An experimental VLT cryo-cooler instrumentation vibration analysis

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ABSTRACT

Cryo-coolers are widely used to provide the required temperature levels of ESO's VLT instrumentation suite, mainly for infrared instruments and their detectors. Nevertheless, mechanical vibrations induced by these refrigerator systems became a serious issue over the last years. Especially for the extremely sensitive VLT-Interferometer even micro vibration levels can be critical. As a consequence ESO started some time ago a comprehensive vibration reduction program. Major tasks involved are the quantification of typical cryo-cooler instrument vibration levels and their impact on the VLT / VLT-I optical stability. This paper describes the design, construction and calibration of a dedicated VLT dummy instrument comprising six powerful state-of-the-art 2-stage cold heads and the subsequent comprehensive vibration measurement test campaign. As a result trendsetting cryo-cooler instrument design and operation recommendations are presented.

Keywords: ground-based instrumentation, VLT/VLT-I, cryo-cooler, cryogenics, vibration measurement, instrument design recommendations

1. INTRODUCTION

Mechanical closed cycle coolers were introduced at ESO about 20 years ago. They are mainly used to provide the required cryogenic temperature levels for infrared instruments and their detectors. Different types of these refrigerators are presently used for the VLT instrumentation suite. Relevant technical papers[1,2,3] describe their pro's and con's, especially regarding their main disadvantage of producing non-negligible levels of mechanical vibrations. It has been reported earlier[4] 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 campaign. Tasks involved are a comprehensive cooler survey, test programs and implementation of alternative low-vibration cryo-coolers, but also the development of advanced passive and active vibration damping systems[5]. In a second phase it involves the development of a so-called VLT dummy instrument to be used for a comprehensive vibration measurement test campaign in order to be able to quantify typical cryo-cooler induced vibration levels and the consequences for VLT respectively VLT-I, and to release design specifications in order to minimize perturbations. The description and the outcome of this VLT vibration measurement campaign form the main part of the presented paper.

During the test campaign the instrument was installed in three different VLT foci arrangements (Cassegrain-focus, Nasmyth-focus and Nasmyth-platform) to be operated in various orientations (vertical / horizontal cold heads, parallel / perpendicular to altitude axis etc.) and with many different operation parameters (cold head fixed or floating mounting, variations of cryo-cooler displacer frequency etc.). For each configuration the telescope vibration levels, respectively the optical path length difference (OPL) of the VLT 8m unit telescope (UT) mirror cells M1, M2 and M3 were measured by means of the VLT acceleration acquisition system called 'Manhattan'. In parallel the dummy instrument characteristic vibration levels were determined using a dedicated mobile vibration measurement set-up. The goal was to generate trendsetting instrument design and operation guidelines, followed later on by significant instrument vibration specifications after critical analyses of all measured data.

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2. VLT DUMMY INSTRUMENT (VLTDI)

Some time ago ESO selected the 2-stage Gifford-McMahon (GM) refrigerator system Oerlikon Leybold COOLPOWER 10MD as their new standard 20K cryocooler[4]. Typical powerful cryogenic VLT instruments require high cooling capacities provided by several of these devices. A typical state-of-the-art instrument often demands three or more cryo-cooler cold heads and accordingly three or more 5 kW compressors to cool the separate temperature levels for detectors, optical structures, thermal shielding etc. In an earlier paper[6] we were describing how the number of compressors, or in other words the massive input power of, for instance 15 kW may be reduced, while maintaining the required number of cold heads. The vibration characteristics of such a single cooler were very well characterized[4], but interaction of a multiple cooler system is complex since depending on many construction details. How such a multiple cryo-cooler instrument is interacting with a VLT 8m unit telescope (UT) or with the extremely sensitive VLT Interferometer (VLT-I) is even more difficult to predict. Experimental investigations promise much more reliable results.

Therefore in ESO's VLT vibration reduction program it was proposed to design and build a dedicated so-called VLT Dummy Instrument (VLTDI) with six standard cold heads arranged in different spatial configurations. Comprehensive test campaigns should focus on the detection of typical vibration levels induced by such an instrument on the VLT, but also revealing preferable cooler arrangements and definition of admissible vibration spectra for present and future astronomical instruments.

2.1 Design and construction

Our goal was to construct a typical 1 ton instrument which is compatible to be installed at the VLT UT Cassegrain rotator adaptors, the Nasmyth rotator adaptors and the Nasmyth platforms. Six cantilever arms are foreseen as rigid interface with the 1.5 m pitch circle of the telescope adaptors.

The main part of the instrument is a 400 liters volume vacuum vessel with several flanges, 1 m in diameter, 0.5 m height and machined out of one block of aluminum alloy. Dedicated 1 m flange covers are installed on either side to close the main openings of the vessel. There are no welded parts involved, standard Viton o-rings were used for all seals. Six closed cycle cooler cold heads were implemented, three in axial configuration (displacer movement direction parallel to telescope rotator adaptor axis) and three in 120º radial symmetric configuration (displacer axis perpendicular to adaptor rotator axis). A 3-axis accelerometer block is mounted at the instrument vessel for vibration sensing.

The vessel contains actually no optics but a GFRP-suspended cryogenic copper structure with power heater resistors, temperature sensors and thermal connections to the 1st stages of the cold heads. A special designed transportation trolley (weight 0.5 ton) allows also easy rotation of the vessel during assembly, integration and testing in different axial configurations. A standard gear box with hand-operated crank is providing a simple and reliable rotational drive mechanism.

Another dedicated stand with two mechanical decoupled compressor units is the second part of the VLTDI. With its two compressors, four additional power modules, manifolds, piping and tubing etc. the stand has a total weight of 0.5 tons.

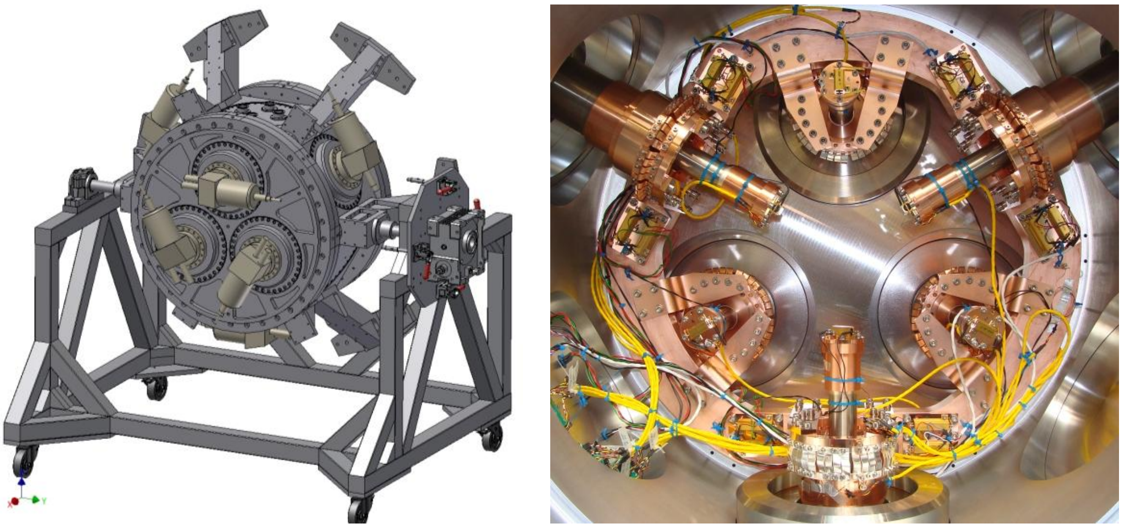

Figure 1: CAD of VLTDI: real size is 2.0m x 1.5m x 2.0m (left); VLTDI inside view: cryogenic structure with six cold heads (right)

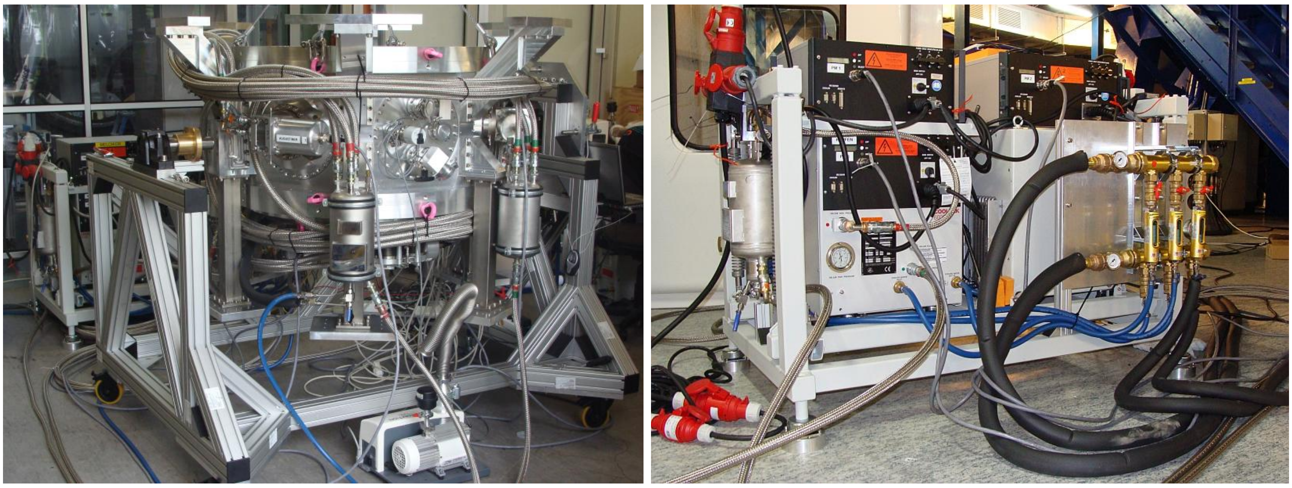

Figure 2: VLTDI and transportation trolley during test phase (left); compressor stand in operation (right)

