
THE LIGO SCIENTIFIC COLLABORATION and the VIRGO COLLABORATION, the AUSTRALIAN SQUARE KILOMETER ARRAY PATHFINDER (ASKAP) COLLABORATION, the BOOTES COLLABORATION, the DARK ENERGY SURVEY and the DARK ENERGY CAMERA GW-EM COLLABORATION, the FERMI GBM COLLABORATION, the FERMI LAT COLLABORATION, the GRAVITATIONAL WAVE INAF TEAM (GRAWITA), the INTEGRAL COLLABORATION, the INTERMEDIATE PALOMAR TRANSIENT FACTORY (iPTF) COLLABORATION, the INTERPLANETARY NETWORK, the J-GEM COLLABORATION, the LA SILLA–QUEST SURVEY, the LIVERPOOL TELESCOPE COLLABORATION, the LOW FREQUENCY ARRAY (LOFAR) COLLABORATION, the MASTER COLLABORATION, the MAXI COLLABORATION, the MURCHISON WIDE-FIELD ARRAY (MWA) COLLABORATION, the PAN-STARRS COLLABORATION, the PESSTO COLLABORATION, the PI OF THE SKY COLLABORATION, the SKYMAPPER COLLABORATION, the SWIFT COLLABORATION, the TAROT, ZADKO, ALGERIAN NATIONAL OBSERVATORY, and C2PU COLLABORATION, the TOROS COLLABORATION, and the VISTA COLLABORATION

(See the end matter for the full list of authors.)

Received 2016 April 27; accepted 2016 May 4; published 2016 July 20

ABSTRACT

This Supplement provides supporting material for Abbott et al. (2016a). We briefly summarize past electromagnetic (EM) follow-up efforts as well as the organization and policy of the current EM follow-up program. We compare the four probability sky maps produced for the gravitational-wave transient GW150914, and provide additional details of the EM follow-up observations that were performed in the different bands.

Key words: gravitational waves – methods: observational

1. PAST AND PRESENT FOLLOW-UP PROGRAM

The first gravitational-wave (GW)-triggered electromagnetic (EM) observations were carried out during the 2009–2010 science run of the initial LIGO and Virgo detectors (Abadie et al. 2012b), featuring real-time searches for unmodeled GW bursts and compact binary coalescences (CBCs; Abadie et al. 2012a, 2012b). GW candidates were identified—typically within 30 minutes—and their inferred sky locations were used to plan follow-up observations with over a dozen optical and radio telescopes on the ground plus the Swift satellite (Gehrels et al. 2004). Tiles were assigned to individual facilities to target known galaxies that were consistent with the GW localizations and that were within the 50 Mpc nominal BNS detectability horizon. Eight GW candidates were followed up. Though none of the GW candidates were significant enough to constitute detections and the EM candidates found were judged to be merely serendipitous sources (Evans et al. 2012; Aasi et al. 2014), the program demonstrated the feasibility of searching in real time for GW transients, triggering follow-up, and analyzing GW and EM observations jointly.

The present program of follow-up of GW candidates involves a large number of facilities and observer teams. Instead of centrally planning the assignment of tiles to facilities, we have set up a common EM bulletin board for facilities and observers to announce, coordinate, and visualize the footprints and wavelength coverage of their observations. The new program builds on the Gamma-ray Coordinates Network (GCN) system that has long been established for broadband follow-up of gamma-ray bursts (GRBs). We distribute times and sky positions of event candidates via machine-readable GCN Notices, and participating facilities communicate the results of observations via short bulletins, GCN Circulars. A key difference is that GRB Notices and Circulars are instantly public, whereas GW alert Notices and follow up Circulars currently are restricted to participating groups until the event candidate in question has been published. After four high-confidence GW events have been published, further high-confidence GW event candidates will be promptly released to the public.

