Mem. S.A.It. Vol. 86, 490

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Laboratory measurements of modal noise on optical fiber

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Abstract. Many scientific instruments are nowadays coupled to the telescope through optical fibers. This is also the case of the current configuration of GIANO, the high resolution near infrared echelle spectrograph installed at the TNG telescope. As experienced and frequent users of the IR optical fiber, the GIANO building team decided to go deep in the characterization of the optical fiber in the IR band, and in particular to understand and analyze the fiber modal noise. This work is also a preparatory study for the future HIRES@E-ELT instrument design. This paper consists in the description of the fiber laboratory tests, and in the explanation of the results. The whole job defines a wider comprehension of the modal noise, and demonstrates the existence of two aspects influencing this noise. The first one, well known in literature, refers to the interferences between the fiber modes at the exit endface of the fiber, and it can be mitigated by mechanical scrambling techniques. The second one, unknown before, is entirely dependent on the way in which light is injected at the entrance of the fiber, and no mitigation have been observed with any classical scrambling technique (e.g. double-scramblers). These considerations apply to both ZBLAN or fused silica optical fiber, and to both circular and octagonal core shape.

1. Introduction

During the first commissioning (end of 2012) of the GIANO instrument, the modal noise was identified inside the GIANO spectrum (about 1 % of the signal). Then the scientific team together with the technical team decided that further investigation on the modal noise in IR optical fiber would have filled a gap in the existing research literature, and it would have been also suitable for the team future technological applications, like HIRES@E-ELT spectrograph. At the beginning of 2014 the study started in the Arcetri IR laboratory, where an experimental set-up had been arranged. The objective was to reproduce the ″telescope+fiber+instrument″ system and to simulate the astronomical observation procedure, consisting in star observation and flat exposure. The ultimate goal was to find the experimental evidence of modal noise in the spectral signal, and to study which aspect of the laboratory set-up could influence the modal noise.

2. The real instrument case - GIANO

GIANO is an infrared (0.95 - 2.5 μm) high resolution (R=50,000) echelle spectrograph that was recently commissioned at the TNG telescope. This instrument was designed and built for direct feeding from the telescope. However, due to constraints imposed on the telescope interfacing during the pre-commissioning phase, it had to be positioned on the rotating building, far from the telescope focus. Therefore, a new interface to the telescope, based on IR-transmitting ZBLAN fibers with 85 μm core, was developed.

The ZBLAN (ZrF4-BaF2-LaF3-AlF3-NaF) fiber is the only fiber working in the entire GIANO observation band. The main drawback of this type of fiber is its fragility and softness, that means a very little tolerance to high mechanical stresses, like small radius bending.

The modal noise evidence depends on the number of excited modes as the light beam enters the fiber end, and this number of excited modes inversely depends on the square of the light beam wavelength. The GIANO condition is unprecedented, since it is the first NIR fiber fed spectrograph. Considering a GIANO reference working wavelength of 1.6 μm, and a HARPS reference working wavelength of 0.5 μm, the excited modes in the HARPS case are in number 10 times greater than in the GIANO case. We experienced that in the GIANO circumstance the modal noise is highly visible.

The modal noise is enhanced when the light beam is truncated along its optical path, and even the entrance slit of a spectrograph can produce this effect. In addition GIANO's optical path has also a Bowen-Wallraven prism that splits the 2 fibers spots in 4 half spots, so that a ″beam-cutting″ effect occurs.

3. What is the modal noise

The modal noise was known since about 1978, when Epworth first mentioned this source of noise in the fourth European Conference on Optical Communication (ECOC, Epworth 1978) . Then the following studies focused on the understanding and on the prediction of this noise and of the related S/N. In the last few years the interest moved to the realization of experimental set-up to test optical fiber performances in astronomical applications (see e.g. McCoy et al. 2012), but no one focused on the ZBLAN fiber or on a wavelength band that reaches 2.5 μm. Moreover the existing studies about fibers are often related to the investigation of the near and far field, while in this work the purpose is to observe the modal noise in the target spectrum.

