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A NEW LONGITUDINAL DISPERSION COMPENSATOR FOR OBSERVING AT LOW SPECTRAL RESOLUTION FROM 0.55 TO 2.45 MICROMETERS AT CHARA ARRAY

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Abstract. The Center for High Angular Resolution Astronomy (CHARA), located in Mount Wilson, California, is an interferometric array of six telescopes feeding instruments observing from 0.55 to 2.45 µm. Since its first operations in 2003, it has been equipped with a Longitudinal Dispersion Compensator (LDC) that made possible observation at low spectral resolution and large spectral bands in the visible and near-infrared. To push the limiting magnitude and the quantity of interferometric data collection, CHARA has decided to replace the current LDC configuration with a more transmissive and performant one. This new solution will allow coordinated operations of the new generation instruments from 0.55 to 2.45 µm. I will present its design and expected performance.

Keywords: spectro-interferometry, group-delay, longitudinal dispersion, long baseline interferometry

1 Introduction

Ground-based stellar interferometers combine the light coming from telescopes separated by hundreds of meters. The highest distance between two telescopes of the Center for High Angular Resolution Array (CHARA) is 330 m. After being collimated in the Coudé train of each telescope, the light is propagated up to the focal laboratory where the spectro-interferometric instruments record dispersed interferometric fringes. However these inteferometric fringes are multiplied by a coherence envelop whose length increases with the spectral resolution of the instrument. High-contrast fringes are observed only at the center of this coherence envelop which position is called group-delay (GD). When the target is not at the zenith, an achromatic geometrical delay introduces an optical path difference between the electromagnetic fields coming from the different telescopes which translates to a non-null GD at the recombination focus. Classically, interferometers like CHARA use optical delay lines (MDL for main delay lines) to equalize the optical paths. However, when MDLs are filled with air, this equalization is chromatical and the GD is nulled only at a given wavelength (e.g. middle of H-band in Fig. 1a). An alternative, currently considered at MROI (Creech-Eakman et al. 2018), is to put these MDL under vacuum. Since 2003, CHARA uses longitudinal dispersion compensator (LDC) to compensate for the dispersion in the R-band where it is the most critical (Berger et al. 2003). A smart set of the thickness of these pieces of glass enables to null the GD at several wavelengths.

CHARA is preparing the arrival of several instruments since 2018. The instrument MIRCx (Kraus et al. 2018) is currently observing at spectral resolution as low as R=20 in H-band (1.45 − 1.75 µm). It is now able to record interferometric data simultaneously in H and J bands (1.15 − 1.3 µm), at least for R=44 (Labdon et al. 2020). The instrument MYSTIC (Monnier et al. 2018) also observes at R=20 in K-band (1.95 − 2.45 µm). Following these two instruments, the visible spectro-interferometer CHARA/SPICA (Mourard et al. 2017) should be commissioned in 2022 for observation in R-band (0.6 − 0.9 µm) at R=140. The development of the fringe-tracker SPICA-FT (Mourard et al. 2018) is in progress inside this instrument with the aim to stabilise the piston disturbance under 100 nm rms for allowing long exposures with the other instruments. To push the limiting magnitude of all the instruments and multiply the data collection with CHARA, a high performance

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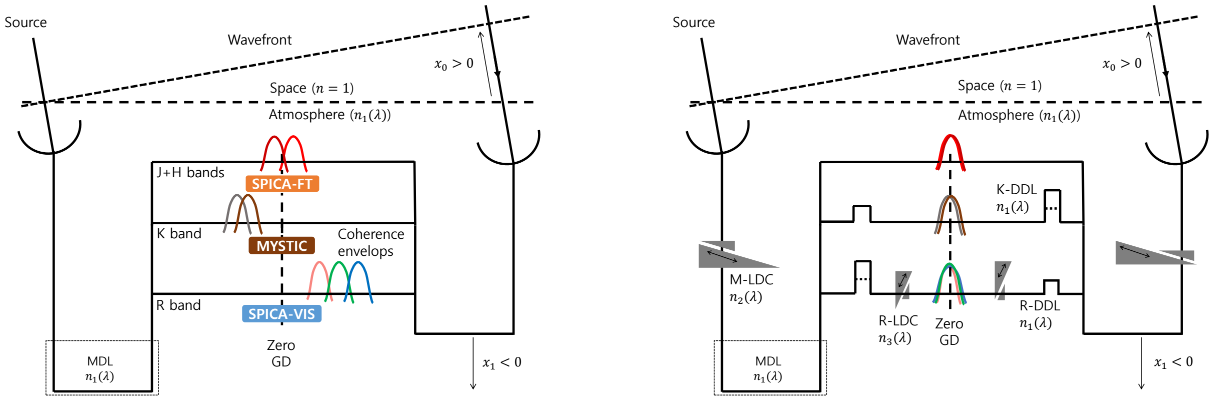


(a) Chromatical equalization using MDL. The fringe contrast is null in R and K bands and low in most of H-band.