2. COMPARISON OF GRAVITATIONAL-WAVE SKY MAPS

In the main Letter (Abbott et al. 2016a), we introduced four GW sky maps produced with different methods: cWB (Klimenko et al. 2016), LIB (Lynch et al. 2015), BAYESTAR (Singer & Price 2016), and LALInference (Veitch et al. 2015). cWB and LIB treat the GW signal as an unmodeled burst; BAYESTAR and LALInference assume that the source is a CBC. The LALInference sky map should be regarded as the authoritative one for this event. Table 1 shows that the areas of the 10%, 50%, and 90% confidence regions vary between the algorithms. For this event, cWB produces smaller confidence regions than the other algorithms. While cWB produces reasonably accurate maps for typical binary black hole (BBH) signals, it can systematically misestimate the sizes of large confidence regions (Essick et al. 2015). The other algorithms are self-consistent even in this regime. Only the LALInference results account for calibration uncertainty (systematic errors in the conversion of the photocurrent into the GW strain signal). Because systematic errors in the calibration phase affect the measured arrival times at the detectors, the main effect is to broaden the position uncertainty relative to the other sky maps.

Table 1 also shows the intersections of the 90% confidence regions as well as the fidelity $F(p, q) = \int \sqrt{pq} \, d\Omega \in [0, 1]$ between the two maps $p$ and $q$. All these measures show that
the sky maps are similar but not identical. Typically, this level of quantitative disagreement is distinguishable by eye and has been observed in large simulation campaigns (Singer et al. 2014; Berry et al. 2015; Essick et al. 2015) for approximately 10%–20% of the simulated signals. This even includes the bi-modality of LIB’s $\theta_{\text{ML}}$ distribution (see the inset of Figure 2 of the main paper), which is associated with a degeneracy between sky location and the handedness of the binary orbit projected on the plane of the sky. Similar features were noted for BNS systems as well (Singer et al. 2014).

3. GAMMA-RAY AND X-RAY OBSERVATIONS

The Fermi Gamma-ray Burst Monitor (GBM; Meegan et al. 2009), INTEGRAL (Winkler et al. 2003), and the Inter Planetary Network (IPN; Hurley et al. 2010) searched for prompt high-energy emission temporarily coincident with the GW event. Although no GRB in coincidence with GW150914 was reported, an offline analysis of the Fermi GBM (8 keV–40 MeV) data revealed a weak transient with a duration of $\sim$1 s (Connaughton et al. 2016). A similar analysis was performed for the instruments on board INTEGRAL (Winkler et al. 2003), particularly the spectrometer’s anticoincidence shield (SPI-ACS; von Kienlin et al. 2003, 75 keV–1 MeV)\(^{382}\). No significant signals were detected, setting upper limits on the hard X-ray fluence at the time of the event (Savchenko et al. 2016). Data from the six-spacecraft, all-sky, full-time monitor IPN, (Odyssey–HEND, Wind–Konus, RHESSI, INTEGRAL–SPI-ACS, and Swift–BAT\(^{383}\)) revealed no bursts around the time of GW150914 apart from the weak GBM signal (K. Hurley et al. 2016, in preparation).

The Fermi Large Area Telescope (LAT), MAXI, and Swift searched for high-energy afterglow emission. The LIGO localization first entered the Fermi LAT field of view (FOV) at 4200s after the GW trigger and was subsequently observed in its entirety over the next 3 hr and every 3 hr thereafter at GeV energies (Fermi-LAT Collaboration 2016). The entire region was also imaged in the 2–20 keV X-ray band by the MAXI Gas Slit Camera (Matsuoka et al. 2009) aboard the International Space Station from 86 to 77 minutes before the GW trigger and was re-observed during each subsequent ~92 minute orbit (N. Kawai et al. 2016, in preparation). The Swift X-ray Telescope (XRT; Burrows et al. 2005) followed up the GW event starting 2.25 days after the GW event, and covered five tiles containing eight nearby galaxies for a total $\sim$0.3 deg$^2$ area in the 0.3–10 keV energy range. A 37 point tiled observation of the Large Magellanic Cloud was executed a day later. The Swift UV/Optical Telescope (UVOT) provided simultaneous ultraviolet and optical observations, giving a broadband coverage of 80% of the Swift XRT FOV. Details of these observations are given in Evans et al. (2016).

