Verification science

The announced nuclear test in the DPRK on 25 May 2009

by Robert G. Pearce, Andreas Becker, Tim Hampton and Matthias Zähringer

In Issues 9 and 10 of *Spectrum* we reported on signals recorded by the International Monitoring System (IMS) relating to the first announced nuclear test in the Democratic People's Republic of Korea (DPRK) on 9 October 2006. When the DPRK announced a second nuclear test on 25 May this year, it was natural that Member States would again focus on IMS performance. Since 2006 the IMS has grown much closer to its eventual 321 monitoring stations, with an additional 65 stations having been certified by May 2009. The capabilities of the International Data Centre (IDC) have also been further enhanced. Moreover, the IMS seismic signals showed that this event was larger. These factors conspired to provide us with high quality signals at many more IMS seismic stations. However, this time the IMS does not appear to have recorded relevant signals at its radioactive noble gas stations, which has come as a surprise to some.

So what can we then conclude from the IMS data?

IMS seismic recordings of the 25 May 2009 DPRK event

On 25 May 2009, the IDC's initial list of events compiled automatically from IMS waveform data (Standard Event List 1, SEL1) contained an event recorded in the DPRK, referred to here as DPRK2. It was located (Figure 1) using 23 IMS primary seismic stations. The location had an 'uncertainty ellipse' of 860 square kilometres (km^2), most of which overlapped with that of the announced DPRK nuclear test of 9 October 2006, referred to here as DPRK1. SEL1 is issued within two hours, which means that a location estimate for this event was made available to Member States within that time without any human intervention.

The IDC issues three SELs with different time delays, in order to provide progressively more accurate and reliable event location estimates as more data become available. Currently the IDC issues SEL1 within two hours of 'real time', SEL2 after about four hours and SEL3 after six hours, in accordance with the timeline envisaged after Entry into Force (EIF) of the Treaty. The lists are dominated by large and small earthquakes; there are typically between 120 and 160 events in each SEL every day. The DPRK2 event in SEL2 and SEL3 incorporated observations from 16 auxiliary seismic stations, which reduced the uncertainty ellipse to an area of 582 km^2.

Events are examined by IDC analysts in order to prepare a Reviewed Event Bulletin (REB) for each day, which contains all events meeting specific criteria. Following guidance from the Member States, IDC typically issues the REB for any day within ten days. In view of the considerable interest generated among Member States by this event, an 'expedited' REB containing all the events for 25 May 2009 was issued on 27 May, in accordance with the envisaged post-EIF timeline. This was made possible by delaying the REBs for other days.

During interactive analysis, signals from this event were found from some additional IMS stations, bringing the total to 31 primary and 30 auxiliary seismic stations in the REB, 59 of which