Modes are the discrete light paths that can travel in a fiber. Each vectorial modal field is defined as an eigenstate of Maxwell's equations within the fiber, and the eigenvalue is the propagation constant of that mode. Different modes have different propagation constants, and they travel different distances in the same time interval. Each light source excites a range of modes, defining a modal power distribution. If the difference between the traveled distances of two modes is less than the coherence length of the modes, the two can interfere and can produce the speckle pattern. In high resolution spectrograph the narrow spectral field of view increases the interference possibility (McCoy et al., 2012). If the input illumination of one fiber endface changes (even for source shifts or tilt), different modes are excited, and variations in speckle pattern occur (Corbett et al., 2006). Microbends and scattering centers in the core/cladding walls affect the speckle pattern in a pseudo random way, and produce power exchange between modes, that means also FRD (focal ratio degradation). Finally any mode filtering through the beam vignetting is a potential source of modal noise, (Lemke et al., 2010).

The modal noise is wavelength dependent: the number of modes, excited by a uniformly-illuminated fiber, is inversely proportional to λ^2 and the fewer the modes, the greater the weight of modal noise on the overall signal (McCoy et al., 2012). According to Snyder et al. (1983) in (1) N_λ is the number of excited modes for a monochromatic source of light, D_{in} is the uniformly illuminated fiber diameter, NA is the numerical aperture of the fiber.

$$N_\lambda = \frac{1}{2}\left(\frac{\pi \cdot D_{in} \cdot NA}{\lambda}\right)^2 \quad (1)$$

4. The laboratory set-up

The experimental set-up is addressed to reproduce the telescope-instrument system, to simulate the scientific observation at the telescope, and to finally investigate the influence of the experimental set-up parameters on the modal noise occurrence. Two optical breadboards realize the experimental set-up: the first simulates the light source, the telescope optical path, and the light injection on the fiber entrance; the second simulates the spectrograph; the two breadboards are linked through the optical fiber under test. The experimental work consisted in testing the fibers performance in terms of modal noise in various set-up arrangements. The light source was an halogen lamp in an integrating sphere, with a pin hole on the output side, with size of 50 μm to simulate the star observation and 600 μm to simulate a flat exposure. At the fiber entrance the tested injection methods were: image plane illumination, pupil plane illumination, and photonic lantern Birks et al. (2015). The used optical fibers were: ZBLAN multimode fiber, 85 μm core diameter, 8 m length; fused silica optical fiber, 85 μm core diameter, 8 m length; octagonal fused silica fiber, 67 μm core diameter, 8 m length. The used scrambling mechanisms were the mechanical one, and the optical double scrambler.

The fiber under-study feeds the light coming from the simulated telescope to the entrance of the simulated instrument. The GIANO-like spectrograph consists of : a first focusing optical system, a roof prism mirror, a parabola, a grating dispersing element, a second focusing optical system, and the IR detector (see Fig.1). The dispersing element (spare part of GIANO) is an echelle grating, with 24.2 lines/mm and 63 degrees blaze angle. A narrow band filter in front of the detector selects the grating order centered at 1645 nm (with a bandwidth of about 8 nm). The camera model is the Xenics Xeva-796 (XC131), based on an InGaSb detector with a 30x30 micron pixel size, 320x256 pixel image sensor, with 0.9 - 1.7 μm wavelength response. The resolving power of the spectrograph illuminated by a 85 μm fiber is about R = 20,000 (Iuzzolino et al., 2014).

