Alignment of the three-mirror anastigmat of the GIANO-TNG high resolution infrared spectrometer

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ABSTRACT

GIANO-TNG is a cryogenic cross-dispersed spectrometer designed to operate at near IR wavelengths (0.9-2.5 μm) achieving a resolving power of $R\simeq 50,000$ and covering most of the spectral range in a single exposure. The core of its optical system consists of a 3-mirror anastigmat (TMA) used in double pass, which acts both as collimator and camera. Thanks to its all-mirrors design, the system is intrinsically achromatic and can be conveniently aligned at optical wavelengths. This papers describes the procedure followed and the results obtained for the alignment of the optics of this instrument.

Keywords: Ground based infrared instrumentation, infrared spectrometers

1. INTRODUCTION

GIANO is a cryogenically cooled cross-dispersed near infrared (0.9–2.5μm) spectrometer[6] which will be installed on the Italian ⌀3.58 m TNG telescope.

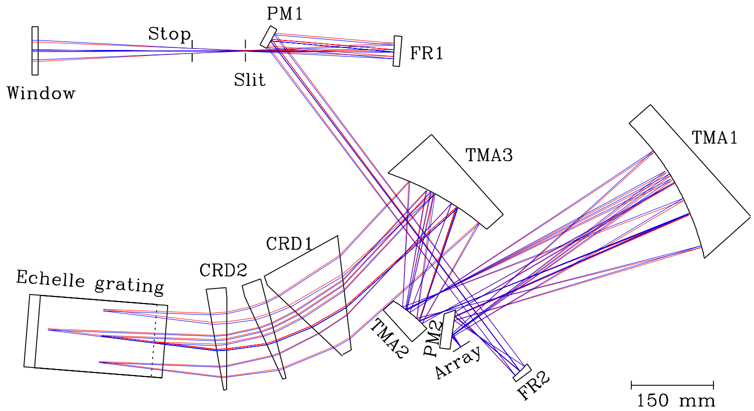
The main characteristics of the spectrometer optics[3] are summarized in Fig. 1 which includes the optical design with ray-tracing and a picture of the system mounted at the Arcetri laboratories during the alignment.

The entrance slit is illuminated by the F/11 beam from the pre-slit optics[1] and feeds the FR1-FR2 focal reducer which re-images the focal plane at F/4.2 on the side of the detector. The flat mirror PM1 is used to fold the beam. The light then enters into the TMA which creates a 100mm collimated beam feeding the cross-dispersing prisms – made of infrasil (CRD1) and ZnSe (CRD2) – and the 23.2 lines/mm R2 echelle grating. The rays reflected from the grating pass again through the prisms and are re-focused onto the array detector by the same TMA system. A flat folding mirror (PM2) is added to conveniently position the array. The detector is a 2048^2 Hawaii-II HgCdTe array with 18 μm pixel pitch.

2. SETUP FOR ALIGNMENT AT OPTICAL WAVELENGTHS

The optical system of GIANO is intrinsically achromatic and can therefore operate at optical wavelengths down to $\simeq$550 nm, the transmission cut-off of the ZnSe prisms (CRD2). By rotating the grating in the plane of Fig. 1 one can therefore tune the wavelength seen by the detector. In particular, one can conveniently use a common, quasi–monochromatic ($\Delta\lambda/\lambda\simeq 3\cdot 10^{-6}$) HeNe laser source to verify the optical quality of the system as follows.

- The 633 nm laser light passes through a 5 μm pin-hole positioned at the spectrometer entrance. The divergent beam created by diffraction is limited to F/11 by a mask positioned on the FR1 mirror.
- A Hawaii-II bare multiplexer (MUX) is mounted in place of the detector. The MUX is sensitive to optical light with a very low efficiency, but enough for the large photon flux produced by the laser.
- The spectrometer produces three images of the entrance pin-hole on the detector, corresponding to grating orders #121, #122 and #123. These can be positioned at different positions of the detector by rotating the grating in the plane of Fig. 1.
- Intra and extra focal images are produced by moving the detector using the motorized focusing system which is a part of the instrument cryo-mechanics.[2]



