Getting Closer to Surface Ground Truth Zero (GT0): Enhanced Geo-Positioning and Geological Site Characterization of Underground Nuclear Test Sites Such as in North Korea Using Openly Available Geospatial Tools Like Google Earth

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**Getting Closer to Surface Ground Truth Zero (GT0):**

- This presentation describes a holistic approach to achieve more precise geo-location and site characterization of potential nuclear-related seismic events in steep terrain when:
  - There are no visible surface disturbances
  - Multiple events provide relative location vectors

- “Imagery Analysis” of commercial satellite imagery can provide the basis for anchoring the relative location vectors to the real world with additional insights *(e.g., tunnel entrances and other identifiable human activity including excavated spoil from tunnels)*

- “Virtual Globes” *(e.g., Google Earth)* provide the means to view that imagery in 3-D perspective and to reduce the range of associated depths of burial (DOB)

- More precise real world locations and more accurate DOBs raise the salience of knowing the geologic setting

- Reconnaissance geologic studies provide insights on host rock competence, and the potential for containment success or failure

- Open-source collateral information provides additional insights to the above

- Future work focuses on empirical means to validate these findings *(e.g., differential interferometry using Radar imagery data of pre- and post-events, and hyperspectral)*

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For CTBTO Science and Technology Conference 2015, 22-26 June 2015
Final CTBTO Estimate of the Location of the DPRK Events

Comparison of the first automatic location estimates of the 2006, 2009 and 2013 Seismic Events in North Korea.

Using seismic information alone, the absolute location accuracy is currently limited to approximately ±16.2 km.

Relative locationing of multiple events requires a real-world anchoring point.

Imagery Analysis of commercial satellite imagery can provide that anchor.

Relative Location Provides a Vector

Epicenters of North Korean Seismic Events from 2006 and 2009
Provided Fixed Separation Distance and Azimuth Via
Relative Re-Location Calculations (Murphy, et al., 2010) and Others Since

Relative Location Vector:
~2.35 kilometers at ~288 degrees from 2006 event to 2009 event

Commercial Satellite Imagery Provides the Setting and Insights on Ongoing Human Activity

At 02:57:51 UTC on February 12, 2013, monitoring stations of the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) and many other stations around the world detected a shallow seismic event with explosion-like characteristics in the Democratic People’s Republic of Korea (DPRK).

http://www.iris.edu/hq/retd/event/1835

http://38north.org/2015/06/punggye060415/
Google Earth Provides Perspective

Punggye Test Site, DPRK

West Portal Area
Support Area
East Portal Area
South Portal Area

21 OCT 2014
Commercial Satellite Imagery Provides Correlation of Human Activity with 2006 Event Helping to Determine Anchor Location

East Portal Area, Punggye-ri Test Site, DPRK

Structures present

PRE-Event
17 SEP 2006

Small buildings/trailers

Tailings spoil pile

East Tunnel Portal must be near upper end of tailings spoil pile

Structures removed or altered

POST-Event
13 OCT 2006

Small buildings/trailers

Tailings spoil pile

©Digital Globe
Relative Location Vector Anchored to Real World

Punggye-ri Test Site, DPRK
Derived Epicenters of Seismic Events from 2006 and 2009 Relative Location Plot
(from Murphy, et al.) Geo-positioned on Google Earth

2009 event
Pabian/Hecker est. (using Murphy, et al., relative location plot)
~one to 1.1 Km tunnel
~490 meters DoB

2006 event
Pabian/Hecker est. (using Murphy, et al., relative location plot)
~one to 1.1 Km tunnel
~310 meters DoB

West Portal Area
South Portal Area
East Portal Area
The Topography (Steep Diverging Terrain) Determines the Anchoring

Finding the Anchor Point:
Divergent topography constrains the placement of the Murphy, et al., relative location plot (Dotted red lines indicate maximum overburden for minimum tunnel length from each portal)

West Portal Area
South Portal Area

Future event?
~1.1 Km tunnel
~380-390 m DoB

~1.25 Km tunnel
~490 m DoB

2006 event
Pabian/Hecker est.
(Using Murphy, et al., relative location plot)

