The Differential Tip-Tilt Sensor of SPHERE

Pierre Baudoz[a,b], Reinhold Dorn[c], Jean-Louis Lizon[c], Thierry Fusco[d], Kjetil Dohlen[e], Julien Charton[f],, Jean-Luc Beuzit[f], Pascal Puget[f], David Mouillet[f], Markus Felt[g], François Wildi[h], Andrea Barrufolo[i], Markus Kasper[c], Norbert Hubin[c]

[a] Laboratoire d'Etudes Spatiales et d'Instrumentation en Astrophysique (LESIA) – Observatoire de Paris, 5 Place Jules Janssen 92195 Meudon France;
[b] Groupement d'Intérêt Scientifique PHASE (Partenariat Haute résolution Angulaire Sol Espace) between ONERA, Observatoire de Paris, CNRS and Université Paris Diderot;
[c] European Southern Observatory (Germany);
[d] Office National d'Etudes et de Recherches Aérospatiales (France);
[e] Laboratoire d'astrophysique de Marseille (France);
[f] Laboratoire d'astrophysique de l'Observatoire de Grenoble (France);
[g] Max-Planck-Institut für Astronomie (Germany);
[h] Observatoire de Genève (Switzerland);
[i] Osservatorio Astronomico di Padova (Italy);

ABSTRACT

The SPHERE instrument aims at detecting giant extrasolar planets in the vicinity of bright stars. Such a challenging goal requires the use of a high performance Adaptive Optics (AO) system, a coronagraphic device to cancel out the flux coming from the star itself, and smart focal plane techniques to calibrate residual uncorrected turbulent and/or static wavefronts. Inside the adaptive optic system, a specific tool is developed in SPHERE to ensure that the star is always well centered on the coronagraph. This tool called Differential Tip-Tilt Sensor (DTTS) measures the position of the star at the same wavelength than the science instruments. It is located very close to the focal plane to minimize drifts between DTTS and the coronagraph. After describing the DTTS, we will describe the tests and laboratory results on stability measurement of the DTTS; stability which is crucial for SPHERE performance.

Keywords: High Contrast Imaging, Coronagraphy, Adaptive optics

1. INTRODUCTION

SPHERE [1], is an exo-planet imager instrument based on extreme adaptive optics, stellar coronagraphy, visible and near-infrared (NIR) high-contrast imagers (ZIMPOL, IRDIS), and a NIR integral field spectrometer (IFS). The prime objective of SPHERE is the discovery and study of new planets orbiting stars by direct imaging of the circumstellar environment. The challenge consists in the very large contrast of luminosity between the star and the planet (larger than ~12.5 magnitudes or ~10^5 flux ratio), at very small angular separations, typically inside the seeing halo. The whole design of SPHERE is therefore optimized towards high contrast performance in a limited field of view and at short distances from the central star. Both evolved and young planetary systems will be detected, respectively through their reflected light (mostly in the visible by ZIMPOL) and through the intrinsic planet emission in the NIR (IRDIS and IFS modes). The proposed design of SPHERE is divided into four subsystems: the Common Path and Infrastructure (CPI) and the three science channels, a differential imaging camera (IRDIS, Infrared Dual Imager and Spectrograph), an Integral Field Spectrograph (IFS), and a visible imaging polarimeter (ZIMPOL, Zurich Imaging Polarimeter). The Common Path includes pupil stabilizing fore optics (tip-tilt and derotator) where insertable polarimetric half-wave plates are also provided, the SAXO [2] extreme Adaptive Optics (AO) system with a visible wavefront sensor, and NIR and Vis coronagraphic devices. ZIMPOL shares the visible channel with the wavefront sensor through a beamsplitter and the NIR beam is shared between the two instruments IFS and IRDIS and an infrared Differential Tip-Tilt Sensor (DTTS), which is part of the SAXO extreme adaptive optics.

