LISA DATA REDUCTION

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ABSTRACT

The passage of gravitational waves changes the arm lengths between corners of the LISA spacecraft formation. These changes are detected interferometrically and recorded as phase measurements. The time series are reduced to reveal several signal types. First, the strong periodic signals from all types of galactic binaries and any strong chirped signals are identified by template fitting, and removed. Then weak, periodic signals and poorly characterized signals (e.g., generic bursts) are searched for. Next, weak signals with complex waveforms, such as from compact objects orbiting massive black holes, are sought with templates. Genetic algorithms, template structure or hierarchical searches are used to efficiently search the very large parameter space. Finally, backgrounds from galactic binaries, extragalactic binaries and the Big Bang will/may be separable by their signatures.

OVERVIEW

The Laser Interferometer Space Antenna (LISA) is designed to detect gravitational waves by interferometrically comparing the separation of free-falling proof masses housed in spacecraft about 5×10^6 km apart. Two spacecraft are located at each corner of a triangular formation orbiting around the Sun. Laser beams are exchanged along the long arms and between the pair of spacecraft at the corner, about 200 km apart. In this paper we describe a candidate scheme for the reduction of LISA data.

This scheme consists of the acquisition of data, the on-board processing of data, the routine ground processing, the strong signal analysis, the weak signal analysis and the background analysis. To help the reader understand the problem, we will also describe the nature of the signals before describing the last three steps of the reduction. As part of the data acquisition, several beat signals are formed, and their phase is measured at each sampling interval. Laser phase noise and clock noise must be corrected on the spacecraft to reduce the required telemetry bandwidth. After telemetry the science data must be decompressed and separated from spacecraft housekeeping data at a mission control centre and then forwarded with payload housekeeping data to a science centre where the payload monitoring and most scientific analyses will take place. The scientific analyses can be roughly broken down into searches for strong signals, searches for weak signals and analysis of the remaining power for information about backgrounds from very many galactic and extragalactic binaries and possibly from the early Universe. The reader can find a more detailed discussion of the data acquisition and the on-board processing in Stebbins *et al.* (1996) and a more extended description of the signal analyses in Stebbins *et al.* (1997).

DATA ACQUISITION

Although all of the LISA spacecraft will be identical, one will be designated the "master." The laser of the master spacecraft will be locked to an on-board reference cavity. That frequency will then be propagated around the formation by offset locking on-board lasers to incoming beams, either from the long arm or from the short path between the two spacecraft at the same corner. For example, the master laser will be sent out through the transmitting telescope along a long arm to a spacecraft at another corner. Light from the master laser will also be sent across the short path to the other spacecraft at the same corner. The lasers on the two receiving spacecraft will be offset-locked (Robertson *et al.*, 1996) with different offset frequencies to the incoming light from the master. The distant spacecraft will return a beam to the master spacecraft for beating against the master and send another beam across the short path to the other spacecraft at the same corner. The spacecraft at the same corner as the master will send beams both back to the master to make a beat signal and over the long arm to the third corner. In this manner, all five slaved lasers will be made to follow the frequency of the master with known offset frequencies and propagation delays. The offset frequencies are roughly 10 kHz, derived from an on-board ultra-stable oscillator (USO).

Four beat signals from the long arms will be measured. Two of these will be telemetered back to the corner with the master spacecraft for the on-board processing by modulation onto the laser beams. Three beat signals from the short paths will also be measured, two of which will be telemetered back to the corner with the master spacecraft for the on-board processing. Beat signals are measured as times series of phase measurements. Beat frequencies will reflect the roughly 10 kHz offset between the two laser frequencies and the gradual changes in path length. If the final orbits are optimized for minimal drift between two sides of the triangle, and are corrected annually, then the relative Doppler frequency is expected to be of order 1 MHz. However, the remaining arm is likely to produce frequencies as high as 15 MHz.

The LISA error budget allocates to the phase measurement process 2 pm/$\sqrt{\text{Hz}}$ or 2×10^{-6} of a cycle for each beat signal. The laser frequency noise is expected to correspond roughly to 5×10^{3} cy/$\sqrt{\text{Hz}}$ at 1 mHz. Consequently, the phase measurement must have a dynamic range of 10^{10}. The accuracy and dynamic range requirements will be met by using a digital approach. Initially, the signal from the optical heterodyne detector is beat against a reference frequency chosen from a comb of frequencies, generated by the USO. The reference frequency will be chosen to give a final beat frequency between 75 and 125 kHz. A tracking filter will be used to remove high frequency phase noise to prevent aliasing. The resulting signal will be converted to positive-going zero-crossing pulses with standard shapes. In each sample interval, the integer number of zero-crossing pulses will be counted and the fraction timed. Finally, the digital phase measurements are filtered to remove phase variations at frequencies above 1 Hz and the data set is reduced to a time delay and a count every 0.5 s.