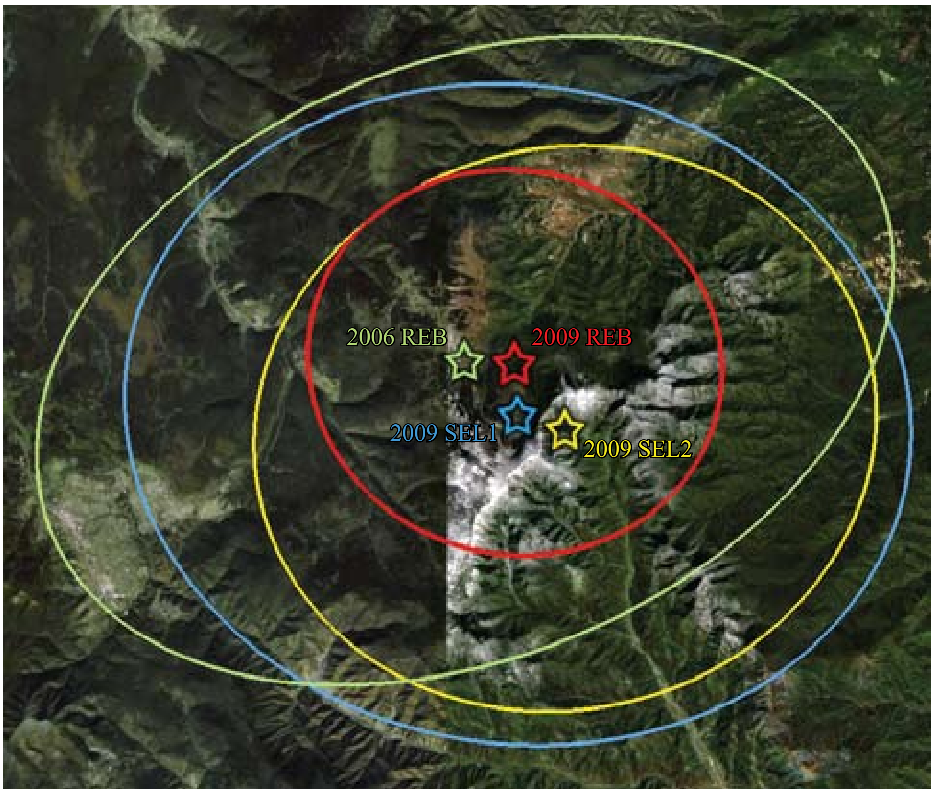

FIGURE 1: LOCATION AND UNCERTAINTY ELLIPSES FOR THE 2006 AND 2009 DPRK EVENTS DETERMINED USING IMS SEISMIC DATA. FOR THE 2009 EVENT, THE FIRST ESTIMATE (SEL1) WAS ISSUED WITHIN TWO HOURS USING IMS PRIMARY SEISMIC STATIONS ONLY, FOLLOWED BY SEL2 WHICH INCLUDED AUXILIARY SEISMIC STATIONS. THE FINAL ESTIMATE OBTAINED FOLLOWING ANALYST REVIEW OF ALL DATA WAS ISSUED IN THE REVIEWED EVENT BULLETIN (REB) WITHIN TWO DAYS. AS EXPECTED, THE UNCERTAINTY ELLIPSES GET PROGRESSIVELY SMALLER AS MORE DATA BECOME AVAILABLE; THAT FOR THE 2006 EVENT IS LARGER THAN THAT FOR 2009 BECAUSE THERE WERE FEWER SEISMIC OBSERVATIONS.

contributed to the location. The location uncertainty was reduced even further, to an area of 264 km^2 (Figure 1).

The Treaty specifies that the IDC should apply an automatic 'event screening' procedure to events in the REB, in order to exclude events which are 'consistent with natural phenomena or non-nuclear man-made phenomena'. Accordingly, experimental event screening criteria are applied to qualifying events in the REB. This leads to a Standard Screened Event Bulletin (SSEB) which is issued about two hours after the REB, and from which some events have been 'screened out'. The SSEB for 25 May 2009 included 36 events which were 'screened out' from a total of 79; DPRK2 was not screened out, and exhibited some clear characteristics of an explosion. Nevertheless, it is important to bear in mind that while the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) makes available IMS data and IDC products to Member States, under the Treaty it remains the responsibility of the States to pass final judgment on their origin.

