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Linking the high-contrast performance with AO internal data and environmental parameters. Lessons learnt from the High Contrast Data Center and perspectives for the ELT

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ABSTRACT

Adaptive Optics internal data include some information about environmental turbulence conditions and the actual wavefront incoming into the science detector. The High Contrast Data Center (HC-DC, previously named SPHERE Data Center) collects all SPHERE data (science detector images and time-stamped AO RTC data statistics) and provides science-ready data products to the community. This is an opportunity to address the question of the relationship between AO internal data and the final high contrast performance. A first application is the interest of a refined prediction of the final high contrast performance as a function of turbulence conditions and AO quality, in order to better prepare the scientific programs, to improve a high-contrast ETC and to optimize observation scheduling. A second application is the use of AO data statistics in order to support and to guide the a posteriori data processing, in particular in the context of large data libraries, as used for reference star differential imaging. A third question is the potential use of extensive AO data telemetry in order to enhance a detailed characterization of the speckle field. This latter goal would also impact the AO archival approach and would raise some additional questions about the optimal data compression. After the current work on the SPHERE data, the center intends to include in the future additional high-contrast data, and in particular from ELT high-contrast (spectro-)imaging modes.

Keywords: high contrast; data center; telemetry

1. HIGH CONTRAST DATA CENTER: MASSIVE ACCESS TO HIGH-CONTRAST DATA

1.1 Data center functionalities

The SPHERE data center [1] has been set up as a service to the community in order to optimize the scientific return of SPHERE at the VLT [2] by providing optimized reduction procedures, services to users and publicly available reduced data. This service, recently renamed to high-contrast data center, has been initiated and is supported by CNRS/INSU, coordinating continuous work in several French observatories and integrating contributions such as improved signal extraction recipes or expertise feedback from several experienced observers. For such a purpose, the center is based on and is complementary to ESO data facility, starting from the ESO primary data archive, and the common instrument data calibration plan and data reduction pipeline. For operational efficiency, all calibration data are retrieved and reduced. Science data are also reduced: this is executed after the data are made public, or as a service upon request from data PIs providing the data access. The goal is to apply the pipeline data reduction in a homogeneous manner, together with traceability of the input parameters and data, quality control, and additional post-processing steps (on top of the ESO pipeline recipes) as from the users' expertise feedback (see for instance [3] and [4] for IRDIS and IFS data). Reduced data also feed back the ESO data archive, where pipeline-processed data can also be accessed[1]. Practically, the center has currently handled 150 To data; it has received 138 PI data reduction requests, and 50% of publications based on SPHERE data acknowledge the use of the center.

In order to operate such a service, the center gathers the overall data with local access, organized within a dedicated database service which makes possible to efficiently extract and relate data with possibly coupled and complex selection criteria. It is also very convenient to execute massive data reduction processed and to keep a clean traceability of the reduction processes, inputs and outputs. Whereas all the organization was primarily design for the observer users' interest, we investigate hereafter the lessons learnt from this capability to probe the large amount of data as a whole, consisting of both AO data, science data, and environmental data (sections 1.2 and 1.3). We start with the question of predictability of the actual adaptive optics performance as experienced on SPHERE depending on conditions, and of how it relates to the final high contrast performance after post-processing (section 2). On top of performance prediction of the system and reduction pipeline as they currently are, we discuss whether the AO and environmental data may actually be used to improve the signal extraction capability (section 3). We finally conclude on perspective for future ELT instruments, and in particular in their high contrast (spectro-)imaging modes (section 4).