2.2 Cryo-vacuum system

The cryogenic system is based on ESO's standard 20K cryocooler COOLPOWER 10MD from Oerlikon Leybold. This cooler offers the advantage of combining very high cooling capacities in two stages (10W@20K and 100W@80K), low vibrations and tuneable displacer frequency[4]. A standard application consists normally of one compressor in combination with one cold head. Operating the six cold heads of the VLTDI would require six corresponding compressor units besides their enormous input power consumption of 6x5 kW = 30 kW. In order to make the system manageable, modifications were implemented as described earlier[6] as advanced refrigerator system version-3 (V3), meaning three cold heads are ran by one compressor plus two additional power modules. This version was built two times to be able to operate all six cold heads in parallel. Two slightly different compressor types were used, which has no technical but more availability reasons. The total input power consumption could therefore be reduced to 10 kW. One COOLPAK 6000 MD and two additional power modules operate the so-called axial configuration cold heads, represented by those devices with even numbers (ch #2, #4, #6), see schematics in figure 3. The radial arranged cold heads #1, #3 and #5 are operated by a newer compressor series called COOLPOWER 6000 MDH, a version where the scroll compressor is for some advantages mounted horizontal. Each of the six cold head motors is driven by its own power module electronics. Cold heads can be started / stopped individually using two so-called remote start-up electronics.
The helium supply of three associated heads is provided by just one corresponding compressor. Each of the four compressor helium in-/outlets is connected by a 20 m long flex line with a 5 liter buffer reservoir, which provides gas distribution to the three individual cold head circles. The twelve flex lines from the four buffers to the cold heads are 6 m long each.
In order to evaluate the characteristics of ESO's standard cold head anti-vibration (AV) mount[5], two heads were equipped with this passive damping system (floating mount), the axial cold head #6 and the radial one #3. The other four heads are hard mounted (fixed mount) to the VLTDI vessel structure.
The main part of the internal cryo-structure is a massive copper ring. It is suspended and thermally isolated from the vessel by six GFRP-struts. All six cooler 1^{st} stages are connected with the cryo-structure by means of combinations of massive copper brackets and mechanically flexible metal foil connections. While each hard mounted head is equipped with 10 stacks of 20 copper foil layers, the AV-mounted ones have 10 stacks of softer Silver foil (less rigid, less vibration transfer). The 1^{st} stage cooling capacity of a multiple cold head system like V3 was measured to 125 W @80 K[6], resulting in a total of 250 W @80 K for the two systems as used for the VLTDI. Knowing that any multiple cold head system has to be run within a somehow critical operation envelope[6], heater resistors were integrated to introduce necessary dissipations. In addition helium pressures and compressor input currents were monitored during operation as described in an earlier paper[6]. A grid of in total 12 temperature sensors is implemented to monitor each individual 2^{nd} stage temperature and the common 1^{st} stage cryo-structure temperature.
The vacuum vessel is equipped with standard valves, a vacuum gauge and several hermetic connectors for heater and temperature sensor harness feedthroughs. A vacuum pressure of some 10^{-7} mbar was typically reached at nominal cryogenic operation temperature.

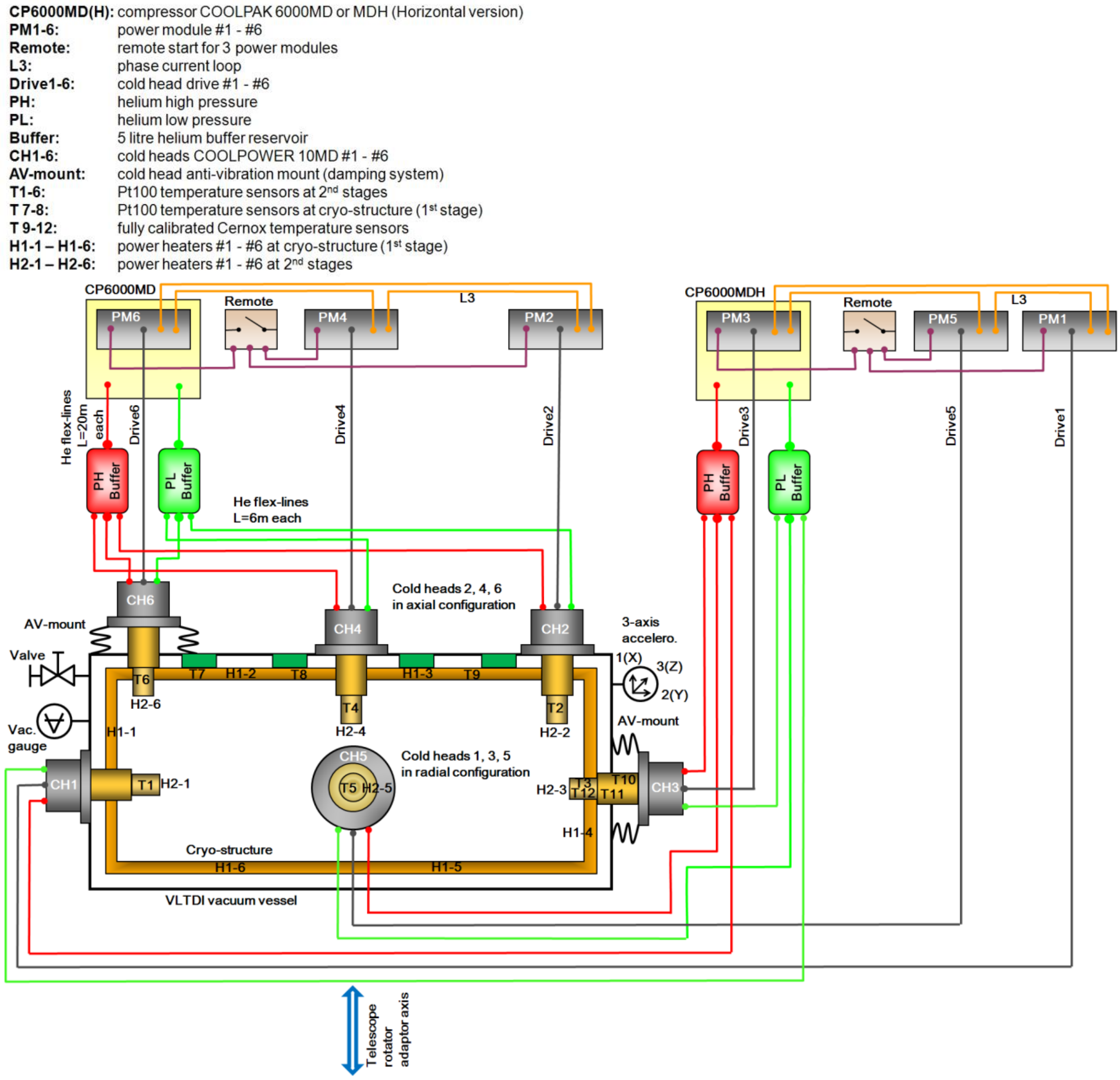

Figure 3: VLTDI cryo-vacuum schematics

2.3 Vibration sensing

For measuring the vibration levels at the dummy instrument itself, shock sensors are mounted at the outer shell of the vessel. Three piezoelectric accelerometers were used to measure simultaneously in three space coordinates. Channel 1 represents the X-axis, which is defined being parallel to the displacer movement axis of the axial cold heads #2, #4 and #6 (and as well parallel to telescope rotator adaptor axis). Channel 2 represents the Y-axis, which is parallel to the displacer movement axis of axial AV-mounted cold head #3. Channel 3 represents the Z-axis, which is in fact 90º to the X/Y-plane but has, due to the 120º partition, a residual 30º inclination with the displacer movement axes of cold heads #1 and #5.

By using the VLT 'Manhattan' system in parallel we were examining for each case the OPLs (cumulative plots in nm rms) of the three individual mirrors as well as their total system OPL in the frequency ranges of interest, in particular above 5Hz (respectively above 1Hz) up to 120Hz, as well as the frequency spectra in form of acceleration power spectral density (PSD in g^2/Hz). Some highlights are shown in the next sections.

3. CASSEGRAIN FOCUS (CF)

3.1 Cassegrain focus set-up

This set of measurements was performed in UT-2. In order to have access to the Cassegrain focus rotator adaptor, the multi wavelength spectrograph X-Shooter was temporarily dismounted from the adaptor ring. After mounting the VLTDI to the adaptor a measurement sequence with 24 different cases CF_01 – 24 was performed. Vibrations were measured in parallel with both, the Manhattan system acquiring data from the UT-2 M1, M2 and M3 mirror cells, and the VLTDI own 3-axis accelerometer system.