4. OPTICAL AND NEAR-IR OBSERVATIONS

The optical and near-infrared observations fell into roughly two stages. During the first week, wide FOV (1–10 deg$^2$) telescopes tiled large areas to identify transient candidates, and then larger but narrower FOV telescopes obtained classification spectroscopy and further photometry. The wide FOV instruments included DECam on the CTIO Blanco telescope (Flaugher et al. 2015; Dark Energy Survey Collaboration et al. 2016), the Kiso Wide Field Camera (KWFC; J-GEM; Sako et al. 2012), La Silla QUEST (Baltay et al. 2007), the Global MASTER Robotic Net (Lipunov et al. 2010), the Palomar 48 inch Oschin telescope (P48) as part of the intermediate Palomar Transient Factory (iPTF; Law et al. 2009), Pan-STARRS1 (Kaiser et al. 2010), SkyMapper (Keller et al. 2007), TAROT-La Silla (Boër et al. 1999, node of the TAROT-Zadko-Algerian National Observatory-C2PU Collaboration), and the VLT Survey Telescope (VST@ESO; Capaccioli & Schiappi 2011, GRAvitational Wave Inaf TeAm, E. Brocato et al. 2016, in preparation)\(^{384}\) in the optical band, and the Visible and Infrared Survey Telescope (VISTA@ESO; Emerson et al. 2006)\(^{385}\) in the near-infrared. They represent different classes of instruments ranging in diameter from 0.25 to 4 m and reaching apparent magnitudes from 18 to 22.5. About one-third of these facilities followed a galaxy-targeted observational strategy, while the others tiled portions of the GW sky maps covering 70–590 deg$^2$. A narrow (arcminute) FOV facility, the 1.5 m EABA telescope in Bosque Alegre operated by the TOROS Collaboration (M. Diaz et al. 2016, in preparation), also participated in the optical coverage of the GW sky maps. Swift UVOT observed simultaneously with XRT, giving a broadband coverage of 80% of the Swift XRT FOV.

A few tens of transient candidates identified by the wide-field telescopes were followed up on the 10 m Keck II telescope (using the DEIMOS instrument; Faber et al. 2003), the 2 m Liverpool Telescope (LT; Steele et al. 2004), the Palomar 200 inch Hale telescope (P200; Bracher 1998), the 3.6 m ESO New Technology Telescope (within the Public ESO Spectroscopic Survey of Transient Objects, PESSTO; Smartt et al. 2015), and the University of Hawaii 2.2 m telescope (SuperNovae Integral Field Spectrograph, SNIFS). The follow-up observations of the candidate counterparts are summarized in Table 3 of the main paper.

An archival search for bright optical transients was conducted in the CASANDRA-3 all-sky camera database of BOOTES-3 (Castro-Tirado et al. 2012) and the all-sky survey of the Pi of the Sky telescope (Mankiewicz et al. 2014), both covering the entire southern sky map. The BOOTES-3 images

---

\(^{382}\) INTEGRAL’s coded-mask imager (IBIS, Ubertini et al. 2003, 20–200 keV) was pointed far outside the GW localization region.

\(^{383}\) The Swift Burst Alert Telescope did not intersect the GW localization at the time of the trigger.

\(^{384}\) ESO proposal ID:095.D-0195,095.D-0079.

\(^{385}\) ESO proposal ID:095.D-0771.
are the only observations simultaneous to GW150914 available to search for prompt/early optical emission. They reached a limiting magnitude of 5 due to poor weather conditions (GCN 19022). The Pi of the Sky telescope images were taken 12 days after GW150914 and searched for transients brighter than \( R < 11.5 \text{ mag} \) (GCN 19034).

5. RADIO OBSERVATIONS

The radio telescopes involved in the EM follow-up program have the capability to observe a wide range of frequencies with different levels of sensitivity, and a range of FOVs covering both the northern and southern skies (Tables 2 and 3 of the main paper). The Low Frequency Array (LOFAR; van Haarlem et al. 2013) and the Murchison Wide-field Array (MWA; Tingay et al. 2013) are phased array dipole antennas sensitive to meter wavelengths with large FOVs (\( \approx 50 \text{ deg}^2 \)) with uniform sensitivity for the LOFAR observations carried out as part of this follow-up program; and up to 1200 \( \text{ deg}^2 \) for MWA). The Australian Square Kilometer Array Pathfinder (ASKAP; Schinckel et al. 2012) is an interferometric array composed of 36 12 m diameter dish antennas. The Karl G. Jansky Very Large Array (VLA; Perley et al. 2009) is a 27 antenna array, with dishes of 25 m diameter. Both ASKAP and VLA are sensitive from centimeter to decimeter wavelengths.