5. The modal noise measurements

In order to enhance the modal noise visibility in 2d images, the investigation strategy consists in two original steps. The first is to acquire a group of frames (400 frames of 500 ms of exposure for each frame), and to compute their mean known as the MEANFRAME. Then the second step is to subtract two subsequent MEANFRAMES, in order to get the evidence of the modal noise. The result of this manipulation (also called SCOOBY 2d image) is then the detection of the time variation of the spectral noise known as modal noise. The 2d SCOOBY spectrum image has a twisted aspect (along the spectral direction) that reminds the scooby-doo key ring (see Fig.2).

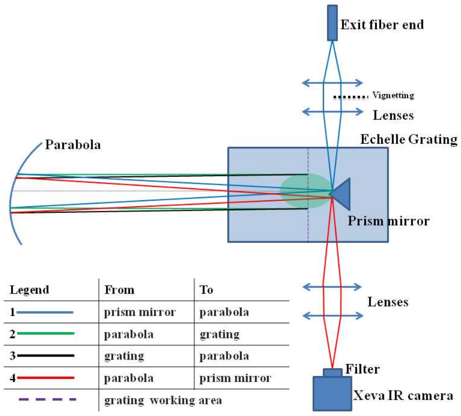

Fig. 1. Simulated spectrograph - optical scheme

The amplitude of the noise is quantified as the RMS (root mean square) of the ratio of the 1d spectra separately extracted from each dark-subtracted MEANFRAME, i.e. we use the same procedure normally used for the flat-calibration of astronomical spectra.

The laboratory system parameters were modified to determine their effects on the modal noise. The influence of the input illumination was studied by changing the size of the pin hole, in order to simulate the star observation (50 μm) and the flat field exposure (600 μm) for a 4 m telescope in good seeing condition. The second version of the test consisted in simulating the star observation with a 600 μm pin hole and the flat field exposure with 600 μm in a situation where the image size is much larger than the fiber core, e.g. for seeing limited conditions at the E-ELT.

The main results can be summarized as follows:

- no modal noise is measured for a 600 μm / 600 μm simulated scientific observation (second version test) with a mechanical scrambling in addition;
- no modal noise is measured for a 50 μm / 600 μm simulated scientific observation (first version test) with a photonic lantern at the fiber entrance and a mechanical scrambling in addition;
- modal noise evidence is found in all other cases (including octagonal fiber and double optical scrambling).

Two additional considerations came from these tests. The first relates to the effectiveness of the scrambling techniques, and just the mechanical method results efficient. The second relates to the fiber material and core shape, and in terms of modal noise reduction no differences were found among the three tested types of fiber.

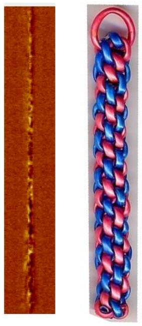

Fig. 2. Example of SCOOBY image spectrum vs the scooby key ring

6. Conclusions

The tests revealed the existence of two influence factors for the modal noise. The first is determined by the input illumination and is due to a not uniform excitation of the supported modes inside a fiber. This first factor was never reported before in any astronomy-related publication. It is not mitigated by any scrambling method or any original fiber core shape (octagonal shape). It is avoidable only with a uniform input illumination of the entrance fiber end, or also with an optical element that uniformly redistributes the transmitted energy among the modes. The main challenge is finding a system that achieves these goals without decreasing the overall throughput of the fiber interface. Preliminary tests with a photonic lantern indicate that this new type of device could be the ideal solution to the problem.

The second factor consists in the changing interference between the modes at the exit of the fiber, and it is strongly influenced by the fiber stresses and imperfections. This second type of noise is present in all types of fibers (including octagonal) and for any type of illumination (including optical double-scrambler and photonic lantern). It can be easily mitigated by mechanical scrambling, i.e. by agitating the fiber. The frequency of the mechanical scrambling must be chosen much higher (ideally a factor of 1000) than the acquisition rate, in order to average in time the modal noise changes.

The modal noise can be eliminated only if the working set-up includes both a uniform input illumination and a mechanical scrambling.

Acknowledgements. This work was financially supported by INAF through the grants "TREX-2011" and "TREX-2012".

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