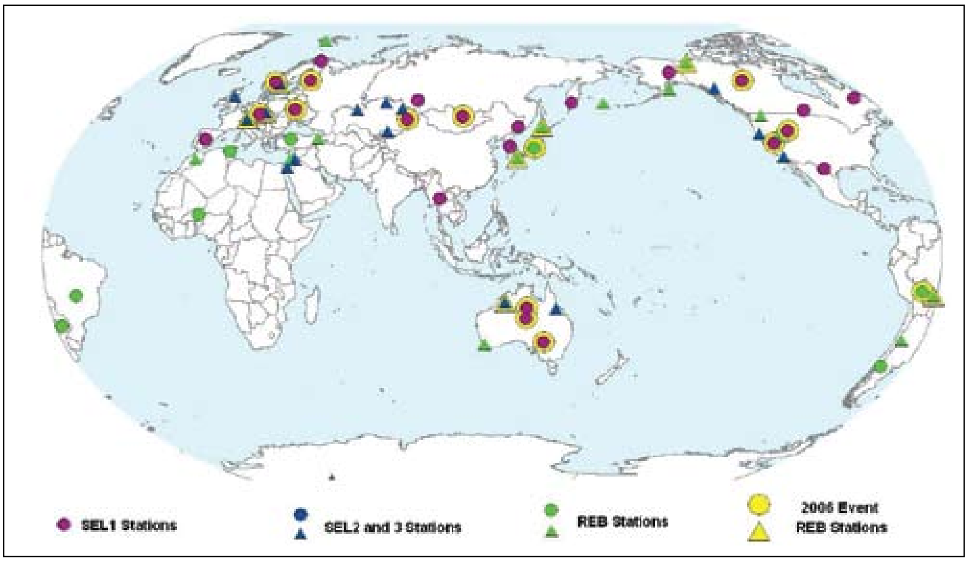

FIGURE 2: IMS SEISMIC STATIONS WHICH RECORDED SIGNALS FROM THE DPRK EVENT OF 25 MAY 2009. THOSE IN RED WERE USED IN THE SEL1 LOCATION ESTIMATE. THE ESTIMATE IN SEL2 INCLUDED ALSO THOSE IN BLUE, AND THOSE IN GREEN WERE MANUALLY ADDED BY ANALYSTS FOR THE REB. STATIONS WITH A YELLOW BORDER WERE USED IN THE 2006 DPRK EVENT. CIRCLES AND TRIANGLES REFER TO ARRAY AND THREE-COMPONENT SEISMIC STATIONS RESPECTIVELY.

Comparison of Seismic Observations for the DPRK events in 2006 and 2009

The REB locations for DPRK1 and DPRK2 differ by less than three km, with the uncertainty ellipse of DPRK2 completely inside that of DPRK1; bearing in mind the sizes of the uncertainty ellipses, this difference in location is hardly significant. Of the 59 stations used to locate DPRK2 (see Figure 2), 17 were certified after DPRK1, meaning that they meet IMS defined requirements and specifications. These 17 stations included four auxiliary seismic stations which were also used in DPRK1, but were subsequently upgraded and certified. It is noteworthy that three of the five seismic arrays closest to the event are new or have been upgraded since DPRK1. This reflects positively on the continuing build-up of the IMS network over the last few years, particularly in Asia.

Radionuclide observations and atmospheric transport modelling

A large part of the radioactive debris from an underground explosion is normally contained within the cavity created by the explosion. However, small traces of radioactive release may be measured at highly sensitive detectors under favourable conditions, even hundreds or thousands of kilometres away. Radioactive noble gases, including xenon, may escape immediately after the explosion by 'venting', or at a later time by 'seepage'. The IMS is designed such that releases from a nuclear test should be detectable at one or more stations in the global network. Radioactive xenon has a half life of a few days, and so offers the best chance of being detected remotely in the IMS network within about three weeks of an event.

At the time of DPRK2, several IMS noble gas stations in the region were operational (see Figure 3), of which only one was operating at the time of DPRK1. This gives an indication of the progressive build-up of the IMS. Noble gas detectors at three of these stations (RN22, RN38 and RN58), were operating continuously at full performance. Their overall detection capability (minimum detectable concentration or MDC) was 0.2 millibecquerel[1] per cubic metre (mBq/m^3) or better throughout the relevant time period.

Although seismic signals originating from a putative underground nuclear explosion travel from the test site to IMS stations along well-defined paths through the Earth in a few minutes, any radionuclide particulates or gas which may reach the Earth's surface above an underground nuclear explosion travel much more slowly. They then spread out through the atmosphere along

[1] The Becquerel is a measure of the strength of radioactivity.