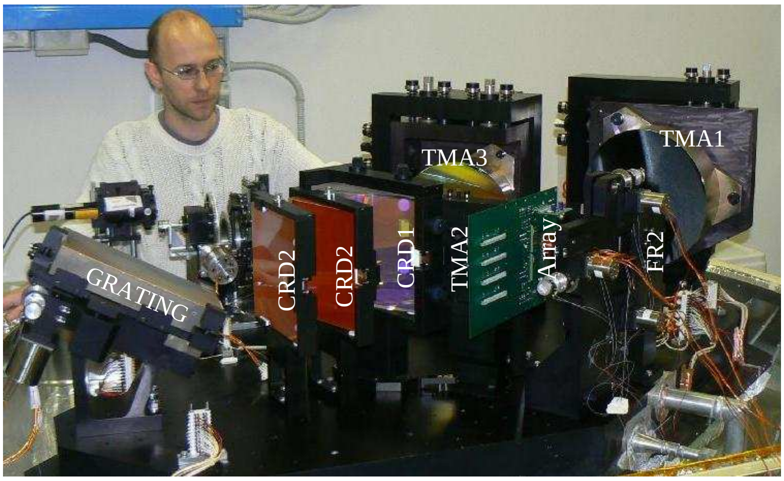


Figure 1. Top: optical layout and ray tracing of the GIANO-TNG high resolution infrared spectrometer. Bottom: picture of the system during alignment at the Arcetri laboratories.

3. THE ALIGNMENT OF THE GIANO MIRRORS

Each of the FR and TMA aluminum mirrors is separately mounted inside an holder which includes micrometric movements over 6 axis. The holder is specifically design to maintain the alignment at cryogenic temperatures.[5] The micrometers have a range of about ± 1 mm. The mirror holders are mounted on the "BeTank", i.e. the aluminum bench which also acts as liquid nitrogen tank.[2] No precise mechanical reference exists, the mirrors are therefore positioned with a typical error of 1 mm. In spite of the large positioning errors, the system can be aligned because of the following, intrinsic properties of the TMA system.

i) A large (several mm) decentering error of a given mirror is fully compensated by a suitable tilt of the same mirror. For example, TMA1 can be shifted by 3 mm and tilted by 20.6' along the same direction with no appreciable change in the image quality.

ii) Reasonably large errors in the alignment of TMA1 and TMA3 can be fully compensated by moving TMA2.[4]

iii) Aberrations introduced by an incorrect alignment of the FR mirrors can be also recovered by a movement of TMA2

Based on the above considerations, we developed an alignment procedure which consists of the following steps.

1. Define a common axis for TMA1 and TMA3. These are elliptical mirrors with foci at easily accessible positions. They can be therefore aligned relative to a common axis using 4 pin-holes placed at the nominal positions of the mirrors foci. The error in the positioning of the pin-hole images is conservatively assumed to be ± 0.5 mm.
2. Position the FR and PM mirrors so that the chief ray, defined by a HeNe laser beam, strikes the various surfaces within 1 mm of the the nominal position.
3. Align the whole system moving TMA2 and optimizing the image quality at different positions on the array.

3.1. Simulation of the alignment procedure

This alignment procedure was simulated using ray-tracing programs. About 5,000 models were generated with the mirrors positions randomly shifted by ± 3 mm relative to their nominal values. Their tilts were randomly chosen with the constraint that the conditions 1,2 above were satisfied. The system was then optimized by tilting and refocusing TMA2 using the 3 images created by the 633 nm laser with the spectrometer in the optical setup (see Sect. 2). In the simulation we also included manufacturing errors parametrized by a random variation of $\pm 0.1\%$ of each of the two focal lengths of the conic mirrors.

The image quality was determined on the spectrometer in its final infrared setup and quantified as `EE(80%)`, the mean diameter of 80% encircled energy of 9 positions at the center, edges and corners of the echellogram. Fig. 2 shows the resulting distribution of `EE(80%)` which is peaked just above the size of 1 pixel and have most ($\sim$98%) of the models with images better than 1.5 pixels.

