National Missile Defense:
When computers make the impossible become reality?

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Abstract

Following a brief historical overview of the lifetime and efficiency of defense systems, the objective of the National Missile Defensive System (NMD) to destroy a small number of attacking warheads by direct kill or nearby explosion will be described. The engagement can be attempted in the boost, post-boost-, midcourse, or re-entry phase. The trajectory of the enemy's warhead has to be determined in real time with detectors based on classical optics, radar, and heat-sensing or laser devices, mostly used in combination. The small size and high speed of the warhead calls for successive precision measurement of its spatial coordinates in extremely short time intervals, an analysis of the data by fast computers, which in turn has to be communicated to the kill vehicle for re-adjustment of its trajectory. The aggressor can choose the date, place and time of launch. In addition he has a great variety of countermeasures at his disposal. Their technologies are common knowledge and inexpensive as compared with the cost of the ballistic missile. An incomplete list contains launching decoys immediately after the boost-phase, jamming the radar, cooling and painting the warhead, changing the mid-course trajectory by thrusters, letting the warhead tumble, increasing the number of warheads attacking at the same time, and interfering with the defender's communication devices or computer center. It can be concluded that NMD will never function as advertised.

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The full text is also available from Time and Defense: The history of Defense Systems and Remarks on the National Missile Defense (NMD).

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What can be learned from High-Energy Physics (HEP) Experiments for the National Missile Defense (NMD)?

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The recording of elementary particles in HEP experiments with visual detectors (bubble chambers, multi-wire proportional chambers) and of (ballistic) missiles and their accompanying decoys for defense purposes (NMD) shows some similarities, but also many substantial differences. NMD entails more, variable and essentially unpredictable difficulties than HEP. Both face the initial and important challenge to determine trajectories with high precision. The purpose of HEP is to obtain new insight into elementary particles and to understand better the laws of nature, of NMD to fend off successfully a hostile attack by a small number of missiles.
In this Annex to the above mentioned papers special emphasis will be put on the inherent problems encountered in the evaluation of bubble chamber (BC) photographs, which means were available to solve them, and what can be learned from it for the immensely more difficult implementation of NMD.

1. Visual detectors in HEP

Most, if not all, challenges in HEP with BCs were addressed, led to solutions, and eventually to interesting, new physics results. Work over decades by a large number of dedicated people, under almost ideal experimental conditions, was the basis for this success.
Bubble chamber technology dates back to its invention by Donald Glaser in 1953 and remained a predominant experimental tool in HEP for almost forty years. About hundred bubble chambers have been built and used for physics experiments at particle accelerators all over the world.
BCs came in various shapes and volumes ranging from a few liters to about 40 cubic meters. More than hundred million stereo-photographs have been taken on film of 35-mm, 50-mm, to 70-mm width, typical photos having lengths between 5 and 10 centimeters, resolution of the photographic emulsion of ~3 micrometers. Total film

exposed in experiments is estimated to be in the range of ten thousand kilometers. Chambers were filled with a variety of liquids and operated at ambient and cryogenic temperatures. Of particular interest in the present context are those filled with liquid hydrogen, since its viscosity is comparable with the one of air.

Bubble tracks produced during the passage of ionizing particles were photographed in dark and bright field illumination. Interaction of particles with the liquid are recorded simultaneously with at least two, but mostly three or more stereo-cameras to allow for unambiguous reconstruction of their trajectories in space. Holographic recording techniques were used on a large scale in small chambers and successfully tried out in giant chambers.

Almost all bubble chambers were imbedded into a strong magnetic field. Electrical charged particles are bend according to the laws of electro-magnetism, positively charged particles in one, negatively charged in the opposite direction. The radius of curvature depends on the mass and speed of the particles and the strength of the magnetic field. All particles suffer energy loss going through matter, are being slowed down, and may even stop within the liquid volume.

Bubble chamber operating conditions were adjusted such that bubbles along the trajectory form an almost continuous string. Most particles traverse the liquid very close to the velocity of light. The entire track is visible instantaneously. The arrival times and direction of the particle beam is known with high precision, synchronized with the chamber’s expansion cycle to produce the necessary superheated state of the liquid. Photographs are taken within a millisecond or less after injection of the beam when bubbles have grown to the required size for photography.

