Responses to referee 2 (Anonymous)

Manuscript SE-2018-102

A Multi-Technology Analysis of the 2017 North Korean Nuclear Test

Peter Gaebler, Lars Ceranna, Nima Nooshiri, Andreas Barth, Simone Cesca, Michaela Frei, Ilona Grünberg, Gernot Hartmann, Karl Koch, Christoph Pilger, J. Ole Ross, and Torsten Dahm

Dear reviewer,

we want to thank you for taking the interest and time to deliver this very helpful and constructive review of our work. We studied your comments and made changes and corrections to the manuscript where necessary. We hope our changes and and corrections are sufficient to make our article suitable for publication soon. Your comments and suggestions certainly helped to improve quality and clarity of the paper.

Respones to your comments are given in the following pages. We first respond to your general comments and then respond to your specific comments as given in your annotated pdf version of the manuscript. Changes made in the manuscript related to your comments are given in blue color, changes by the authors after rereading the manuscript are given in grey color. Changes related to the comments by the first reviewer Felix Schneider are given in green color. Page and line numbers refer to the originally submitted manuscript.

Thank you again,
best regards

Peter Gaebler and co-authors

General Comments

G1 COMMENT: The document as such appear to be rather a catalog of result that a multi-technology analysis, which could be achieved through establishing the objective of such an approach and adding discussion and transition between methods and technologies.

RESPONSE: Thank you for this comment. Indeed the results are obtained within the disciplines of seismology, infrasound monitoring, remote sensing and atmospheric transport modeling. But we want to stress, that there are cross-links where the methods and technologies complement each other and lead to a consistent multi-technology picture of the event analysis. For example this is true for the hypocenter estimation of the event, where remote sensing and seismological methods are combined to achieve aboslute information about the epicenter and the depth of the event. This is described on page 4 lines 20-25. Also for example we use data from different DRPK events to infer the epicenter location. As the area of surfacedisplacement of the 2017 event is of great extent and no definite epicenter location can be derived from the 2017 test, data from the January 2016 event is used, which showed a clear a distinct maximum of surface displacement (see page 15 line 9-12). To clarify cross-connections between

the methods and technologies we adapted the manuscript text at some positions.

CHANGES IN THE MANUSCRIPT:
(a) page 9 line 14: Added following transition sentence: *For a shallow event in that magnitude range it is expected to record infrasound signals in distances of up to hundreds of kilometers (Mutschlecner and Whitaker, 2005).*
(b) page 11 line 32. Added following transition sentence: *The strong surface deformations at the surface observed for the 2017 test might lead to pathways and the subsequent release of radionuclides, especially gaseous radionulcides such as 133Xe, from the test site. Potential measurements of radionuclides are discussed in the following Section 5.*
(c) page 15 line 9: Changed sentence to underline the cross-link between seismology and remote sensing technologies.

G2 COMMENT: Noteworthy, the link between the different seismological methods should be emphasized and discussed, and in particular the differences in estimations.

RESPONSE: Also here the different seismological methods can be interpreted as stand-alone results. But for example depth is estimated using multiple different methods (double difference method, moment tensor analysis and depth phase method). The different estimations and also the resulting differences are discussed on page 13 lines 11-16. Furthermore we for example discuss the influence of topography on the estimation of the body wave magnitude and therefore also the influence on the estimated yield (page 20 lines 20-33). Of course in the field of seismology, many more interdependencies can be imagined and have to be further elaborated, for example the possibility to estimate yield reversely over collapse-strength/cavity size. Further interdependency analysis is beyond the scope of this study.

G3 COMMENT: The fusion of results between technologies also needs to be further introduced and discussed.

RESPONSE: To our understanding, *Data Fusion* applies to the first phase when grouping data of different IMS technologies which potentially belong to the same critical event. Our multi-technology analysis covers more aspects of an Expert Technical Analysis, where a critical event is investigated in depth with additional methodologies. We added text concerning data fusion in the introduction of the manuscript.

CHANGES IN THE MANUSCRIPT: page 2 line 16: Added text concerning data fusion. *To assess the connection between radionuclide detections and potential source events atmospheric tranport modeling (ATM) is applied. Grouping data from different IMS technologies that is attributed to the same critical event is refered to as data fusion.*

G4 COMMENT: Questions that the manuscript should answer are:
(a) what are the author trying to achieve by having a multi-technology approach?
(b) and in the end, did they achieve it and if not, what was the reason? (technology/resolution limitations, insufficient knowledge at the interface between technologies...?)

RESPONSE:
(A) By applying a multi technology analysis we try to give an overall characterization of the explosion and its consequences, ideally connected with a reliable yield estimate and a statement on the type of the device. All these points are covered in the manuscript.
(b) Yes, the evidence from this study would be compelling enough to state a treaty violation in the context of the CTBT. Beyond this, neither the yield estimate nor the radionuclide evidence was sufficient for full characterization of the nuclear device which would be of further interest for intelligence quarters and policy makers. The main reasons are the high uncertainties in yield estimation and the largely contained radionuclides. A potential On-Site Inspection could achieve additional evidence. We added

text in the conclusions to underline the achievement of the multi-technology analysis.

