Search for Gravitational Waves in the Data of Scanning Astrometric Missions

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Abstract

The project presented here is a study with the goal to determine if it is in principle possible to detect gravitational waves (GW) with a scanning astrometry satellite. We have systematically investigated how continuous, plane gravitational waves influence a Gaia-like astrometric solution. Furthermore, a suitable GW search algorithm has been designed which is able to handle the massive amounts of data from a real mission, like Gaia. This poster shows the current status of the project and gives some results on how a GW influences the astrometric solution. In addition, ongoing and future work is discussed.

Introduction

Astrophysics and cosmology predict that many different types of GW sources exist, emitting GWs in a broad frequency spectrum. However, in the GW frequency range of about 10^{-7} Hz to 10^{-5} Hz the proposed GW detectors are rather insensitive or completely blind [1]. In principle, one possible remedy in this frequency range (and beyond) is to use high-accuracy space-based astrometric data of the type that is becoming available in the framework of Gaia (see Figure 1).

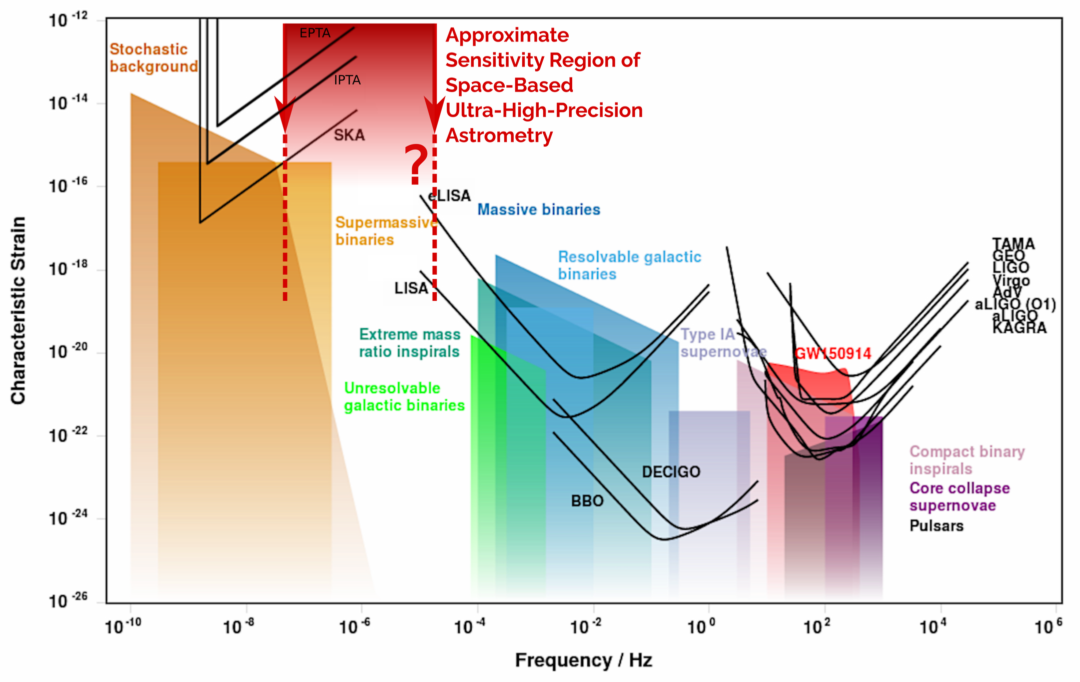

Figure 1: Approximate GW frequency region for space-based astrometry. The sensitivity, in terms of strain sensitivity, which can be reached in the end is still to be determined. Background image credit: `http://rhcole.com/apps/GWplotter/` [1]

We have investigated how a GW influences the astrometric solution of a Gaia-like mission, in particular what errors occur [2, 3]. Furthermore, we developed a sophisticated detection algorithm which should be able to detect a GW signal using Gaia-like astrometric measurements [4]. For simplification we assume to have a single (detectable) plane GW which is constant in frequency and amplitude. Possible GW sources for this measurement principle are super massive black hole binaries in galaxy centers [4].