2. THE DIFFERENTIAL TIP-TILT SENSOR

2.1. Purpose of the DTTS

The average image position (or optical axis position) on the coronagraphic mask is a main specification for the SPHERE instrument. Indeed, the precise positioning and repositioning of the image on the coronagraph is crucial for the fine calibration of the residual speckles left uncorrected by the AO. The accuracy of this mean position has to be better than 0.5 milliarcseconds (mas; with a goal of 0.2 mas). The global error on the mean position depends on :

- The residual uncorrected tip-tilt fluctuations at very high frequency (considered here as a noise). The studies on SAXO have shown than such fluctuations will be lower than 2 mas instantaneously, assuming a 1 kHz frame rate for the AO tip-tilt. Considering a 1 s integration time, this leads to a residual error of 0.06 mas.
- The differential refraction effect (between visible and IR wavelengths). Such an effect can been estimated to 0.16 mas per second (linear evolution with time) in the typical case of a 45° Zenith angle.
- The differential thermal or mechanical effects between WFS and imaging path. Such an effect has been estimated to 0.031 mas per second (linear evolution with time).

Considering all the possible parameters involved, we believe that a solution based on an open loop model of each differential evolution will not be accurate enough to reach the absolute position performance. As an example, a 10 % error on the model will lead to a residual shift of mean image position of 0.02 mas per second and then it will be over the specification for a 25 s observation time. A detailed study of the possible ways to measure tip-tilt on the imaging path has led to the choice of an auxiliary sensor located as close as possible to the coronagraph focal plane device. This instrument called Differential Tip-tilt Sensor (DTTS) is a specific tool developed inside SAXO to ensure that the star is always well centered on the coronagraph.

Obviously, this DTTS must be mechanically stable with respect to the coronagraph. A global estimation of thermal drift and dynamical errors has shown that the DTTS must be stable to 0.22 mas/hour to fulfill SPHERE requirements in terms of performance. This can be divided in the two axis with a required precision better than 0.14 mas/hour/axis. For the F/D=40 beam of SPHERE, this means a stability of the DTTS measurement (i.e. detector) compared to its interface with SPHERE bench better than 0.22 μm/hour/axis.

2.2. DTTS description

The DTTS is located at the shortest possible distance of the coronagraph to minimize differential movement between both elements. The DTTS records focal plane images in the IR with a bandwidth identical to one of SPHERE infrared filter. To avoid any differential movement between the DTTS detector and the coronagraph, the number of optical elements of the DTTS has been kept very small. A beamsplitter located a few tens of centimeters upstream of the coronagraph focal plane reflects 98% of the light to the IR instruments (see Figure 1). The residual 2% are transmitted to the DTTS. Between the beamsplitter and the DTTS detector, there is only two optical refractive elements: a cryostat window and an IR cold filter. This filter is centered on λ_0=1.536 mm with a bandwidth of 50 nm ($\lambda/\Delta\lambda$=30). A cold stop is also inserted inside the cryostat to minimize the IR background received by the detector and leaves an unvignetted field of view of 4.2 arcseconds on the F/40 beam delivered by SPHERE.

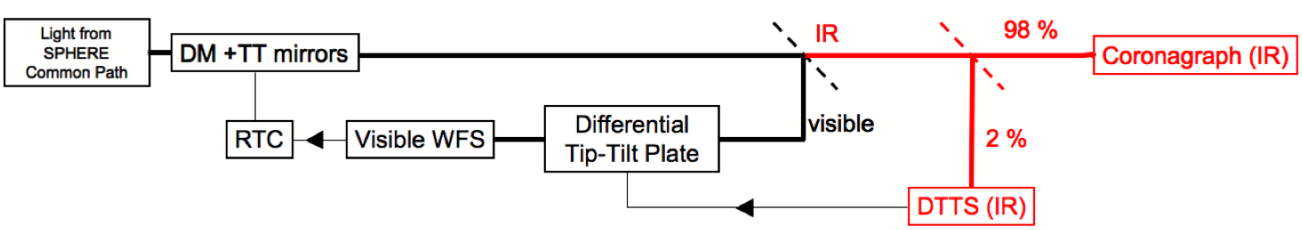

Figure 1. Schematic representation of the Differential Tip Tilt Sensor (DTTS) loop which gathers the DTTS, the RTC and the Differential Tip Tilt Plate (DTTP)