1.2 AO performance, raw coronagraphic contrast and final contrast

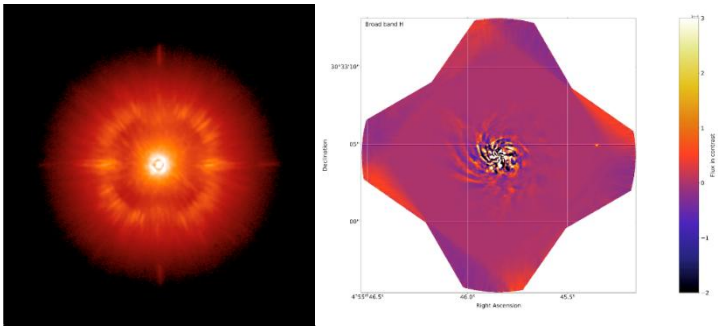

Figure 1: Examples of SPHERE IRDIS reduced imaging data. Left: raw contrast as seen on the stellar coronagraphic halo. Right: Final contrast performance for the detection of circumstellar emissions after stellar halo subtraction.

In the following, we will distinguish within the calibrated and reduced data, the information about:

1. *the raw coronagraphic contrast*: as can be seen on the calibrated images of the coronagraphic stellar halo (Fig 1, left). This image is closely related to the AO performance during the science integration: under the approximation (which is reasonable in the case of SPHERE observations on bright sources, well centered on the coronagraph) of small residual wavefront errors and of an ideal coronagraph (removing the coherent light), the coronagraphic image is proportional to the power spectrum density of the residual wavefront phase [5].

[1] https://www.eso.org/sci/publications/announcements/sciann17534.html

Coronagraphic images are very good quantitative and visual indicators of the AO performance and of the structure of the remaining defects [6].

2. *the final contrast performance*: obtained after the stellar halo subtraction for the detection capability of potential circumstellar emissions. This performance does not only involve the quality of the raw contrast, but also the stability and the total field rotation over the observing sequence, together with the stellar subtraction recipe.