MWA started observing 3 days after the GW trigger with a 30 MHz bandwidth around a central frequency of 118 MHz and reached an rms noise level of about 40 mJy beam\(^{-1}\) in a synthesized beam of about 3\(^{\prime}\). The ASKAP observations used the five-element Boolardy Engineering Test Array (BETA; Hotan et al. 2014), which has an FOV of \( \approx 25 \text{ deg}^2 \) and is a fully phased array using dipole antennas sensitive to meter wavelengths with \( \approx 3 \text{ deg}^2 \) uniform sensitivity for the ASKAP observations carried out as part of this follow-up program; and up to 1200 \( \text{ deg}^2 \) for MWA. The Australian Square Kilometer Array Pathfinder (ASKAP; Schinckel et al. 2012) is an interferometric array composed of 36 12 m diameter dish antennas. The Karl G. Jansky Very Large Array (VLA; Perley et al. 2009) is a 27 antenna array, with dishes of 25 m diameter. Both ASKAP and VLA are sensitive from centimeter to decimeter wavelengths.

The Australian Square Kilometer Array Pathfinder (ASKAP; Schinckel et al. 2012) is an interferometric array composed of 36 12 m diameter dish antennas. The Karl G. Jansky Very Large Array (VLA; Perley et al. 2009) is a 27 antenna array, with dishes of 25 m diameter. Both ASKAP and VLA are sensitive from centimeter to decimeter wavelengths.

MWA started observing 3 days after the GW trigger with a 30 MHz bandwidth around a central frequency of 118 MHz and reached an rms noise level of about 40 mJy beam\(^{-1}\) in a synthesized beam of about 3\(^{\prime}\). The ASKAP observations used the five-element Boolardy Engineering Test Array (BETA; Hotan et al. 2014), which has an FOV of \( \approx 25 \text{ deg}^2 \) and is a fully phased array using dipole antennas sensitive to meter wavelengths with \( \approx 3 \text{ deg}^2 \) uniform sensitivity for the ASKAP observations carried out as part of this follow-up program; and up to 1200 \( \text{ deg}^2 \) for MWA. The Australian Square Kilometer Array Pathfinder (ASKAP; Schinckel et al. 2012) is an interferometric array composed of 36 12 m diameter dish antennas. The Karl G. Jansky Very Large Array (VLA; Perley et al. 2009) is a 27 antenna array, with dishes of 25 m diameter. Both ASKAP and VLA are sensitive from centimeter to decimeter wavelengths.

The VLA performed follow-up observations of GW150914 from \( \approx 1 \) to \( \approx 4 \text{ months} \) after the GW trigger, and targeted selected candidate optical counterparts detected by IPTF. VLA observations were carried out in the most compact array configuration (D configuration) at a central frequency of \( \approx 6 \text{ GHz} \) (primary beam FWHP of \( \approx 9\), and synthesized beam FWHP of \( \approx 12\)). The rms sensitivity of these VLA observations was \( \approx 8\text{–}10 \mu\text{Jy beam}^{-1}\).

The authors gratefully acknowledge the support of the United States National Science Foundation (NSF) for the construction and operation of the LIGO Laboratory and Advanced LIGO as well as the Science and Technology Facilities Council (STFC) of the United Kingdom, the Max-Planck Society (MPS), and the State of Niedersachsen/Germany for support of the construction of Advanced LIGO and construction and operation of the GEO 600 detector. Additional support for Advanced LIGO was provided by the Australian Research Council. The authors gratefully acknowledge the support of the National Science Foundation, the Ministry of Science and Education of Spain, the Science and Technology Facilities Council of the United Kingdom, the Higher Education Funding Council for England, the National Center for Supercomputing Applications at the University of Illinois at Urbana-Champaign, the Kavli Institute for Cosmological Physics at the University of Chicago, the Center for Cosmology and Astro-Particle Physics at the Ohio State University, the Mitchell Institute for Fundamental Physics and Astronomy at Texas A&M University, Financiadora de Estudos e Projetos, Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro, Conselho Nacional de Desenvolvimento Científico e Tecnológico and the Ministério da Ciência, Tecnologia e Inovação, the Deutsche Forschungsgemeinschaft, and the Collaborating Institutions in the Dark Energy Survey.

