MSc Program
Environmental Technology & International Affairs

A Synergetic Analysis of Verification Technologies of I.A.E.A and C.T.B.T.O for Nuclear Non-Proliferation and Security

A Master's Thesis submitted for the degree of
"Master of Science"

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Vienna, June 2016

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Affidavit

I, **PUSHKAL CHHAPARWAL**, hereby declare

1. that I am the sole author of the present Master's Thesis, "A SYNERGETIC ANALYSIS OF VERIFICATION TECHNOLOGIES OF I.A.E.A AND C.T.B.T.O FOR NUCLEAR NON PROLIFERATION AND SECURITY", 82 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
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ABSTRACT

The existence of nuclear weapons and the risk of proliferation of nuclear weapons poses a big threat to the world. Aiming at nuclear non-proliferation, IAEA and CTBTO were established with separate verification regimes. This dissertation examines the role of the respective verification regimes of these organisations by understanding their working principles & parameters in order to identify and assess possible synergies between their verification technologies through case studies and analysis. It aims to answer critical questions on existing verification regime, current opposition to synergies, possible synergies in context of non-proliferation and feasibility studies of such synergies with their strengths & weakness.

The thesis offers a descriptive account of the organisational objectives, mandate and current technologies of the IAEA and CTBTO to develop a strong background for their synthesis. This study is significant because till date, no systematic investigation has considered developing a synergy model, as done in this thesis, in the form a combined dataset system aiming at a stronger, more accurate and efficient non-proliferation regime.

For arriving at the research strategy, in depth technical analysis of the currently employed methodologies was done to identify the key variables and parameters for synergising each technology between IAEA and CTBTO. Exhaustive analysis based on existing studies and models was performed to deduce the synergies via different cases and scenarios. The findings from the research illustrates on the potential synergies and the nature of nuclear activity based on the various parameters and values providing qualitative and quantitative analysis for the thesis. Empirical calculations are used to determine the net impact of the considered synergies.

While concluding the thesis, results, strengths and limitations of the study are discussed with clear focus on future research and recommendations considering the strong potential of an enhanced verification regime for nuclear non-proliferation and security.

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LIST OF ABBREVIATIONS

IAEA	International Atomic Energy Agency
CTBTO	Comprehensive Test Ban Treaty Organisation
NPT	Nuclear Non Proliferation Treaty
UN	United Nations
FAO	Food And Agriculture Organization
PTBT	Partial Nuclear Test-Ban Treaty
GSE	Group of Scientific Experts
CD	Conference on Disarmament
WMO	World Meteorological Organization
UNDP	United Nations Development Programme
PTS	Provisional Technical Secretariat
IMS	International Monitoring Systems
IDC	International Data Centre
ESA	Environment Sampling Analysis
TIMS	Thermal Ionization Mass Spectrometry
SIMS	Secondary Ion Mass Spectrometry
ICPMS	Inductively Coupled Plasma Mass Spectrometry
HESL	Hot Environmental Sample Laboratory
IDA	Isotopic Dilution Analysis
SEM	Scanning Electron Microscope
SIA	Satellite Imagery Analysis
SAR	Synthetic Aperture Radar

NDA	Non Destructive Analysis
SQ	Significant Quantity
IMCA	Inspector 2000 Multichannel Analyser
MMCA	Miniature Multichannel Analyser
MOX	Mixed Oxide Fuel
MGAU	Multi-Group Analysis for Uranium
ECGS	Electrically Cooled Germanium System
ISOCS	In Situ Object Counting System
CHEM	Cascade Header Enrichment Monitor
KEDG	K Edge Densitometer
HLNC	High Level Neutron Coincidence Counter
UWCC	Underwater Coincidence Counter
AWCC	Active Well Coincidence Counter
PSMC	Plutonium Scrap Multiplicity Counter
GCI	Global Communications Infrastructure
CBM	Confidence-building measures
RN	Radionuclide
ATM	Atmospheric Transport Modelling
SRS	Source Receptor Sensitivity
SEL	Standard Event List
REB	Reviewed Event Bulletin
SSEB	Standard Screened Event Bulletin
ARR	Automatic Radionuclide Report
DOB	Depth Of Burial
LWR	Light Water Reactor

ACKNOWLEDGEMENTS

For the completion of this Master Thesis I would to express my deepest appreciation and gratitude to my thesis supervisor **Dr. Kaluba Chitumbo** of **Technical University of Vienna** for his constant guidance, advice and encouragement. Dr. Chitumbo has an attitude and substance of a genius, he continually conveyed a spirit of supporting fresh and innovative ideas into the research and an excitement in regard to his teaching. Without his unwavering support, commitment and persistent help this academic dissertation would not have been possible.

