Tomographic reconstruction method and application to MLDC data challenges 1.1.1 to 1.1.4

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Sky map construction

Details of the method have been reported in the following papers:

1. S. D. Mohanty, R. K. Nayak, Phys. Rev. D, **73** 083006 (2006).
2. R. K. Nayak, S. D. Mohanty, K. Hayama, Proc. 6th LISA symposium (2006).

The figure below shows a schematic of the basic steps involved. Actual details are available in reference 1 above.
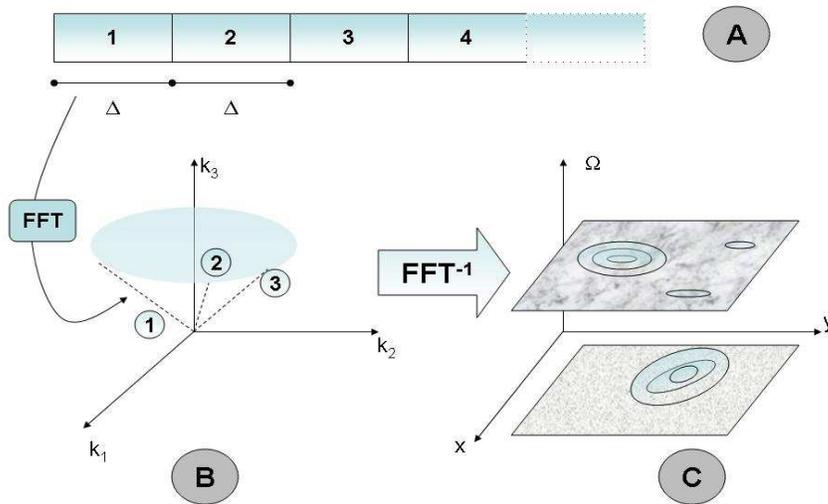
A. The time series of a TDI variable (duration 1 year) is split into Δ sec long segments (overlapping is optional).
B. The FFT of each segment is arranged on a cone in a three dimensional space. This is the space of wave vectors corresponding to a particular choice of coordinates for representing the spatio-temporal *signal density* function.
C. A three dimensional inverse FFT is applied[1] to yield **sky-maps**: **x** and **y** are position coordinates on the sky and **Ω** is the source frequency. The quantity

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[1] More precisely: This step actually involves a sequence of a 3D FFT followed by a 1D FFT. However, the two can be combined into a single operation. Thus, computing the sky-maps for a given x,y and Ω actually involves computing a particular integral over the azimuthal angle in (k_1, k_2, k_3) space.

plotted as a function of position is, loosely speaking, the magnitude of the density function of monochromatic (in the barycenter frame) sources.

The subsequent steps, not shown in the figure above, are:

D. Sky maps are constructed for the other TDI variables.
E. A sky-position dependent weight factor vector is used to combine the three sky maps into one. This step is meant to account for the rotating antenna pattern of LISA.

Estimating binary parameters: A monochromatic source (e.g., a Galactic binary) appears in the sky map as a convolution of a delta-function with a point-spread function **P(x,y,Ω).** In the current state of development, we can only reconstruct these three parameters. Error in estimation comes from the ambient noise, comprised of instrumental noise and unresolved binaries, and from the superposition of the side lobes of the psf. In most cases, the effect of the latter is dominant.

Estimating location and frequency: an incomplete pipeline

We are currently investigating various deconvolution methods to remove the effects of the point spread function. One such method that was explored is the P-Clean method (K.Hayama, S.D.Mohanty, R. Nayak, Proc. 6th LISA symposium). However, this method has not been characterized well enough to use with confidence. Other methods being investigated are Maximum Likelihood deconvolution, Landweber method, Richardson-Lucy and their Wavelet based analogs. It is important to note that **the binary parameters reported for the MLDC were obtained by visual analysis of the sky-maps. No deconvolution method was used to mitigate the effect of the psf.** The performance reported here is, thus, a **lower bound** on what should be possible in the future. We need more experience with the use of deconvolution methods in order to complete the reconstruction pipeline.

Visual inspection is more than adequate for the challenges with binaries spaced widely in frequency space (challenges 1.1.1 to 1.1.3). However, to rapidly scan the large number of bins involved in these data sets, we integrated the power in each sky map and plotted the integrated power as a function of frequency. Maps with peaks in the integrated power were then picked for visual inspection.

Another effect of the lack of a deconvolution step is the inability to retrieve weak sources that lie near stronger ones. The brightness of the latter swamps out the weaker sources and simple visual inspection fails.

Computational costs

The construction of each sky-map entails a fixed computational cost. The cost of a future deconvolution step is currently not known but appears to be comparable, based on our experience with P-Clean, if not less. *On a desktop with 2.1 GHz CPU, it takes about 3 to 5 sec to construct each sky map (for the position resolution used here).* The data set that took the maximum time to analyze was 1.1.2 and 1.1.3 since the number of frequency bins involved was close to .25 million. Construction of the sky maps took 18 hours on the same desktop as above. The step to compute integrated power took only 5 min.

Summary of results and lessons learned

- *For technical reasons, the method currently can not distinguish between sources in the upper and lower hemispheres.* **The values of Latitude we have given are absolute values.**
- Challenge 1.1.5: This was too dense a spacing of binaries for the method to work successfully without using a deconvolution algorithm. We have, therefore, not shown results for this dataset. Nonetheless, we did run the pipeline on the training set and found 20 binaries, in a 90 bins wide frequency band, that were real sources.
- The method appears to reconstruct frequencies of the binaries quite accurately but for the case of well isolated binaries (challenges 1.1.1 to 1.1.3), we get typical errors in the training set of around 3 degrees in both latitude and longitude. This seems to be the result of our, as yet, non-optimal method for addressing LISA's rotating antenna pattern.
- The position error in Challenge 1.1.4 is typically very large for weaker sources and this appears to be an effect of the superposition of psf sidelobes coming from nearby bright sources. The bright source positions are reconstructed more accurately (about the same as for isolated sources).
- The challenge was useful in emphasizing the key directions for future improvements in the tomographic approach: Attaching a deconvolution step and better handling of amplitude modulation.