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In-flight flux self-calibration procedure for cosmological surveys

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Summary. — Spectroscopic surveys in astrophysics and cosmology require an accurate knowledge of the non-uniformity in the transmission of light introduced by the telescope optics, which yields a non-uniform response all over the focal plane. In this work, we report a preliminary study on the in-flight flux self-calibration procedure and we characterize the expected precision on the reconstruction of the response function for a typical astrophysical survey.

1. – Modern cosmological spectroscopic surveys

Through cosmological studies, the structure of our Universe on large scales and its beginning and evolution can be investigated. This implies the need to observe large areas of the sky both in the visible and near infrared bands, in order to understand how galaxies are distributed, how they formed and how their shapes are deformed along the line of sight through the gravitational Weak Lensing effect. In particular, thanks to the use of spectroscopic and photometric instruments that equip the space telescopes on satellite, the distance of the observed sources can be recovered through the measure of their redshift z. In order to satisfy the accuracy requirements on this measurement, an extended calibration of all the components of the telescope and of the scientific instruments is required. Many calibrations can be performed on the ground: however, there are effects that can be only characterized once the satellite is in flight. The core of this paper is one of them.

2. – In-flight flux calibration

The same source, seen through different pointings of the telescope, and consequently falling on different points of the focal plane, is recorded with different numbers of photon counts. This is not only due to the intrinsic statistical nature of counts measures: it is

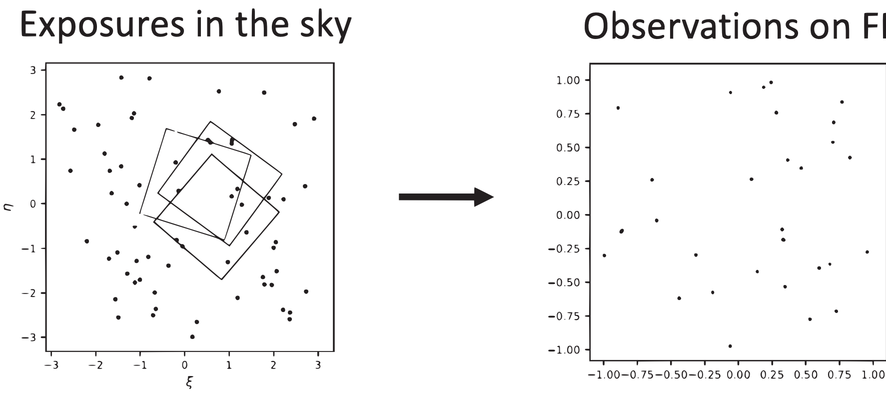

Fig. 1. – Example of the observation process. The same sources are observed through different exposures in the sky (left); different parts of the focal plane are thus correlated, since the same sources are detected in different positions (right).

also due to a systematic effect introduced by the internal telescope optics, that in turn reflects into an effective response function on the focal plane, depending on the position in which a source happens to be observed. The response function typically consists of an attenuation of the signal of the order of a few percent moving toward the edges of the focal plane. The counts of the observed sources are then systematically altered, depending on the detector coordinates in which that source is observed. Moreover, this effect may lead to a critical loss of statistic: some sources in fact would be too faint to be used for scientific purposes. It is then necessary to accurately reconstruct this unknown response function.

The method consists in observing the same bright sources through a set of random and partially overlapping pointings: in this way, the same sources will be recorded in different positions on the focal plane, and we can relate different spatial areas of the detector because they observe the same physical objects (as shown in fig. 1). The real flux rates of the sources and the unknown response function can be derived from this set of measures through the method of the least squares, that is, minimizing the following χ^2 variable:

$$\hat{\chi}^2 = \sum_k \sum_{i \in k} \frac{(c_{i(k)} - \hat{f}(x_{i(k)}, y_{i(k)}\,|\vec{q})r_k t_i)^2}{\sigma^2_{i(k)}}, \tag{1}$$

in which the experimental counts $c_{i(k)}$ (from a simulation in our case) are compared to the expected ones. The expected counts are the theoretical rates r_k of the sources multiplied by the exposure time t_i of the i-th exposures and by the attenuation function $\hat{f}(x_{i(k)}, y_{i(k)}\,|\vec{q})$, calculated in the focal pair coordinates in which the k-th source was observed during the i-th exposure. In order to be reconstructed by the minimization algorithm, the response function needs to be decomposed on a bi-dimensional basis on the focal plane, whose coefficients are stored in $\vec{q}$. The unknowns of this problem are then the real count rates r_k and the parameters $\vec{q}$.

The solutions are found with an iterative procedure, by minimizing the χ^2 function (1) with respect to the real rates keeping the coefficients fixed, and vice versa, until the convergence of the algorithm. The uncertainties on the reconstructed parameters are then derived from the full covariance matrix of the problem.