~1-1.1 Km tunnel
~310 m DoB

2009 event
Pabian/Hecker est.
(Using Murphy, et al., relative location plot)

~.5 Km tunnel
~220 meters DoB
(Highly improbable, given that the relative location plot would place the 2009 event up or across the valley from the west portal)

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1104 m
4/2005
Getting Closer to Surface Ground Truth Zero (GT0) (by getting to within 500m of the real location)

Green dashed circles show 500 meter error radius necessary for GT0 for 2006 and 2009 tests using Pabian/Hecker center-points

Image © 2013 DigitalGlobe

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Open Source Collateral Information Provides Insights

Comparison of French Nuclear Test Tunnel Layout for Containment with that purportedly used by North Korea

NOTE: The 1998 Pakistani test tunnel was about one kilometer long and “… designed in the form a double-S shape” and “… shaped like a fishhook to be self-sealing”


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Combining All the information on a Virtual Globe

Punggye-ri Test Site, DPRK

Mt. Mangap (el. 2190 m)

2009 Event (Location from Pabian/Hecker 2012)

2013 Event (Location derived from Steven Gibbons/NORSAR plot 2013)

Suspect 2010 Event (approx. rel. location derived from Zhang and Wen)

Conjectured surface projection of a tunnel layout from WEST PORTAL incorporating containment strategy per DPRK broadcast animation video (Tunnelling may still be ongoing)

Alternative new tunnel, IF there was a problem with the original tunnel (e.g., radiological contamination due to re-entry?)

See Disclaimer on First Slide
Reconnaissance Geologic Mapping Combined Extrapolations From Nearby Ground Truth With Geomorphometrics and Drainage Analysis
Reconnaissance Geologic Survey Findings: Summary Points

- Low probability for the existence of Precambrian (Proterozoic, “Matenrei”) limestone/dolomite in the immediate vicinity of the nuclear test site. This mitigates the likelihood of any prompt venting due to non-condensable carbon dioxide gas generation.

- Evidence for a lithological boundary at the foot of Mt. Manthap within the main area of the Punggye-ri nuclear test site.

- The 2006 nuclear test occurred (via the “East Portal”) in basement host rock characterized as highly foliated and highly fractured, either Precambrian Saitoku gneiss (as mapped) or “Meisen schistose granite” probably of Mesozoic/Jurassic age (and exhibiting attributes similar to the nearby Saitoku quartz porphyry).

- The 2009 and 2013 tests occurred (via the “West Portal”) in a more competent plutonic host rock, either Mesozoic/Cretaceous Tokureido diorite (as mapped), a very hard rock comparable to granite, or, alternatively, a less fractured variation of a Mesozoic granite, which, in either case, likely provides better containment and better coupling.

Note: New tunneling at the “West Portal” (subsequent to the 2013 test) is ongoing, and additional nuclear testing can be expected to occur in that same competent host rock sometime in the future.
Reconnaissance Geologic Survey Findings: Summary Points, Cont.

- Such geologic differences could be one possible contributing factor in the prompt release of detected radionuclides associated with the 2006 event; and explain why the eastern tunnel complex was subsequently abandoned; and provide a reason why the 2009 and 2013 events did not vent (apart from a late detection in 2013, possibly the result of a post-event reentry in April 2013).

- Additional tunneling at a third portal (at the “South Portal”) likely located in host rock that is similar to that used in association with the latter two tests (but perhaps having higher water saturation).

- A stratified Quaternary volcanic sequence (likely including basalts, tuffs, and rhyolites) is readily distinguishable and forms the top 200 meters of Mt. Manthap and includes a thin capping layer of Shintokuri olivine basalt (evident as a prominent scarp along the western and northern portion of the test site). This sequence lays noncomformably upon the basement rocks situated within the test site proper.
Google Earth Pro Provides Means for Generating Geologic X-Sections and Visualization of Depth of Burial and Effective Overburden

For CTBTO Science and Technology Conference 2015, 22-26 June 2015

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## Comparison of Estimates of Depth of Burial for Recorded Seismic Events by Varying Techniques

