10^{-3}\ m/s^2 = 9.81\ N = \sim 10\ N$

Forces can be derived accordingly for all measured acceleration amplitudes. Some approximated examples are given below:

20 dB mg:	F = 100 N	≡ 40 dB N
0 dB mg:	F = 10 N	≡ 20 dB N
-20 dB mg:	F = 1 N	≡ 0 dB N
-40 dB mg:	F = 0.1 N	≡ -20 dB N
-60 dB mg:	F = 0.01 N	≡ -40 dB N
-80 dB mg:	F = 0.001 N	≡ -60 dB N

4.3 VLT UT instrument vibration specification

The specification for the VLT Cassegrain-focus, Nasmyth-focus and Nasmyth-platform cryo-cooler instrument vibration and force acceptance levels are shown in the next figure and tables. The fundamental signals must be below the coarse dashed lines and all spike amplitudes must be below the fine dashed lines.

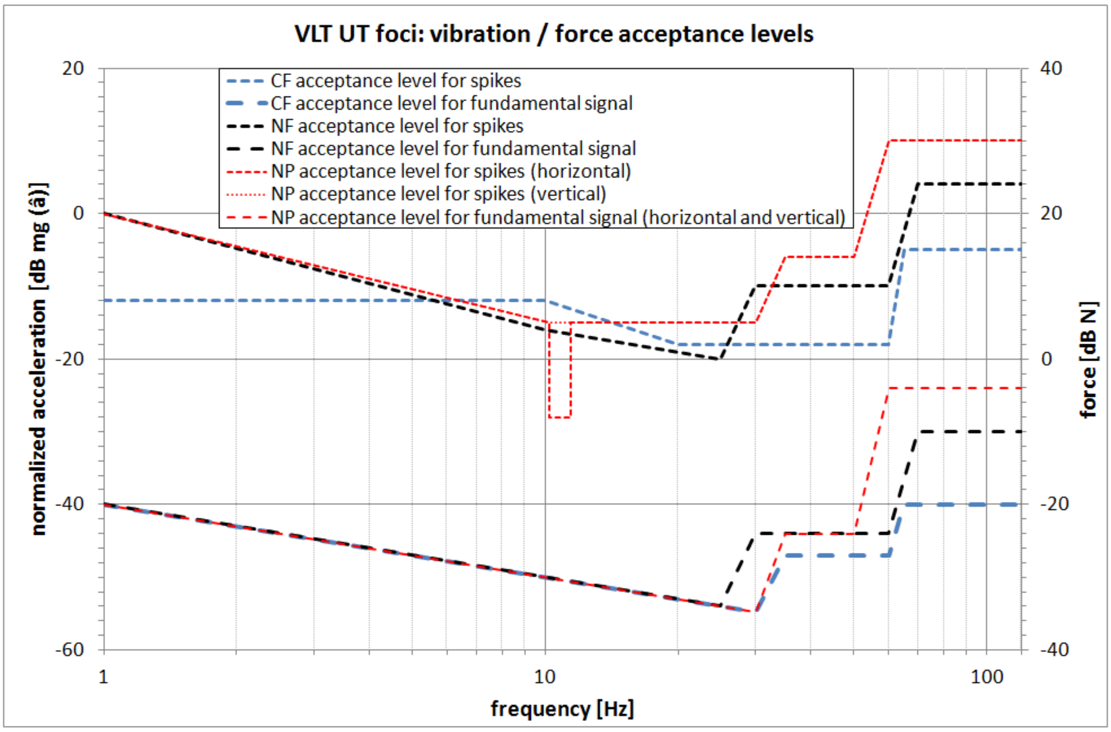

Figure 9: Cassegrain-focus (CF), Nasmyth-focus (NF) and Nasmyth-platform (NP) vibration and force acceptance levels. The Nasmyth-platform specification is different for horizontal and vertical oriented cold heads.