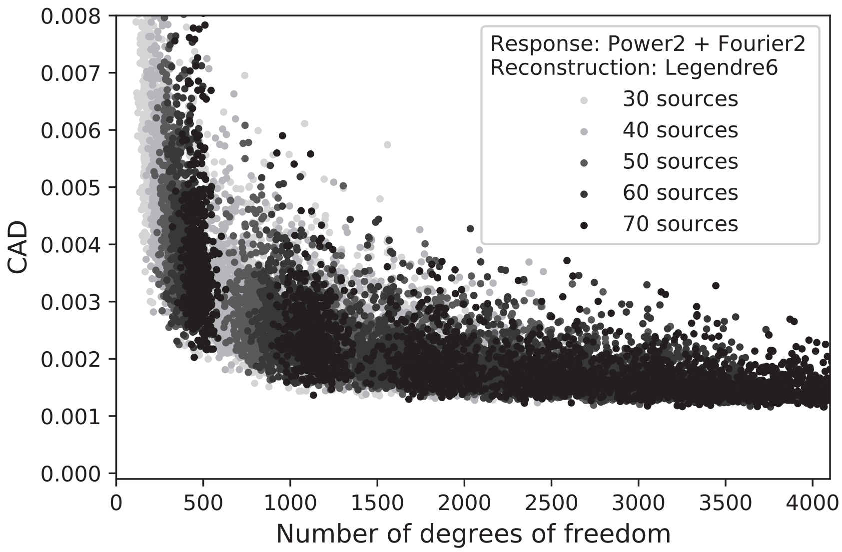

Fig. 2. – Example of the CAD metric as a function of the number of degrees of freedom.

The minimization algorithm was validated through statistical tests, in which the guess response function was parametrized on the same basis of the input one, in order to check if the coefficients of the basis were correctly estimated. The same experiment (that is, set of exposures on the same sources) was repeated about 1000 times. We then studied the residuals on the coefficients, on the real rates and on the same response function, all defined as (true value − reco value)$/\sigma_{\rm reco}$. Since those distributions were found to be Normal, we concluded that the algorithm was unbiased.

3. – Mock-up tests in realistic conditions

The algorithm helped us to look for the best configuration of exposures and observed sky area for the optimization of the survey. The scheduled time dedicated to the calibration is always limited within the context of a space mission: it would be useful to reach good results in the reconstruction of the response function with a low number of exposures. Also, one would like to properly perform this calibration even in those regions where the density of bright sources is lower, *i.e.*, at high galactic latitudes. We thus studied how the goodness of the reconstruction varies as a function of the mean number of sources in the field of view and of the number of random exposures taken. For each combination of these quantities, 500 realizations were obtained, randomly extracting both sources and pointings, in order not to be biased by a single specific configuration. The input function was found to be decreasing to the edges of the detector, as one expects, but it was further complicated by the superimposition of an oscillating behaviour.

We defined three different kinds of metric to quantify the goodness of the reconstruction:

- The *maximum absolute difference* (MAD) is defined as the maximum of the absolute difference between the mockup $f(x,y)$ and the reconstructed $\hat{f}(x,y\,|\vec{q})$, MAD := $\max(|f(x,y)-\hat{f}(x,y\,|\vec{q})|)$, evaluated on the whole domain of the focal plane.

- The *cumulative absolute difference* (CAD) is defined as the spatial integral of the absolute difference between the mock up $f(x, y)$ and the reconstructed $f(x, y)$, $\text{CAD} := \int_{\text{FP}} |f(x, y) - \hat{f}(x, y\,|\vec{q}\,)|\text{d}S$, where the surface integral is over the whole focal plane.

- The *unusable fraction*, given a *threshold* (UF(th%)) is defined as the fraction of the focal plane where the absolute deviation $|f(x, y) - \hat{f}(x, y\,|\vec{q}\,)|$ exceeds a certain threshold.

As one intuitively would expect, we verified that increasing the number of both sources in the sky and exposures improves the goodness of the reconstruction of the response function. The most interesting result instead (see fig. 2) is that the real driver of the goodness of the reconstruction is the number of degrees of freedom $N_{\text{dof}} \equiv \sum_k \sum_{i\in k} 1 - \sum_k 1 - \sum_{\ell=1}^{N} 1$, that is the total number of observations minus the number of estimated parameters (the real rates of the sources and the coefficients of the reconstructed response function). Since the total number of observation is proportional (in first approximation) to the product of the number of sources and the number of exposures, this means that good results can be obtained also with a limited number of exposures, as long as the number of sources in the field of view is sufficiently high. On the other hand, this kind of calibration can be performed at high galactic latitudes too if a greater number of exposures is taken.

Also the degree of the reconstruction basis chosen to fit the unknown response function can alter the goodness of the reconstruction: as long as the number of degrees of freedom is not too low, increasing the terms in the bi-dimensional basis allows to more accurately fit an *a priori* unknown and arbitrarily complicated response function.

4. – Conclusions

The algorithm implemented in this work extends and generalizes the method described in [1]. We improved the estimation of the uncertainties on the reconstructed parameters accounting for the full covariance matrix instead of implying any kind of simplification. We generalized the reconstruction to different kinds of bi-dimensional bases, that in principle can be totally arbitrary. Finally, with statistical tests we quantitatively demonstrated that our algorithm is unbiased.

As far as a typical modern spectroscopic survey is concerned, we created a quantitative method to evaluate the goodness of the reconstruction of the response function through the definition of specific metrics. We concluded that the flux calibration can be performed with a limited set of exposures and, consequently, in a limited time: this last feature is of utmost importance for every space mission. For this reason, the calibration procedure we implemented can be applied to the upcoming Euclid survey [2], and to any other experiment where the use of standard candles as calibration sources is limited, because the spatial variation of the response function is reconstructed from the observation of initially unknown sources.

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