1.3 AO data and Environmental data

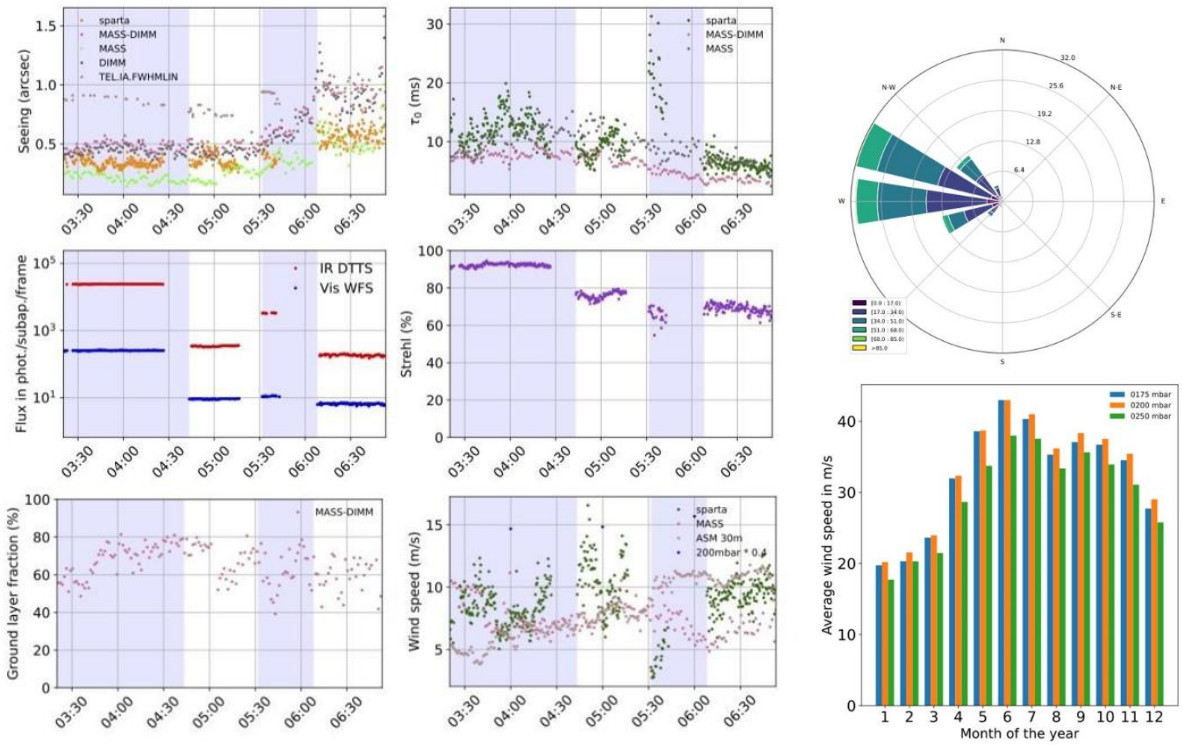

Figure 2 AO telemetry and environmental data relevant to high contrast performance. Left: example of a one-night summary of AO telemetry data and seeing monitor information, systematically archived and extracted by the center. Right: statistics on the wind direction and speed at 200mbar (jet stream altitude, as queried from the ECMWF) [20] (top: color indicates the speed, radius the occurrence, and azimuth is the direction; bottom: speed average depending on the month, as averaged of the 2014-2022 period), as from the re-analysis of ECMWF).

On top of calibration and science data, the center gathers seeing monitor and AO telemetry data. The latter consists of the stellar flux as detected in visible and NIR by the AO loop sensors, of the turbulence properties (seeing, coherence time) and AO correction (SR) as estimated from the residual wavefront sensor measurements. By default, this information is automatically recorded and archived during the science data acquisition, with a moderate time sampling of ~30 s, in order to provide some independent follow-up complementary information on the image quality conditions (the full AO telemetry is not recorded on the SPHERE system). These (publicly accessible) data are automatically retrieved in the data center. It allows to make systematic night summaries (as illustrated in Fig 2, left) or to massively correlate such conditions with the science data products.

Concerning environmental data, it is also possible to revisit the large-scale atmospheric model data, and to extract the relevant information at the position of the observatory (see Fig 2, right). Gathering such information helps to build up an appropriate statistical understanding the environmental conditions which is a strong basis for average expectations in general. It also strongly helps to test and discuss the ability to predict on a short-term basis, for operational short-term scheduling purposes. Such predictions can significantly improve the ability to satisfy the user-defined specifications of turbulence conditions required to execute their observation, and thus improve the telescope time efficiency (Fig3 left, [7,

8]). This motivates some re-enforced effort to obtain reliable predictions of wind and turbulence conditions within one to few-night timescales (Fig 3, right, [9,10]).
Whereas, this prediction capability is of well-recognized interest and represents on-going work, especially in the perspective of ELT operations, this context also emphasizes the interest to well understand the relationship between such conditions and the corresponding AO performance or final contrast performance.

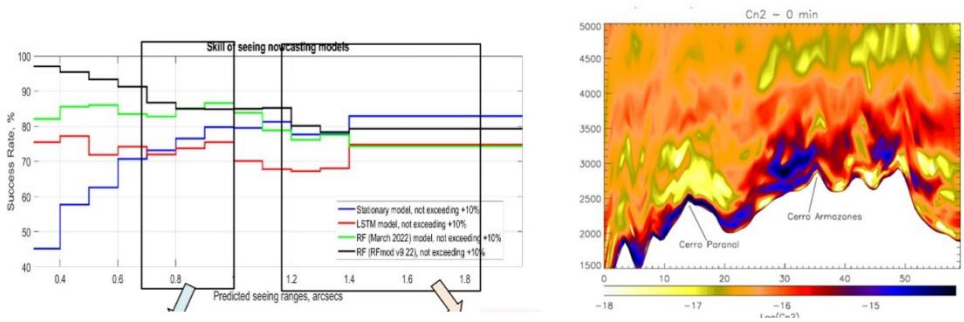

Figure 3 Interest and on-going work on the capability to predict turbulence conditions on short/mid-term timescales. Left: Impact of various prediction models on the fraction of successful observation blocks executions satisfying the user requirements. There is a potential very significant impact in the (most important) cases of severe user requirements for good seeing. (From Otarola+ [7]). Right: work on turbulence vertical profile predictions based on mesoscale models, specifically applied to observatories locations (Masciadri+ 2013 [9])

