Topic	Identification and collection of ground truth events
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Version	October, 2011; **DOI: 10.2312/GFZ.NMSOP-2_IS_8.6**

1 Introduction

Accurate event locations are essential for seismic hazard studies and for developing and testing three-dimensional velocity models of the Earth. However, as the main objective of producing earthquake catalogues is to achieve completeness down to the lowest detectable magnitude levels, published bulletins inevitably contain a mixture of accurate, good and poor locations. Thus, event locations in earthquake catalogues should always be treated with caution.

Published bulletins give little indication about the accuracy of the event locations. One common mistake is to consider the formal uncertainties (error ellipse, origin time and depth uncertainties) as measures of *accuracy*. The error ellipsoid provides a statistical estimate of *precision* derived from the *a posteriori* (Flinn, 1965), *a priori* (Evernden, 1969), or a mixture of the two (Jordan and Sverdrup, 1981) distributions of travel-time residuals of the observations with respect to the underlying travel-time and error-distribution models and the procedure of calculation used in the location (see Glossary terms *accuracy* and *precision).*

The calculation of formal uncertainties relies on the assumption that the error processes are Gaussian, have zero mean and are uncorrelated. Unfortunately, these assumptions are often violated in seismic locations. Picking errors may exhibit heavy tails (Buland 1986) and onset times tend to be picked late with decreasing event size (Billings et al., 1994; Douglas et al., 1997, 2005).

More crucially, travel-time predictions suffer from systematic errors due to three-dimensional velocity structures left unmodeled by the commonly used Earth models. One of the classic examples of location bias due to unmodeled 3D Earth structure is the Longshot explosion (29, October 1965, Aleutian Islands). The ray paths to nearly all stations sample the Aleutian slab, a subducted oceanic lithosphere with high seismic velocity, causing arrival-time predictions for these paths to be systematically late, which results in a 26 km location error to the north-northwest (Herrin and Taggart, 1968; Bormann, 1972). Note that such a travel-time prediction bias can be further amplified by the fact that similar ray paths from closely spaced stations will generate correlated travel-time prediction errors (Chang et al., 1983; Myers and Schultz 2000; Bondár and McLaughlin, 2009a; Bondár and Storchak, 2011).

Since the error ellipse measures precision but not accuracy, researchers considered various metrics to assess the location accuracy of events based on network geometry. We summarize these efforts below and describe the IASPEI Reference Event List maintained by the International Seismological Centre (ISC; www.isc.ac.uk).

2 Identifying Ground Truth (GT) events

Sweeney (1996) investigated the feasibility of selecting ‘reference events’ (events where the hypocentres can be considered known to high accuracy) in continental regions from global bulletins, such as those published by the International Seismological Centre and the US Geological Survey National Earthquake Information Centre (NEIC) that contain predominantly teleseismic arrival time data. He suggested that locations from these catalogues have an accuracy of 10–15 km when the largest azimuthal gap between stations surrounding the epicenter is less than 200° and at least 50 first-arriving P phases are used. Sweeney (1998) revised these selection criteria and found 15 km (or better) epicentre accuracy for teleseismic networks with an azimuthal gap of less than 90° and with at least 50 first-arriving P phases that were used in the location.

Engdahl et al., (EHB; 1998) produced a “groomed” ISC catalogue by using the *ak135* travel-time tables (Kennett et al., 1995), later phase (including depth phases) arrival times, and station-specific travel-time corrections. Myers and Schultz (2001) estimated that the epicentre accuracy in the EHB catalogue is 15 km or better at the 95% confidence level for events not in subduction zones when the largest azimuthal gap is less than 90°.

Bondár *et al.* (2001) introduced the nomenclature of ‘ground truth’ categories (GT*x*, where ‘*x*’ designates epicentre location accuracy in kilometres (i.e., the true epicentre lies within ‘*x*’ km of the estimated epicentre) to describe the location accuracy of events in the Ground Truth data set assembled at the Prototype International Data Centre, Arlington, USA (1995-2002).