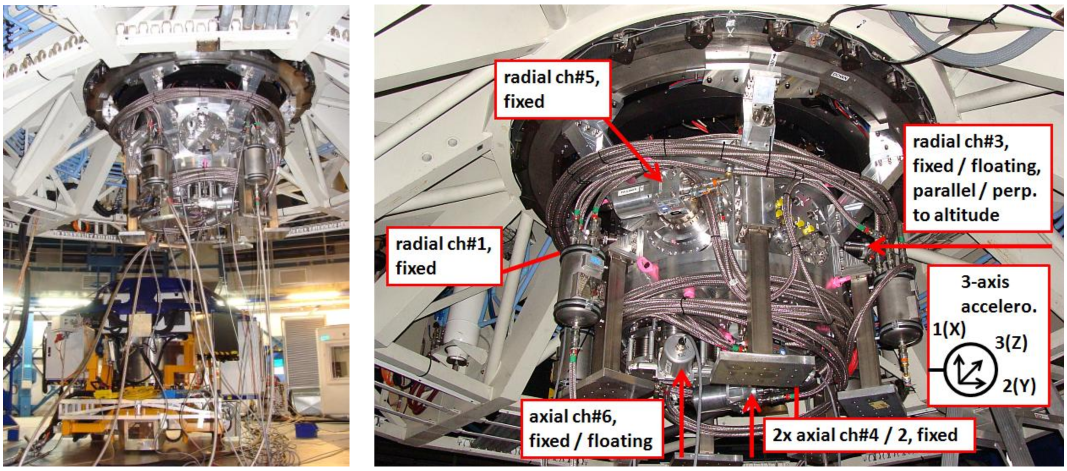

Figure 4: VLTDI at Cassegrain focus: coordinates and orientations. Axis-1 (X) = parallel to coldheads ch#2, 4, 6; axis-2 (Y) = parallel to ch#3; axis-3 (Z) = with 30° inclination to ch#1 and #5

3.2 CF telescope vibration

CF_01 - 06: Six cases with one ***radial*** cold head ***parallel*** to altitude: 1; 2; 3 with ***fixed*** cold head running at 60; 90; 120 rpm; 4; 5; 6 with ***floating*** cold head at 60; 90; 120 rpm. The damping effect of the floating configurations is clearly visible, especially at 24 Hz and 37 Hz, and to a lesser extent at very low frequencies. M1 and M2 are quasi insensitive to any changes, while excitations caused by a fixed mounted cold head are affecting M3, mainly at higher speed (120rpm).

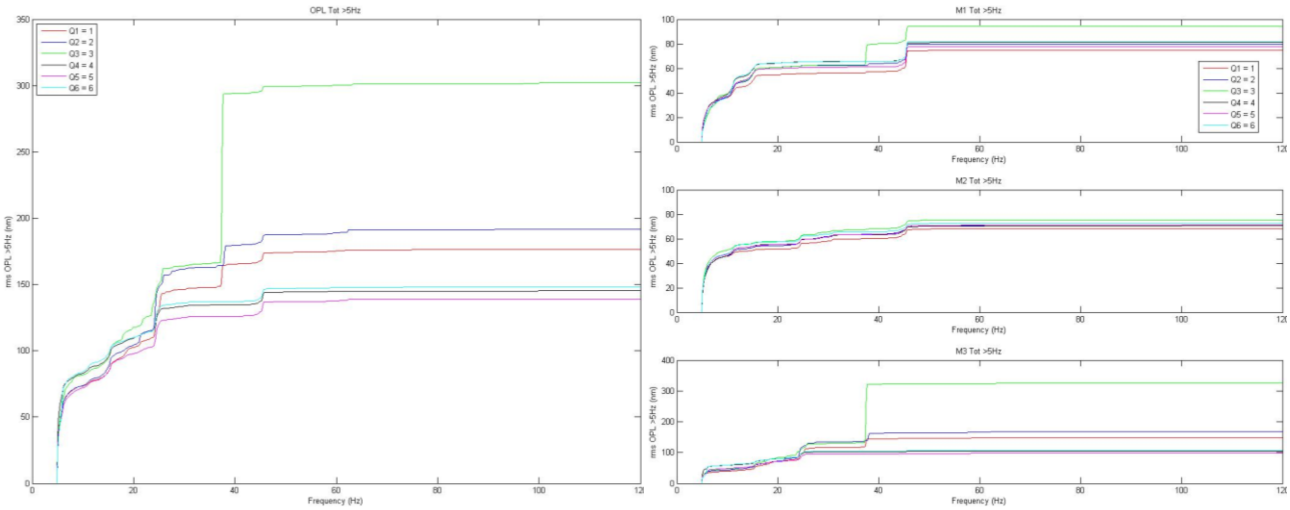

Figure 5: CF_01 - 06: OPL >5Hz in nm, total system (left) and individual mirrors M1, M2, M3 from top to bottom (right)

CF_07 - 12: Six cases with one ***radial*** cold head ***perpendicular*** to altitude: 7; 8; 9 with ***floating*** cold head running at 60; 90; 120 rpm; 10; 11; 12 with ***fixed*** cold head at 60; 90; 120 rpm. The damping effect of the floating configurations is clearly visible, especially at 58 Hz on M3, and to even larger extent at very low frequencies. Looking at the acceleration spectra (fig. 8), there are large modes appearing on all 3 mirrors for the fixed cold head configurations of 60 rpm (1 Hz and harmonics), 90 rpm (1.5 Hz and harmonics) and 120 rpm (2 Hz and harmonics), which are well suppressed for the according floating cases. The perpendicular/fixed cases are producing unacceptable high OPLs, while the measured total OPLs of the perpendicular/floating cases are much smaller, being in the same range as the previous parallel/floating ones, ~400 nm >1 Hz and ~130 nm >5 Hz.

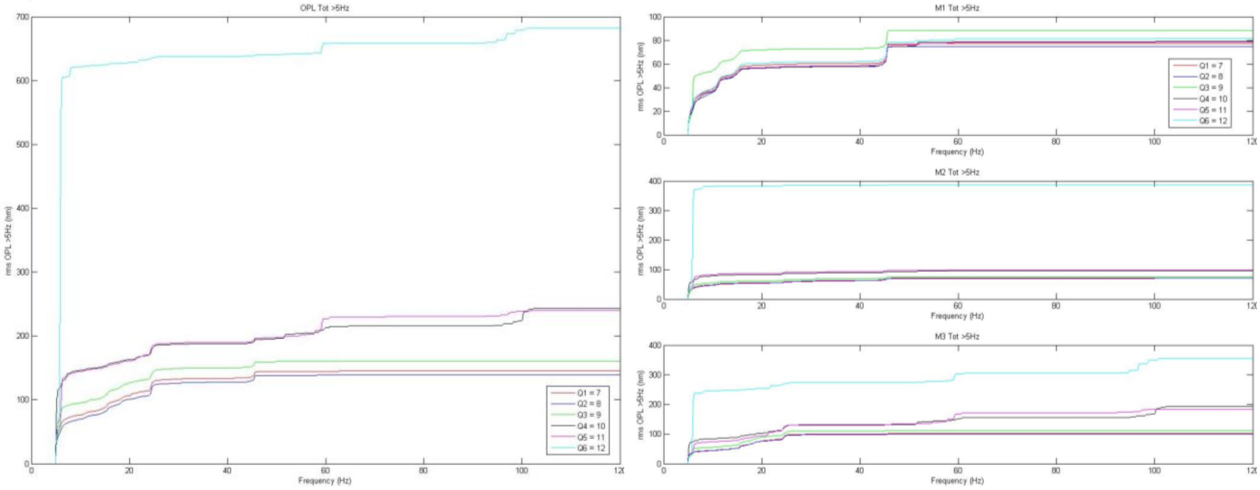

Figure 6: CF_07 - 12: OPL >5Hz in nm, total system (left) and individual mirrors M1, M2, M3 (right)

CF_13 – 18: Six cases with one ***axial*** cold head:13; 14; 15 with fixed cold head running at 60; 90; 120 rpm; 16; 17; 18 with floating cold head at 60; 90; 120 rpm. M1 is quasi insensitive to any changes, other than M2, M3. The damping effect of the floating configurations is clearly visible, especially around 60 Hz on M3, and also to a large extent at low frequencies. Looking at the acceleration spectra (fig. 8), there are large modes appearing on M2 and M3 for those fixed configurations with 60 rpm (1 Hz and harm.) and 120 rpm (2 Hz and harm.), but to a lesser extent for 90 rpm (1.5 Hz and harm.). Those modes <10 Hz are well suppressed in the according floating cases. The measured total OPLs of the axial/floating cases are for all motor speeds in the same range as the previous radial/floating ones, ~400 nm >1 Hz and ~130 nm >5 Hz. If fixed mount is unavoidable an axial configuration with a motor speed of 90 rpm has to be preferred.