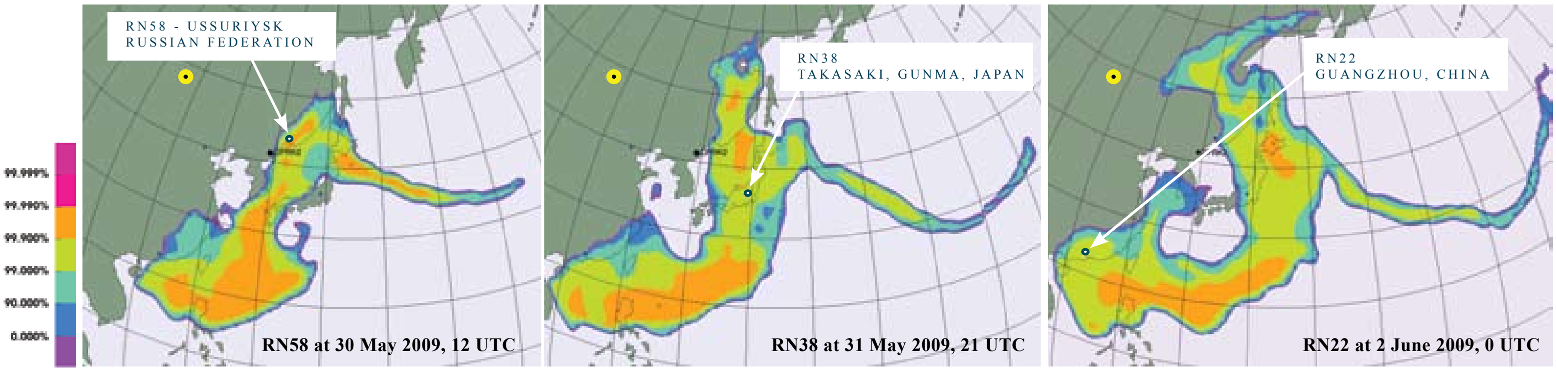

FIGURE 3: EVOLUTION OF THE DETECTABLE RADIOACTIVE PLUME AS CALCULATED FOR AN IMMEDIATE VENTING SCENARIO, PLOTTED AT THE TIMES OF THE STRONGEST ARRIVALS AT (1) RN58, RUSSIAN FEDERATION, (2) RN38, JAPAN AND (3) RN22, CHINA. FOR EXPLANATION SEE TEXT. IMS NOBLE GAS STATIONS OPERATING AT THE TIME OF DPRK2 ARE SHOWN; THE ONLY ONE OPERATING IN THIS REGION AT THE TIME OF DPRK1 IS HIGHLIGHTED BY A YELLOW CIRCLE - RN45, MONGOLIA.

paths which are dictated by the prevailing air movements (in other words, the weather). Atmospheric transport calculations based on millions of daily weather observations are therefore essential to interpret the radionuclide observations (or non-observations) made at IMS stations after days or weeks.

A comprehensive simulation study of atmospheric transport and dilution showed that several IMS stations were in a position to detect a release at the time and place of DPRK2; in other words, air was indeed transported to IMS stations from the site of the event. However, the simulation together with the observations showed that none of these stations detected a visible signal that could be attributed to DPRK2.

Figure 3 illustrates the distribution of a hypothetical radioactive xenon plume at the time of its highest concentration at the above-mentioned three stations. Only those parts of the plume which are above the minimum detectable concentration are shown. The plume was calculated under the assumption of immediate venting at the time and place of DPRK2, and under the assumption that zero containment corresponds to the full release of the radioactive xenon (^{133}Xe) generated by a four kiloton (kt) TNT equivalent explosion, (4×10^{16} Becquerel). For a containment of 90 percent, the detectable plume would cover the area shaded in green and yellow and orange. For a containment of 99.9 percent the detectable plume would cover only the areas in orange. As the stations in this region did not record signals at the corresponding times, it is concluded that the containment of any generated xenon (under the hypothesis that this was a nuclear test) was above 99.9 percent.