Influence on the Astrometric Solution

It is obvious that a (un-modeled) time dependent, global signal like a GW will introduce errors to the source parameters (position, proper motion and parallax) of sources. With respect to GWs, source errors exist in two "regimes" depending the GW frequency:

- The period of the wave is larger than the time-span of observational data
  - Astrometric model absorbs the positional shift either in the position or proper motion parameters.
  - This depends on phase of the wave.
- Wave periods smaller than the time-span of observational data
  - All of the source parameters are influenced to some extend.
  - See sky-error plots in Figure 4
  - A substantial part of the signal will remain un-modeled in the residuals of the astrometric solution:
    This potentially allows us to search for a GW signal!

The behavior of the astrometric errors over the wave frequency is shown in Figure 3, the figure is generated by running multiple full mission simulations each with a GW with different frequency.

Satellite Attitude vs. GW Signal

Parts of a GW signal are indistinguishable from certain changes in the satellite attitude, which is fitted from the data. This is a general problem which affects all global signals as described in [5]. Only half the difference of the signal in along-scan (AL) direction of both fields-of-view is invariant with respect to some small rotation of the satellite attitude. This is the only part of the signal which can potentially be measured if the basic-angle of the instrument is stable enough. Further results of this part of our investigation are:

- Across-Scan (AC) residuals are completely unusable for GW detection
- AL residuals appear to contain some 70% of the signal, depending on the measure one takes.
- An ideal PGW signal with strain of 10 mas has a RSE (robust scatter estimator) of 2.2 mas in AL: the AL residuals of a full mission simulation have RSE of 1.5 mas in this case.
- The correlation coefficient between such a ideal signal and the AL residuals is around 0.75.

A further illustration of this can also be found in Figure 2, there we compare the distributions of the ideally measurable signal with the AC and AL residuals of the astrometric solution.

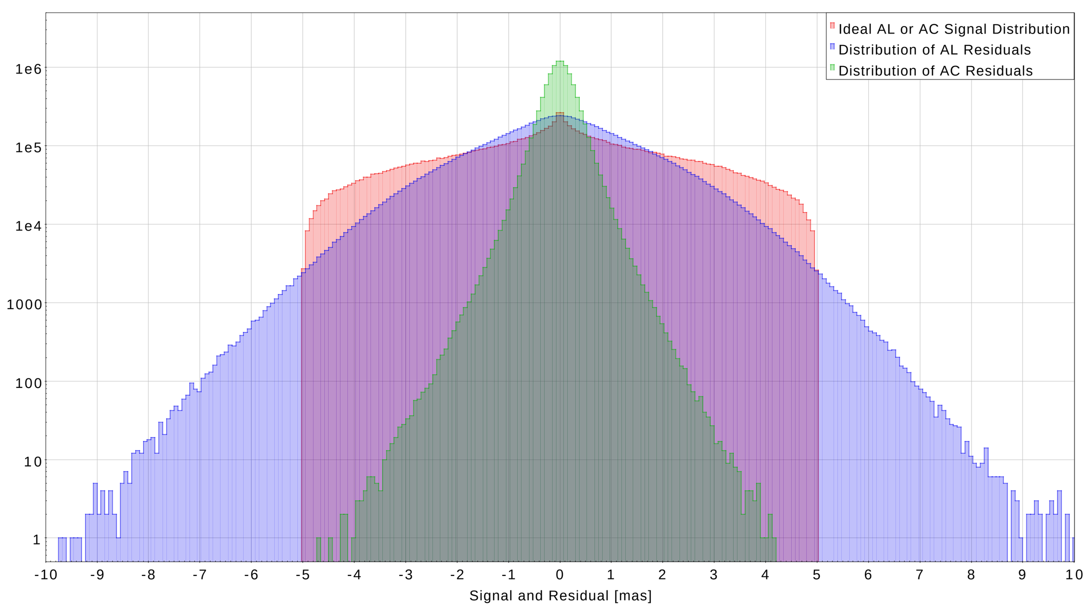

Figure 2: Comparison of the ideally measurable signal and AL and AC residual distributions. One can clearly see that the AC residuals are very small because the attitude in AC has absorbed the GW signal. The AL residual distribution contains large parts of the GW signal and is smeared out because of the errors in the attitude and parameters of the sources.