The cryostat is a continuous flow cryostat developed at the European Southern Observatory (ESO). Its principle uses the over pressure produced by the natural evaporation of the liquid nitrogen tank to circulate the coolant to the cryostat via a vacuum insulated line. The coolant is then circulating into a cold plate, which directly cools the chip carrier. The coolant continues via a second annular heat exchanger, which surrounds the first one, acts as radiation shield and cools the radiation shield of the head. Before leaving the cryostat, the gas turns in a third heat exchanger where it is warmed up close to ambient temperature in order to avoid any risk of condensation along the exhaust pipe. A PID controller is used to controller the temperature of the cold plate by action on a small electro-magnetic valve which leave coolant circulate in the tubing. A second controller is used to control the temperature of the gas in the warm heat exchanger. The detector temperature can reach temperature as low as 87 K. A third PID controller is used to stabilized the temperature detector plate to 87.5 K ± 0.005 K. In order to keep a good vacuum over a long period of time the cryostat is also fitted with a small sorption pump.

The detector is a Hawaii I 1024x1024 array with a detector board designed at ESO. The cryogenic setup consists of a detector board and a flex-rigid detector cable with a single vacuum connector. The four quadrants of the detector are read by four outputs at a pixel framerate of 250 kHz. A dedicated reading mode has been implemented to allow rapid recording of small windows anywhere inside one quadrant. The same window is read in each four quadrants but only one is used in our application. The electronics developed by ESO allows Detector Integration Time (DIT) as short as 1ms for small windows of 10x10 pixels. This aspect is crucial since SPHERE will observe a large range of stellar magnitude (from H=-2 to H=8) and we want to avoid any neutral density filters inside the DTTS to minimize thermal and mechanical drift with respect to the coronagraph focal plane. The data acquisition system is based on the New General detector Controller developed at ESO.

2.3. DTTS loop correction

The DTTS loop works as described below :

1. Acquisition of star images with speed varying from 1Hz to 1kHz !! (depending on guide star magnitude which varies from H=8 to H=-2).
2. Computation of residual movement from DTTS data with a frame rate of 1Hz
3. Application of correction on the Differential Tip-Tilt Plate inside the visible wavefront sensor (WFS) arm. This plate is a refractive element which can be oriented to introduce small displacements of the optical beam in front of the visible WFS.

3. DTTS TEST RESULTS

As described in the previous section, the DTTS detector must be stable with respect to its interface with the SPHERE bench with an accuracy of 0.14 mas/hour per axis. A study of the different effects that can introduce drifts on the DTTS has shown that the main contributor is temperature variation inside and outside the cryostat. The temperature variation of SPHERE bench at DTTS location is expected to be lower than 0.25 °C/hour while the detector temperature is well stabilized at 87.5 K ± 0.005 K. The detector effects (flat field, background) can potentially introduce drifts but of several orders of magnitude lower than temperature variation.

3.1. Description of the tests set-up

To verify that the DTTS can reach the expected stability, we implemented a bench to test the movement of the DTTS detector with respect to the interface between the SPHERE bench and the DTTS cryostat. We kept the set-up as simple as possible to avoid errors from the test apparatus. The mechanical plate that is located on the front side of the cryostat defines the interface. To measure the motion of the detector compared to this plate, we installed a mechanical structure in front of the cryostat window to hold a light source. The first attempt using an off-the-shelf cemented microlens at the end of an optical fiber has failed. Indeed, the structure holding the microlens proved to be very sensitive to temperature. We decided to use a dedicated mechanical structure without lenses. The assembly must be as simple as possible to avoid any flexure or dependency to temperature. As shown in Figure 2, an IR monomode optical fiber is mounted in a mechanical structure attached to the entrance plate of the cryostat. The infrared source is a pigtailed laser fiber at 1.31 μm (the final IR filter centred at 1.5 μm is replaced by a similar filter which transmits light at 1.31 μm). On the mechanical structure which holds the fiber, a pinhole of 165 μm diameter has been cemented to keep the size of the light beam on the detector small enough (roughly 60 pixels). The fiber is off axis compared to the mechanical structure and compared to the detector because the centre of the detector is too noisy for precise centroid measurement. This off-axis position is very useful because it allows us to rotate the test apparatus to verify its sensitivity to temperature variation and confirm that we are not measuring effects from the test source. A picture of the cryostat during the test and a schematic view of the mechanical structure holding the optical fiber is shown in Figure 2.