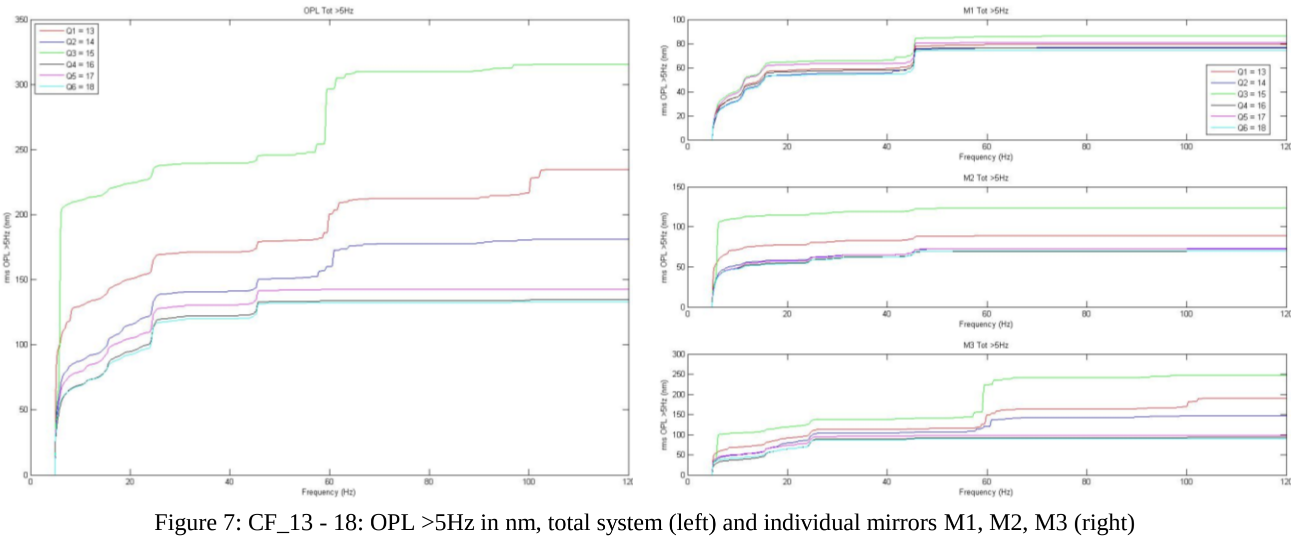

Figure 7: CF_13 - 18: OPL >5Hz in nm, total system (left) and individual mirrors M1, M2, M3 (right)

CF_19 – 24: Five different ***multiple*** cold head cases plus all heads off (fig. 9): 19 with ***two axial fixed***: relatively low OPL: 260 nm > 5Hz (-> preferred for two heads). 20 with ***three axial fixed***: high OPL, mainly due to perturbations on M2, M3. 21 with ***three axial fixed plus two radial fixed***: even effecting M1 at 1.33 Hz; 2.66 Hz etc. (80 rpm), and 2 Hz; 4 Hz etc. (120 rpm), plus interferences at 3.33 Hz and 4.33 Hz etc. (fig. 8); M1 is otherwise insensitive. 22 with ***three axial fixed plus three radial fixed***: highest OPLs measured. 23 with ***three radial fixed***: relatively low OPL: 310 nm >5 Hz (-> preferred for 3 heads). 24 with ***all cold heads off***: total OPL ~400 nm >1 Hz respectively ~130 nm >5 Hz.

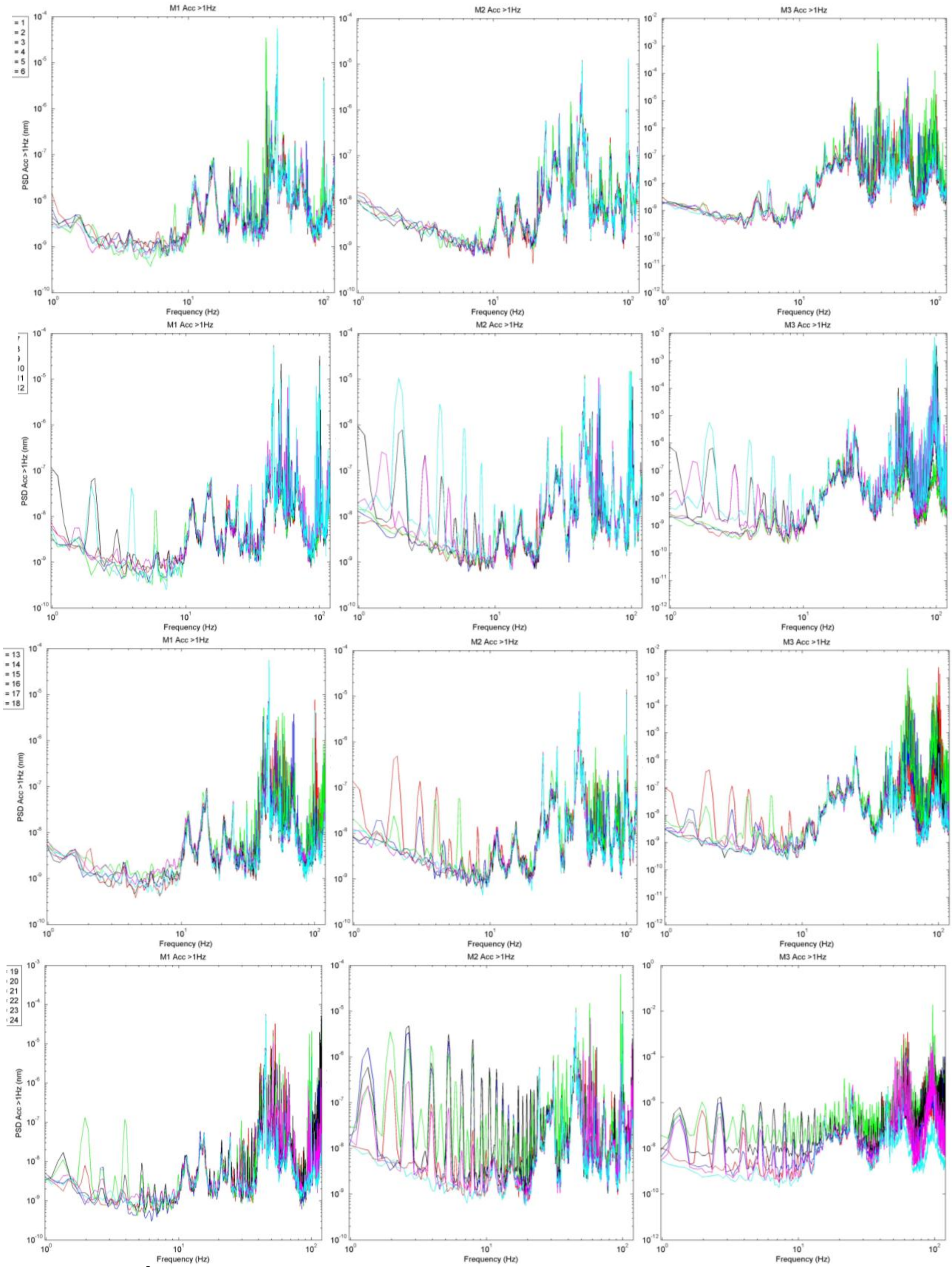

Figure 8: PSD in g^2/Hz for M1, M2, M3 (left to right); CF_01 – 06 (1. row), 07 – 12 (2. row), 13 – 18 (3. row), 19 – 24 (4. row)

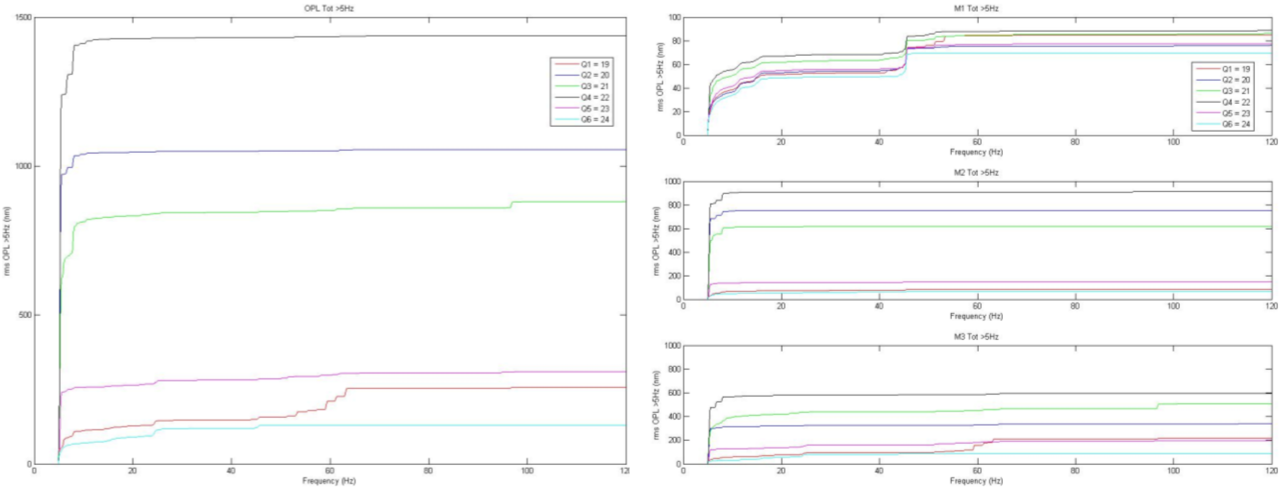

Figure 9: CF_19 – 24: OPL >5Hz in nm, total system (left) and individual mirrors M1, M2, M3 (right)

The presented cumulative plots are also detecting sensitive modes. A common OPL increase for different cases, or a step in the 'cold-heads-off' curve are indications. Those are at ~10.8 Hz (M1), 18.8 Hz, 24.2 Hz (M3), 30 Hz (M2), 41 Hz, 44 Hz, 47 Hz etc. Our goal was to find configurations which are not additionally exciting these telescope system modes.

4. NASMYTH FOCUS (NF)

4.1 Nasmyth focus set-up

This second set of measurements was performed with VLTDI installed at Nasmyth-B focus of UT-1. During all measurements, the cooling system of CRIRES was switched off (CRIRES is installed at the UT-1 Nasmyth-A platform, whereas its three compressor units are located at the telescope platform below). 47 different cases were investigated. Some examples covering NF_01 – 42 are discussed below.

