Geographic and Annual Influences on Optical Follow-up of Gravitational Wave Events

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Abstract
We investigate the effects of observatory location on the probability of discovering optical/infrared (OIR) counterparts of gravitational wave sources. We show that, for the LIGO–Virgo network, the odds of discovering OIR counterparts show some latitude dependence. A stronger effect is seen to arise from the timing of LIGO–Virgo observing runs during the year, with northern OIR observatories having a better chance of finding the counterparts in northern winters. Assuming identical technical capabilities, the tentative mid-2017 three-detector network observing run favors southern OIR observatories for the discovery of electromagnetic counterparts.

Key words: gravitational waves – methods: observational

1. Introduction
The detection of gravitational waves (GWs) by LIGO (Abbott et al. 2016b; The LIGO Scientific Collaboration et al. 2016a, 2016b) marks the beginning of the era of GW astronomy. Continued improvements in the sensitivity of GW detectors will increase the frequency of detections, enabling detailed study of a variety of sources and source populations.

A key step in the study of GW sources is the detection of electromagnetic (EM) counterparts. While GW signals carry information about physical and geometric properties of the source, the study of EM counterparts will yield complementary information necessary to complete our astrophysical understanding of the source (Nissanke et al. 2013; Singer et al. 2014). Several groups around the world partook in efforts to follow-up the first GW detections (Abbott et al. 2016a, 2016c), leading to the discovery of a candidate gamma-ray signal potentially associated with the binary black hole merger event GW150914 (Connaughton et al. 2016). There is greater potential for the existence of EM counterparts of GW sources such as binary neutron star mergers or supernovae, and several groups will take part in follow-up activities for future GW triggers.8

The localization of a GW source by a pair of GW detectors depends on source parameters and signal strength, and is rather coarse: the 90% credible regions of the sky localization often span hundreds of square degrees (Berry et al. 2014; Singer et al. 2014; The LIGO Scientific Collaboration et al. 2016a). Imaging such large sky areas to find specific transient counterparts poses formidable challenges (see Singer et al. 2015). Various aspects of this challenge have been examined in detail, including theoretical modeling of light curves of GW events (Tanaka & Hotokezaka 2013; Kasen et al. 2015; etc.), assessing the detectability of EM counterparts (Metzger & Berger 2012; Cowperthwaite & Berger 2015), comparing follow-up capabilities of various facilities (Nissanke et al. 2013; Kasliwal & Nissanke 2014), and strategies for coordination and optimal follow-up (Singer et al. 2012; Chan et al. 2015; Ghosh et al. 2015; Rana et al. 2016). The search for optical counterparts of GW sources is driving scientific interest for upcoming projects like BlackGEM9 (Bloemen et al. 2015) and the Gravitational-wave Optical Transient Observer (GOTO10).

In this work, we examine another factor that can influence the odds of successful follow-up: the location of the observatory. GW detectors are not uniformly sensitive to the entire sky, which introduces a sky-position-dependent bias in the detection and localization of sources (Fairhurst 2011). It is then fair to ask, for instance, if observatories located on the same continent as the two LIGO detectors are “better placed” for the search for electromagnetic counterparts of GW sources. A second location-related effect comes from the timing of the LIGO science runs. For instance, for an observing run during the northern winter would mean that, on average, a larger part of the localization region is visible to northern observatories during the long nights. We examine the effects of these two factors on the follow-up capabilities of various observatories. We also note that these factors were independently studied using a different set of methods, by Chen et al. 2017 recently.

We frame our question and describe our methods in Section 2. We explore the effects of seasons on the observing capabilities of various telescopes in Section 3. We consider the overall effects of geographic location and timing of the LIGO observing runs for two- and three-GW detector networks in Section 4, and conclude by discussing the implications in Section 5.

2. Method
The principal aim of this work is to investigate the effects of (1) location, and (2) timing of the GW observing run during the

8 A partial list of groups that have signed memoranda of understanding with the LIGO–Virgo collaboration is available at https://gw-astronomy.org/wiki/LV_EM/PublicParticipatingGroups.
9 BlackGEM—https://astro.ru.nl/blackgem/.
10 GOTO—http://www.goto-observatory.org/.
year on the probability of finding EM counterparts of GW sources from ground-based observatories.