Bondár et al. (2004a) developed GT selection criteria based on network geometry to assess the location accuracy of events published in earthquake bulletins. The selection criteria identify GT5 candidate events at the 95% confidence level if they are located:

(1) with at least 10 stations, all within 250 km;

(2) with an azimuthal gap of less than 110°;

(3) with a secondary azimuthal gap of less than 160°;

(4) with at least one station within 30 km from the epicentre.

The GT5 selection criteria above have been successfully applied to identify GT5 candidate events by introducing the notion of secondary azimuthal gap (defined as the largest azimuthal gap which has been filled by just a single station). The secondary azimuthal gap is particularly sensitive to a station with disproportionately large data importance that may introduce location bias. The secondary azimuthal gap criterion implicitly invokes constraints on both the azimuthal gap and the minimum number of stations, but it is insensitive to clustering of stations that may generate correlated travel-time prediction error structures.

To remedy these issues, Bondár and McLaughlin (2009b) revisited the GT5 selection criteria. To avoid the *Pg/Pb* and *Pg/Pn* cross-over distance ranges, which are prone to phase identification errors, they considered stations up to 150 km only. They also introduced a new metric that measures the deviation from the optimal, azimuthally uniformly distributed network of local stations. The network quality metric is defined as the mean absolute deviation from the best-fitting uniformly distributed network of stations and the actual network. Provided that the event-to-station azimuths are sorted by increasing values, the metric is given by the expression

$$\Delta U = \frac{4\sum_{i=1}^{N}\left|esaz_i - (unif_i + b)\right|}{360N}, 0 \le \Delta U \le 1$$

where N is the number of stations, $esaz_i$ is the *ith* event-to-station azimuth, $unif_i = 360i / N$ for $i = 0, ..., N - 1$, and $b = \text{avg}(esaz_i) - \text{avg}(unif_i)$. The network quality metric is normalized; ΔU is 0 when the stations are uniformly distributed in azimuth and it is 1 when all the stations are aligned at the same azimuth. Since large azimuthal gaps or potentially correlated stations (stations at similar azimuth) introduce deviations from the optimal, uniformly distributed network, the metric is sensitive to both sources of potential bias. The metric is similar to the non-parametric Kolmogorov-Smirnov statistic, which measures the maximum absolute deviation between two distributions.

The revised selection criteria identify GT5 candidate events at the 95% confidence level if an event is (re)located:

(1) with stations within 150 km;

(2) with $\Delta U \le 0.35$;

(3) with a secondary azimuthal gap ≤ 160°;

(4) with at least one station within 10 km from the epicentre.

Depth and origin time typically have lower accuracy than the epicentre, since the accuracy of these parameters is not governed by the network geometry but depends on the accuracy of the velocity model as well as the availability of depth-sensitive phases (e.g., depth phases such as pP and sP, or of core reflections such as PcP). The criterion for the existence of a station virtually on top of the event is aimed to ensure that there is sufficient resolution in the data to constrain the depth, so that depth will not trade-off with the epicentre.

The Bondár et al. (2004a, 2009b) criteria were used to identify candidate GT5 events in the EHB bulletin for the IASPEI Reference Event List hosted by the ISC (www.isc.ac.uk). Note that the location accuracy criteria described in this section are most relevant to continental earthquakes. Subduction zone events are likely to have a larger (and systematic) location uncertainty due to the travel-time bias introduced by the subducting slab, even if the station coverage satisfies the location accuracy criteria. Nevertheless, identifying GT5 events in subduction zones becomes more viable owing to the increasing number of ocean bottom seismometer arrays deployments worldwide. Agencies operating ocean bottom seismometer deployments are encouraged to share their data with the international scientific community.

It should be emphasized that the GT selection criteria above assume that no special effort has been made to remove location bias through the use of an optimal velocity model or path-specific travel-time predictions, or through special analysis of waveforms to improve phase picks. With such an expert seismic analysis, location accuracy of a few kilometers can be achieved (e.g. Boomer et al., 2010; Richards et al., 2006).