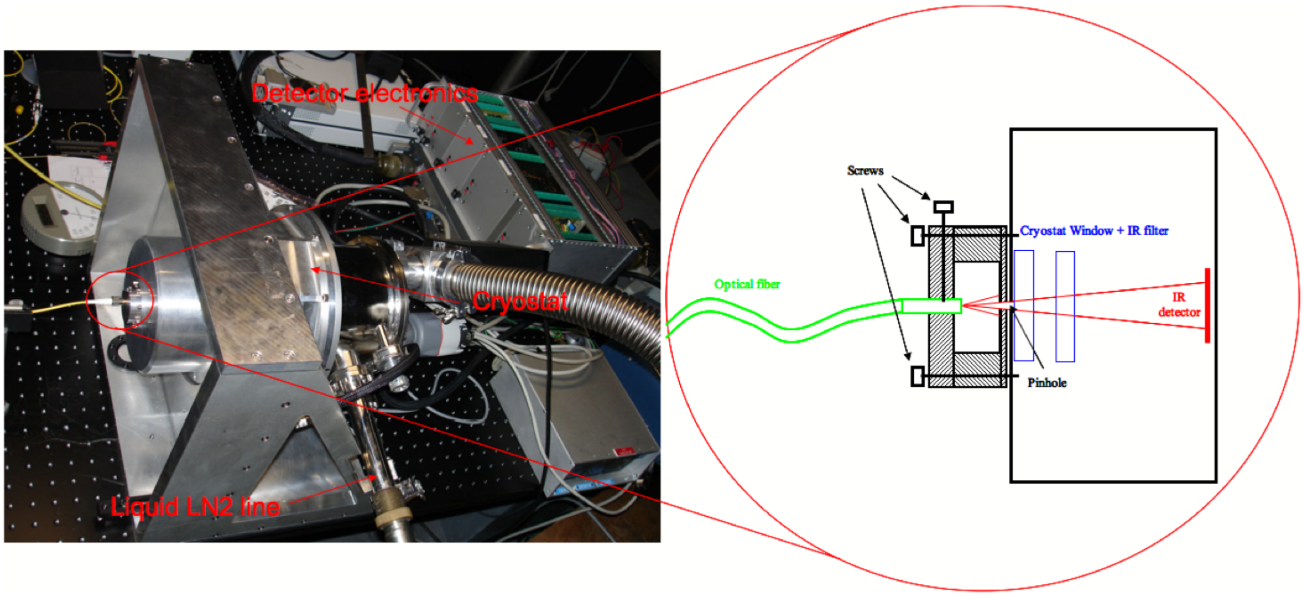

Figure 2 : Right: Picture of the DTTS cryostat during tests. Left: Schematic view of mechanical structure holding the optical fiber used to test the stability of the DTTS

For a period of 18 days, we collected a large set of data with maximum temperature variation of 10°C. We tested 3 orientations of the mechanical structure. The impact of orientation is small compared to the data dispersion and we will process the data of all orientations the same way in all the following section. The typical Detector integration times (DIT) were DIT=90 ms and the number of DIT (NDIT) was choosen so that the DIT.NDIT was 30 s long. Each DIT.NDIT of 30s is recorded on the computer as well as the room temperature. The cryostat temperature is stabilized at better than 5 mK precision and we assume that this temperature variation is so small compared to room temperature that it can be ignored. The center of gravity is measured (using weighted COG algoritm [3]) on each image and compared to the room temperature.