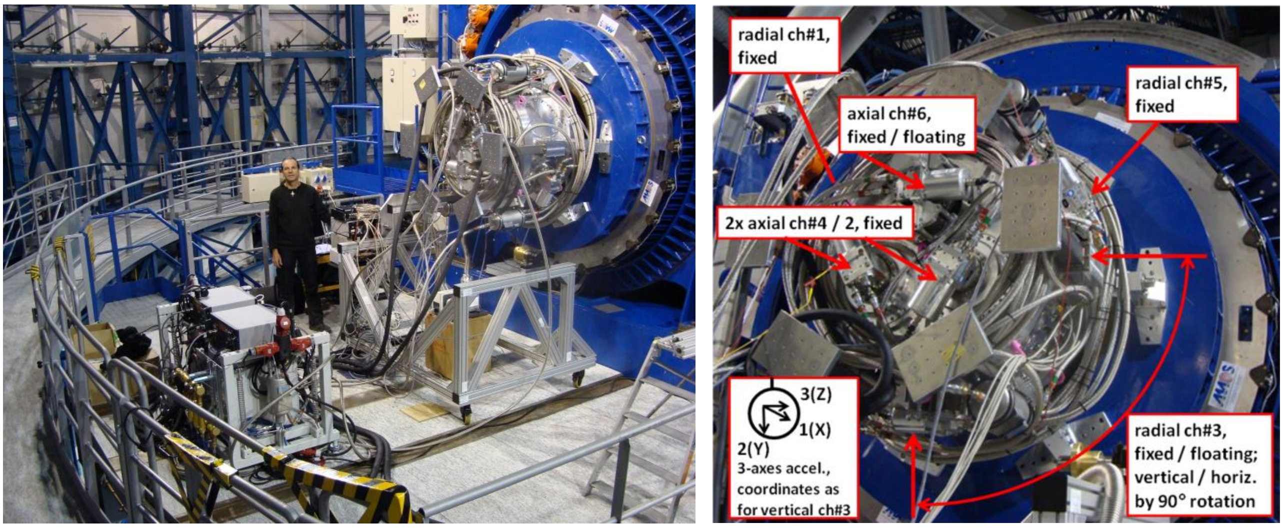

Figure 10: VLTDI at Nasmyth-B focus: coordinates and orientations. Axis-1 (X) = parallel to ch#2, 4, 6; axis-2 (Y) = parallel to ch#3; axis-3 (Z) = with 30º inclination to ch#1 and #5.

4.2 NF telescope vibration

NF_01 / 10: We investigated six cases with one ***radial horizontal*** cold head: 1; 4; 7 with ***fixed*** cold head running at 60; 90; 120 rpm versus 10; 11; 12 with ***floating*** cold head at 60; 90; 120 rpm. The measured OPLs are in general relatively low. There is also not much of a difference in OPL between the fixed and floating cases observable.

NF_01 – 09: Nine cases each with one ***radial horizontal fixed*** cold head but with varying motor speed: 1= 60 rpm; 2= 70 rpm; 3= 80 rpm; 4= 90 rpm; 5= 100 rpm; 6= 110 rpm; 7= 120 rpm; 8= 130 rpm; 9= 150 rpm. Measured OPLs are in general relatively low considering fixed mountings. Different motor speeds are mainly influencing M3. Case 9 (150 rpm) is worst and is even inducing comparably higher vibrations on M2. However, cases 3 (80 rpm) and 8 (130 rpm) are producing the lowest impact on M3 and are therefore preferable configurations (fig. 11).

NF_13 / 22: We investigated six cases each with one ***radial vertical*** cold head: 13; 14; 15 with ***floating*** cold head running at 60; 90; 120 rpm versus 16; 19; 22 with ***fixed*** cold head at 60; 90; 120 rpm. Measured OPLs are in general relatively low and are comparable to those of the radial horizontal cases. There is not much of a difference in OPL between the fixed and floating cases observable, or there is at least no systematic distribution. Case 22 (fixed, 120 rpm) created somewhat higher disturbances at 28 and 45 Hz on M2.

NF_16 – 24: Nine cases each with one ***radial vertical fixed*** cold head but with varying motor speed: 16= 60 rpm; 17= 70 rpm; 18= 80 rpm; 19= 90 rpm; 20= 100 rpm; 21= 110 rpm; 22= 120 rpm; 23= 130 rpm; 24= 150 rpm. Measured OPLs are in general relatively low considering fixed mountings. Although the measured total OPLs >1 Hz are in the same range as for the horizontal or floating cases, there some abnormalities >5 Hz appearing. Varying motor speeds are to some extent influencing M2 and M3 different. Cases 21-24 (110-150 rpm) are inducing comparably higher vibrations on M2, while M3 is somewhat more perturbed in case 23 (130 rpm). All other cases 16-20 (60-100 rpm) are producing low impacts for all mirrors and are preferable configurations (fig. 12).

NF_10 – 15: A comparison of ***horizontal*** versus ***vertical***, demonstrated by means of 3 cases, each with one ***radial floating*** cold head: 10= hor. 60 rpm; 11= hor. 90 rpm; 12= hor. 120 rpm; 13= ver. 60 rpm; 14= ver. 90 rpm; 15= ver. 120 rpm. Generally a vertical oriented cold head seems to be slightly better than horizontal. Radial cold heads at motor speeds <100 rpm are producing lower perturbations on all three telescope mirrors compared to higher speed, which should be avoided. Vertical cases 13 (60 rpm) and 14 (90 rpm) gave the best results (fig. 13).

NF_25 / 36: We also investigated six cases each with one ***axial (horizontal)*** cold head: 25; 28; 31 with ***fixed*** cold head running at 60; 90; 120 rpm versus 34; 35; 36 with ***floating*** cold head at 60; 90; 120 rpm. The measured OPLs are in general relatively low and are comparable to those of the radial cases. Floating cases are better than fixed ones, even though not much (marginal passive damping effect). By trend a lower motor speed (<120 rpm) is better than a higher one.

NF_25 – 33: Nine cases each with one ***axial (horizontal) fixed*** cold head but with varying motor speed: 25= 60 rpm; 26= 70 rpm; 27= 80 rpm; 28= 90 rpm; 29= 100 rpm; 30= 110 rpm; 31= 120 rpm; 32= 130 rpm; 33= 150 rpm. Measured OPLs are in general relatively low and are comparable to those of the radial cases. Although there is not much of a difference there are some cases causing less perturbations than others. The high speed cases 32 (130 rpm) and 33 (150 rpm) are having one of the lowest OPL values, while 120 rpm should be avoided as it is degrading the OPL of M2. Any motor speed below 120 rpm (min. 60 rpm) looks agreeable (fig. 14).

NF_37 – 42: Five different ***multiple*** cold head NF cases plus all heads off (fig. 15):
37 with ***two axial fixed*** at 120 rpm: is almost as good as all head off.
39 with ***three axial fixed*** at 80 rpm: relatively high OPL from excitations at 5Hz on M3 and at 10.5 Hz on M1 and M2. Total OPL >1 Hz = 520 nm resp. total OPL >5 Hz = 175 nm, that is +70 nm resp. +35 nm higher than with cold heads off (case 38).
40 with ***three axial fixed plus two radial fixed*** at 80 rpm / 120 rpm: relatively high OPL from excitations at 5Hz on M3, at 10.5 Hz on M1 and M2, around 30 Hz on M2.
41 with ***three axial fixed plus three radial fixed*** at 80 rpm: surprisingly quite low OPL with just one remarkable excitation at 30 Hz on M2 (latter caused by the radial heads). Incidental cold head excitation compensation is feasible.
42 with ***three radial fixed*** at 80 rpm: relatively low OPL with just one remarkable excitation at 30 Hz on M2.
38 with ***all cold heads off*** (and as before CRIRES cooling off): defining the current telescope system background without any closed cycle cooler influence:
OPL > 1 Hz: total = 450 nm; M1 = 300 nm; M2 = 275 nm; M3 = 175 nm
OPL > 5 Hz: total = 140 nm; M1 = 60 nm; M2 = 42 nm; M3 = 75 nm
We conclude that the preferred multiple cold head configurations for a Nasmyth focus instrument are the ones with either two axial or three radial heads.

