Inverse Chop Addition: Thermal IR background subtraction without Nodding
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Overall, the thermal background is the biggest challenge at infrared wavelengths beyond 2.5 µm and results primarily from the warm telescope and atmosphere. At 12 µm, this background is several orders of magnitude brighter than most astronomical sources. Very accurate background measurement and subtraction methods are required to reach the fundamental photon shot-noise limit of the thermal background. The classical method is the combination of chopping and nodding. In classical chopping, the secondary mirror is switching back and forth between the on-axis and an off-axis position. After subtracting the images obtained at these positions from each other, the background is greatly reduced. Since the thermal emission from the telescope structure is not uniform, and the on-axis and off-axis positions see slightly different parts of the optics, a “chop residual” (or “thermal offset”) persists. That residual is usually removed by nodding, i.e. pointing the telescope to the off-axis position and repeating an inversed chopping sequence. In the ideal case, the residuals cancel each other and the observation is only limited by the shot noise of the background. In reality, the residuals do not vanish and the shot noise limit is often not reached.

The Mid-infrared ELT Imager and Spectrograph (METIS) is one of three scientific first generation instruments on the European Extremely Large Telescope (ELT). METIS will cover the wavelength range between 3 - 19 µm and will enable observations of dust-obscured and warm structures in the universe at five times the angular resolution of current 8 - 10m class telescopes. Due to the large size (4.2m) and mass of the ELT secondary mirror, it cannot provide classical chopping. While classical nodding is technically feasible, it would not be time efficient, due to overheads in the re-acquisition of the Adaptive Optics guide star. This necessitates novel approaches to thermal IR background removal.

Several proposed methods could address this problem, including “three beam chopping” (Landau et al. 1992), a weighted average method, similar to the LOCI algorithm (Marois et al. 2010), “drift scanning” (Heikamp et al. 2014) and “slow-scanning” (Ohsawa et al. 2018). However, none of these methods have yet become mature and robust background subtraction technique for thermal-IR cameras at major observatories. Therefore, we examined the origin and strength of chop residuals with VISIR on the VLT. We found that they seem to invert when chopping “down” instead of “up” (or “left” instead of “right”) for not too large chop throws (Pietrow 2016). This implies that the chop residuals could be removed by chopping between three positions instead of two, where the two-off axis positions must be symmetric about the on-axis position. While this has already been shown to work with single-pixel detectors by Landau et al. (1992), it has never been demonstrated to work on array detectors, which usually require more accurate calibrations. In addition, our method differs from theirs due to limitations in the secondary mirror control of the VLT. Therefore, we employed an alternative approach, combining chop difference frames whose chop direction differs by 180°, a technique we call “inverse chop addition”.

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We first tested this scheme with a telescope "at rest" (tracking disabled) and then applied it to observations of the star HR 2652. These observations were taken on March 24th, 2016, between 23:29:00 and 23:38:00 UT, and consisted of a set of eight chop/nod observations. We observed through the J8.9 filter at a chop frequency of 4 Hz, with a chop throw of 10”, and a chop direction of 0, 90, 180, and 270 degrees.\footnote{Data can be found in table 2.2 of (Pietrow 2016) or by emailing the first author.} This allowed us to directly compare the results from classical chop/nod reductions with inverse chop addition under near identical conditions within the same dataset. (Certain permutations of these frames can be used to construct inverse chop addition pairs, while others can be used to obtain classical chopping and nodding). The observations were made close to zenith to test the method with high on-sky rotation.

The first row of Fig. 1. shows the four directions of the chopper throw in the data, with the corresponding nod frames in the second row. Adding the first two panels of the top row gives the first inverse chop addition frame on the bottom row. Subtracting the first images of row one and two yields the classical chop/nod frame displayed as the second image of the bottom row. The same can be done to obtain the remaining two difference frames. We compare the effectiveness of the reduction using the mean of the background and the sum of the source. These are represented by the big red rectangle and the small black square, respectively. (See Table 1.) For the vertically chopped frames we find a mean background signal of 0.07 ± 0.20 ADU for inverse chop addition, and 0.19 ± 1.17 ADU for classical chopping/nodding. For the horizontally chopped frames we find a mean background of 0.66 ± 1.22 ADU for inverse chop addition and 0.65 ± 1.18 ADU for classical chopping/nodding. The source counts are slightly lower in the inverse-chop added frames, giving us a S/N of 158,227 versus 162,574 for the vertical frames and 146,925 versus 156,096 for the (noisier) horizontal frames, which corresponds to a 0.4% and 2.65% decrease respectively. The origin of this difference needs further investigation. Nevertheless, the high quality (low noise) of the inverse chop addition method looks very promising.

In conclusion, inverse chop addition is a useful alternative to classical chopping and nodding, giving us an identical background noise level at a much lower operational cost. It will be of particular relevance for thermal infrared observations at the ELT where nodding will only be available with significant operational overheads. We note that a precise knowledge of the chop residual structure is not required as long as it is symmetric about the chop origin. We have recently obtained calibration observations with VISIR in order to quantify the conditions and timescales under which the symmetry of the chop residual holds, which will form the basis of future work. Finally, unlike most other aforementioned methods, inverse-chop addition is compatible with current generation chopping mirrors.

|                  | Vertical                          | Horizontal                       |
|------------------|----------------------------------|----------------------------------|
| Noise            | 0.07 ± 1.20                      | 0.66 ± 1.22                      |
| Source           | 189812                           | 179721                           |
| S/N              | 158,227                          | 146,925                          |

Table 1. Data from bottom row of Fig. 1 comparing inverse-chop addition and classical chopping and nodding in two directions. The noise is given as the mean and standard deviation of the red rectangle in the figure. The source signal is given by the the sum of the counts in the black square of the figure.

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Figure 1. The top row shows from left to right: the chop difference frames of HR2652 taken with chop angles of 0, 180, 270 and 90 degrees and the corresponding nod frames in the middle row. Note the inverted signal on the background pattern for opposing chop angles. The panels in the bottom row compare inverse chop addition with classical chopping and nodding along two chop directions. The red rectangle represents the region used for background calibration and the black square represents the region used for obtaining source counts. See table 1 for exact values.

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