Table 1: Cassegrain-focus: vibration and force acceptance levels for fundamental signal and spikes in tabular form

CF acceptance level for fundamental signal			CF acceptance level for spikes		
frequency	**normalized acceleration specification**	**force specification**	**frequency**	**normalized acceleration specification**	**force specification**
1 Hz	-40 dB mg (â)	-20 dB N	1 -10 Hz	-12 dB mg (â)	8 dB N
1 - 30 Hz	-3 dB/oct.	-3 dB/oct.	10 - 20 Hz	-6 dB/oct.	-6 dB/oct.
30 Hz	-54.8 dB mg (â)	-34.8 dB N	20 - 60 Hz	-18 dB mg (â)	2 dB N
30 – 35 Hz	+35 dB/oct.	+35 dB/oct.	60 – 65 Hz	+112.6 dB/oct.	+112.6 dB/oct.
35 – 60 Hz	-47 dB mg (â)	-27 dB N	55 – 120 Hz	-5 dB mg (â)	15 dB N
60 – 65 Hz	+60.6 dB/oct	+60.6 dB/oct.			
65 -120 Hz	-40 dB mg (â)	-20 dB N			

Table 2: Nasmyth-focus: vibration and force acceptance levels for fundamental signal and spikes in tabular form

NF acceptance level for fundamental signal			**NF acceptance level for spikes**		
frequency	**normalized acceleration specification**	**force specification**	**frequency**	**normalized acceleration specification**	**force specification**
1 Hz	-40 dB mg (â)	-20 dB N	1 Hz	0 dB mg (â)	20 dB N
1 - 25 Hz	-3 dB/oct.	-3 dB/oct.	1 -10 Hz	-4.8 dB/oct.	-4.8 dB/oct.
25 Hz	-54 dB mg (â)	-34 dB N	10 Hz	-16 dB mg (â)	4 dB N
25 – 30 Hz	+38 dB/oct.	+38 dB/oct.	10 - 25 Hz	-3 dB/oct.	-3 dB/oct.
30 – 60 Hz	-44 dB mg (â)	-24 dB N	25 Hz	-20 dB mg (â)	0 dB N
60 – 70 Hz	+63 dB/oct	+63 dB/oct.	25 – 30 Hz	+38 dB/oct.	+38 dB/oct.
70 - 120 Hz	-30 dB mg (â)	-10 dB N	30 - 60 Hz	-10 dB mg (â)	10 dB N
			60 – 70 Hz	+63 dB/oct.	+63 dB/oct.
			70 – 120 Hz	4 dB mg (â)	24 dB N

Table 3: Nasmyth-platform, horizontal cold heads: vibration and force acceptance levels in tabular form

Specification for horizontal cold heads					
NP acceptance level for fundamental signal			**NP acceptance level for spikes**		
frequency	**normalized acceleration specification**	**force specification**	**frequency**	**normalized acceleration specification**	**force specification**
1 Hz	-40 dB mg (â)	-20 dB N	1 Hz	0 dB mg (â)	20 dB N
1 - 30 Hz	-3 dB/oct.	-3 dB/oct.	1 -10.2 Hz	-4.5 dB/oct.	-4.5 dB/oct.
30 Hz	-54.75 dB mg (â)	-34.75 dB N	10.2 Hz	-15 dB mg (â)	5 dB N
30 – 35 Hz	+48.3 dB/oct.	+48.3 dB/oct.	10.2 – 11.4 Hz	-28 dB mg (â)	-8 dB N
35 – 50 Hz	-44 dB mg (â)	-24 dB N	11.4 - 30 Hz	-15 dB mg (â)	5 dB N
50 – 60 Hz	+76 dB/oct	+76 dB/oct.	30 – 35 Hz	+40.5 dB/oct.	+40.5 dB/oct.
60 - 120 Hz	-24 dB mg (â)	-4 dB N	35 - 50 Hz	-6 dB mg (â)	14 dB N
			50 – 60 Hz	+60.8 dB/oct.	+60.8 dB/oct.
			60 – 120 Hz	10 dB mg (â)	30 dB N