(b) Perfect compensation using MDL, DDL and LDC. The fringe-contrast is high for all instruments.

Fig. 1: Shift of the coherence envelops due to longitudinal dispersion and solutions to correct it.

fringe-tracking is necessary in H-band altogether with low dispersion on the whole observed wavebands. Yet, the current LDC is accountable for 1 magnitude loss in K-band and does not allow a coordinated and optimal operation of the new generation of instruments. The CHARA consortium decided to change the LDC for a more transmissive and complete solution that will enable, with the help of differential delay lines (DDL) in the different instruments, to compensate for the longitudinal dispersion from 0.6 to 2.45 µm, paving the way for very wide band coordinated operations.

We performed a numerical minimisation of the dispersion with all possible LDC configurations involving 340 glasses available in the main glass catalogs. Regarding our constrains in the CHARA optical path, we figured out a solution consisting in two stages of LDC made of SF66, whose transmission and dispersion laws garanty a SNR attenuation higher than 90 % from 0.6 to 1.9 µm and 47 % from 1.9 to 2.5 µm. We present here this solution.

2 Minimising the phase dispersion using LDCs

2.1 Phase dispersion minimisation

Tango (Tango 1990) paved the way for longitudinal dispersion compensation on a large waveband using LDC in the context of the SUSI interferometer (Davis 1994). The phase dispersion after propagation in the optical delay lines is a non-linear function of the wavenumber that can be approximated by a Taylor development around the central wavenumber of the concerned waveband. Doing that, the GD at the chosen wavenumber is the coefficient of the first degree of the polynomial and the terms of higher degree are contributors to the dispersion function which accounts for the chromatism of the GD on the large band. With this formalism, each additional LDC enables to null a coefficient of higher degree in the Taylor expansion.

Yet powerful and intuitive, this formalism is not perfectly adapted to our situation, as we need to correct with common glasses and individual differential delay lines the dispersion on four discontinuous wavebands. We developped a criteria of maximisation of the fringe contrast on the whole concerned waveband. A complete explanation of the criteria can be found in Pannetier et al. (2021) but here is a short demonstration.

For simplicity and because it is easy to generalise it to more telescopes, we study the case of a two-telescopes interferometer. We define $\mathbf{n}$ as the refractive index of all media (MDLs, DDLs, LDCs). All media are present in the two arms and $\mathbf{x}$ is the vectors of their thicknesses difference. The Phase-Delay (PD) between two arms at the wavenumber σ is:

$$\Phi(\mathbf{x}, \sigma) = 2\pi\sigma \sum_{k=1}^{n} n_k(\sigma) x_k \tag{2.1}$$

In the spectral channel S, the fringe contrast attenuation due to the chromatism of the PD is:

Table 1: Signal-to-noise attenuation in the four spectral bands where spectro-interferometers observe.

Band	R	J	H	K
Solution chosen for CHARA	0.90	0.93	0.94	0.47
Alternative solution using an infrared glass	0.92	0.99	0.99	0.99

$$C_S(\mathbf{x}) \simeq \exp\left(-Var_\sigma[\Phi(\mathbf{x},\sigma)]/2\right) \tag{2.2}$$

The maximisation of C over all the involved spectral channels S is obtained from the minimisation of the variance of the dispersion. Our criteria is quadratic in $\mathbf{x}$ so its minimisation gets a unique solution:

$$\mathbf{x}_0 = \mathbf{M}^{-1} \cdot \mathbf{d} \tag{2.3}$$

where $\mathbf{M}$ is the covariance matrix of all the dispersion laws and $\mathbf{d}$ is the achromatic GD to null.

Using this criteria, we tried out all the possible configurations involving one or two stages of LDCs made of glasses picked up within 340 of the main glasses catalogs (SCHOTT*, OHARA†, CDGM‡). All dispersion laws have been downloaded from ZemaxGlass package§. We figured out the ten best solutions in term of dispersion correction and used the signal-to-noise ratio (SNR) attenuation factor

$$\Gamma = TV^2$$

to conclude on the final performance taking into account both intensity transmission T and fringe contrast V^2.

