Results of the Chromatic Differential Astrometry Demonstration Bench and Application to the *SPICA* Mission

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ABSTRACT

We present experimental results from the Color Differential Astrometry (CDA) test bench. The CDA is expected to enable direct characterization (astrometry and spectra) of Giant Extra-Solar planets very close to their parent star, thus complementing the direct imaging instruments (aimed at outer planets). The goal of this experiment is to validate high precision spectro-astrometric measurements at the level of a few 10^{-4} pixels through a comparison between a numerical model of the method and a "real-world" setup. Once validated, these results can be extrapolated to several spectrometric instruments onboard *SPICA*, provided the noise sources of the instrument are sufficiently well known, as they are in our experiment. The CDA observing mode can be used with the SCI (SPICA Coronagraphic Imager) without any additional hardware device. The SCI benefits from a tip-tilt stabilization of the optical beam with a moderate accuracy (< 0.1 pixel 0−peak), possibly enough to reach $\sim 10^{-4}$ pixels differential astrometric accuracy. We show that theoretical predictions are consistent with experimental results in our experiment and how it can be extrapolated to the *SPICA* mission.

1. SCIENTIFIC OBJECTIVES

The goal of the proposed method is to be able to spectrally and atsrometrically characterize close-in, highly irradiated extrasolar planets. Planetary atmosphere models predict that such planets orbiting beyond 0.1 AU exhibit more or less contrasted spectral features. The case studies in that framework are G and M-type stars. The CDA allows the direct recovery of the stellar spectral types, the planetary orbital separation, and the distance of the system. The closest separations favor the signal at short wavelength (where the higher temperature of the planet compensates the smaller angular separation in the photocenter displacement — see below), whereas the largely separated planets are better measured towards longer wavelength. Also, planets with not-so-short separations show significantly larger variations of the signal over the spectrum, which might offer interpretation in terms of atmospheric composition and physical characteristics.

2. CDA AND APPLICATION TO *SPICA*

Constraints on the instrumental stability and on the required precision in general are very much relaxed thanks to the colour-differential aspect of CDA. i.e. the fact it measures photocenters relatively between some spectral channel and a reference channel chosen appropriately. The possibility to measure the relative position of an image with a precision much higher than its equivalent size was first shown by (Beckers (1981)). As a reminder, the photocenter is the angular vector $\vec{\epsilon}(\lambda)$ measured at time t and wavelength λ, which can be written as:

$$\vec{\epsilon}(t,\lambda) = \frac{\int \vec{r}\, o(\vec{r},\lambda)dr}{\int o(r,\lambda)dr} + I(t,\lambda) + b(t,\lambda) \tag{1}$$

where $\vec{o}(r,\lambda)$ represents the angular brightness distribution of the source observed by the telescope in the spectral channel of wavelength λ, $I(t,\lambda)$ represents the global effects and biases from the instrument, and $b(t,\lambda)$ the fundamental noises. By measuring the photocenter difference $\epsilon(\lambda) - \epsilon(\lambda_{\mathrm{ref}})$, and since any channels λ and λ_{ref} are measured simultaneously, their biases and variable effects, mostly achromatic, are largely suppressed. In order to correct also for the chromatic effects, a calibration using an reference star is also required, and repeated at a period corresponding to the timescale where variations of chromatic effects become critical in the noise budget.

3. THE CDA LABORATORY DEMONSTRATION

We developed a numerical model of the CDA including a number of noise sources that are affecting the performance of the method. In parallel we set-up a laboratory experiment in order to validate this model.

3.1. **Methodology**

The methodology of this work is therefore to thoroughly study and characterize the individual components of the experiment (optics, opto-mechanical mounts, detectors...) and derive parameters that serve as inputs for the numerical model. Our goal is then to be able to provide realistic estimations of the mode based on numerical simulations with an actual *real-world* experiment. Thus this experiment is not to be considered as a simulator of the mode onboard *SPICA*. The outputs of this work is to provide a numerical model that can be used to simulate the performance of the CDA on *SPICA*.

3.2. **Numerical Simulator**

Our estimates for the potential, feasibility and limits of the observing mode presently proposed were computed using a front-to-end simulation software (written in *Yorick*), which allows to compute:

- the theoretical astrophysical signal. In the present case we considered either the case of an extrasolar planets (for some given orbital separation, albedo, temperature and host star type parameters) for estimating the detection potential, or the simpler case of a laboratory white light source, in order to allow the comparison with the experiment.
- The "fundamental noises" associated with the observations. These noises include the photon, thermal and read-out noises, for a number of basic observational and detector parameters.
- The instrumental effects, which are principally: the non-homogeneity and variation of detector gain table, the tip-tilt of the beam (and its variations, possibly introduced as a power spectrum) during the acquisition, and the beam pointing/re-pointing accuracy.

The precision and accuracy on the calibrated measurement are derived by comparing, over a statistically significant number of events, the simulated measurements on a science and a calibration source. Other effects considered by the detector include the possible use of a coronagraphic mask, the detector non-linearity as a function of flux, the intra-pixel effects and the binning of pixels along spatial or spectral directions. All these effects are defined within some given instrumental parameters set-up (e.g. SCI/*SPICA* or our experimental bench) but are individually adaptable, either for updating technical characteristics or for exploring a range of values.