ON-BOARD PROCESSING

Since the wavelength of the master laser is used to measure distances between LISA spacecraft, laser phase noise affects the phase measurements in the same way as do actual length changes. Likewise, USOs provide the offset frequencies used in laser locking, the intermediate frequencies for beating against the optical heterodyne signals and the timing in phase measurements. Thus oscillator phase noise, at the level present in available space-qualified USOs, will also affect the phase measurements. In this section, we describe procedures for correcting both of these noise sources on-board the spacecraft.

The laser phase noise can be estimated from the apparent variations of any one arm, because in the frequency band of interest the actual lengths of the long arms are very stable. An estimate of the laser phase noise can be formed by dividing the Fourier transform of the phase signal by the transfer function of a path of the appropriate length. The laser phase noise information from a single arm degrades near frequencies corresponding to harmonics of the round-trip travel time. However, a weighted mean of the laser phase noise estimates from two arms can be used to circumvent this problem. By this correction algorithm the laser phase noise can be reduced down to the level of the measurement noise, if the arm lengths are known well enough and the measurement system has sufficient dynamic range.

Our model of laser phase noise at frequencies between 1×10^{-4} and 1 Hz is based on the thermal stability of the reference cavity to which the master laser is locked below about 3 mHz and the locking noise of Salomon *et al* (1988) at higher frequencies. Representative values of the fractional laser frequency noise from this model are $2\times10^{-11}/\sqrt{\text{Hz}}$ at 0.1 mHz, $1\times10^{-13}/\sqrt{\text{Hz}}$ at 1 mHz and $2\times10^{-15}/\sqrt{\text{Hz}}$ at 10 mHz. To correct for this to a measurement noise level of 4 pm/$\sqrt{\text{Hz}}$ requires that the phase noise be reduced by a factor of 8×10^{-10} at 1 mHz - compatible with the dynamic range described in the previous section.

On-board laser phase noise correction permits a factor of 5 data compression before telemetry across 0.3 AU. One disadvantage of laser phase noise correction is a small fractional error in the amplitude and phase of gravitational wave signals in some cases. These errors appear correctable for sources where the source direction and polarization can be determined.

Current USOs have an Allan standard deviation of 1 to 2×10^{-13} for periods of 1 to 1000 s. This corresponds to a fractional frequency noise of $6\times10^{-12}/\sqrt{\text{Hz}}$ at 1 mHz. For 5×10^{6} km arm lengths, even if the round-trip laser Doppler shift were kept down to 10 kHz, the resulting noise in measuring variations in the length of one arm is 9 pm/$\sqrt{\text{Hz}}$. While frequent orbital maneuvers would keep the Doppler shifts for two arms small, the Doppler shift for the third arm would still be large. Instead, the USO phase noise will be measured with a method suggested by Danzmann (Hellings *et al* 1996). In this method, the USOs will operate in much the same manner as the lasers, where one USO will function as the "master" and the other USOs will be offset locked to it. Sidebands of perhaps 200 MHz, derived from the USOs, will be modulated onto the laser beams, and the phase noise of the master oscillator will be determined the same way as the laser phase noise.

ROUTINE PROCESSING AND DATA FLOW

After the on-board processing, the data will be compressed and prepared for telemetry. Upon receipt at a ground station the data will be forwarded to the ESOC Mission Control Centre where payload and spacecraft housekeeping data will be separated from the science data. The payload and science data and some relevant spacecraft information will then be forwarded to the LISA Science Centre for payload monitoring, science data quality assurance checks and science processing. The phase time series will be converted to path length difference time series. Gaps will be filled where possible, residual orbital effects will be removed, and strain time series will be formed and Fourier transformed.

NATURE OF THE SIGNALS

We expect that LISA data will contain information from many sources with widely differing characteristics. One possible reduction process for deducing astrophysical information from the data is described in the following sections. In this section we survey the variety of signal characteristics from the better understood sources to illustrate the challenges of the data reduction process. Exotic sources which are not well understood now may be the most interesting sources, but we do not consider them here. Note that while we describe the signals by their inherent spectral properties, the orbital motion of the LISA antenna will modulate the phase of signals from all sources and, together with the antenna sensitivity pattern and source polarization, will modulate the amplitude.

The expected signals can be roughly grouped into four main categories. First, the simplest and most common signals will be simple periodic signals generated by binary systems of compact objects, such as neutron stars, white dwarfs and small ($<20\ M_{\odot}$) black holes. There will be very many of these sources in the Milky Way. The galactic close white dwarf binaries should be so numerous that there will be a continuum below roughly 1 mHz caused by the confusion of multiple sources per frequency bin in a one year long data string. The stronger galactic sources may rise 2 orders of magnitude above the continuum. Extragalactic sources of this type will be far more numerous, and will dominate galactic binaries above about 3 mHz.