To undertake these comparisons, we need to disentangle the telescope capabilities from location and seasonal effects. We can phrase the question as follows: “If a telescope based at site $X$ can cover $N$ square degrees on the sky to the requisite sensitivity in a single night, what would be the probability of it finding the EM counterpart?” We answer this question by simulating follow-up optical/infrared (OIR) observations of a set of simulated GW events from various ground-based locations at various times.

The timescale of evolution of kilonovae are experimentally unconstrained. Several models indicate that these transients may evolve on timescales of a day or longer (Metzger et al. 2010; Roberts et al. 2011; Tanaka et al. 2014; Rosswog et al. 2014; Metzger 2016). As a result, in this study we limit ourselves to the overall observability of the GW localization region, which is dominated by the diurnal cycle. We do not consider the sub-day response time of an observatory, namely the minimum delay between the GW trigger and the first possible observation from a given location. As the object visibility from a given site varies only slightly between successive days, the observability calculated for the first twenty four hours after the trigger serves as a good proxy for the entire duration of the follow-up. This implies that our work is not applicable to some kilonovae models that predict a rapidly evolving component of the lightcurve with timescales of hours rather than days (see for example Kulkarni 2005; Metzger et al. 2015).

As a representative sample of locations of ground-based observatories, we select all OIR telescopes that participated in the follow-up of GW150914 (Abbott et al. 2016c). To fill a gap in Asia, we include Hanle (Prabhu et al. 2006), the site of the upcoming 0.7 m robotic telescope, the Indian element of the “Global Relay of Observatories Watching Transients Happen” (GROWTH11). The sites considered in this work are shown in Figure 1, and listed in Table 1.

2.1. Simulated GW Events

We use GW events from binary neutron star coalescence simulations by Singer et al. (2014), who used realistic detector sensitivity for LIGO–Hanford (H), LIGO–Livingston (L) and Virgo (V) at various stages of the GW network to recover the injected events that meet pre-defined detection thresholds. They calculate sky localization of these events using BAYESTAR (Singer & Price 2016), and supply the products as HEALPix files (Gorski et al. 2005). Singer et al. (2014) had simulated detections by LIGO in a period from August 18 to October 19 for two observing sessions, with GW detector sensitivity corresponding to the O1 and O2 observing runs. We note that the actual sensitivities attained in LIGO–Virgo observing runs may be somewhat different from their adopted values, thereby altering the localizations to some extent. The final data set12 contains 630 two-detector HL events at O1 sensitivity, while for O2 sensitivity it has 365, 15 and 14 events for HL, HV, and LV respectively, and 81 three-detector events with O2 sensitivity. Their dates do not match the actual dates of the O1 GW observing run, and are inconsistent with expected dates for O2. Further, the dates may introduce a seasonal bias in the comparison of various locations, as southern observatories will get longer nights in northern summer, and vice versa. Hence, we need to move these simulated events to different dates for comparison.

The sensitivity of LIGO, and hence the localization of detected events, is fixed in geocentric coordinates (Fairhurst 2009). The simulated GW detections can thus be reassigned to any other time when the relative orientations of the geocentric and celestial coordinate systems are the same. Thus, the event localization region in celestial coordinates remains unchanged if any event is moved to the same sidereal time on another day. As a further generalization, events can be moved to an arbitrary time stamp by considering the sky localization in geocentric coordinates, and transferring it to appropriate celestial coordinates at the new time stamp (see for example Evans et al. 2015).