These maps of a hypothesized migrating plume are derived from a large body of observed meteorological data, and this demonstrates the crucial importance of meteorological information acquired in connection with the Cooperation Agreement between the CTBTO and the World Meteorological Organization (WMO). The meteorological conditions, and hence the pattern of atmospheric transport, were substantially different at the times of DPRK1 and DPRK2, and this reminds us of the fundamental importance of atmospheric transport modelling (ATM) in the interpretation of IMS radionuclide observations or non-observations.

The above simulation is called 'forward modelling' because a release is postulated, and the ATM is stepped forward in time to generate the evolving plume as it would develop under the observed meteorological conditions. The results are confirmed by performing 'backtracking' calculations (not shown here). These calculations begin with a notional sample of air at an IMS station at a given time, and trace it backwards in time and space (again using the prevailing meteorological conditions) in order to determine what regions of the globe it could have originated from, and at what sensitivity these regions were monitored, at any past time. These so-called 'Fields of Regard' are computed routinely for all radioactive xenon and particulate samples. For the latter, they are also appended to every Reviewed Radionuclide Report (RRR) issued as a standard product by the IDC.

All the above calculations refer to a hypothesized release at the time of DPRK2 ('venting'). The CTBTO has also investigated how sensitive the IMS network is for detecting seepage that may have occurred at a later time, again under the hypothesis that this was a nuclear test. The maximum possible daily seepage consistent with the observed non-detection of radioactivity is shown in Figure 4, on a logarithmic scale, for each day of the three-week period following the event. The sensitivity of the network varies during this period due to variations in the meteorological transport conditions relevant for each sample from each station, and is accessible from the relevant ATM backtracking (Field-of-Regard) calculations. On all days, the network sensitivity to the DPRK2 event location was sufficiently high to still detect a xenon-133 release of 100 Tera-Becquerel (TBq), a global reference value that corresponds to a 90 percent contained one kt underground nuclear explosion. On all but three days the network's daily threshold source strength at the DPRK2 event location was even one to three orders of magnitude below (thus better than) the 100 TBq baseline.

The non-detection of radioactivity after DPRK2 may be seen as somewhat surprising in view of the fact that DPRK1, though evidently smaller, was associated with relevant radioactive noble gas observations. The probability of detecting radioactive xenon traces from an underground explosion depends mainly on three factors. Firstly the degree of containment of the radioactive noble gases must be taken into consideration: if this were to be 100 percent then there is nothing to be detected. Secondly, detectability is affected adversely by the decay of radioactive xenon and the dilution of any release during its dispersion by atmospheric transport away from the release site towards IMS stations. Thirdly, the detection systems must be sufficiently sensitive to detect a relevant release that reaches them. This sensitivity may be compromised by a 'background' arising out of releases from nuclear reactors or radiopharmaceutical production unconnected with the possible release of interest.

Of the above factors, station detection capability is under our control, and ATM calculations enable us to diagnose the transport and dilution of any release as it spreads. However, the extent of containment of radioactive material below the surface remains largely unknown. From sensitivity studies (Figure 4) it is concluded that, under the hypothesis that this was a nuclear test, containment was well above 99.9 percent. However, whether planned or unintentional, it is extremely difficult to guarantee such a level of containment in advance. Similarly, the ATM calculations have been well-determined after an event, but different (unforeseeable) meteorological conditions can result in predicted detectabilities at different IMS stations that vary by many orders of magnitude. These two factors make it virtually impossible for a potential Treaty violator to predict the detectability of a nuclear test by IMS radionuclide stations in advance.