Table 4: Nasmyth-platform, vertical cold heads: vibration and force acceptance levels in tabular form

Specification for vertical cold heads					
NP acceptance level for fundamental signal			**NP acceptance level for spikes**		
frequency	**normalized acceleration specification**	**force specification**	**frequency**	**normalized acceleration specification**	**force specification**
1 Hz	-40 dB mg (â)	-20 dB N	1 Hz	0 dB mg (â)	20 dB N
1 - 30 Hz	-3 dB/oct.	-3 dB/oct.	1 -10.2 Hz	-4.5 dB/oct.	-4.5 dB/oct.
30 Hz	-54.75 dB mg (â)	-34.75 dB N	10.2 - 30 Hz	-15 dB mg (â)	5 dB N
30 – 35 Hz	+48.3 dB/oct.	+48.3 dB/oct.	30 – 35 Hz	+40.5 dB/oct.	+40.5 dB/oct.
35 – 50 Hz	-44 dB mg (â)	-24 dB N	35 - 50 Hz	-6 dB mg (â)	14 dB N
50 – 60 Hz	+76 dB/oct	+76 dB/oct.	50 – 60 Hz	+60.8 dB/oct.	+60.8 dB/oct.
60 - 120 Hz	-24 dB mg (â)	-4 dB N	60 – 120 Hz	10 dB mg (â)	30 dB N

5. CONCLUSION

In order to define admissible vibration specifications for VLT cryo-cooler instruments a comprehensive series of vibration test spectra were critically analyzed and the results from the OPL measurements recorded during an extensive test phase with the VLT 'Manhattan' system (measuring vibrations of telescope mirrors M1, M2 and M3), were taken as reference for being in an acceptable range or not. For generating an applicable vibration specification there are two main criteria which are determining. Both must stay below certain limits: first the fundamental acceleration (or force) level, and second the spike amplitudes of first frequency and subsequent harmonics, which in case of GM-type coolers are caused by their characteristic periodic displacer stroke dynamics. These limits were accordingly defined as 'acceptance level for fundamental signal' and 'acceptance level for spikes'.

We found that cryo-cooler instruments are having different impact on each of the three VLT UT foci. Due to different structure robustness, these three foci configurations are having different characteristics, resulting in three individual specifications. The Cassegrain-focus is the most sensitive, while Nasmyth-focus and even more Nasmyth-platform are somewhat more robust, resulting in somewhat higher vibration acceptance levels towards higher frequencies. However, the platform configuration has a very critical mode around 10.8Hz with strong impact on the telescope OPL. In addition different sensitivity of the platform was detected for horizontal or vertical mounted cold head configurations. From measurements in UT-1 it is assumed that the exact frequency of the critical platform mode is slightly varying for all four UTs. The presented results for Nasmyth-platform are in principle valid for UT-1 only, while for the other UTs the exact frequency of the mode would need further clarification.

In the scope of this work, ESO developed and established a mobile, independent, comparable and universal applicable instrument vibration verification methodology. Their mobile vibration sensing set-up is in principle applicable to any potential instrument. It is foreseen to verify conformity of each instrument in early development phases, but latest before final acceptance testing.

Although we are confident that the below presented specifications were developed with great care and are appropriate to better control vibrations induced by UT instruments, we are also aware that the reference data are based on 'Manhattan' measurements only. Recently, the fringe tracker IRIS discovered some more VLT-I incompatible vibrations in the 100-120 Hz range caused by KMOS, which were not detected by the Manhattan system. An instrument upgrade introducing anti-vibration mounts to the three KMOS cold heads was eliminating the issue meanwhile.

By means of the recommended instrument design and cryo-cooler operation parameters as presented earlier[5], we intend not to excite any of the known critical telescope modes and to keep vibration levels as low as required. To ensure correct implementation, it is obligatory that instrument teams are consulting ESO expertise already from early conceptual design phases on.

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