2.2. Selection of Dates

To disentangle the effects of location and annual variability in follow-up, we first consider an idealized case where all detections are on the dates of the equinoxes, where all sites on Earth have the same amount of night time. To evaluate the extent of annual

11 GROWTH—http://growth.caltech.edu.

12 The simulated localization files are available at http://www.ligo.org/scientists/releases/2years/.

Figure 1. Locations of observatories considered in this work. We include all ground-based optical/infrared observatories that were involved in following up GW150914. We also include Hanle as a representative observatory in Asia.
| Site                          | Telescope/Instrument | Latitude | Longitude  | Altitude | Reference | URL                                                                 |
|------------------------------|----------------------|----------|------------|----------|-----------|----------------------------------------------------------------------|
| Blenheim, New Zealand        | BOOTES-3             | 45°S     | 169°41'E   | 27 m     | Castro-Tirado et al. (2012)                                         | http://bootes.iaa.es/en/ |
| Mt. Siding Spring, Australia | Skymapper            | 31°16'S  | 149°04'E   | 1163 m   | Keller et al. (2013)                                                | https://en.wikipedia.org/wiki/Siding_Spring_Observatory |
| Sutherland, South Africa     | MASTER-SAAO          | 32°17'S  | 20°18'E    | 1760 m   | Lipunov et al. (2010)                                               | http://observ.pereplet.ru |
| La Serena, Chile             | DECam (CTIO)         | 30°10'S  | 70°48'W    | 2207 m   | Abbott et al. (2012)                                                | http://www.ctio.noao.edu/noao/ |
| La Silla, Chile              | TAROT-LaSilla        | 29°15'S  | 70°43'W    | 2400 m   | Boër et al. (1999)                                                  | http://tarot.obs-hp.fr/infos/ |
| Cerro Paranal, Chile         | VST                  | 24°37'S  | 70°24'W    | 2600 m   | Capaccioli & Schipani (2011)                                       | http://www.eso.org/public/teles-instr/ |
| Salta, Argentina             | TOROS                | 24°36'S  | 67°19'W    | 4650 m   | Diaz et al. (2014)                                                  | http://toros.phys.utb.edu/ |
| Mauna Kea, Hawaii            | W. M. Keck           | 19°49'N  | 155°28'W   | 4145 m   | Faber et al. (2003)                                                 | http://www.keckobservatory.org/about/ |
| Haleakala, Hawaii            | PanSTARRS            | 20°42'N  | 156°15'W   | 3052 m   | Kaiser et al. (2010)                                                | http://neo.jpl.nasa.gov/programs/ |
| Canary Islands, Spain        | Liverpool            | 28°45'N  | 17°52'W    | 2363 m   | Steele et al. (2004)                                                | http://telescope.livjm.ac.uk/About/ |
| Hanle, India                 | Hanle                | 32°47'N  | 78°52'E    | 4500 m   | Prabhu et al. (2006)                                                | http://www.iiaa.res.in/iao_site |
| Palomar, USA                 | PTF                  | 33°21'N  | 116°51'W   | 1712 m   | Law et al. (2009)                                                   | https://en.wikipedia.org/wiki/Palomar_Mountain |
| Mt. Ontake, Japan            | Kiso                 | 35°47'N  | 137°37'E   | 1130 m   | Takase et al. (1977)                                                | http://www.ioa.s.u-tokyo.ac.jp/kisohp/TELS/tels_e.html |

**Note.** See Figure 1 for a plot of these locations.
variations, we also simulate observations for cases where all events occur at the summer or winter solstice. These cases are discussed in detail in Section 3.

Next, in Section 4 we consider a set of dates for the first and second LIGO–Virgo observing runs, O1 and O2. For O1, we use the actual dates: 2015 September 12 to 2016 January 12. We note that papers by the LIGO Scientific Collaboration have eventually redefined O1 to span from 2015 September 12 to 2016 January 19. These small changes in dates do not significantly alter our results. For O2, we consider specific possible dates to allow our analysis to be performed, and the likely split into two parts. We consider O2A, with Hanford and Livingston detectors, to span the period from 2016 December 1 to 2017 February 28. For our example, Virgo is taken to join these two detectors in O2B, spanning the period from 2017 April 1 to May 31. Considering that not all detectors will be functioning throughout these phases, we undertake separate analysis of O2B into two-detector events (Section 4.1) and three-detector events (Section 4.2).