Detailed location studies typically make use of multiple-event methods (e.g. Douglas, 1967; Dewey 1972; Jordan and Sverdrup, 1981; Pavlis and Booker, 1983; Got et al., 1994; Waldhauser and Ellsworth, 2000; Zhang and Thurber, 2003; Engdahl et al., 2006; Bondár et al., 2008; Myers et al., 2007, 2009). Multiple event methods are known for precise *relative* locations, but a loss of accuracy – manifested as a consistent bias for all locations – is well documented (Douglas, 1967; Jordan and Sverdrup, 1981; Pavlis and Booker, 1983). Therefore modern multiple event location techniques utilize independent GT information such as existing reference events (e.g. Ritzwoller et al., 2003; Bondár et al., 2004b), seafloor bathymetry (Pan et al., 2002), satellite imagery (e.g. Bennett et al., 2010; Fisk 2002), InSAR (e.g. Biggs et al., 2006; Parsons et al., 2006), and active fault lines (Waldhauser and Richards, 2004) to provide absolute location constraints.

Despite the utilitization of multiple event methods, location precision of a few kilometers still requires the attention of an expert to construct a well-posed multiple-event problem, develop or validate travel-time models, and groom the data set.

3 IASPEI Reference Event List

The IASPEI Commission on Seismic Observation and Interpretation (CoSOI) Working Group on Reference Events for Improved Locations has coordinated the global effort of collecting and validating ground truth events in the past decade. The International Seismological Centre (ISC) hosts the database of the IASPEI reference event list. Ground truth events can be searched, downloaded or submitted through the ISC website, www.isc.ac.uk/GT/index.html.

The ISC updates the ground truth database annually. Because the ISC bulletin contains parametric data reported by various agencies with little indication of the procedures of how the actual measurements were made, it is advisable to follow a more conservative approach when identifying GT events. Therefore the Bondár and McLaughlin (2009b) ground truth selection criteria, that were specifically developed for assessing the quality of locations in a bulletin without any further special analyses, are applied to select GT candidate events from the reviewed ISC bulletin. The GT candidate events are relocated using the local stations only (within 150 km of the epicentre). The subsequent outlier analysis may reject some of the GT candidates. The members of the IASPEI CoSOI Working Group review the identified GT events, and the accepted GT events are added to the IASPEI Reference Event List. The Working Group also vets events submitted by researchers.

The IASPEI Reference Event List contains 7,410 GT0-5 events (as of August 2011) with some 525,000 phase onset time readings. The GT database consists of both earthquakes and explosions (nuclear or chemical). Figure 1 shows the number of events by type and category.

