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OctApps: a library of Octave functions for continuous gravitational-wave data analysis

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Summary

Gravitational waves are minute ripples in spacetime, first predicted by Einstein's general theory of relativity in 1916. Their existence has now been confirmed by the recent successful detections of gravitational waves from the collision and merger of binary black holes (Abbott, 2016) and binary neutron stars (Abbott, 2017) in data from the LIGO and Virgo gravitational-wave detectors. Gravitational waves from rapidly-rotating neutron stars, whose shape deviates from perfect axisymmetry, are another potential astrophysical source of gravitational waves, but which so far have not been detected. The search for this type of signals, also known as continuous waves, presents a significant data analysis challenge, as their weak signatures are expected to be buried deep within the instrumental noise of the LIGO and Virgo detectors. For reviews of continuous-wave sources, data analysis techniques, and recent searches of LIGO and Virgo data, see for example Prix (2009) and Riles (2017).

The *OctApps* library provides various functions, written in Octave (Eaton, Bateman, Hauberg, & Wehbring, 2015), intended to aid research scientists who perform searches for continuous gravitational waves. They are organized into the following directories:

- `src/cw-data-analysis`: general-purpose functions for continuous-wave data analysis.
- `src/cw-line-veto`: functions which implement detection statistics which are robust to instrumental disturbances in the detector data, as described in (Keitel, Prix, Papa, Leaci, & Siddiqi, 2014).
- `src/cw-metric-template-banks`: functions which determine the number of filtering operations required to search for continuous waves over various astrophysical parameter spaces, described further in (Wette & Prix, 2013) and (Leaci & Prix, 2015).
- `src/cw-optimal-search-setup`: functions which determine the optimally-sensitive search for continuous gravitational waves, given a fixed computing budget, following the method of (Prix & Shaltev, 2012).
- `src/cw-sensitivity`: functions which predict the sensitivity of a search for continuous waves, following the method of (Wette, 2012).
- `src/cw-weave-models`: functions which characterize the behaviour of *Weave*, an

implementation of an optimized search pipeline for continuous waves (Wette, Walsh, Prix, & Papa, 2018).

Many of these scripts make use of C functions from the LSCAlgorithmLibrarySuite(LALSuite), using SWIG to provide the C-to-Octave interface.

In addition, *OctApps* provides various general-purpose functions, which may be of broader interest to users of Octave, organized into the following directories:

- `src/array-handling`: manipulation of Octave arrays and cell arrays.
- `src/command-line`: includes `parseOptions()`, a powerful parser for Octave function argument lists in the form of key–value pairs. Together with `octapps_run`, a Unix shell script, it allows Octave functions to also be called directly from the Unix command line using a `--key=value` argument syntax.
- `src/condor-jobs`: submission of jobs to a computer cluster using the HTCondor job submission system. It includes `depends()`, a low-level function written using Octave's C++ API which, given the name of an Octave function, returns the names of all Octave functions called by the named function; it is used to deploy a self-contained tarball of Octave `.m` files to a remote node on a computer cluster.
- `src/convert-units`: functions which convert between different angular units, and between different time standards.
- `src/file-handling`: parsing of various file formats, such as FITS and `.ini`.
- `src/general`: miscellaneous general-purpose functions.
- `src/geometry`: mathematical operations associated with geometric objects, e.g. computing the intersection of two lines.
- `src/histograms`: includes `@Hist`, an Octave class representing a histogram, with various method functions which perform common statistical operations, e.g. computing the cumulative distribution function.
- `src/lattices`: mathematical operations associated with lattice theory, e.g. computing the nearest point in a lattice to a given point in space.
- `src/mathematical`: miscellaneous general mathematical functions, including some C functions incorporated from the GNU Scientific Library (Galassi, 2009), using SWIG to provide the C-to-Octave interface.
- `src/plotting`: helper functions for plot creation and output in TeX format.
- `src/statistics`: miscellaneous statistical functions, particularly for probability distributions.
- `src/text-handling`: various functions for creating formatted text output.
- `src/version-handling`: handling of version information, particularly from the Git version control system.

Development of *OctApps* is hosted on GitHub; a test suite of all functions in *OctApps* is regularly integrated on Travis CI. The README file provides instructions for building, testing, and contributing to *OctApps*, as well as a full list of prerequisite software required by *OctApps*. A reference manual for *OctApps* in HTML format is available; documentation of each *OctApps* function can also be accessed through the `help` function in Octave.

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LIGO-P1800078-v4.

References

Abbott, B. P. et a. (2016). Observation of Gravitational Waves from a Binary Black Hole Merger. *Physical Review Letters*, *116*, 061102. doi:10.1103/PhysRevLett.116.061102

Abbott, B. P. et a. (2017). GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral. *Physical Review Letters*, *119*, 161101. doi:10.1103/PhysRevLett.119.161101

Eaton, J. W., Bateman, D., Hauberg, S., & Wehbring, R. (2015). *GNU Octave version 4.0.0 manual: A high-level interactive language for numerical computations*. Retrieved from http://www.gnu.org/software/octave/doc/interpreter

Galassi, M. et a. (2009). *GNU scientific library reference manual - third edition*. Retrieved from https://www.gnu.org/software/gsl

Keitel, D., Prix, R., Papa, M. A., Leaci, P., & Siddiqi, M. (2014). Search for continuous gravitational waves: Improving robustness versus instrumental artifacts. *Physical Review D*, *89*, 064023. doi:10.1103/PhysRevD.89.064023

Leaci, P., & Prix, R. (2015). Directed searches for continuous gravitational waves from binary systems: Parameter-space metrics and optimal Scorpius X-1 sensitivity. *Physical Review D*, *91*, 102003. doi:10.1103/PhysRevD.91.102003

Prix, R. (2009). Gravitational Waves from Spinning Neutron Stars. In W. Becker (Ed.), *Neutron Stars and Pulsars*, Astrophysics and space science library (Vol. 357, p. 651). Berlin/Heidelberg: Springer. doi:10.1007/978-3-540-76965-1_24

Prix, R., & Shaltev, M. (2012). Search for continuous gravitational waves: Optimal StackSlide method at fixed computing cost. *Physical Review D*, *85*, 084010. doi:10.1103/PhysRevD.85.084010

Riles, K. (2017). Recent searches for continuous gravitational waves. *Modern Physics Letters A*, *32*, 1730035–685. doi:10.1142/S021773231730035X

Wette, K. (2012). Estimating the sensitivity of wide-parameter-space searches for gravitational-wave pulsars. *Physical Review D*, *85*, 042003. doi:10.1103/PhysRevD.85.042003

Wette, K., & Prix, R. (2013). Flat parameter-space metric for all-sky searches for gravitational-wave pulsars. *Physical Review D*, *88*, 123005. doi:10.1103/PhysRevD.88.123005

Wette, K., Walsh, S., Prix, R., & Papa, M. A. (2018). Weave: a semicoherent search implementation for continuous gravitational waves. *submitted to Physical Review D.*