Conclusions

DPRK2 provided a tangible reminder that the IMS network has developed substantially since 2006, and it provided a further demonstration that the IMS network and the IDC processing systems are capable of detecting and locating an event of special interest, and making a preliminary location available to Member States automatically within two hours. In this case even the SEL1 location had an area of uncertainty smaller than the 1000 km^2 maximum area permissible for an on-site inspection after EIF, and satisfied the requirement that it should not exceed 50 km in any direction. Moreover, the IMS seismic data showed clear characteristics of an explosive source, and was not 'screened out' as an event consistent with a natural origin. The newly installed IMS noble gas stations, together with ATM calculations based on observed meteorological data, have allowed the CTBTO to determine with good precision the maximum release of radioactive xenon that could have occurred under various release scenarios, under the hypothesis that the event was indeed a nuclear test. In arriving at a conclusion on the nature of any suspicious event, the Member States will have the opportunity to integrate the results from all IMS monitoring technologies, and other sources of data, in order to arrive at their final judgement as to the nature of the event, while after EIF there would additionally be the potential for conducting an on-site inspection under the Treaty. ■

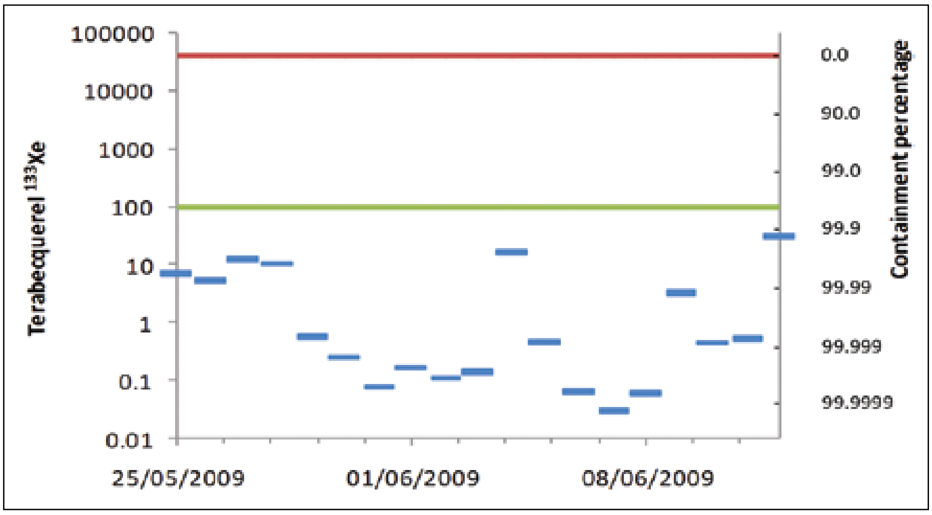

FIGURE 4: MAXIMUM POSSIBLE DAILY RELEASE OF RADIOACTIVE XENON AT THE LOCATION OF THE DPRK2 EVENT WHICH WOULD BE CONSISTENT WITH NON-DETECTION AT THE IMS STATIONS RN22, RN38 AND RN58 (BLUE BARS). THE RED LINE DENOTES THE TOTAL AMOUNT OF ^{133}XE PRODUCED BY A NUCLEAR DEVICE WITH AN EQUIVALENT YIELD OF FOUR KT OF TNT. THE GREEN LINE DENOTES THE MINIMUM REQUIRED RELEASE SENSITIVITY (BASELINE) AGAINST WHICH THE IMS GLOBAL COVERAGE IS EVALUATED.

Biographical note

Dr. Robert G. Pearce worked at the CTBTO International Data Centre for ten years until April 2009, latterly as Chief of the Monitoring and Data Analysis Section. Prior to this, he held appointments at three universities. He has also worked at the UK Government's Blacknest research group.

Dr. Andreas Becker joined the CTBTO as an Atmospheric Sciences Officer in 2001 and is in charge of atmospheric transport modelling (ATM) software development at the IDC. Before this he worked in Germany as a senior scientist developing ATM systems for environmental measurement campaigns.

Tim Hampton joined the CTBTO in 1998 and is part of the team maintaining and operating the IDC application software to generate and distribute products and services. Prior to that, he worked in the UK for 10 years on test-ban monitoring issues.

Dr. Matthias Zähringer is a physicist who joined the CTBTO in 2007 as the Senior Radionuclide Officer at the IDC. Prior to that, he worked at the German Federal Office for Radiation Protection mainly on issues of environmental radioactivity monitoring and emergency preparedness. ■