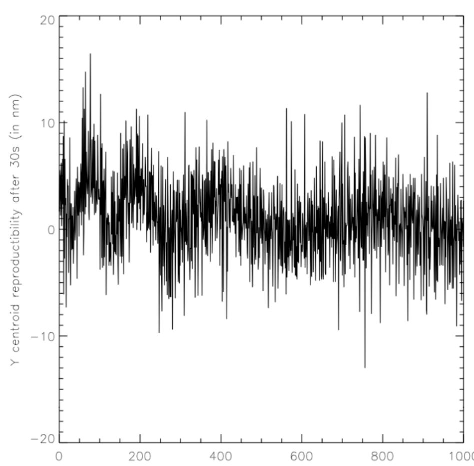

Figure 3 : Precision of centroid measurement in nm.

3.2. Precision of measurements

The precision is estimated by comparing centroid estimations separated by 30 s only. It is more a measure of the readout noise effect on the reproducibility after 30s but since we are not interested in absolute measure of position, this is corresponding to our actual precision. During 30s, the maximum temperature variation is about 0.01°C. Thus, it seems realistic to suppose that the temperature effect on this noise estimation is negligible. We found a precision for the estimation of the centroid of 5 nm RMS, much lower than the needed precision (Figure 3).

3.3. Variation of the temperature

Three orientations were detected in three different areas of the detector since the fiber is off-axis compared to the detector centre. The comparison of absolute positions is then not possible between these orientations. Then, we decided to centre the mean position measured for each orientation to a zero value in X and Y. We can then show the centroid positions as a function of days (Figure 4) remembering that positions of orientations 1, 2, and 3 are independent. However, it is clear that the variation of centroid positioning is less than 2 mas total for each orientations while the variation of temperature is about 10 °C.