The Collaborating Institutions are Argonne National Laboratory, the University of California at Santa Cruz, the University of Cambridge, Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas-Madrid, the University of Chicago, University College London, the DES-Brazil Consortium, the University of Edinburgh, the Eidgenössische Technische Hochschule (ETH) Zürich, Fermi National Accelerator Laboratory, the University of Illinois at Urbana-Champaign, the Institut de Ciències de l’Espai (IEEC/CSIC), the Institut de Física d’Altes Energies, Lawrence Berkeley National Laboratory, the Ludwig-Maximilians Universität München and the associated Excellence Cluster universe, the University of Michigan, the National Optical Astronomy Observatory, the University of Nottingham, The Ohio State University, the University of Pennsylvania, the University of Portsmouth, SLAC National Accelerator Laboratory, Stanford University, the University of Sussex, and Texas A&M University.

The DES data management system is supported by the National Science Foundation under Grant Number AST-1138766. The DES participants from Spanish institutions are partially supported by MINECO under grants AYA2012-39559, ESP2013-48274, FPA2013-47986, and Centro de Excelencia Severo Ochoa SEV-2012-0234. Research leading to these results has received funding from the European Research Council under the European Union’s Seventh Framework Programme (FP7/2007-2013) including ERC grant agreements 240672, 291329, and 306478.

The Fermi LAT Collaboration acknowledges support for LAT development, operation, and data analysis from NASA and DOE (United States), CEA/Irfu and IN2P3/CNRS (France), ASI and INFN (Italy), MEXT, KEK, and JAXA (Japan), and the K.A. Wallenberg Foundation, the Swedish Research Council and the National Space Board (Sweden). Science analysis support in the operations phase from INAF (Italy) and CNES (France) is also gratefully acknowledged. The Fermi GBM Collaboration acknowledges the support of NASA in the United States and DRL in Germany.

GRAWITA acknowledges the support of INAF for the project “Gravitational Wave Astronomy with the first detections of adLIGO and adVIRGO experiments.”

This work exploited data by INTEGRAL, an ESA project with instruments and science data center funded by ESA member states (especially the PI countries: Denmark, France, Germany, Italy, Switzerland, Spain), and with the participation of Russia and the USA. The SPI ACS detector system has been provided by MPE Garching/Germany. We acknowledge the German INTEGRAL support through DLR grant 50 OG 1101.

IPN work is supported in the US under NASA Grant NNX15AU74G.

This work is partly based on observations obtained with the Samuel Oschin 48 in Telescope and the 60 in Telescope at the Palomar Observatory as part of the Intermediate Palomar Transient Factory (iPTF) project, a scientific collaboration among the California Institute of Technology, Los Alamos National Laboratory, the University of Wisconsin, Milwaukee, the Oskar Klein Center, the Weizmann Institute of Science, the TANGO Program of the University System of Taiwan, and the Kavli Institute for the Physics and Mathematics of the universe. M.M.K. and Y.C. acknowledge funding from the National Science Foundation PIRE program grant 1545949. A.A.M. acknowledges support from the Hubble Fellowship HST-HF-51325.01. Part of the research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

J-GEM is financially supported by KAKENHI Grant No. 24103003, 15H00774, and 15H00788 of MEXT Japan, 15H02069 and 15H02075 of JSPS, and the “Optical and Near-Infrared Astronomy Inter-University Cooperation Program” supported by MEXT.

The Liverpool Telescope is operated on the island of La Palma by Liverpool John Moores University in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias with financial support from the UK Science and Technology Facilities Council.

LOFAR, the Low Frequency Array designed and constructed by ASTRON, has facilities in several countries, which are owned by various parties (each with their own funding sources), and that are collectively operated by the International LOFAR Telescope (ILT) foundation under a joint scientific policy. R. Fender acknowledges support from ERC Advanced Investigator Grant 267697.