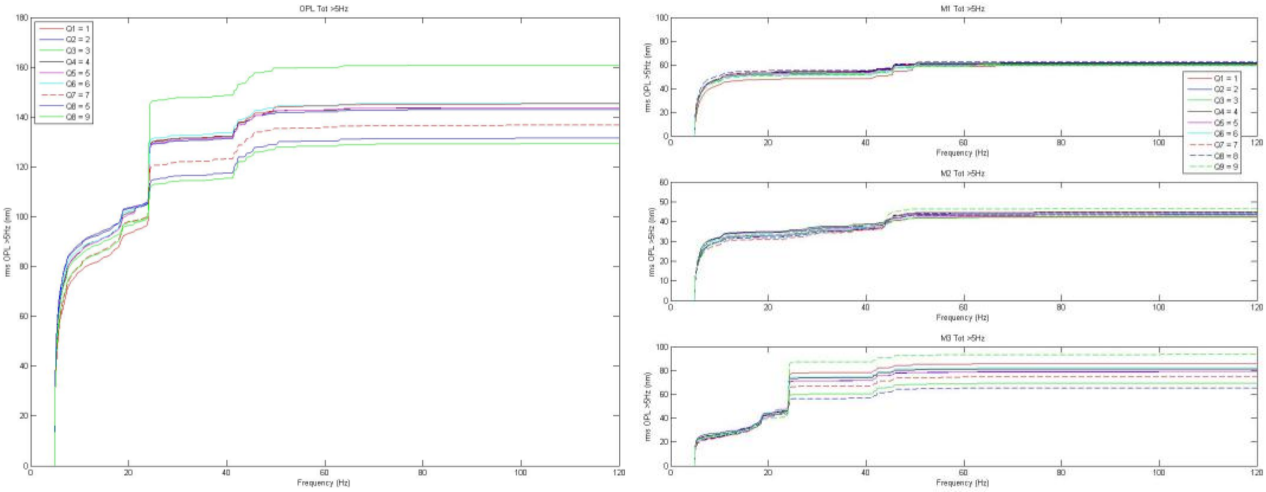

Figure 11: NF_01 - 09: OPL >5Hz in nm, total system (left) and individual mirrors M1, M2, M3 (right)

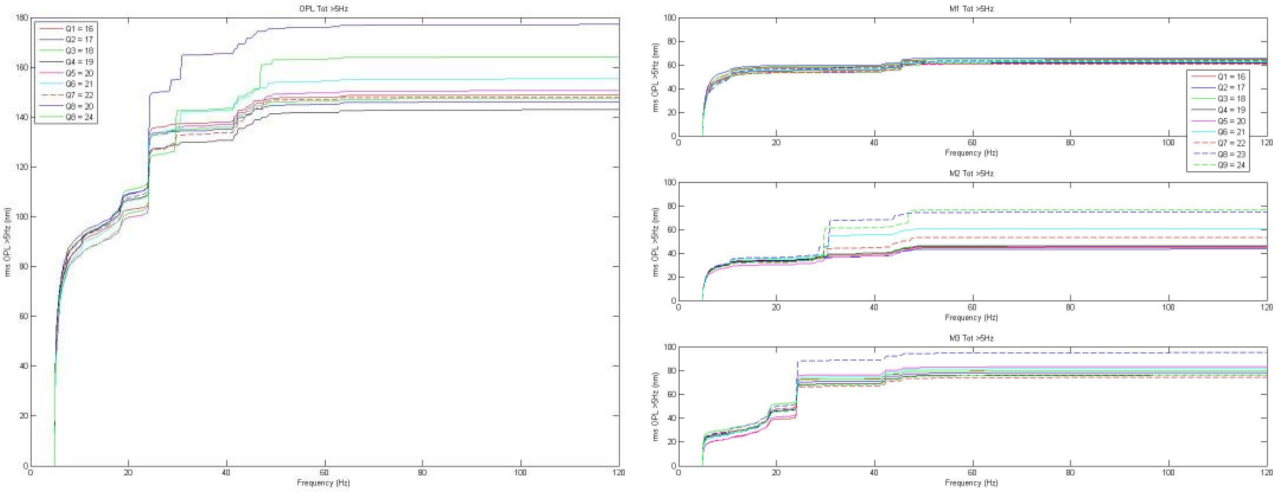

Figure 12: NF_16 - 24: OPL >5Hz in nm, total system (left) and individual mirrors M1, M2, M3 (right)

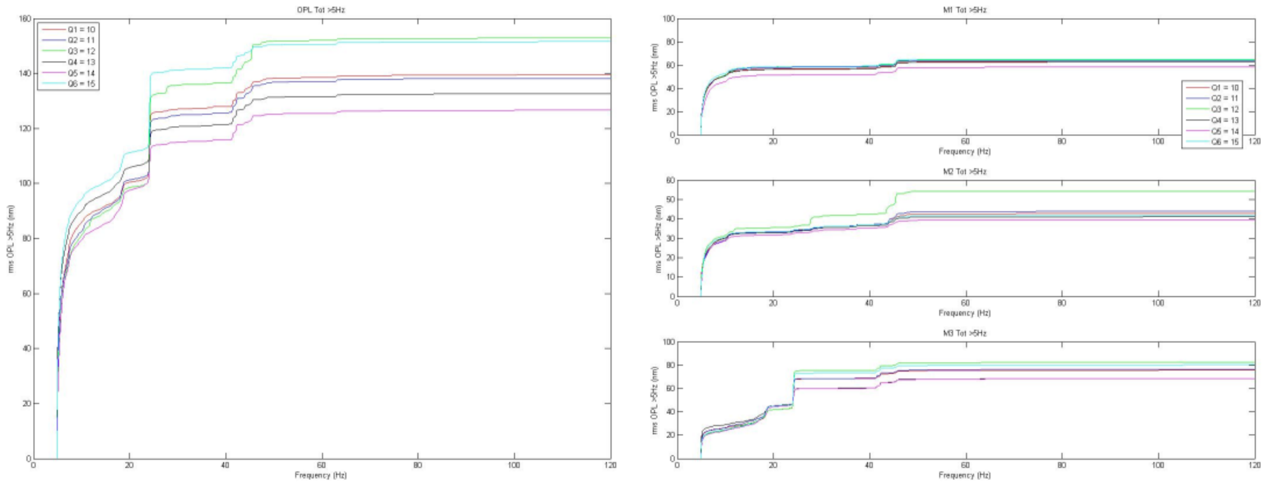

Figure 13: NF_10 – 12 horizontal; NF_13 – 15 vertical: OPL >5Hz in nm, total system (left) and individual mirrors M1, M2, M3 (right)

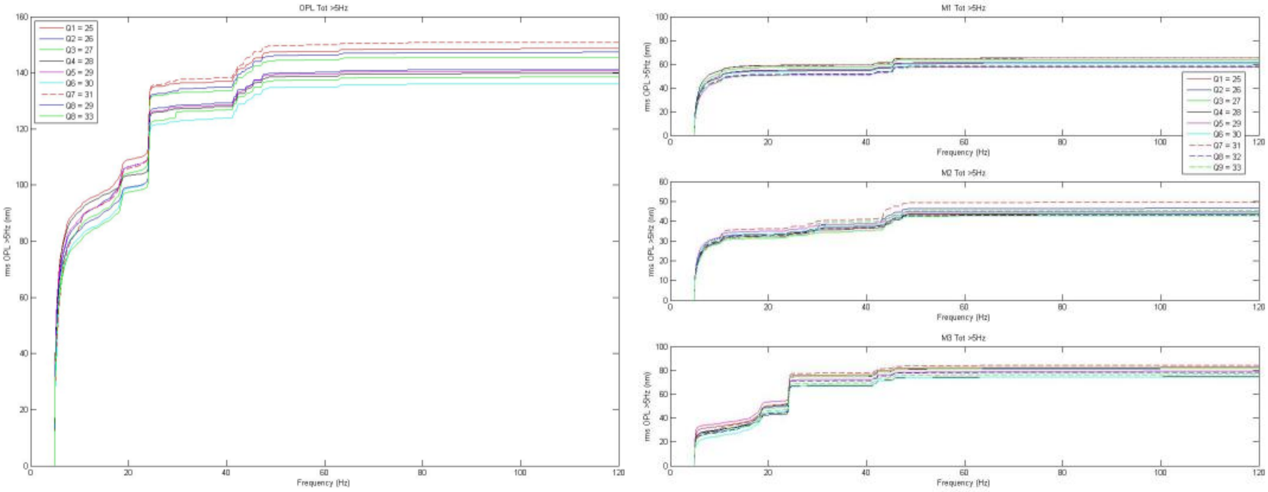

Figure 14: NF_25 - 33: OPL >5Hz in nm, total system (left) and individual mirrors M1, M2, M3 (right)

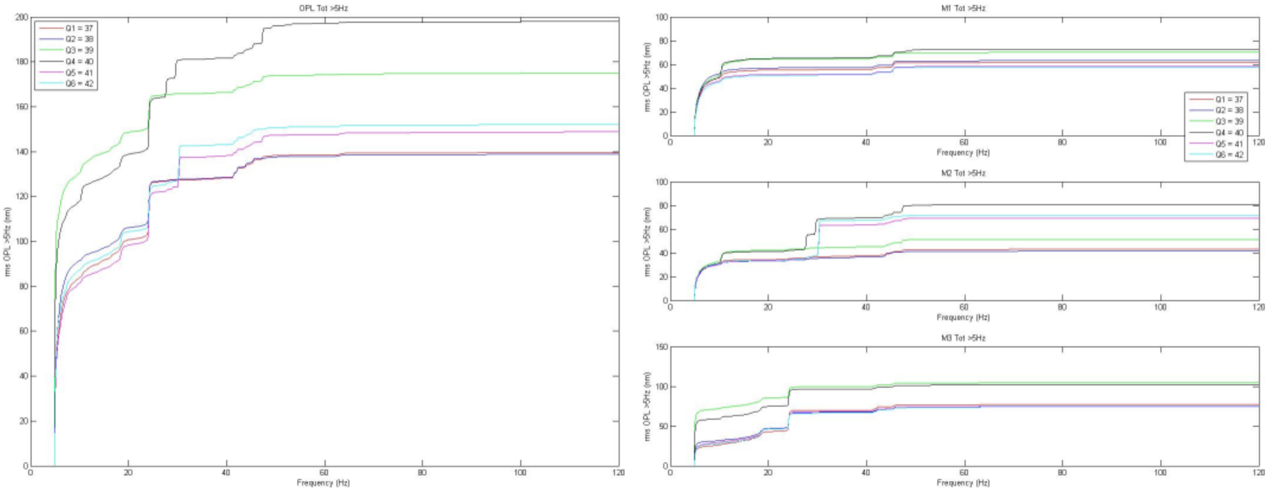

Figure 15: NF_37 – 42: OPL >5Hz in nm, total system (left) and individual mirrors M1, M2, M3 (right)