2. PERFORMANCE PREDICTION CAPABILITY

2.1 From environmental data to AO performance

As mentioned above, the coronagraphic stellar is a direct indication of the AO correction quality, and more specifically of the structure of the residual wavefront errors. In the case of bright source observation, the dominant contributors to the noise budget are i/ the wavefront "fitting error", associated to the limited number of the deformable mirror actuators, and responsible of the outer separations, and ii/, at short separations, the temporal error due the finite lag between the measurement (at 1.3 kHz in the case of SPHERE) and correction times. Corresponding simulations can nicely reproduce the observations (Fig 4, left, [11]), and the high-altitude wind direction (ie the fastest turbulence layer which drives the AO temporal error) is well consistent with the observed stellar halo elongation (Fig. 4, right).

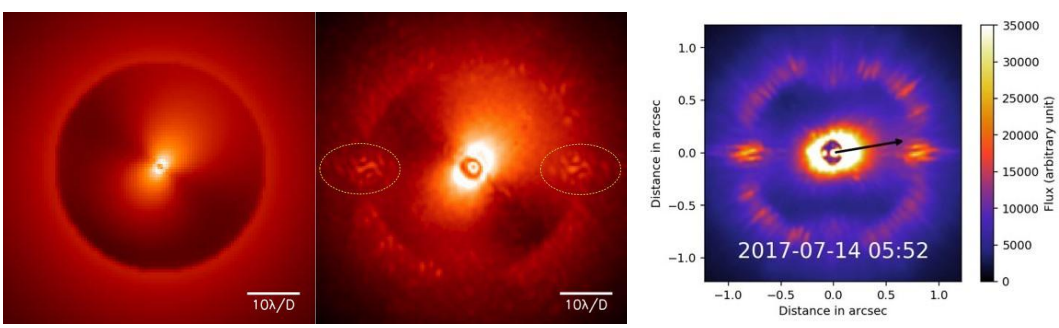

Figure 4 Coronagraphic stellar halo consistent with identified main limitations on bright targets. Observed image (middle) in comparison to simulations (left) for adjusted wind parameters [11]. Right: in case of independent measured of the high altitude wind direction (black arrow), it nicely matches the actually observed direction of main stellar halo elongation

This direct correlation between the coronagraphic raw contrast on bright sources and AO temporal error can be checked on large data sets [12], and such an identification of the primary high contrast images is a strong support to identify major avenues for upgrading of SPHERE instrument [13,14].

It is possible to precise the relation between the environmental conditions and the obtained imaging raw coronagraphic contrasts, based on large data sets, such as GPI [15] or SPHERE [16] imaging surveys. In the latter case, Courtney-Barrer et al [16] could use the SPHERE data center and handle a data set of 80000 individual images, and achieve an accuracy of ~0.3 mag raw contrast prediction (at 300 mas separation for the star). This prediction accuracy is measured

by applying an empirical model of the impact of environmental conditions (as trained on a dedicated training data set) onto a complementary test data set. The interest for such an empirical prediction capability is not restricted to the user information for preparing observation proposals; it is also meant for operational purposes such as supporting real-time quality control, and to optimize the short-term scheduling.

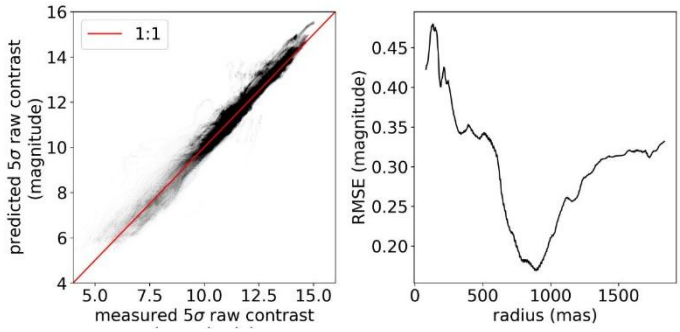

Figure 5 Raw contrast prediction capability, based on an empirical model trained on a large SPHERE imaging data set [16]. Left: correlation between predicted and measured raw contrast at 300 mas (on a test data set). Right: root mean square error of the prediction as a function of the separation from the star.