MASTER Global Robotic Observatory is supported in parts by Lomonosov Moscow State University Development program, Moscow Union OPTICA, Russian Science Foundation 16-12-00085, RFBR15-02-07875, National Research Foundation of South Africa.

We thank JAXA and RIKEN for providing MAXI data. The MAXI team is partially supported by KAKENHI grant Nos. 24103002, 24540239, 24740186, and 23000004 of MEXT, Japan.

This work uses the Murchison Radio-astronomy Observatory, operated by CSIRO. We acknowledge the Wajarri Yamatji people as the traditional owners of the observatory site. Support for the operation of the MWA is provided by the Australian Government Department of Industry and Science and Department of Education (National Collaborative Research Infrastructure Strategy: NCRIS), under a contract to Curtin University administered by Astronomy Australia Limited. The MWA acknowledges the iVEC Petabyte Data Store and the Initiative in Innovative Computing and the CUDA Center for Excellence sponsored by NVIDIA at Harvard University.

Pan-STARRS is supported by the University of Hawaii and the National Aeronautics and Space Administration’s Planetary Defense Office under grant No. NNX14AM74G. The Pan-STARRS-LIGO effort is in collaboration with the LIGO Consortium and supported by Queen’s University Belfast. The Pan-STARRS1 Sky Surveys have been made possible through contributions by the Institute for Astronomy, the University of Hawaii, the Pan-STARRS Project Office, the Max Planck Society and its participating institutes, the Max Planck Institute for Astronomy, Heidelberg, and the Max Planck Institute for Extraterrestrial Physics, Garching, The Johns Hopkins University, Durham University, the University of Edinburgh, the Queen’s University Belfast, the Harvard-Smithsonian Center for Astrophysics, the Las Cumbres Observatory Global Telescope Network Incorporated, the National Central University of Taiwan, the Space Telescope Science Institute, and the National Aeronautics and Space Administration under grant No. NNX08AR22G issued through the Planetary Science Division of the NASA Science Mission Directorate, the National Science Foundation grant No. AST-1238877, the University of Maryland, Eotvos Lorand University (ELTE), and the Los Alamos National Laboratory. This work is based
(in part) on observations collected at the European Organisation for Astronomical Research in the Southern Hemisphere, Chile as part of PESSTO, (the Public ESO Spectroscopic Survey for Transient Objects Survey) ESO programs 188.D-3003, 191.D-0935.

Some of the data presented herein were obtained at the Palomar Observatory, California Institute of Technology. S.J.S. acknowledges funding from the European Research Council under the European Union’s Seventh Framework Programme (FP7/2007-2013)/ERC Grant agreement No. [291222] and STFC grants ST/L001123/1 and ST/L000709/1. M.F. is supported by the European Union FP7 programme through ERC grant No. 320360. K.M. acknowledges support from the STFC through an Ernest Rutherford Fellowship.

F.O.E. acknowledges support from FONDECYT through postdoctoral grant 3140326. Some of the data presented herein were obtained at the European Southern Observatory, Paranal, Chile. We acknowledge ESO personnel for their assistance during the observing runs.

This is LIGO document LIGO-P1600137-v2.

Software: Astropy (Robitaille et al. 2013), HEALPix (Górski et al. 2005).

REFERENCES


Brachler, K. 1998, Mercu, 27, 4


Capaccioli, M. & Schipani, P. 2011, Mgrs, 146, 2


Emerson, J., McPherson, J., & Sutherland, W. 2006, Mgrs, 126, 41


Keller, S. C., Schmidt, B. P., Bessell, M. S., et al. 2007, PASA, 24, 1

Klimenko, S., Vedovato, G., Drago, M., et al. 2016, PhRvD, 93, 042004


Robitaille, T. P., Tollerud, E. J., Green, A. H., et al. 2013, PASA, 30, e007


Singer, L. P., & Price, L. R. 2016, PhRvD, 93, 024013


Veitch, J., Raymond, V., Farr, B., et al. 2015, PhRvD, 91, 042003


AUTHORS