The chamber temperature can be adjusted with the help of heat exchangers in such a way that turbulence in the liquid is minimized and bubble density maximized.

Films are developed in the usual way. Then the photographs are being scanned for interesting aspects of tracks, such as kinks, multi-prongs, and sudden energy loss, etc. This first process can stretch over any period of time, sometimes over years, with one first, followed sometimes repeated scans. Interesting interactions of incoming charged (or neutral) particles are being measured with (semi-) automatic track following machines in all views to allow for their reconstruction in three-dimensional space. The immediate task is to find corresponding track images in the various views. This task is being helped by the fact, that invariably tracks have tiny distinguishing features, like delta electrons, or major interaction after a certain distance. The measurements are then fed into computer programs. Figs 1a, 1b, 1c show the same interaction of a neutrino with a nucleus as seen with three conventional cameras, fig. 1d the event vertex recorded on a hologram.

A large number of experiments were performed in neutrino beams. The neutrino is an electrical neutral weakly interacting particle, leaves itself no track in the BC, but produces after an interaction with a nucleus a bundle of charged particles. One of the main challenges in these experiments was to find out if events contained a m-meson, more or less interlocked with other particles (Fig. 2). This task can be compared with the goal to find the warhead amidst the cloud of surrounding decoys.

The results of the geometry program (reconstruction of trajectories in space) go then through a kinematics program. There the tracks are fitted by curves within the plane of the particle (circles, spirals, taking into account energy loss) to find out detailed

characteristics of the particles (mass, momentum, spin, etc.) and check for elastic scattering (kinks on the track). This physics evaluation may take from minutes to months for a single event. It may require re-measuring to eliminate errors of various origins (operator error on the measuring machine, overlooking of scattering, etc.).
The third stage consists of physics interpretation of the result, which has to satisfy among other criteria the two basic conservation laws of energy and momentum. Results are also often compared with simulation experiments (Monte Carlo programs) to check the compatibility with previous established theories or to explain deviations by new physics hypotheses.
A wealth of technical and experimental experience has been accumulated in BC construction,
BC operation and physics analysis, stretching from cryogenics, thermodynamics, optics, fast mechanics, superconductivity, data analysis, to computer programs with hitherto unknown complexity and size, limited only by the storage capacity of computer in this period. Much of the acquired knowledge found already application in many fields; last not least some of it may help to understand better the challenges of NMD.

2. Ballistic missiles and their intended intercept by NMD

As has been explained in detail in the text of the main paper, a distinction has to be made between the boost, pre-boost, mid-course and reentry phase of the missile. Here only the similarities between visual detection in HEP and the mid-course (several hundred kilometers over ground) in NMD will be described.
NMD has to follow a similar three-stage pattern as the above-described HEP experiments. They will be sketched in this section.

2.1 The launch detection

The first and probably most daunting task of the NMD is to find out if, when, from where and in which direction an adversary will or has already launched an attack with a missile. Obtaining this information will always encounter enormously large uncertainty. The time for detection, observation and making measurements on the path of the booster is limited to some 200 seconds and must be done from high altitude. Geo-stationary satellites at 36’000 kilometers altitude will not provide any sufficient accuracy on the further path of the missile.

2.2 The trajectories

The second stage in NMD is the determination of trajectories of the objects in mid-course (exo-atmospheric). Assuming the difficult first objective has been mastered to satisfaction, it is known that the missile and its decoys travel along trajectories, no longer affected by atmospheric drag, and only determined by the force of gravity

(Kepler's laws). The impact of this force is somewhat analogous to the magnetic field acting on high-speed particles in HEP experiments.

The objects are in a Keplerian (elliptical) orbit. To specify the plane of a ballistic trajectory requires two parameters, two more are required to select a unique ellipse, and a fifth parameter is needed to specify the orientation of the ellipse in the plane. A sixth parameter giving position along the ellipse which uniquely specify the trajectory. These geometry conditions can be formulated in a set of equations. A major task will be to estimate with sufficient accuracy the impact of measurement errors into the determination of the missile's trajectory. If the missile is equipped with a thruster, than it can change its course within or out of the plane (makes a kink similar to elastic scattering of a particle in the bubble chamber). After the deviation the whole process has to be started from anew, applying again the laws governed by the force of gravity. The similarities between the two tasks, HEP and NMD, stop already at this point.