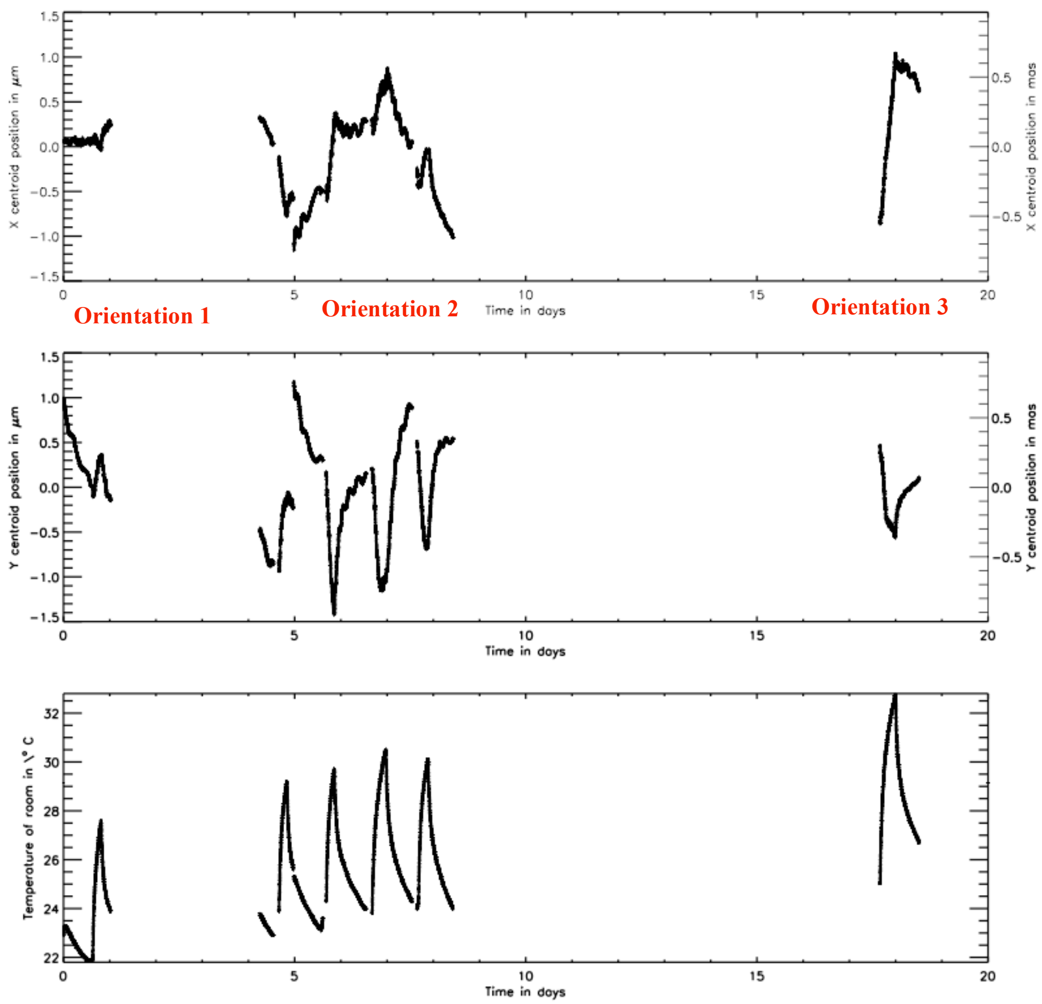

Figure 4 : Centroid position in X and Y for 3 orientations of the mechanical structure compared to the temperature variations.

3.4. Results applied to SPHERE

To estimate the sensitivity to room temperature of the DTTS, we looked at the maximum variations of positions for different temperature evolution. Using all the data, we estimate the maximum (max-min) and the average movement of the centroid position in X and Y during a 0.25, 0.5 and 1°C change. The result is shown for 0.25°C variation in Figure 5. The results for the 3 temperature changes are reported in Table 1. For 0.25°C and 0.5°C temperature variation, the RMS value is well under specs but the maximum variation is 30 % over the specifications. However, these out-of-specifications values represent a small part of the total data (0.8% for X axis and 3.3% for Y axis). We recall that the specifications are 0.14 mas/h per axis with an expected temperature drift inside SPHERE enclosure of 0.25 °C/h.