CHANGES IN THE MANUSCRIPT: Added text on page 16 line 6: *The combination of the results from the different technologies and methods yields a reliable estimation of hypocenter, magnitude, explosive energy, source mechanism as well as an indication for delayed leakage of ^{133}Xe from the test site. The cross-links between the different results complement each other in a consistent manner.*

Specific Comments

0 Abstract

0.1 COMMENT: page 1 line 16: ehance → enhance.

RESPONSE: Typo corrected.

CHANGES IN THE MANUSCRIPT: page 1 line 16: ehance → enhance.

1 Introduction

1.1 COMMENT: page 2 line 9: remove *or in space.* This is covered by the Outer Space Treaty, not the CTBT.

RESPONSE: Thank you for this comment, you are correct. Space is not covered by the CTBT.

CHANGES IN THE MANUSCRIPT: page 2 line 9: removed the words *or in space.*

1.2 COMMENT: page 2 line 11: are still missing ratification → have still not ratified.

RESPONSE: Changed as suggested.

CHANGES IN THE MANUSCRIPT: page 2 line 11: are still missing ratification → have still not ratified.

1.3 COMMENT: page 2 line 22: even definite → even though definite.

RESPONSE: Changed as suggested.

CHANGES IN THE MANUSCRIPT: page 2 line 22: Added the word *though.*

1.4 COMMENT: page 3 line 2: *successful test of a fusion bomb* Please provide a reference.

RESPONSE: We now provide a reference to a press release by the Korean Central News Agency regarding the successful test of H-bomb for ICBM.

CHANGES IN THE MANUSCRIPT: page 3 line 2: Added reference KCNA2017.

1.5 COMMENT: page 3 line 8: Typo. As there is not → as there is no.

RESPONSE: Thank you for pointing that out, the typo is corrected.

CHANGES IN THE MANUSCRIPT: page 3 line 8: As there is not → As there is no.

1.6 COMMENT: page 3 line 17: in teleseismic → at teleseismic.

RESPONSE: Changed as suggested.

CHANGES IN THE MANUSCRIPT: page 3 line 17: in teleseismic → at teleseismic.

1.7 COMMENT: page 3 line 19: Additionall, → Additionally.

RESPONSE: Typo corrected.

CHANGES IN THE MANUSCRIPT: page 3 line 19: Additionall, → Additionally.

1.8 COMMENT: page 3 line 19-20: *is estimated by 2D-waveform modeling to estimate.* Repetition of estimate.

RESPONSE: Thank you for this comment, we avoided the repetition by using the term *assess.*

CHANGES IN THE MANUSCRIPT: page 3 line 20: estimate → assess.

1.9 COMMENT: page 3 line 21: Typo: test site, The → test site. The

RESPONSE: Typo corrected.

CHANGES IN THE MANUSCRIPT: page 3 line 21: changed comma to point.

2 Seismological Investigations

2.2 Estimation of Hypocenter Depth and Seismic Moment

2.2.1 COMMENT: page 4 line 30-32: *However, such a depth phase approach needs high-frequency waveforms above 1 Hz to resolve the onset of the depth phase, and may be difficult from single stations recordings if the signal to noise ratio (SNR) is poor at teleseimsic distances.* Incomplete sentence.

RESPONSE: You are right, thanks for the comment. There was something missing. We added *to be performed* to the text to form a complete sentence.

CHANGES IN THE MANUSCRIPT: page 4 line 31: Added the word *to be performed* to form a complete sentence.

2.2.2 COMMENT: page 5 figure 3: Issue with the figure.

RESPONSE: Issue should be resolved, sorry for the inconvinience.

2.2.3 COMMENT: page 6 line 11: *from (Bassin et al, 2000)* parenthesis to fix.

RESPONSE: Thank you for the comment, the brackets are correct, but the term CRUST2.0 was missing in front of the brackers. Corrected in the text now.

CHANGES IN THE MANUSCRIPT: page 6 line 11: Added the term *CRUST 2.0* in front of the citation of Bassin et al, 2000.

2.2.4 COMMENT: page 6 line 20: *(compare Dahm er al., 2007)* Compare with - can you be more specific.

RESPONSE: This is a misplaced reference. I removed the term *compare Dahm et al., 2007* from the manuscript.

CHANGES IN THE MANUSCRIPT: page 6 line 20: removed the citation of Dahm et al., 2007.

2.2.5 COMMENT: page 6 line 20: Interesting → Of interest.

RESPONSE: Changed as suggested.

CHANGES IN THE MANUSCRIPT: page 6 line 20: Interesting → Of interest.

2.2.6 COMMENT: page 23 figure 3: Figure should be redone/corrected, it is incomplete.

RESPONSE: See comment 2.2.2.

2.3 Moment Tensor Inversion of the Test and the Main Aftershock

2.3.1 COMMENT: page 7 figure 5: Difficult to read on paper version - author should improve quality/resolution/size.

RESPONSE: Due to the format of the EGU latex template the figure is smaller than it will be in the final form. I would suggest to wait for the final editing of the manuscript and then redo the figure if required.