<table>
<thead>
<tr>
<th>Year</th>
<th>Reference and technique</th>
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<tbody>
<tr>
<td>2006</td>
<td>------</td>
</tr>
<tr>
<td>480</td>
<td>Avants (2014, PhD) – Green’s function and scattering by realistic topography</td>
</tr>
<tr>
<td>610</td>
<td>Zhang &amp; Wen (2013, SRL) – Relative seismic locations and satellite imagery</td>
</tr>
<tr>
<td>200</td>
<td>Murphy et al. (2013, BSSA) – Broad-band spectral P ratio</td>
</tr>
<tr>
<td>X</td>
<td>Murphy et al. (2013, BSSA) – RMS arrival time residuals</td>
</tr>
<tr>
<td>100</td>
<td>Pasyanos et al. (2012, BSSA) – Narrow-band regional amplitude envelopes</td>
</tr>
<tr>
<td>310</td>
<td>Pabian &amp; Hecker (2012, BAS) – Relative seismic and tunnel entrance locations, and available</td>
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<tr>
<th>Year</th>
<th>Reference and technique</th>
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<tbody>
<tr>
<td>2009</td>
<td>------</td>
</tr>
<tr>
<td>430</td>
<td>Israelsson &amp; Chun (2011, CTBT S&amp;T) – Depth phase reflections</td>
</tr>
<tr>
<td>550</td>
<td>Israelsson &amp; Chun (2011, CTBT S&amp;T) – Pg-Pn times</td>
</tr>
<tr>
<td>X</td>
<td>Rougier et al. (2011, GRL) – Hydrodynamic models producing no surface disturbance in granite</td>
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<tr>
<td>200</td>
<td>Ni et al. (2010, SRL) – Waveform mismatch</td>
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<th>Year</th>
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<td>2013</td>
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<td>640</td>
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<td>430</td>
<td>------</td>
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<td>400</td>
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**So the NK09 DOB is 500-600 m.** That Avants find NK09 to be shallower than NK06 seems unlikely given the higher yield of NK09. Also, the deeper DOB of Avants for NK13 compared to NK09 seems a little inconsistent since most relative locations put NK13 at a location with less available overburden. Unless they tunnelled downwards and/or drilled a vertical that at the end of a horizontal tunnel. (A possibility that cannot be negated or verified based on available information)

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Recommendations for Future Work:

• If both pre- and post-test radar imagery for each event (including any future events) could be obtained, interferometric coherent change detection might reveal subtle surface disturbances yielding even greater precision with respect to the event geo-locations.

• The application of high resolution synthetic aperture radar (SAR) imagery could also help to shed new light on the underlying lithologies and the extent of foliations and fracturing.

• Obtain and analyze hyperspectral spectral imagery (e.g., from HYPERION) of the most recently excavated spoil material from both the “West Portal” and the “South Portal” and the recently exposed sections of bedrock on the western slopes (due to torrential rain erosion).

• Obtain a higher resolution (1 meter) digital elevation model (DEM) to more precisely cross-correlate ground survey-mapped areas with non-ground survey-mapped areas.
Recommendations for Future Work:
Synthetic Aperture Radar (SAR) interferometry (necessitates pre-and post test imagery acquisitions)

"Deformation on the ground causes phase changes in radar signals that appear as the rainbow-coloured patterns. Each colour cycle corresponds to a deformation of 28 mm deformation. The maximum deformation is more than 10 cm."

http://www.esa.int/spaceinimages/Images/2014/09/Napa_Valley_quake

Hyperspectral Imagery to verify geologic mapping

http://speclab.cr.usgs.gov/PAPERS/tetracorder/
Key Analytical References:

- Incorporated Research Institutions for Seismology (IRIS) http://www.iris.edu/hq/retm/event/1835
Questions!

Molte Grazie!

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Back-Up Slide: Geologic Anecdotes:
Rock Pillar Photographed in 1932 Can Be Found on
Google Earth, and a Similar One Is Near the East Portal

Location is ~2 Kilometers west of Saitoku (Punggye-ri)

Quartz Porphyry pillar
(as located on Google Earth)

Inferred lithological boundary

“East Portal” (abandoned)

From 1932 Japanese geologic report:

See Disclaimer on First Slide
Back-Up Slide: Plot of all published yield estimates (averaged) as found in open sources