The observation of the trajectories of the missile and its decoys will be done from detectors, installed on a number of fast-moving satellites on elliptical orbit. They have to be at a certain altitude and region to see the missile. Irrespective which detection method is used (optical, radar, infrared, etc.) at least two, better three or more, detectors have to record the missile "simultaneously" to reconstruct its actual position in space. Tracking has to be made by repeated observation within intervals as short as possible. This gives a sequence of separated points in space, which have to be attached to each other. A reconstruction of all trajectories should be possible in principle, but will hit enormous practical and computer problems, as being discussed in section 3.

2.3 The engagement and counter measures

The third task in NMD is to launch and guide the kill vehicle such as to find and destroy the incoming warhead by impact. This initially favored program ran into severe problems. Therefore, nearby explosion of small nuclear warheads are again under discussion to reduce the requirement for precision guidance of the kill vehicle.

A multitude of counter measures is available for the aggressor to interfere with the measurement, like jamming radar, cooling the warhead, deploying decoys, increase the number of attacking missiles, etc. They had been discussed in depth in the main paper and will not be repeated here.

3. New challenges for NMD

Low-altitude satellites carry the detector(s) and circle the Earth once within a few hours. They "see" the missile only for a short period of time. At least two "observers" have to be present in the right region of space to take an instantaneous recording. If they use radar, than the beam may switch across the missile once every ten seconds by moving around in a circle of 360°. During this time interval the missile typically traverses a distance of 70 kilometers.

Instead of obtaining a continuous trajectory like in bubble chambers observers see only points in space, like stars in the sky. To connect the correct points to form a continuous line is a tremendous task. The possible even more challenging undertaking is to find out the corresponding line from the other observing satellite(s). Only then reconstruction in space is possible and can follow. Whereas in bubble chambers all tracks have distinguishing features (like little delta electrons, kinks, etc.), the missile or the decoys leave behind no similar feature. All combinations of connecting lines between points for all “views” have to be tried out, an overwhelming task for the NMD computers.

3.1 The stereo basis

From bubble chamber experiments we learned the important lesson that reconstruction depends to a high degree on the mechanical stability and geometry of the stereo-base. Equally important are the knowledge of the direction of the optical axes, centering of camera lenses, lens aberration, their barrel distortion, temperature gradients in the optical assembly, variations of the refraction index of the liquid with temperature, turbulence, to name just the most important ones.

The optical constants in BC were determined first by putting test objects at well-defined places inside the empty chamber. Reference marks were fixed to the inside of the chamber vessel or the windows and their relative position measured by geodetic techniques. The test object was reconstructed from the photos taken with all cameras. The process was repeated with liquid inside the chamber to determine the influence of its refractive index on the optical constants. In yearlong iterations of the geometry programs the precision of reconstruction could be improved to have accuracy of the order of 100 micrometers of space coordinates (typically bubble diameters of 500 micrometers) in volumes of some thirty cubic meters.

There is no rigid stereo basis in NMD. Most of the above mentioned parameters are subject to change in a discontinuous manner. They are only roughly known for NMD, introduce and add up possibly to big errors in position determination. There is no fixed reference system in space attached to the surface of our planet. The position of stars as reference system is not particularly helpful in the context of NMD.

3.2 Atmospheric turbulence

Optical conditions in bubble chambers could be optimized, which is not all the case as a remedy when recording spatial coordinates of missiles. Observation of missile launches and follow-up measurements are required at all possible weather conditions if the NMD project should make any sense. The transparency of the atmosphere may not allow recording some parts or the entire trajectory. No satisfactory solution for this problem has been presented.

3.3 Identification of objects during the measurement of the trajectories

In bubble chambers the penetrating m-mesons could be identified with additional electronic detectors outside the chamber vessel behind absorbing shielding, whereas other particles were stopped by it. There is no corresponding identification technology for NMD and there is no chance to know a priori which object is the warhead. Presently, the only means available to the defense is to attach sophisticated sensors into the kill vehicle to do this job.

The conservation laws of energy and momentum are of no help for NMD. Neither the initial speed and direction of the attacking missile, nor its mass, or the duration of its boost-phase are known with any sort of accuracy that would permit prediction about its future flight path or intended target.