2.3. Analysis

We load and analyze the HEALPix files in python using healpy and astropy (Robitaille et al. 2013). We consider the 99% credible region for GW localization, and hereafter refer to it as a “patch.” Observations are simulated for a period of 24 hr from the trigger, and limited to night time (Sun at least 18° below the horizon). We also impose an upper bound on the zenith angle of observations, based on two principles: most telescopes cannot point arbitrarily close to the horizon, and quality of data is poor for observations at high airmass (high zenith angle). We choose an airmass of ∼2.5, so that only parts of the patch that rise at least 24° above the horizon are observed. We do not include any constraints based on lunar phase or lunar angle. Certain site-specific conditions like weather, instrument breakdowns, etc. are too variable to be meaningfully included in an analysis. Hence, we exclude these factors from our simulations, as is often done in such studies (Singer et al. 2012; Kasliwal & Nissanke 2014; Rosswog et al. 2016 etc.).

After filtering out the HEALPix pixels satisfying the above conditions, we sort them by probability of containing the EM counterpart, and add up the probabilities for the 99% field of view. There might also be scenarios where a large part of the patch is visible from the site, but only for a short time, for instance, an event occurring overhead just before morning twilight. However, the time taken to image N square degrees to a given depth can vary drastically between different telescopes. This in turn may limit the fraction of the visible patch that can be imaged through the night. As our focus is to compare geographic locations rather than telescopes and instruments, we do not consider these two effects in our simulations.

3. Observations at Solstices and Equinoxes

As discussed in Section 2.2, we first compare the various observatory locations in terms of their coverage for GW events on equinoxes. First, consider the case of all 1024 GW events moved to the fall equinox. For each event, we calculate the probability observable from each location, and find that all sites have comparable performance on the day of the equinox. As an example, in Figure 2 we show histograms of the probability of finding the counterpart by imaging the best visible 30 deg² from two sites—Blenheim, New Zealand and Haleakala, Hawaii—which respectively had the worst and best median performance in this category. It is seen that both extremes actually have very similar performance in this case.

In order to simplify visual comparisons, in the rest of this paper we use box-and-whisker plots (Figure 2, lower panel). The filled box spans the central 50% of the histogram, extending from the lower quartile to the upper quartile. In other
words, 25% of the events have observable probability less than
the left edge of the box, while it is greater than the right edge
for another 25%. The range between these two points is called
the inter-quartile range (IQR). “Whiskers” plotted on either
side of the box extend to 1.5 × IQR. Any outlier points
outside the whiskers are marked by red “+” signs. Since we are
primarily interested in properties of the distribution rather than
specific outliers, we have often scaled the plots such that some
of the outliers are beyond the plot limits. The line and star
inside the box show the median and mean of the distribution.

Next, we investigate the variations over the year by
simulating observations of the same 1024 (O1 + O2) two-
detector patches, but moved to the dates of the solstices. As
expected, we see that northern observatories perform better
during the winter solstice, owing to longer nights, while
southern observatories perform better during the summer
solstice. For example, Figure 3 shows the performance of
La Serena, Hanle, and Palomar Mountain on the equinoxes and
solstices, showing clearly the reversal of favored seasons
between the northern and southern hemispheres.

While the overall performance of the various sites for
equinox observations is similar (Figure 5), looking at the
median values of observable probabilities shows some
interesting trends (Figure 4). We see that on the equinoxes,
sites at mid-latitudes have a few percent higher probability of
finding the optical counterpart of a GW event, as compared to
observatories in the temperate zones. This can be explained by
a combination of two effects: (i) the two LIGO detectors detect
more sources at mid-declinations as compared to equatorial or
polar declinations, and (ii) sites further from the equator have a
progressively smaller fraction of the sky accessible even on the

18 If the histograms were Gaussian, the ends of the whiskers would be at 4.7σ
on either side of the mean.

Figure 3. Location-wise performance comparison between La Serena, Hanle,
and Palomar, for all the O1 and O2 two-detector events. Events were shifted to
the day of vernal equinox (green), summer solstice (yellow), fall equinox
(chocolate) and winter solstice (blue). The three panels’ distributions of
observable probabilities are calculated using telescopes that can image 3, 30
and 300 deg² respectively within 24 hr of the trigger.