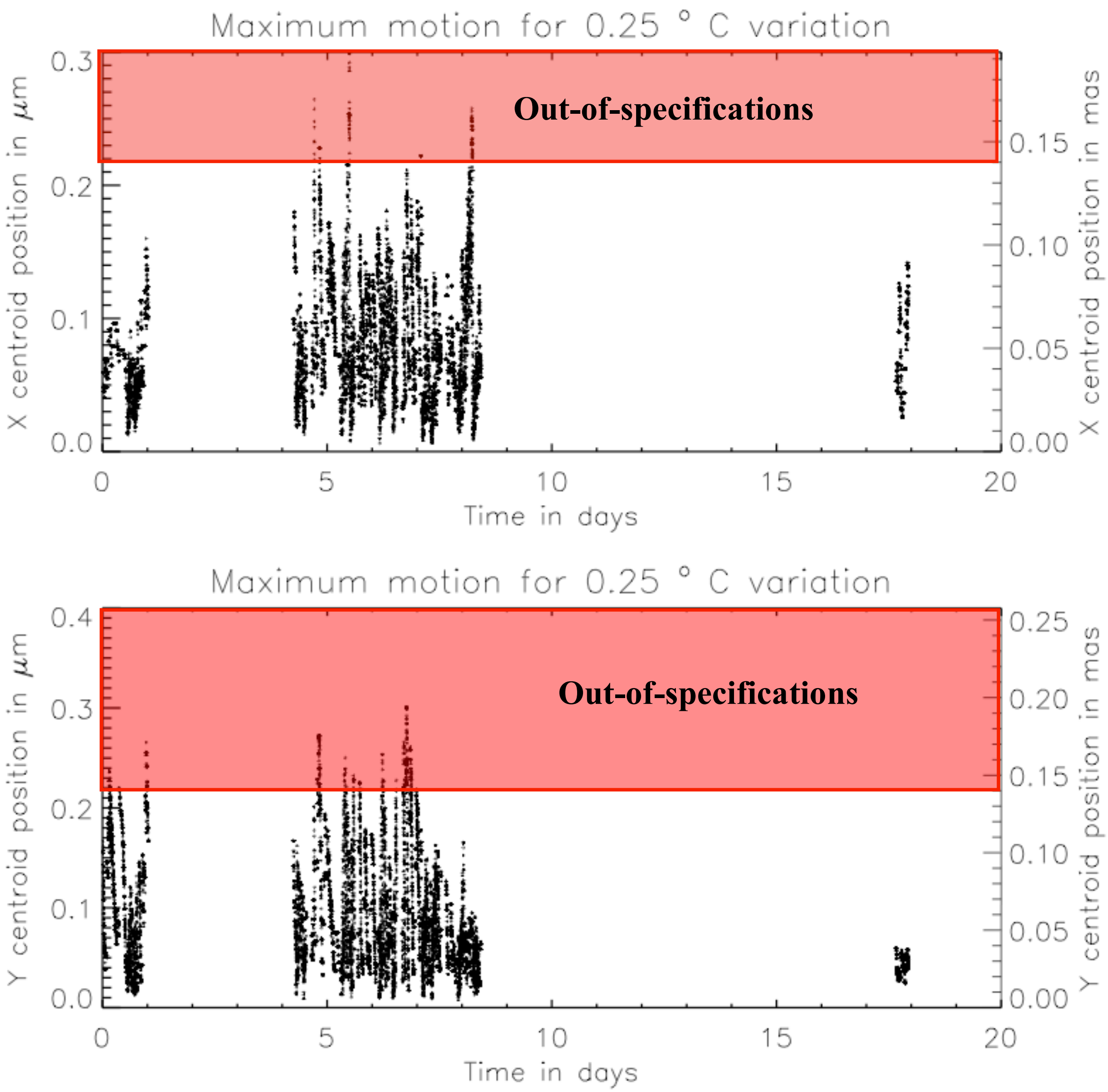

Figure 5 : Position variation in X and Y when temperature change by 0.25 °C outside the cryostat.

	Temperature Change			
Position variation in mas		0.25 °C	0.5°C	1°C
	Max-Min in X	0.19	0.24	0.44
	Max-Min in Y	0.19	0.26	0.48
	RMS in X	0.05	0.08	0.12
	RMS in Y	0.06	0.1	0.18
Percentage of out-of-specs	X axis	0.8 %	9.6 %	33%
	Y axis	3.3 %	22 %	57%

Table 1 : Position variation as a function of temperature change outside the cryostat. In red are the values that are not compliant with the requirement of 0.14 mas/hour per axis.

4. CONCLUSION

We described the Differential Tip-tilt Sensor (DTTS) that will be used inside SPHERE, the VLT planet finder, to ensure the star is always centered accurately on the coronagraph. The DTTS is a very simple cryostat that records the star image and performs a center of gravity to estimate the exact position of the beam. Correction is applied to the visible wavefront sensor beam with a framerate of 1Hz to a tilting optical substrate located in the visible wavefront sensor path. We tested the thermo-mechanical stability of the DTTS with respect to room temperature evolution. Over several days, the total amplitude variation is smaller than 3 µm (corresponding to about 2 mas on SPHERE) for temperature variation larger than 10°C. An estimation of the sensitivity of DTTS for several room temperature change has been calculated. The RMS value obtained is below the SPHERE requirements (0.14mas/hour/axis) if room temperature variation is below 0.5 °C /hour. The Min-Max variation is a bit above the requirements but it represents a small part of the data, especially for a temperature variation of 0.25°C/hour which is the expected SPHERE temperature evolution.

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