3.4 Precision of measurement

The following order of magnitude comparison between NMD and HEP with BCs, regarding the required precision, is very preliminary. A warhead has a conical shape, is about 2 meters long and has on the bottom a 70 centimeters diameter. It could be approximated by a sphere of about 1-meter diameter, compared to the 500 micrometer of a bubble in the FNAL chamber. The warhead has a speed of 7 kilometers per second, might fly at an altitude between 100 and 400 kilometers. Assuming detection by radar every 10 seconds, the volume to be observed is about 1 million cubic meters. When taking these values as a start, a back-of-the-envelope calculation can be made. The comparison shows that the required precision of NMD has to be better right away by several orders of magnitude than the one obtained after years of dedicated research in HEP.

3.5 The time factor

As mentioned in section 1, there is no time pressure on the experimenter in HEP other than to be first in the detection of a new elementary particle or a new law of physics. The situation for NMD is dramatically different. The entire defense system can never be tested under real operating conditions, but is intended to work the first time. Any miscalculation, misinterpretation, or computer bug may lead to complete failure and enormous loss of human life.

3.6 The size of computer programs

In the framework of the Space Defense Initiative (SDI) estimates had been made about the size of computer programs. They led to some twenty million lines, to be written by a large group of computer specialists. NMD may even become more demanding for the software.

Experience in BCs with considerably smaller sized programs (size for optical constants about 5’000, for kinematics more than 10’000 instructions) showed, that they invariably never worked during their first application. It is estimated that some 20 to 30 physicists/programmers worked more than 50 percent of their time on it, and more than 100 physicists/programmers with less than 50 percent.

Programming technology and size (some hundred thousand instructions) for recent and planned colliding beams experiments in HEP come closer to the demands of NMD.

3.7 Security and reliability aspects of computer and programs

The sheer size of the computer programs in NMD requires a large number of software programmers, who work efficiently together. They have all to go through security clearance, since “terrorists” may incorporate into a (sub) program deliberately bugs that are hardly detected by any routine program.

Computers installed on satellites need to have a long reliable lifetime. Components should be radiation hardened to withstand over an extended time period exposure by cosmic radiation.

These requirements play a subordinate role for HEP experiments.

4. Conclusion

This Annex is intended to reinforce the arguments put forward in the main article. There is some hope that the presentation of visual recordings, obtained with detectors like bubble chambers, will have more impact upon a scientifically less-educated public and its decision to go ahead with NMD than any theoretical papers. It may encourage people to scrutinize press information, which report about successes of NMD tests. These tests have almost nothing in common with the realities.

The promoters of NMD have recently decided to classify further test information, arguing that the aggressor may learn to overcome the defense. The interpretation of this action is left to the reader.

5. Figure Captions

Figs.1a, 1b, 1c Photos taken simultaneously with three cameras of a neutrino interaction in the Fermi National Accelerator Laboratory (FNAL) 15-Foot Bubble Chamber, filled with a neon/hydrogen mixture. They were taken in bright field illumination. The chamber was exposed to a neutrino wide-band beam produced by 900 GeV/c protons on the production target (Experiment E-632). The neutrino enters from the bottom of the photo and leaves no bubble track since it is a neutral particle. The three views demonstrate the challenge to find corresponding tracks in the three views for geometrical reconstruction of the trajectories of the particles in space. To compare with trajectory of a ballistic missile, consider only those tracks which turn to the right, or the left, but not both!

Fig. 1d is the replay of the hologram of a small section around its event vertex, taken with a modified in-line technique. Holography calls for very advanced optical arrangement and mechanical stability, which will not be obtainable within NMD.

Fig. 2 Photo from experiment E-532, with some twenty particles produced by a neutrino interaction. It demonstrates the difficulty to proof that the interaction contains or not a m-meson and to identify it unambiguously. It shows some similarity with the task of finding the warhead in a spray of decoys.

Fig. 3 Photo taken in the CERN 2-m hydrogen bubble chamber exposed to a charged particle beam. The p-meson enters from the bottom of the picture. It has a first interaction at point A, producing three new particles and has a small kink. A second interaction occurs at point B. This BC event has similarities with NMD, when the trajectory in the boost phase can be well measured. The post-boost phase requires complete reassessment of the trajectory, after point A, and again after point B. A complete follow-up and reexamination is necessary when all “decoys” are released.