Figure 4. Annual variations in median observable probability for different
latitudes. The different colors and symbols show median observable probability
on the days of the vernal equinox (green circles), summer solstice (yellow
squares), fall equinox (pink triangles) and winter solstice (blue pentagons).
Upper panel: for each site, we compute the median of the probability covered
for 1024 (O1 + O2) two-detector events, with a telescope limited to observing
100 deg² during the night. Lower panel: median probability of finding the
counterpart for a source localized by the three-detector HLV network, with the
same telescopes limited to observing 100 deg² during the night.
more stark if the localization improved. In the limiting case, if GW sources were pinpointed on the sky by the GW detectors, the observable probability would be governed by the latitudinal variation of detector sensitivity function (Fairhurst 2011) and would vary more strongly with the fraction of the sky visible at night. Indeed, this is the case with improved localizations provided by a network of three GW detectors. We repeat our simulations using GW events that were detected by the HLV network, and find that solstice-to-solstice changes in the median observable probability can be as high as 60% (Figure 4, lower panel). For reasons discussed in Section 4.2, results for the three-detector network should only be considered qualitatively, not quantitatively.

4. Example Observing Runs

As a specific case, we repeat our simulations using the actual dates of the first LIGO science run (O1) and a set of example

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**Figure 5.** Probability of finding optical counterparts for simulated two-detector events on the fall equinox. The simulation sample includes events with O1 and O2 sensitivity. The observatories are sorted by latitude and color-coded by continent as in Figure 1. The best-case scenario, considering only solar exclusion angle but ignoring horizon constraints, is plotted in the rightmost column. On comparing the location-wise performance for 1, 3, 10, 30, 100, 300, 1000, and 3000 deg², we see that all sites perform comparably with a very slight trend along the latitude.
dates of O2. Although the dates of O2 are uncertain, we aim to
give an overall perspective of how observatories at different
locations may perform under these conditions. The qualitative
nature of these results will be insensitive to \( \sim 10 \) day shifts in
dates.

### 4.1. Two-detector Network

Our two-detector sample consists of 630 events with O1
sensitivity, and 394 events with O2 sensitivity. The latter are
split as 365, 15, and 14 events for HL, HV, and LV
respectively. The smaller number of Virgo-detected events
arises from expected sensitivity and uptime of the three
detectors, as discussed in Singer et al. (2014). As discussed in
Section 2.2, O2 is expected to be subdivided into O2A and
O2B. For our simulations, we distribute the 365 HL events
randomly in both parts of the run, and keep the 29 HV/LV
events in O2B.

As O1 was conducted during northern winter, one expects
northern observatories to perform better than southern ones.
and this expectation is borne out by simulations (Figure 6). Mauna Kea and Haleakala have the best chance of discovering an optical counterpart, with a median probability of 0.30 for a camera capable of imaging 100 deg$^2$ in a night. Blenheim, the southernmost location in this study, had a median probability of 0.22 of imaging the optical counterpart with the same resources. Incidentally, the localization of GW150914 happened to peak in the southern skies (Abbott et al. 2016a), while localizations of GW151226 and LVT151012 were more uniformly spread over declination (The LIGO Scientific Collaboration et al. 2016a). Thus, small-number statistics worked in favor of southern observatories in O1.

The assumed split dates of O2 span approximately northern winter and spring, slightly favoring northern observatories in O2A and southern ones in O2B. The net result is that the timing of observing runs slightly favors northern observatories, but the overall performance of observatories is dominated by their latitude, following a similar trend as the equinoxes (Figure 7).
The number of two-detector detections involving Virgo in O2B is rather small, and does not alter the trends in any significant manner.

4.2. Three-detector Network: HLV

The joint detection of any GW event by all three GW detectors drastically changes the follow-up scenario. The median area encompassing 90% probability of containing the true source drops from several hundreds to a few tens of square degrees (Singer et al. 2014). We now investigate how this affects the follow-up from various locations.