2.2 High contrast performance prediction

The next step is a tentative prediction of the final contrast performance (in opposition to the raw contrast discussed above), after the stellar halo subtraction. Obviously, this task is more difficult, including additional parameters such as the stellar properties, total integration time, pointing direction (airmass), and total field rotation during the observation sequence. For a given type of post-processing algorithm, applied systematically on large data sets, it is also possible to use a dedicated part of the data for training purposes, and discuss the prediction performance on a complementary test sample. Bissot et al used an AI approach, fed with the above considered environmental and observation parameters, and show promising preliminary results (Fig. 6). Here again, access to large data, coupled with systematic and homogeneous data processing capabilities are a key step to progress on such approaches.

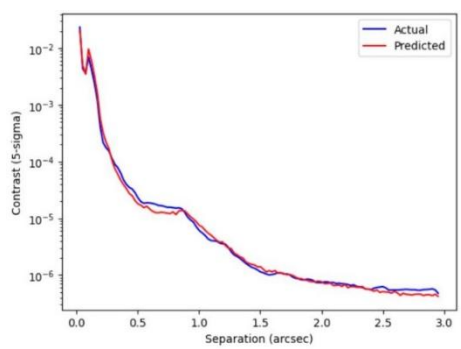

Figure 6 Post-processing contrast prediction, using an AI-trained model from environmental and observation data parameters (preliminary result, Bissot et al).

3. AO TELEMETRY IN SUPPORT TO SIGNAL PROCESSING

More than understanding the actual dependencies of the high contrast images as a function of environmental and AO telemetry data for user and operational purposes, one important issue is to investigate whether the use of such data would also practically support the signal processing for improved performance. Here again, any progress and conclusion on this needs to be studied on existing large data sets. This is mostly on-going work but it is interesting to emphasize two main prospects on this way.

3.1 Reference differential imaging: the need for navigation guiding through very large data libraries

Stabilizing the pupil orientation, in order to stabilize as much as possible any optical feature in the high contrast image, induces the astronomical field of view to rotate on the detector, at a known rate. This effect is commonly used to identify and subtract the static stellar halo wrt a rotating off-axis emission. This method is known as angular differential imaging (ADI) and is quite efficient for point-source detection, especially at large separations and/or for large field rotation observations (where the discrimination will be the most powerful). Alternatively, reference differential imaging (RDI) consists in using other stellar observations (free of circumstellar emission). These additional images are used to generate a space where to identify the best estimate of the stellar halo in the observation of science interest. A significant gain can indeed be obtained in case of circumstellar disks (especially when far from the edge-on orientation) and even for point-source, at very short separations (Fig 7 extracted from Xie et al 2022 [18])