3 The new Longitudinal Dispersion Compensator for CHARA

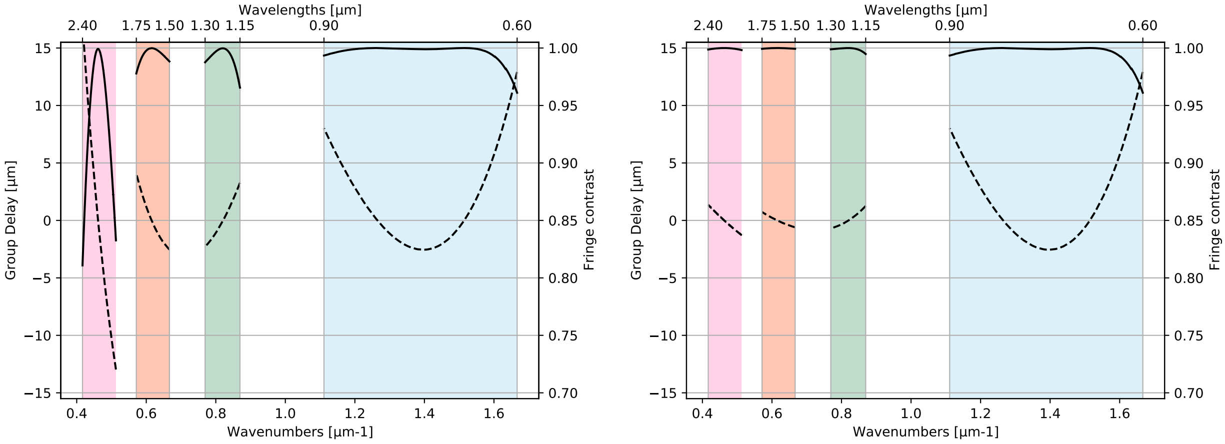
3.1 Two stages of SF66-made LDCs

Fig. 1b presents the setup of the solution we figured out. The DDLs in SPICA-VIS's and in MYSTIC's optical paths enable to null the average GD on these bands and on the H-band (using the MDL). Then, a first LDC stage (maximal thickness: 14 mm for 90 m of MDL) made of SF66 is placed in the common optical path to correct the dispersion residuals from J to K bands. A second LDC stage (maximal thickness: 9 mm for 90 m of ODL) made of the same material is placed in SPICA-VIS's optical path to correct the dispersion on this large band. The final fringe contrast is kept higher than 95% on the R, J and H bands and on half of the K-band. Fig. 2a presents the theoretical fringe contrast in the case of coordinated operations with the three main instruments in their low spectral resolution mode. Finally, we estimate in Table 1 that the SNR attenuation due to dispersion residuals and transmission loss from the LDC keeps higher than 90% in R, J and H bands and 47% in K-band when all instruments are observing simultaneously with their low spectral resolution mode.

3.2 Using infrared glass for high SNR in the K-band

SF66 absorbs 13% of the energy in the middle of the K-band (2.19 µm) and the dispersion residuals are responsible for a minimal fringe contrast of 78% in the two extreme spectral channels of the K-band. To further improve the K-band, the solution would be to remove the main LDC and to install a LDC made of an infrared glass like ZnSE in the optical path common to J, H and K bands, just after the first dichroic plate. Doing that, we get a high transmission in all spectral bands and the low dispersion residuals give fringe contrasts higher than 97% on the whole band. Fig. 2b presents the theoretical fringe contrast in the case of coordinated operations with the three new instruments dispersing with their low spectral resolution mode. We see in Table 1 that the final SNR attenuation is higher than 99% and 92% respectively in the infrared bands and in R-band. Unfortunatly, the current installation in CHARA focal laboratory doesn't allow to put a LDC at this position.

*https://www.schott.com/english/index.html
†https://www.oharacorp.com/
‡http://cdgmglass.com/
§Courtesy Nathan Hagen, https://github.com/nzhagen/zemaxglass



(a) Chosen solution with two LDC made of SF66. (b) Solution involving a LDC made of infrared glass.

Fig. 2: Fringe-contrast (solid line) and GD (dashed line) after the dispersion minimisation using the two presented solutions during a coordinated operation with R=140 in R-band and R=20 in J, H and K bands.

4 Conclusion

We presented the best solution available in the current state of CHARA focal laboratory for maximising the overal SNR over the waveband $0.6 - 2.5$ µm for the in-coming generation of low spectral resolution spectro-interferometers SPICA, MIRCx and MYSTIC. The overall configuration finally garanties a SNR attenuation higher than 90 % from 0.6 to 1.9 µm and 47 % from 1.9 to 2.5 µm. Moreover, the low phase dispersion in the H-band will increase the performance of the SPICA-FT fringe-tracker, which is a critical condition for high performance with the observing instruments SPICA-VIS and MYSTIC.

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