Testing Giano Spectral Stability


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ABSTRACT

Giano is a high resolution (R≈50,000) infrared spectrograph with a near-complete coverage of the 0.95-2.5 microns wavelengths range. It was assembled in Arcetri-INAF (Florence) and is being shipped to its final destination at the TNG telescope (La Palma).

We present our measurements of internal wavelength stability of Giano spectra. We are using a new approach which gives both the wavelength and field tilts. We also show the comparison with the usual mono-dimensional approach.

Keywords: Spectroscopy, Ground base infrared instrumentation

1. INTRODUCTION

Giano is an optimized near infrared spectrograph which can yield, in one shot, 0.95-2.5 μm spectra at high resolution (up to R=46,000 with a 0.5” slit) maintaining a high throughput on the whole spectral range. The detector is a Rockwell HAWAII2, 2048×2048 18μm pixel, with PACE FPA.

This instrument has been built in the framework of the Second Generation Instrumentation Plan for the Telescopio Nazionale Galileo (TNG, La Palma, Spain). Giano will be shortly installed at Nasmyth A focus of TNG and will then enter its final commissioning phase.

Among the science target for Giano there is the search and characterization of extraterrestrial planets around cold red stars, which requires a very high grade of wavelength calibration accuracy.

In the last laboratory development phase, in Arcetri-INAF laboratory (Florence), we performed some tests to assess the instrument stability on wavelength calibration.

2. BACKGROUND

To measure the presence of rocky exo-planet around cool red stars, we need an high resolution infrared spectrometer capable of measuring the Doppler shift of the star with a precision around 1m s^{-1} which translates in a 3 · 10^{-4} pixels accuracy.

Giano design is particularly suited to this kind of measure for its still unique ability to obtain a near complete NIR spectra of a star in a single exposure, maximizing the efficiency of telescope time use, and avoiding many internal cross calibration nightmares.

The design and development of Giano needed special care from the beginning to attain such an ambitious goal, and many error sources were identified and avoided in the design phase or corrected during the development.

To make real measurements of this kind we need to acquire a large number of stellar spectra and to calibrate carefully them in order to gain the desired accuracy by means of accumulating signal to noise ratio.

The calibration is obtained measuring a standard Hollow-cathode lamp spectrum. In laboratory we used a Thorium-Argon lamp whose stability is high enough for our purposes, while at telescope we will use a Uranium-Argon lamp which will have more useful line in the scientific wavelength range.

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The standard method for high precision matching of a number of lines is normally the linear pattern matching method. This method consists of extracting the relevant part of the spectrum and performing a 1-dimensional correlation with the standard spectrum.

We were interested not only in the wavelength shift, but also in investigate alignment problems, so we tested a 2-dimensional image correlation technique. As far as we know, such application of this method has not been tried in the analysis of astronomical spectra.

We performed also some verification of the method. We applied our approach to synthetic bi-dimensional spectra and we confronted our shift measurements with 1-dimensional cross correlation.

### 3. CROSS CORRELATION

Just doing a best fit between spectra taken at different times did not give us the required sensitivity, so we have to take in a more robust method: we chose the 2D cross correlation technique.\(^5\)

This technique is commonly applied in image processing area to the problem of template matching. This method has been originally developed for the purpose of finding one or more instances of a given reference template, or pattern, into a larger image.

We use this approach to evaluate the small shifts between different spectra. When we perform a cross correlation between two images, assuming we have a small rigid shift, we obtain a function with a huge peak which contains nearly all our signal to noise ratio. It is now straightforward to perform a local bi-dimensional fit and to obtain the coordinates of the maximum, which are the shifts we look for.
Among the several functions proposed to measure the degree of similarity between an image and a given pattern, the Zero mean Normalized Cross-Correlation (ZNCC) is widely used, due to its robustness in template matching, since it tolerates uniform brightness variations of the image.\(^2\)

The Zero mean Normalized Cross-Correlation can be written as

\[
ZNCC(i, j) = \frac{\sum_{m=0}^{M-1} \sum_{n=0}^{N-1} (I(i + m, j + n) - \mu(\tilde{I})) \cdot (T(m, n) - \mu(T))}{(\sum_{m=0}^{M-1} \sum_{n=0}^{N-1} (I(i + m, j + n) - \mu(\tilde{I}))^2) \cdot (\sum_{m=0}^{M-1} \sum_{n=0}^{N-1} (T(m, n) - \mu(T))^2)}
\]

\(\mu(\tilde{I})\) and \(\mu(T)\) denote the mean intensity value of the sub-image related to the position \((i, j)\) and to the pattern \(T\).

Due to this normalization, the ZCNN coefficient is independent of changes in brightness or in contrast of the image, which are related to the mean value and standard deviation.

We can give an estimate both of the spatial displacement and spectral error of the measure if this procedure is applied to all the images of the same spectra acquired in a run spanning from hours to several days.

4. DATA ANALYSIS

We developed a standard procedure to obtain the distance between two frames containing or a single spectrum or the average of two different groups of spectra. For sake of development speed, we wrote our procedure using a 4\(^{th}\) generation mathematical language, the open source Octave script language. This choice offered us the right balance between ease of development/test of different approaches and computational speed. At the end of development we were able to process the few thousand frames of a night in about one hour.