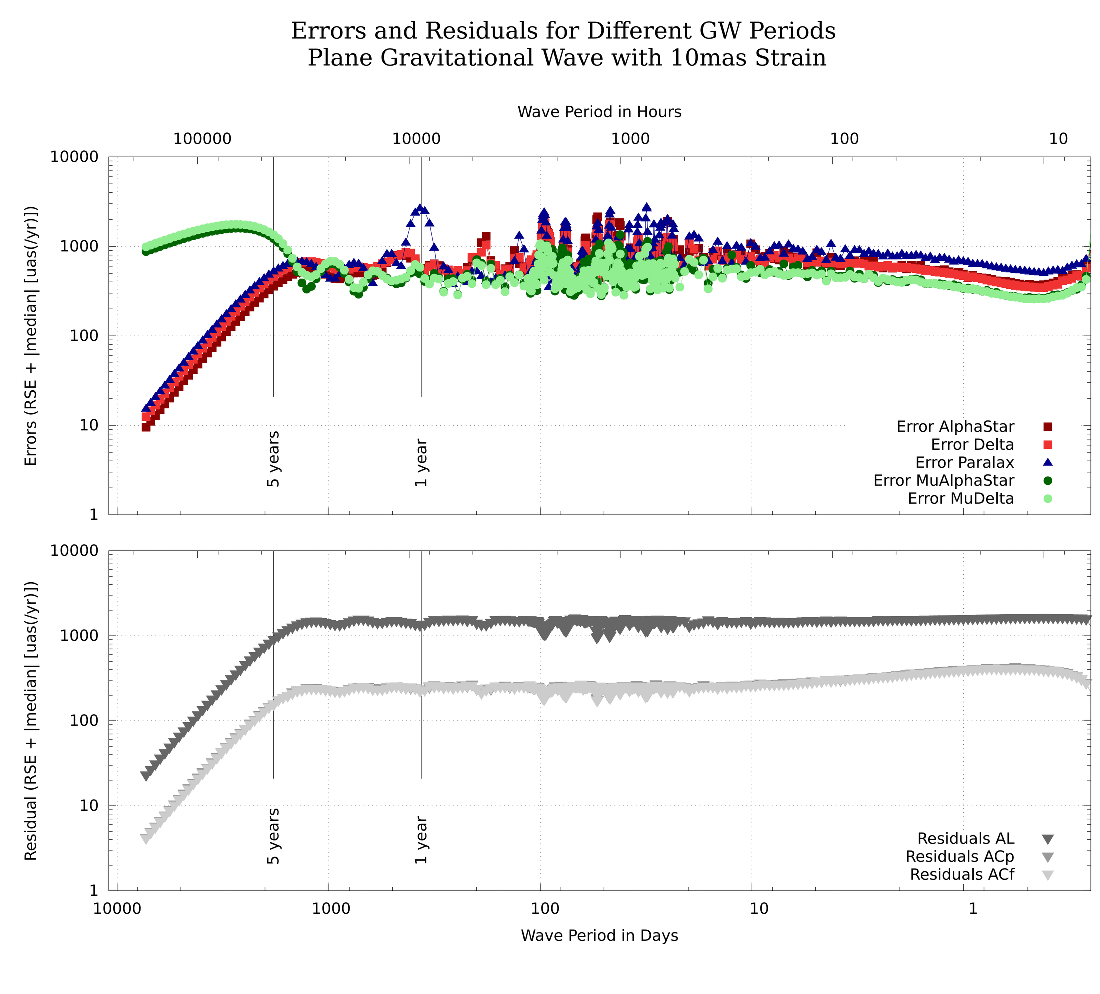

Figure 3: Response of the astrometric errors and the solution residuals on GWs with different periods on a 5 year mission. The simulated GW signal for each period has a total strain of 10 mas, and the phase has been chosen so that the signal is zero in the middle of the observational data. Clearly visible is the low frequency regime for wave periods longer than 5 yr: the proper motion errors are high, since the wave signal for a single source is almost a linear motion on the sky in this case. For GW periods shorter than 5 yr, the astrometric errors are fluctuating and show multiple local peaks which are related both to scanning law and to the details of the source model (see the peak in the errors of estimated parallaxes for a GW with the period around of 1 year)

Detection Algorithm

While it is in principle possible to perform some kind of a non-linear least-squares fit directly on the AL residuals to search for a GW signal, the large amount of data and the highly non-linear nature of the problem makes this approach infeasible. Hence, the core idea of our algorithm is to compress the data and to use Vectorial Spherical Harmonics (VSH) in order to determine the presence of a signal in a directional independent way. Furthermore, we envision the exploitation of some divide and conquer scheme to optimize the search of the GW frequency. The outline of our algorithm is as follows:

- Delivered by the astrometric solution is: $(t, \mathbf{u}, r_{AL}, \mathbf{s})$ with t is observation time, $\mathbf{u}$ is the sky position of the source, r_{AL} is the astrometric residual (i.e. our "observation") and $\mathbf{s}$ is the AL scan direction
- Convert them to normal points using time-binning and sky pixelization (i.e. the "mean" observation and scan direction for a given time-span and sky pixel): $(\overline{t}, \mathbf{u}_{pix}, \overline{r_{AL}}, \overline{\mathbf{s}})$
- Fitting the components of two vector fields $\mathbf{V}_c$ and $\mathbf{V}_s$ so that $\overline{r_{AL}} = \mathbf{s} \cdot \mathbf{V}_c \cos\Phi + \mathbf{s} \cdot \mathbf{V}_s \sin\Phi$ with $\Phi = 2\pi\Omega_{GW}\overline{t}$ dependent on the wave frequency Ω_{GW} and the observation time $\overline{t}$
  - Here one can do divide and conquer and get the $\mathbf{V}_c$ and $\mathbf{V}_s$ components for multiple frequencies simultaneously
- Fitting VSH coefficients from the components of both vector fields $\mathbf{V}_c$ and $\mathbf{V}_s$ computed before of all sky pixels
- Analysis of the VSH coefficients with respect to a GW signal, determining the GW parameters
- Fit the GW model using the parameters from above and uncompressed data directly in the astrometric solution

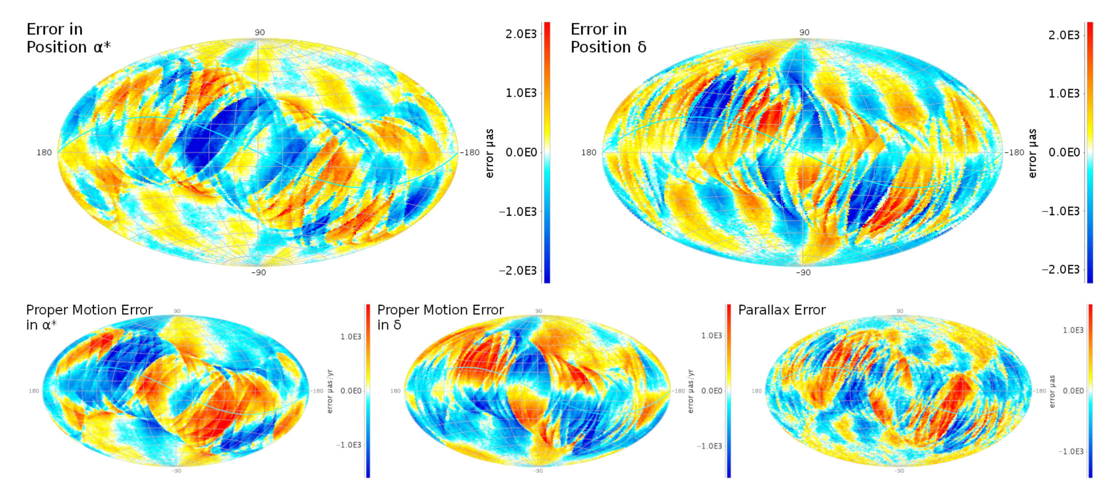

Figure 4: Distribution of the errors of the source parameters on the sky for a simulated GW with a period of ≈ 200 d, a total strain of 10 mas coming from the direction $\alpha = 0°; \delta = 0°$. The values shown here are the RSE + |median| values of the errors of all sources per HEALPix. The shape of the pattern on the sky changes substantially with GW frequency.

Current and Future Work

Currently we are implementing the search algorithm, this should allow us to perform end-to-end simulations of the whole detection pipeline. The resulting software will be made ready to process real data from the Gaia mission as well. Next steps are to obtain a better understanding of the detection statistics and the interplay between different calibrations and the detectability of a GW signal.

Summary of Results

- Ultra high precision scanning astrometry can in theory detect continuous GWs
- Interesting for GW with periods shorter than data-coverage
  - Upper frequency limit given by instrument calibrations and "stability" of emitters
- Attitude determination and basic angle stability are practical problems
- Search algorithm is formulated, implementation ongoing

References and Acknowledgements

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