Second, pairs of black holes near coalescence, if they exist, would generate chirped signals. Intermediate mass black holes ($\sim 10^2$-$10^4\ M_{\odot}$) would produce signals around and above 1 mHz. These signals could exceed the instrumental noise and the confusion level by as much as several hundred times, even out to a redshift of $z=1$. If massive ($\sim 10^4$-$10^7\ M_{\odot}$) black hole binaries produced by galactic mergers occur frequently enough to be seen, they would have signal-to-noise ratios of up to several thousand for sources at $z=1$ in the last year before coalescence.

Third, compact objects, such as small (3-20 $M_{\odot}$) black holes, trapped in highly relativistic orbits about massive black holes in galactic nuclei can emit gravitational radiation with complex waveforms having multiple periodicities. These sources may well be detectable at cosmological distances, but with only moderate signal-to-noise ratios.

Finally, the very large number of galactic and extragalactic binaries, mentioned above, will at some level give an apparently stochastic background. In the region below 1 mHz where galactic binaries dominate, this background will be spatially anisotropic. Between 1 and 3 mHz, the galactic sources rapidly become sparse with increasing frequency, revealing an extragalactic background at a lower level, which is nearly isotropic. Although the gravitational wave background from the Big Bang is very uncertain, and the scenarios under which LISA could detect it are not well understood, if it were detectable at mHz frequencies by LISA, then one would expect the cosmological background to be quite isotropic.

STRONG SIGNAL ANALYSIS

A few gravitational wave sources will be known beforehand from electromagnetic observations, and comparisons of the actual signals with the predicted waveforms will check the LISA sensitivity and gravitational theory. However, almost all of the gravitational wave sources will be identified by searching over the space of possible source and direction parameters with templates. Strong signals are those for which the parameter space can be greatly reduced by inspection of the strain power spectrum and for which the parameters can be well estimated by fitting templates to one source at a time. The identification of strong periodic signals will produce the source direction, as well as the signal amplitude, frequency, eccentricity, polarization and phase. This process will be applied iteratively until the remaining signals are too weak to be treated this way.

The next step in the data processing is the identification and removal of possible strong non-periodic signals, like chirped signals. For strong enough non-periodic sources, the parameter space can again be significantly reduced by examining the original spectra and spectra based on subsets of the whole time series. There will also have to be a search for strong, unexpected types of sources with discovery filters.

The strong-signal processing phase will produce a catalog of strong sources with estimates of their directions and the parameters of the emitting systems. And, an intermediate time series with the strong sources removed will be produced which will be the starting point for weak signal processing.

WEAK SIGNAL ANALYSIS

The search for weak signals will start with an initial fitting of individual templates for periodic and chirped signals to the time series with strong signals removed. This will involve a large number of pre-computed templates and will tentatively identify the weak sources. Then the fitted signals for the strong and the weak sources are combined and refit to the original time series. The results will then be catalogued and removed from the data set.

The second step will be to search for the complex waveforms described two sections previously. The phase of these multi-periodic signals has information about several source parameters, and a brute force search would require a very large grid of templates. A more sophisticated search strategy is desirable. Among the candidates for the search strategy are several based on a combination of "steepest descent" methods and random restarts in order to avoid local maxima in the filtered signal strength. Two such approaches are the use of genetic algorithms and simulated annealing. Another approach which is being investigated for ground-based gravitational wave searches is the hierarchical method. Since many of the parameters involve time, the number of templates increases very rapidly with the length of the data set. So, a hierarchical search would first apply coarser filters to a shorter duration time series, and then higher resolution filters for the promising regions of parameter space would be applied to longer duration time series.

BACKGROUND ANALYSIS

Although the binary confusion noise level is uncertain because the space densities of some types of develop a statistical model for the distribution of different types of binaries throughout the galaxy based on the distribution of resolved galactic binaries. Then this model would be extrapolated to somewhat lower and higher frequencies, with available information on the initial period distribution and evolution of different types of close binaries. The predictions of the galactic confusion limit model could then be compared with the observations to possibly improve the model. Next, an attempt would be made to fit the confusion noise from extragalactic binaries, using the frequency dependence of the spectral amplitude. If essentially all of the isotropic component can be fit in this way, there will be no way to separate out a possible contribution from events in the early universe, such as a primordial gravitational wave background or gravitational waves from an early phase transition. However, if the observed isotropic spectral amplitude does not fit that expected for extragalactic binaries, the difference would be a candidate for gravitational waves coming from the early universe.

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