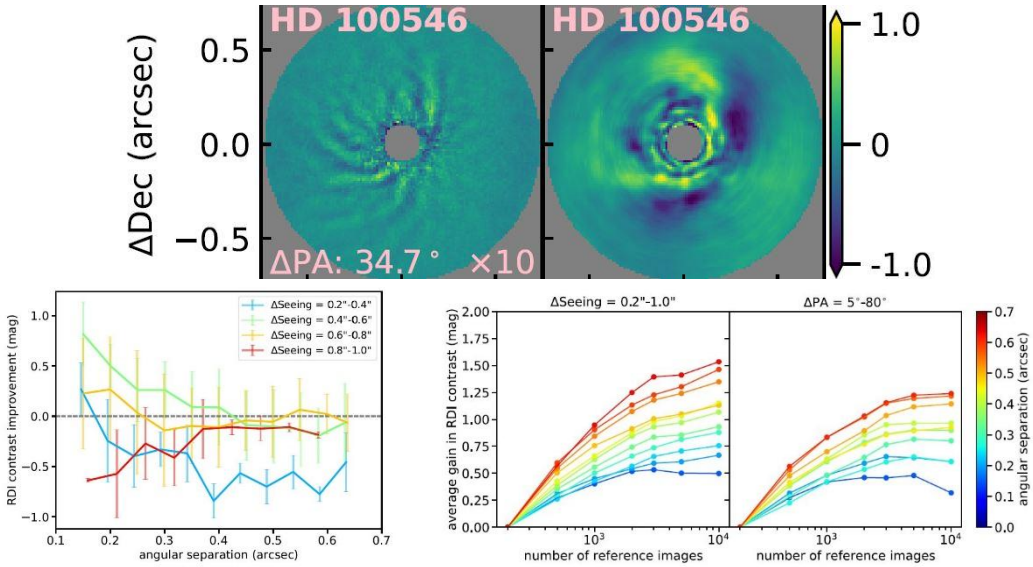

Figure 7 Comparison of Reference Differential Imaging (RDI) wrt Angular Differential Imaging (ADI) for stellar halo subtraction (figure from Wie+ 2022, [18]). Top: resulting extended circumstellar disk detection in ADI (left) and RDI (right). The remaining flux is strongly attenuated due to self-subtraction in case of ADI (and the flux is multiplied by a factor 10 for visualization purposes). Bottom left: RDI over ADI contrast gain in case of point-source detection. RDI over-performed ADI at short separations and in the seeing range (as estimated from RTC values) corresponding to the majority of the reference library only. Bottom right: improvement of RDI performance as a function of the number of the reference images used in the library (for various separations: colors, and averaged over a range of seeing or a range of field rotation).

However, the performance study over a very large data set (~ 10^5 individual images obtained in the same observing mode of SPHERE, [18]) evidences the importance of the reference library size. Handling such a huge data set requires to collect all the data and to build an progressively improving knowledge of the instrument. Practically, it also implies some data pre-selection to be applied for the relevant reference images for a given observation (as already mentioned previously [17]). This pre-selection is dependent on environmental conditions, and this motivates further work to optimize such pre-selection for more efficient data handling and better performance.

3.2 Taking benefit from the AO WFS instantaneous information on the residual WFE?

Up to this stage, we only considered either external (environmental) or AO telemetry data as indicators of the "conditions" of the observations, which could be useful for better understanding of the observation performance properties, for operational purposes with short- and medium-term scheduling, and even for improving RDI signal extraction. For such goals, statistics of the AO telemetry data, averaged over durations of typically 10s of seconds or even minutes, as they are commonly available by now. We may consider the interest of using the instantaneous AO wavefront sensor (WFS) data, at the kHz sampling rate. The corresponding amount of data is very significant, especially in the perspective of ELTs, and will probably require a strong and demonstrated scientific gain in order to be

implemented. Such demonstration is not established yet, but we can emphasize the reason why this is worth investigating and the current foreseen work. The conclusion of this work might have some impact on the AO data archiving scheme.

Why would the AO instantaneous data be valuable for high contrast imaging? Whereas the time-averaged WFS data include some information on the incoming turbulence and on the provided image quality (variances of the residuals), the individual sensor information includes the information of the actual current wavefront error (WFE), although it might be at quite a low signal to noise ratio, given the very high sampling rate. Ideally, most of the information is to be used, as much as possible in real-time, and all current efforts on AO predictive control laws aim at minimizing such residuals, and in particular any correlated part of them. At the end, we should look for the possible use of any remaining information for a posteriori processing.