2.3.2 COMMENT: page 7 line 20 : *still show a good SNR* Define what is a good SNR, can there be a qualitative metric?

RESPONSE: Thank you for this valid comment. Good in this context means, that the signal strength is sufficient to be used for MTI analysis. I modified parts of the sentence for clarification.

CHANGES IN THE MANUSCRIPT: Modified text on page 7 line 20.

2.3.3 COMMENT: page 7 line 25 : page 25 figure 5: Ok on the PDF, but difficult to read on printout.

RESPONSE: Please see comment 2.3.1.

2.5 Influence of the Mt. Mantap Topography

2.5.1 COMMENT: page 8 line 19: in 0.8 km depth → at 0.8 km depth.

RESPONSE: Changed as suggested.

CHANGES IN THE MANUSCRIPT: page 8 line 19: in 0.8 km depth → at 0.8 km depth.

3 Infrasound

3.1 COMMENT: page 9 line 28: *Infrasonic forerunner* Is it forerunner or could it explained by the ground coupling effect, since 1) an area could be radiating rather than a single point or 2) the ground-coupling location is located closer to the station, which suggest longer seismic propagation and shorter infrasound path.

RESPONSE: The signal recorded after about 1350 seconds shaping a third PMCC signal group is suspected to be a separate detection following another propagation path, since its trace velocity and back-azimuth directions differ from those of the Is2 detection. It was estimated to be an acoustic forerunner, since the observed celerities still have adequate acoustic values indicative of an early infrasound arrival. Nevertheless it is also possible that the sound is related to the infrasound radiation of an extended epicentral (or near-epicentral) area instead of an epicentral point source (reviewers proposal 1)). We added this possibility to the manuscript text. Reviewers proposal 2) is an option that is covered in larger detail by a study on seismo-acoustic coupling following the underground nuclear test. It is added to the manuscript as a supplement following the comments and requests of the first reviewer. Also see the response to comment 2 regarding this supplementary information.

CHANGES IN THE MANUSCRIPT: page 9 line 27-29: We added *to infrasound radiation from an extended (near-)epicentral source region* in the text.

3.2 COMMENT: page 10 line 7-8: *Figure 11c models the propagation from the test site epicenter to the station I45RU using parabolic equation and ray-tracingmethods for the attenuation of signal amplitude and the connection of source and receiver by eigenrays.* Walker et al for Tohoku earthquake and Le Pichon et al for 2005 Chilean earthquakes came up with representation for ground coupling regions that could be of value here.

RESPONSE: Investigations on ground coupling regions (where seismic wave signatures are in certain surface regions converted into infrasound then propagating to the station) were already requested to be discussed in further detail by the first reviewers. We added a supplement to the manuscript to present results from this study. Ground coupling regions and corresponding detections are described there. We take into account the proposed references and added them to the supplement.

3.3 COMMENT: page 10 line 16: in 400 km → at 400 km.

RESPONSE: Changed in the manuscript as suggested.

CHANGES IN THE MANUSCRIPT: page 10 line 16: in 400 km → at 400 km.

3.4 COMMENT: page 31 figure 11: see comment in 3.1 about the forerunner.

RESPONSE: We want to refer you to our response to comment 3.1.

4 Remote Sensing Studies

4.1 COMMENT: page 11 line 25: Typo: calcultes → calculates.

RESPONSE: Typo corrected.

CHANGES IN THE MANUSCRIPT: page 11 line 25: calcultes → calculates.

4.2 COMMENT: page 11 line 29: related to test → related to the underground test.

RESPONSE: Changed as suggested.

CHANGES IN THE MANUSCRIPT: page 11 line 29: related to test → related to the underground test.

5 Radionuclide Monitoring and Atmospheric Transport Modeling

5.1 COMMENT: page 12 lines 12-15: *The IMS station RN58 (Ussurysk, Russia) would have been affected, but was not operational at that time. Station RN38 (Takasaki, Japan) would have been missed by the plume from the potential release from the test site which is typical for the season. Stations further downwind, for example in Northern America, would have required a larger release for activity concentrations to exceed the detection threshold.* Sentences should be rewritten if possible less conditional and more specific.

RESPONSE: We made slight adjustements in the text. We feel that the sentence is clear now. Please comment further if you do not agree with our formulation.

CHANGES IN THE MANUSCRIPT: page 12 line 11: Text slightly changed to make it more specific and less conditional.

5.2 COMMENT: page 12 line 23: *Nyongbyon County.* Incomplete. For clarity, it should be homogenized with the figure showing the nuclear facility.

RESPONSE: We used the term Yongbyon Research Center in the text now for clarification. The research complex is shown in the figure. I hope this solves the problem.

CHANGES IN THE MANUSCRIPT: page 12 line 23: Slight adjustments to the text.

5.3 COMMENT: page 13 line 1: *delayed small releases.* Please explain and clarify the 1) delay and 2) "small".

RESPONSE: *Delayed:* The potenital releases under discussion took place within 30 to 50 days after the test. *Small:* Small refers to required source term in the order of roughly 10^{11} Bq. This number is given in the prior sentence on page 12 line 35.