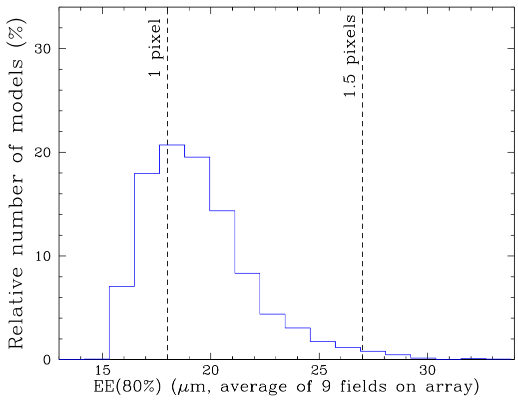


Figure 2. Predicted optical quality of the GIANO spectrometer achievable with the alignment procedure described in Sect. 3. The histogram is the distribution from 5,000 models with randomly distributed starting configurations. See Sect. 3 for details.

3.2. Results of the alignment procedure

Using the spectrometer in the optical setup described in Sect. 2 we created "mosaics" of intra and extra focal images to visually evaluate the amount and direction of the optical aberrations. Two examples are shown in the left-hand panels of fig. 3.

We first determined the TMA2 position along the optical path (Z) by manually shifting the holder until a reasonably focused image was visible on the detector at its nominal position. A movement of 1 mm of TMA2 along Z requires a refocusing of 7 mm of the detector. Since the detector refocusing range along Z is about 2 mm, the positioning of TMA2 is about 0.3 mm.

We then iteratively adjusted each of the TMA2 micrometers to decrease the asymmetry and elongation of the defocused images. We first operated with the three micrometers on the back of the mirror, which regulate the tilt. Once a quite good image was achieved we fine-tuned the adjustment using the lateral micrometers, which regulate the mirror shift and which have a $\sim$5 smaller effect on the image quality. The procedure converged and the final image, shown in the right-hand panel of Fig. 3, has a FWHM of about 1.5 pixels.

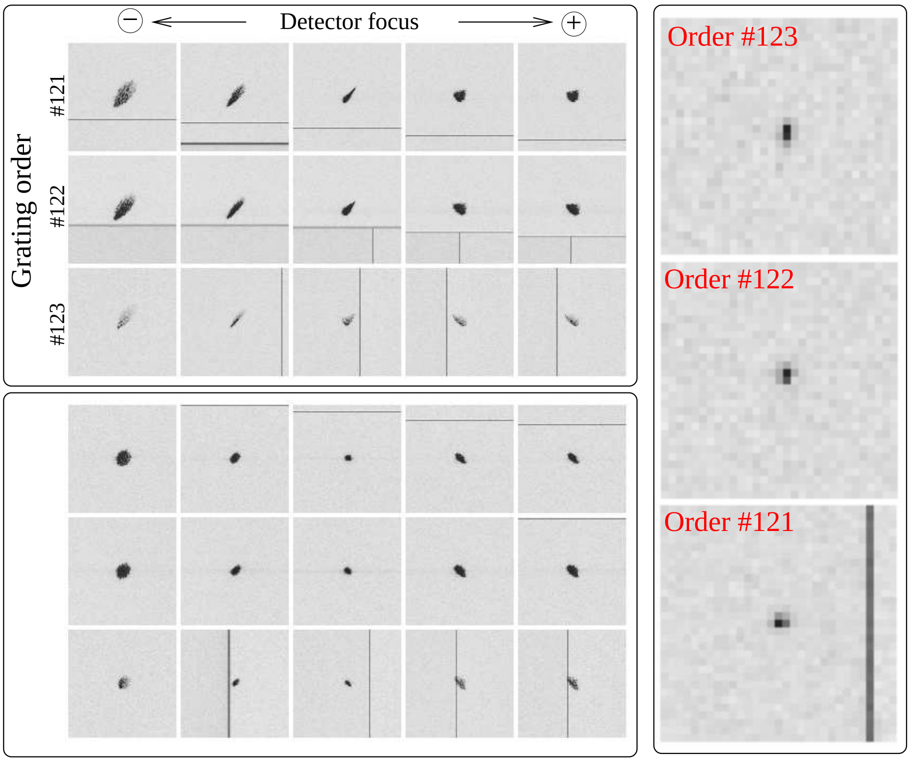


Figure 3. Left panels: intro and extra focal images during various phases of the alignment of GIANO with the HeNe 633 nm laser. The dark stripes are intrinsic defects of the Hawaii-II multiplexer.
Right hand panel: zoomed view of the images when the system is aligned and focused. See Sect. 3.2 for details

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