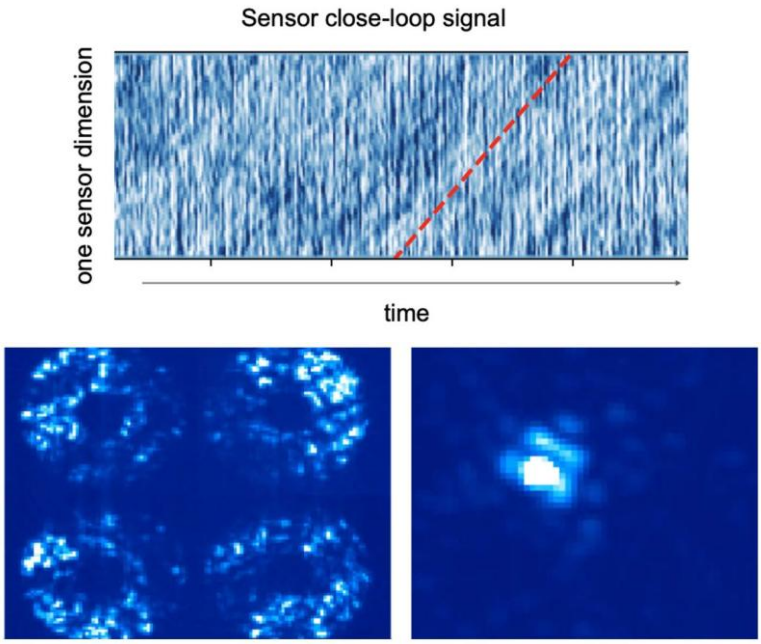

Figure 8 Examples of short-exposure AO WFS data. Top: one line of the SPHERE sensor data evolution with time. Patterns along an inclined line are indicative of correlated residuals associated to a given wind speed. Such a dominant speed is indicated by the red dashed line (M. Bonse, private comm). Bottom: example of pyramid WFS data and corresponding visible short-exposure science focal image that can be recorded and synchronized on Subaru/ScexAO system (O. Guyon, private comm).

Considering the intrinsic potential interest of such an information, but also the practical impact in terms of short-exposure data archiving requirements, M. Bonse leads a collaborative study on this subject, starting with collecting an appropriate working data set on a bright star. It will include properly time-stamped and synchronized short-exposure images from both the WFS, and low-noise science camera in NIR and in visible. This is currently possible on the Subaru/ScexAO system (O. Guyon, private comm). Depending on the preliminary steps, this might trigger a community data challenge in 2024.

4. TOWARDS HIGH CONTRAST ON ELT

Lessons learnt from the SPHERE observations confirm how much high contrast imaging is sensible to AO residuals. Hence, the detailed study of the achieved high contrast performance is naturally closely related to the development of AO up to its performance limits. Using large data sets obtained in diverse actual observation conditions is complementary to numerical or in-lab test studies, and it drives qualitatively new improvements for both the operational efficiency and the post-processing performance.

Eventhough the first-generation of ELT instruments cover general-purpose broad science cases, high contrast observation modes are also already included in METIS, MICADO, HARMONI; later-on, the exact expectations and performance requirements for ANDES SCAO is also to be precised, and finally, these first steps and the derived experience will also feed the design of the PCS instrument optimized for high-contrast. ESO strongly stimulates

community exchanges among instrument designers and users, with topical inter-instrument working groups [20][2], in order to benefit from such lessons learnt and complementary expertises. Here again, we can note that "High contrast imaging" is clearly identified as an important topic; it is also closely related to other critical working groups, namely "Simulated PSF and AO performance", "Instrument simulation", and "Astro-weather".

On the data center side, the SPHERE-DC, working on the basis of the instrument calibration plan and the delivered pipeline recipes, and in complementarity to ESO data management facilities, is considered as a positive experience. It is beneficial to many users and also, as mentioned here, it makes possible or strongly facilitates qualitatively new investigations on large-scale data sets in an efficient and process-controlled manner. On the French side, the project has been confirmed for the future, and even enlarged in scope, in order to consider including new future instrument data, within the domain of high contrast (spectro-)imaging. The center is renamed for "High Contrast Data Center" (HC-DC). The next step is to enrich the contacts with the upcoming relevant instruments experts to feed this operating infrastructure. It should be noticed that, with reasonable investment, the integration of processing recipes within the data center appeared in the past experience to benefit not only to users, but also to the instrument developers to help qualify and improve the systematic data and performance qualification. Such further developments will be pursued in collaboration with the consortia, and ESO. They should be also kept closely related to the experts in the next generation AO facilities.

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