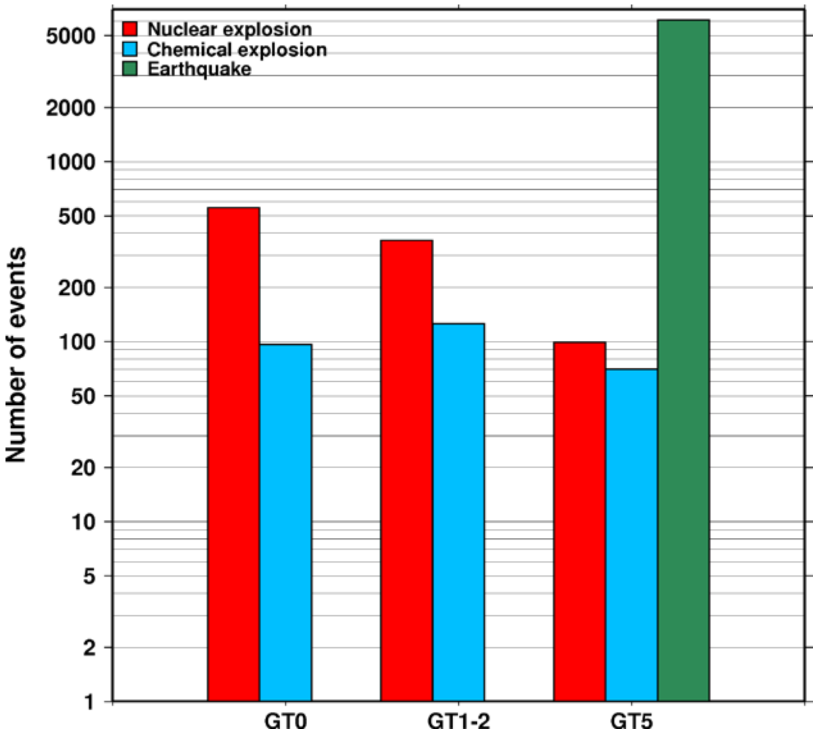

Figure 1 Number of events by event type and GT category.

Figure 2 shows the geographical distribution of the GT events color, and symbol coded by their GT category. Note the uneven distribution of events due to the lack of dense local networks on many parts of the globe. In order to fill in gaps in GT coverage, we encourage researchers who run temporary local network deployments to submit GT event candidates. This particularly applies to Africa, South America, and South-East Asia.

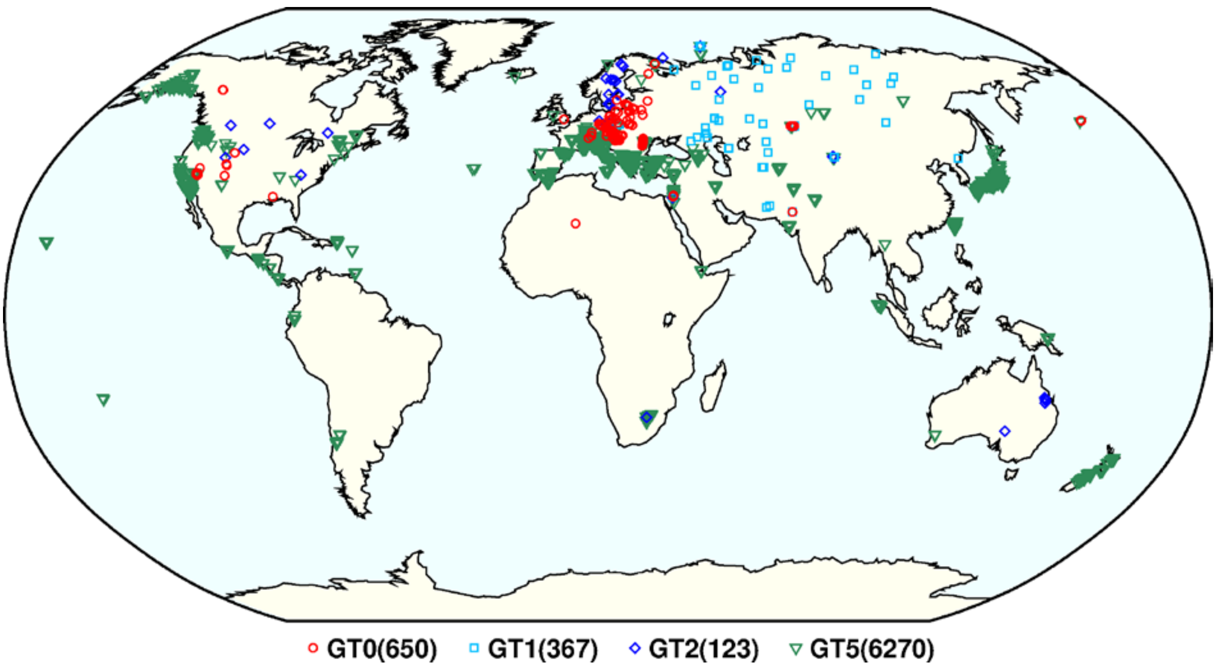

Figure 2 Geographical distribution of GT0-5 events in the IASPEI Reference Event List.

Acknowledgement

Thanks go to Bob Engdahl for his careful review and proposed valuable amendments.

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