5. NASMYTH PLATFORM (NP)

5.1 Nasmyth platform set-up

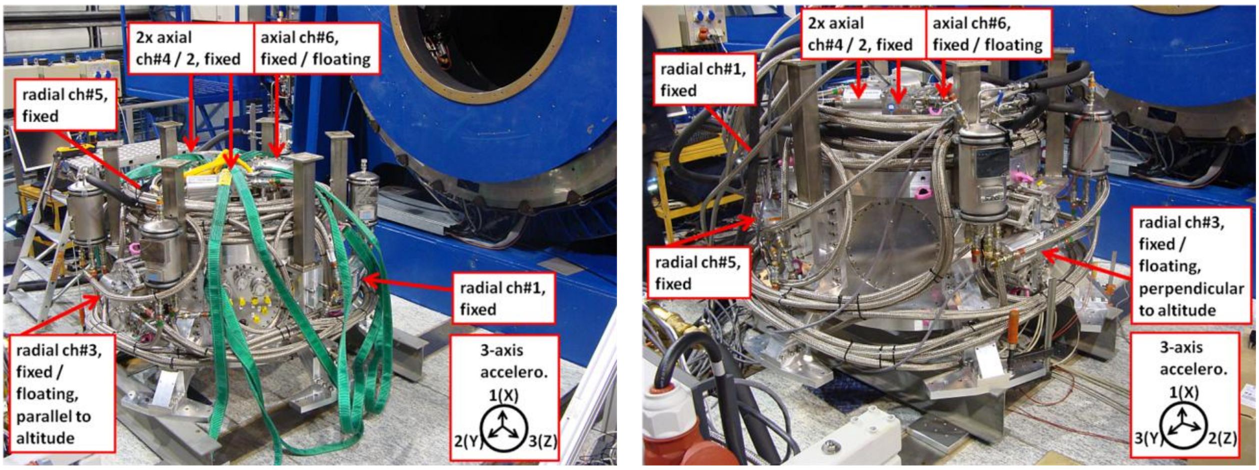

Figure 16: VLTDI at Nasmyth-B platform: ch#3 parallel to altitude (left) or perpendicular to altitude (right), coordinates as before

This third set of measurements with Manhattan was performed at the Nasmyth-B platform of VLT UT-1. The VLTDI was mounted at the platform structure in similar configuration as for example the CRIRES instrument, therefore so-called radial cold heads are always horizontal and axial cold heads are vertical. We investigated two different main arrangements, either with one radial cold head parallel to altitude, or perpendicular to altitude.
During all measurements with Manhattan, the cooling system of CRIRES was switched off (CRIRES is installed at the UT-1 Nasmyth-A platform, whereas its three compressor units are located at the telescope platform below). 56 different cases were investigated. Some examples are discussed next.

5.2 NP telescope vibration

NP_ 01 – 09: Nine NP cases each with one ***radial horizontal fixed*** cold head ***parallel to altitude*** but with varying motor speed: 1= 60 rpm; 2= 70 rpm; 3= 80 rpm; 4= 90 rpm; 5= 100 rpm; 6= 110 rpm; 7= 120 rpm; 8= 130 rpm; 9= 150 rpm. For some certain cases the measured OPLs are relatively high. This is caused by a sensitive telescope mode around 10.8 Hz when being excited by a multiple harmonic of the cryo-cooler's first frequency. Usually all three mirrors are affected.

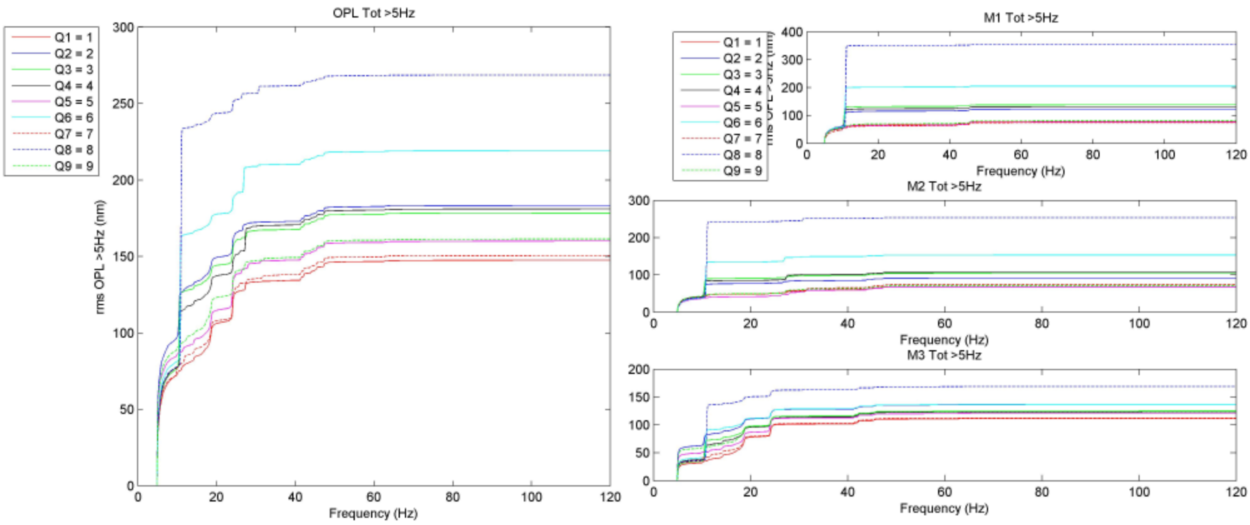

Figure 17: NP_01 – 09: OPL >5Hz in nm, total system (left) and individual mirrors M1, M2, M3 (right)

We tried to find some explanations for these findings:
Case 8 (130 rpm -> 2.17 Hz x5 = 10.83 Hz) is producing the highest OPL increase of in total +150 nm @ 10.8 Hz.
Case 6 (110 rpm -> 1.83 Hz x6 = 11 Hz) gives a factor of 2 less than case 8, with +80 nm @ 11 Hz.
Three cases are producing another factor of 2 less; they are in the same range with +40 nm increase at ~ 10.5 Hz: Case 4 (90 rpm -> 1.50 Hz x7 = 10.5 Hz); Case 3 (80 rpm -> 1.33 Hz x8 = 10.67 Hz); Case 2 (70 rpm -> 1.17 Hz x9 = 10.5 Hz).
The other four cases have almost no effect at 10.8 Hz as their corresponding harmonics are not matching with the mode: Case 1 (60 rpm -> 1 Hz with harmonics at 10; 11 or 12 Hz); Case 5 (100 rpm -> 1.67 Hz with harmonics at 10 or 11.67 Hz); Case 7 (120 rpm -> 2 Hz with harmonics at 10 or 12 Hz); Case 9 (150 rpm -> 2.5 Hz with harmonics at 10 or 12.5 Hz). Some other known telescope modes at 18.8 Hz, 24.2 Hz and at 41 / 47 Hz are producing roughly the same OPL increases for all cases.

Conclusion: For platform mounted cryo-cooler instruments the preferred configurations for a cold head parallel to altitude are to operate them at 60; 100; 120 or 150 rpm. The other speed options should be avoided. Floating mounted cold heads are producing lower OPL increases and are preferred.

NP_13 – 21: Nine NP cases each with one ***axial vertical fixed*** cold head but with varying motor speed: 13= 60 rpm; 14= 70 rpm; 15= 80 rpm; 16= 90 rpm; 17= 100 rpm; 18= 110 rpm; 19= 120 rpm; 20= 130 rpm; 21= 150 rpm. There are two noticeable cases, 18 and 20 with higher OPL increases at 10.8 Hz on M1 and M2. Those correspond to 110 and 130 rpm, which is similar to the horizontal cases but nevertheless on a much smaller level (< +20 nm @ 10.8 Hz). All other cases produce similar increases in OPL for the known telescope modes at 10.8 Hz, 18.8 Hz, 24.2 Hz and at 41 / 47 Hz.

Conclusion: For platform mounted cryo-cooler instruments the preferred configurations for a vertical cold head are to operate them at 60; 70; 80; 90; 100; 120 or 150 rpm. Floating mounted cold head are preferred.

NP_25 – 30: We also investigated various different ***multiple*** cold head cases for Nasmyth platform instruments: Generally speaking also for multiple cold head configurations of a Nasmyth platform instrument it should be avoided to excite the sensitive 10.8 Hz mode. While 80 rpm is compliant for vertical mounted cold heads, it is absolutely not for horizontal ones. 60 rpm, 100 rpm or 120 rpm for example are compliant with both, vertical and horizontal orientations.

Preferred multiple cold head configurations for Nasmyth platform instruments are:

- Two or three axial vertical heads at 60-100 rpm or 120 rpm as far as compliant with multiple operation specifications as described earlier[6]
- Combinations of up to three axial vertical heads at 80 rpm (or any other recommended speed) plus up to two radial horizontal heads at 120 rpm (or any other recommended speed)

NP_31 – 36: M***ultiple*** cold head NP cases each combining one ***radial horizontal, parallel to altitude*** with one ***axial vertical*** cold head: 31; 32; 33 with ***two fixed*** cold heads running at 60; 90; 120 rpm; 34; 35; 36 with ***two floating*** cold heads at 60; 90; 120 rpm. We discovered that 90 rpm is not suitable for both, radial and axial configurations. Fixed heads operated with that speed create the highest OPL with an increase of +45 nm at 10.8 Hz.