Singer et al. (2014) provide only 81 events detected by the HLV network. As the net area of each localization patch is a small fraction of the entire sky, any study using this sample will suffer from small-number statistics. Indeed, averaging the all-sky probabilities for these 81 events shows a bias toward the southern skies (Figure 8, blue circles). We work around this problem in two steps. First, we translate these patches into trigger times (and right ascensions) to get 400 new sky localizations as discussed in Section 2.1. Next, we randomly select 20% of the patches with localization peaking in the southern hemisphere, and drop them from the set. This almost removes the unexpected north–south asymmetry in the full sample (Figure 8, brown stars). This gives us a final set of 403 patches, which we distribute randomly over the dates of O2B for simulating follow-up of three-detector events.

The well-constrained sky localizations from the three-detector network lead to very different distributions of observable probability as compared to a two-detector network. Observatories at most locations can cover nearly the entire patch if it rises at that location, but cover almost zero probability otherwise. Figure 9 highlights this effect for telescopes that can cover 30 deg^2 in a single night. At all observatories, a large fraction of events have $p_{\text{obs}} < 0.05$ or $p_{\text{obs}} > 0.95$. The overall result is that the observable probability from any given location (Figure 10) is completely dominated by seasonal effects. For the dates of O2B used in this work, our simulations show the southern locations stand a better chance of finding optical counterparts of GW sources. As the 403 patches used in these simulations were generated from just 81 events, we caution the reader that these results should be interpreted qualitatively.

5. Discussion

We investigate the effects of observatory locations on the probability of discovering OIR counterparts of GW sources. We show that the odds of discovering the expected EM counterparts with day- or longer evolution timescales show some latitude dependence, but weak or no longitudinal dependence.

The annual timing of observing runs has a much larger effect on the observability of GW localization regions, and dominate over geographic variations. These effects too are stronger for observatories at high latitudes, where the length of the night is most strongly affected by the seasons. Chen et al. (2017) have independently reached similar conclusions using a different methodology and slightly different assumptions.

Our simulations show that northern observatories had slightly better odds of discovering the EM counterparts of GW sources in O1, though the small-number statistics of just two detections and one candidate dominated this effect. Based on our assumed sample dates of the second observing run O2, all observatory locations have a comparable chance of finding EM counterparts.

In mid-2017, O2B may discover the first three-detector GW event, with much better localization than two-detector networks, simplifying ground-based follow-up. This season favors southern observatories, giving them a significantly higher chance of discovering counterparts of such GW events.
In order to compare the performance of various OIR observatory sites, we have assumed identical equipment at all locations. In practice, this is not the case and instrument characteristics like imaging depth and field of view will play a strong role in successful detection of an EM counterpart. Coordinated observations among multiple sites (Singer et al. 2012), use of galaxy catalogs (Hanna et al. 2014; Gehrels et al. 2015), and enhanced scheduling algorithms (Chan et al. 2017; Ghosh et al. 2015; Rana et al. 2016) will help observatories to boost their chances of detecting electromagnetic counterparts.

We have taken a representative sample of observatories and considered a set of example dates of LIGO–Virgo observing runs for our simulations. To facilitate further exploration on these lines, our simulation codes are available at https://github.com/emvarun/followup-and-location. Users will also have to download the Singer et al. (2014) data set from http://www.ligo.org/scientists/first2years/. In these python codes,

Figure 10. Probability of finding optical counterparts for simulated three-detector events with example O2B dates. Details are as in Figure 5. While box-plots are not the best representations of these bi-peaked distributions (see Figure 9), we use them for consistency with other plots. The better performance of southern locations can be attributed primarily to the season. As we increase the sky coverage, the mean probability of finding a counterpart increases rather slowly beyond 30°.
users can easily add/remove sites and change simulation dates. The codes produce a set of plots, summary tables, and a detailed table for the observable probability of each event from each location.

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Software: NumPy (van der Walt et al. 2011) and Matplotlib (Hunter 2007), Astropy (Robitaille et al. 2013, http://www.astropy.org), HEALPix (Gorski et al. 2005), Healpy (https://healpy.readthedocs.org/), Ephem (https://pypi.python.org/pypi/pyephem/).

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