3.3. **Experiment Implementation**

The optical bench is shown on Figure 3 of Abe et al. (2012). It shows the optical layout of our bench and the actual realized implementation. The light is emitted by a so-called super-continuum pulsed white laser from Leukos. it is connected to an off-axis reflective collimator. The beam is then going through two parabolic mirrors used in a symmetric "W" configuration. At the two parabola focal points (where pupil images are formed) a tip-tilt mirror and a linear 50 gr/mm grating sit. The final dispersed image is directed to a SBIG ST-10XME camera and to a tip-tilt monitoring Prosilica camera. When possible each element of the bench was characterized by individual, independent experiments. We evidenced (and understood) differential mechanical drifts between the tip-tilt and the SBIG cameras that were beyond our requirements (< 0.01 pixel RMS on the SBIG detector). However, the actual stability of the bench was enough to compare it to the *SPICA* specifications.

4. **RESULTS**

4.1. **Experimental Precision of CDA**

The measured flat-field and dark-field data were first analyzed to estimate the roughness (i.e. spatial variation) and time variation of the detector gain. Within a time scale of about an hour, the standard deviation of the table gain happens to be $\approx 2 \times 10^{-3}$ both spatially and temporally, associated with a power spectrum very similar to a white noise. The slower (and larger) variations were removed by the differential process. Also, the measurement of the beam tip-tilt was approximately 0.1 pixel RMS over the same time length.

At the present, we obtain an RMS precision of about 0.02 pixel per short frame on the differential photocenter, i.e. about 2×10^{-4} pixel for the cumulated 1.25 hours of integration period on the science source, with the same amount of time spent on calibration frames.

4.2. **Comparison between Simulation and Experiment**

With the measured table gain roughness and stability parameters introduced in the simulator along with the tip-tilt statistics, we obtain from the a Monte-Carlo simulation a precision of about 1.5×10^{-4}. The ratio between the measured and simulated CDA precisions is therefore 1.3, which represents a good agreement considering a number of unknown values among the secondary effects. This difference would translate quadratically by a factor 1.7 on the required observation time for reaching a given precision, with respect to our simulated estimations.

4.3. **Application and Extrapolation to SCI/*SPICA* and Conclusions**

Applying this to SCI/*SPICA* is a more tricky task, since actual table gain and tip-tilt stability, as well as the pointing accuracies or the possible calibration cycle period of the instrument are not yet known. We assumed in Figure 1 four

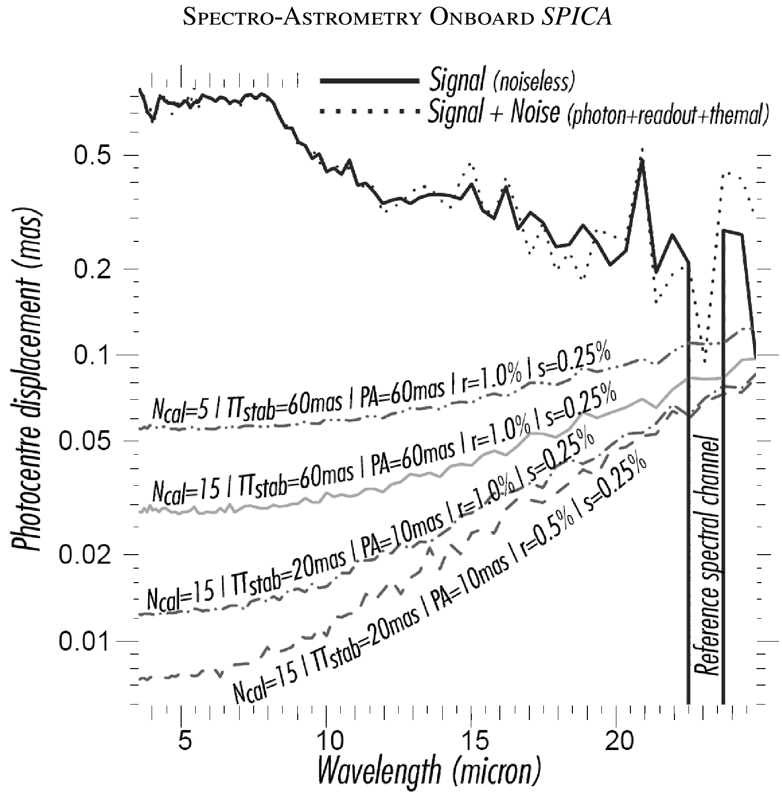

Figure 1. Simulation of a G8V star at 10 pc with different observing condition hypotheses (Ncal: number of calibration cycles; TTstab: Tip-tilt stability (mas);PA: pointing accuracy (mas); r: gain spatial roughness; s: gain temporal stability).

different cases combining the following parameters: either 5 or 15 calibration cycles, tip-tilt stability of 20 or 60 mas, pointing accuracy between science and calibration source of either 10 or 60 mas, detector gain table roughness of 1 %, and detector gain table relative stability of 0.25 %. The plain black curve is the noiseless photocenter signal, and the dotted one corresponds to the noisy signal with photon, readout and thermal noises only.

The fair agreement found between our test bench measurements and the simulator in the visible range gives us confidence that our simulations for *SPICA* are not unrealistic, with these parameters. In order to fully realize the experiment's objectives (better image stabilization in the science detector), we realized that we were limited by several instability issues. These are currently being studied so that an improved version of our bench is envisaged.

REFERENCES

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