Finally when looking at some selected NP 'best cases' in comparison with 'all cold heads off': The overall variation of these seven cases is in the range of just 10 nm, which is mainly caused by typical uncertainties at low frequencies (<10 Hz). Case 13 with one axial vertical cold head is actually indistinguishable from 'all heads off', but also the other cases produce really low OPLs. Although the two involved multiple cold head cases are at the higher end of the distribution they are still very good and recommended.

NP_01 with one ***radial horizontal*** cold head ***parallel to altitude, fixed, 60 rpm***
NP_10 with one ***radial horizontal*** cold head ***parallel to altitude, floating, 60 rpm***
NP_13 with one ***axial vertical*** cold head, ***fixed, 60 rpm***
NP_22 with one ***axial vertical*** cold head, ***floating, 60 rpm***
NP_25 with ***two axial vertical*** cold heads, ***fixed, 120 rpm***
NP_31 with one ***radial horizontal plus*** one ***axial vertical*** cold heads, ***fixed, 60 rpm***
NP_37 with ***all cold heads off***

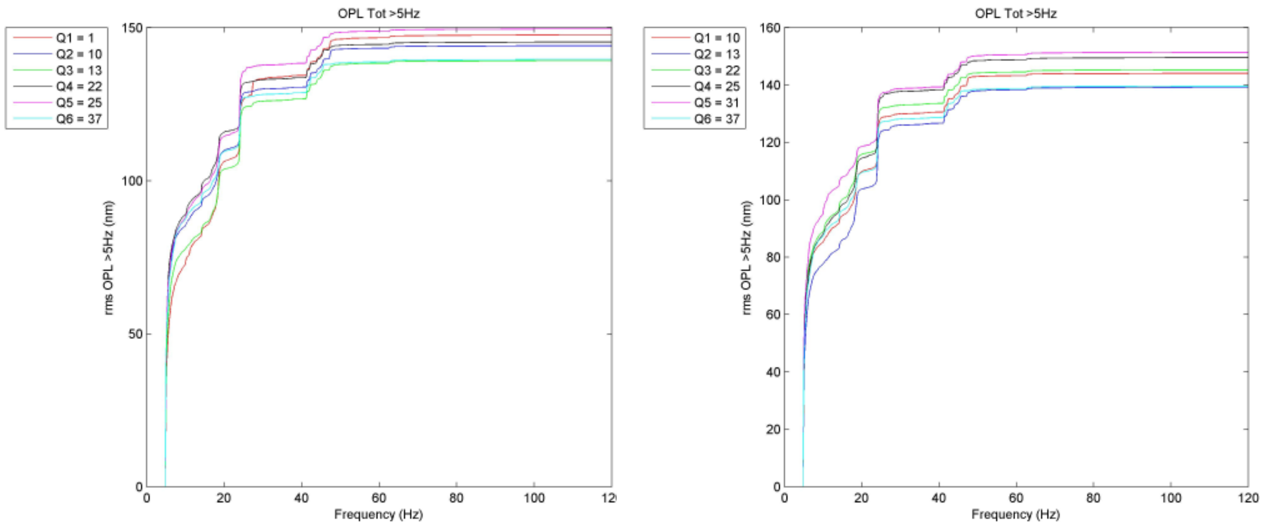

Figure 18: Some best NP cases in comparison: total system OPL >5Hz in nm

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6. CONCLUSION

6.1 Telescope background

For all three investigated instrument mounting options (CF, NF, NP) the telescope system vibration background level was acquired having all VLTDI cryo-coolers shut down. The background level is a composite interference of the individual contributions from the OPLs measured for the VLT UT mirrors M1, M2 and M3. In a first approximation the background level was diagnosed to be identical for all investigated UTs and foci configurations. The lowest values of total OPLs were measured to ~400 nm for the frequency range >1 Hz respectively ~130 nm for frequency range >5 Hz.

6.2 OPL limits

Providing a 'good VLT-I operation practice', the actual admissible limit of total generated OPL >5 Hz is around 200 nm. Within the frame of this work package, the acceptable limit of total generated OPL including cryo-cooler instrument induced vibrations was including some margin defined to 180 nm for frequencies >5 Hz, respectively to 480 nm >1 Hz.

Table 1: Measured telescope background OPL and defined limits including cryo-cooler instruments

	M1 backgr.	**M2 backgr.**	**M3 backgr.**	**Meas. telescope backgr.**	**Defined limit incl. CCC inst.**
OPL>1Hz (nm)	275	275	175	400	**480**
OPL>5Hz (nm)	60	40	70	130	**180**

6.3 VLT cryo-cooler instrument design and operation recommendations

In this section those tested cryo-cooler instrument configurations are listed which were found not to exceed the defined total OPL limits as described above in section 6.2. The following recommendations can be regarded as requirements and guidelines for the design and operation of VLT cryo-cooler instruments.

Table 2: Cassegrain focus cryo-cooler instrument design and operation requirements

Number of cold heads and orientation (CF)	**Mounting:** fixed/floating	**Cold head space orientation**	**CCC motor speed (rpm)**	**Remarks (bold is preferred)**
1 radial	Floating (only!)	Parallel/perp. to altitude (adaptor is rotating)	60 / 90 / 120	Other speeds feasible, but not tested
2 radial	Floating (only!)	Parallel/perp. to altitude (adaptor is rotating)	80	Actually not yet tested, but feasible to be ok
3 radial (=VISIR arrangement)	Floating (only!)	Parallel/perp. to altitude (adaptor is rotating)	80	fixed version **NOT** ok
1 axial	Floating (only!)	Parallel to CF rotator adaptor axis	60 / 90 / 120	Other speed options feasible
2 axial	Floating (only!)	Parallel to CF rotator adaptor axis	120	<120 rpm also feasible but not tested

Table 3: Nasmyth focus cryo-cooler instrument design and operation requirements

Number of cold heads and orientation (NF)	**Mounting:** fixed/floating	**Cold head space orientation**	**CCC motor speed (rpm)**	**Remarks (bold is preferred)**
1 radial	Fixed or **floating**	perp. to alt. + horiz./vert. (adaptor is rotating)	60 / 70 / **80** / 90 / 100	Bold is preferred
(2 radial)	Fixed or **floating**	perp. to alt. + horiz./vert. (adaptor is rotating)	(80)	tested **not ok with 120rpm**, but with 80 rpm feasible
3 radial (=KMOS arrangement)	Fixed or **floating**	perp. to alt. + horiz./vert. (adaptor is rotating)	**80**	Other speeds feasible, but not tested (60-90)
1 axial (=new HAWKI; =NACO)	Fixed or **floating**	Parallel to altitude	60/70/80/90/100 /110 / 130 / 150	Bold is preferred
2 axial (=old HAWKI arrangement)	Fixed or **floating**	Parallel to altitude	60 - **120**	Tested with 120 rpm to be very good; <120 rpm feasible
~~*3 axial*~~				***NOT*** recommended
~~*3 axial + 2 radial*~~				***NOT*** recommended
3 axial + 3 radial	Fixed or **floating**	See above	80	Fixed version tested to be ok; floating presumably better

Table 4: Nasmyth platform cryo-cooler instrument design and operation requirements

Number of cold heads and orientation (NP)	**Mounting:** fixed/floating	**Cold head space orientation**	**CCC motor speed (rpm)**	**Remarks (bold is preferred)**
1 radial / parallel to altitude	fixed	horizontal	60 / 100 / 120 /150	Do **not use 80 rpm** for any radial NP head
	Floating	horizontal	60 / 90 / 120	Other speed options feasible but not tested
(1 radial / perpendicular to altitude)		horizontal		Tested but data lost
2 radial / parallel and 60º to altitude	Fixed or **floating**	horizontal	**120**	60 rpm is also feasible; bold is preferred
1 axial	Fixed	vertical	60 / 70 / 80 / 90 / 100 / 120 / 150	Use these speed options only
	Floating	vertical	60 / 90 / 120	Same speed options feasible as for fixed but not tested
2 axial	Fixed or **floating**	vertical	**120**	≤ 100 rpm is also feasible but not tested
3 axial	Fixed or **floating**	vertical	**80**	< 80 rpm is also feasible but not tested
1 axial + 1 radial / parallel to altitude	Fixed	1 vertical + 1 horizontal	60	90 and 120 rpm not ok
	Floating	1 vertical + 1 horizontal	60 / 90 / 120	Run heads with same speed
3 axial + 2 radial / parallel and 60º to altitude	Fixed or **floating**	3 vertical + 2 horizontal	**80 + 120**	Heads of same orientation to be ran with same speed
(2 axial + 2 radial)	Fixed or **floating**	2 vertical + 2 horizontal	80 + 120	Actually not tested but feasible to be ok; also with speed options for radial heads (60 / 100 rpm)
(1 axial + 2 radial) (=CRIRES arrang.)	Fixed or **floating**	1 vertical + 2 horizontal	80 + 120	
(2 axial + 1 radial)	Fixed or **floating**	2 vertical + 1 horizontal	80 + 120	

6.4 Outlook

Our findings are defining essential requirements for VLT specific next generation instruments, but offer also a valuable prospective for the instrument design of ESO's next generation telescopes, in particular the European Extremely Large Telescope E-ELT.

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