We benefit from the open-source Octave-Forge libraries, which contains some of the elementary building blocks we used to assemble our procedures, as an optimized cross correlation function, a non linear best fit function etc.

To minimize the effect of detector irregularities and bad pixels, our procedure extracts, for each spectral line, a 10×10 pixels sub-image. Except for brightest ones, nearly all lines fit well in such a box. These sub-images are arranged in a square matrix, which has a size much smaller than the original image. An example is given in figure 1.

Besides avoiding the adverse effect of detector peculiarities, such a sub-image extraction and composition greatly reduces computation time. We are still in the range of the more precise direct cross correlation, avoiding the FFT enabled one, affected by rounding errors.

From the bi-dimensional cross correlation function, again, we extract the central sub-image, featuring the big central peak, which denotes that the rigid shift is dominant over the image deformations, as expected.

We fit a bi-dimensional Gaussian on the central peak, and the linear offsets of the fitted function is our best estimate of the linear displacement of the two original images.

In case of longer wavelength, in the K band, we pre-subtract from the correlation function a mono-dimensional Gaussian, to remove the effect of the baseline. We expect to perform such a procedure on the full absorption spectra of real stars.

To obtain our best estimate of calibration errors we have performed two different analysis. The first approach is intended to evaluate the intrinsic limit of our approach.

We selected several instances of two sets of frames, arranged in a slope nulling schema (ABBA). For instance the first set was the mean of images 1,2,7,8 and the second was the mean of 3,4,5,6. We expected the mean of shifts measured was zero, and we obtained values consistently less than \(7 - 8 \cdot 10^{-7}\). We note this is not our accuracy, but an evaluation of the method limit, by the nulling technique.

The second analysis aims at evaluating the real precision obtained. We evaluate the shift \(S_i\) of successive groups of spectra against the first one. The number of frames summed up in each group simulates a different exposure time.
Figure 2. Our evaluation of calibration error with a mosaic of 100 lines in a single detector quadrant observed for 40sec as a function of time distance between successive calibrations.
We mark as calibrations a subset of these groups, separated by a time interval $T$ and we perform a linear interpolation between their offsets.

We then accumulate the difference $D_i$ between $S_i$ and the linear interpolation of the calibration groups.

The standard deviation of $D_i$ is our best estimator of the accuracy of Giano Doppler shift method, as a function of the time interval between calibrations $T$.

We found that for 40sec calibration, taken every 10 minutes, with only 100 lamp lines used, our measurement error is around $5 \cdot 10^{-4}$. Figure 2 gives the estimate error as a function of time distance of calibration measures.

5. METHOD VERIFICATIONS

To verify the accuracy of our method, we performed two tests on critical aspects of our procedure.

As a first test we have generated a set of random intensities synthetic lines and we arrange them in a $10 \times 10$ matrix inside an image. Then we generated a series of similar images, with increasing shift, both in wavelength and in spatial direction. We measure then the shift by means of our method. We then found that accuracy is good at small shift, while at larger ones (more than .1 pixel) we got measures of 10-15% less than the actual shift. We will investigate the origin of this underestimate, which does not affect real measurements, which are in a much smaller region. See figure 3.

Our second verification test consists of the reproduction of our full chain of procedures, but using flattened images: i.e. we arranged our sub-images containing the calibration lines in a long strip. Then we summed up in the spatial direction and we performed all the described calculations in a one dimensional way.

The measured displacements of the two methods agreed within the expected error, so to evaluate the relative advantages, we performed the quality test described above on the linear measurement chain.

We found the linear approach has an higher nulling residue, while the foreseen calibration error agrees with the two dimensional one for longer calibration intervals, and is somehow worse for shorter intervals.

6. FUTURE IMPROVEMENTS

The laboratory measurements show that Giano spectral calibration is already near the ambitious goal we looked for. To further improve this accuracy, some actions can be taken:
More line in calibration field In the laboratory measurement we used only around 1/4 of readily available lines, all in the same detector quadrant. If we take advantage of the full detector, we would have 4 times the lines with a foreseen improvement of a factor of 2.

Larger sampler window We chose a fixed sampler window of 10×10 pixels, which is enough to accommodate the average strength line. If we give to our extraction routine some size flexibility, we may get more accuracy from strong lines.

A different calibration lamp The standard Th-Ar lamp has been changed by a U-Ar lamp which has more lines in the range of scientific interest. The proximity of calibration lines to the scientific ones, and their increased number have the potential to improve our accuracy.

A different maximum fitting function We used a bi-dimensional Gaussian to fit the cross correlation function maximum. We have hints that, for larger shifts, this can not be the best choice. A better suited function could reduce the uncertainty on our maximum determination.

Fine tuned integration time Now our measurement are performed with our fastest integration time of 10 sec. If we adjust this time to match the best compromise between not saturating too many strong lines and getting a better signal/noise on week ones, we foresee a gain in overall precision.

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We, as members of the GIANO Team, wish to dedicate also this part of our project to the memory of Sandro Gennari who prematurely died on July 30th 2007. We all thank Sandro for his great work on astronomical technologies and GIANO as well as for his immense courage and humanity. We deeply miss him.

REFERENCES