I would also like to thank other professors and researchers at the Technical University of Vienna, Diplomatic Academy of Vienna and Vienna Center for Disarmament and Non Proliferation, especially **Professor Hans Puxbaum** and **Professor Paul Brunner** for their constant support, advice and encouragement, their motivation helped in improving the quality of research. I would also like to express my gratitude to **Mrs. Isabelle Starlinger**, our ETIA program manager for her dedication and constant instructions in support of successful thesis writing and submission.

Special thanks to my friends and colleagues at the Technical University of Vienna and Diplomatic Academy of Vienna specially **Ms. Maria Wirth** for their unwavering camaraderie, support and help. Friends and classmates from the ETIA program have been a pillar of support and to them I say “We might part now, but it’s only to meet again”.

I owe my deepest gratitude to my family for their unparalleled support and motivation throughout the ETIA program. I dedicate this thesis to my parents and my late grandfather who gave me the opportunity of pursuing this dynamic Master’s Program and more importantly, for being a constant source of strength, for always believing in me and boosting my morale during difficult times.

1. INTRODUCTION

1.1 OUTLINE OF THE THEME

The devastation and havoc unleashed by the sole use of nuclear weapons shocked the world and since then mankind has been resolute not to repeat such an incident so as to prevent further devastation. Although, the cold war ended 25 years back, the existence of thousands of nuclear weapons and the continuing threat still looms large globally. Although the likelihood of a nuclear war between the erstwhile superpowers United States and Russia may have decreased, but still the existence of large stockpiles of nuclear warheads makes their accidental or unauthorized use a big risk today.

This threat is even larger and more serious considering the risk proliferation of nuclear weapons poses to the world, more are the countries conducting nuclear tests and possessing weapons, higher are the chances of a nuclear war or illicit capture of weapons from terrorist organisations. Also, given the fact that if countries who are actively engaged in regional conflicts become rogue and get access to nuclear weapons technology, it can highly destabilize not just the specific countries but also the region and cause huge loss of human life and environment. (Nuclear Threat Initiative 2015).

Thus, it is imperative to take preventive measures to avert any such potential catastrophes and to ensure safety and security of people from nuclear weapons. With this objective, the International Atomic Energy Agency was founded in 1957 and has since become widely known for being the world's "Atoms for Peace" organization in the United Nations Organisations. Set up in 1957 as the global centre for cooperation in the nuclear field, it functions with its Member States and multiple partners globally to promote the safe, secure and peaceful use of nuclear technologies.

The Treaty for Non Proliferation of Nuclear weapons (NPT) was adopted and implemented in 1970 by the IAEA of the United Nations. It stressed and had its origins in the 1963 Treaty which sought to ban any form of nuclear test either on land, outer space or underwater. (IAEA 1970)

Through the NPT it was agreed that proliferation of nuclear weapons would increase the chances of a nuclear conflict and thus it called for a strong mechanism & framework in the IAEA aimed at preventing the spread of nuclear weapons although, without compromising the facilitation of the IAEA for the cooperation and development of peaceful nuclear activities. (IAEA 1970). The IAEA has since utilised and updated the various verification technologies for keeping its mandate.

The Comprehensive Test Ban Treaty Organisation (CTBTO) had a similar beginning which led to its foundation. Although there were initial attempts in the 1950's & 1960's under the 'Atoms for Peace' program calling for a ban of all kinds of nuclear tests, the cold war impeded the process. Post-cold war, there was renewed enthusiasm for negotiating CTBT. After years of negotiating and following the 1995 NPT review conference, the CTBT was finally adopted in September, 1996. (CTBTO 2012a).

The CTBTO has a different framework and mechanism for verification as compared to the IAEA, and has its own monitoring and data collection facilities which shall be elaborated in the thesis. From their mandates, the NPT treaty of the IAEA seeks to primarily limit the vertical proliferation by limiting the growth of nuclear weapons by state, while the CTBTO primarily aims at limiting the horizontal proliferation by seeking an end to all forms of nuclear testing thus restricting the development of a nuclear weapon by states.

Also, another temporary limitation is that CTBTO is a preparatory commission and has yet not entered into force and can only make its assessments using the verification mechanisms and data centres only after a nuclear test has occurred. However, IAEA is a recognized and active organisation which has the power and mandate to make precautionary checks and inspections on the facilities of the member states which it may suspect are diverting to development of a nuclear weapons program. Thus, in the context of disarmament & from the nature of the mandate and the authority, IAEA is a 'proactive' organisation while CTBTO is a 'reactive' one.

Considering the stated threats emerging from nuclear proliferation, there is a strong need for a solid and robust non-proliferation mechanism which prevents states from developing this technology and eases the early detection of nuclear weapons tests. Thus, apart from non-proliferation, even those states that have violated their IAEA mandated nuclear safeguards commitments and are suspected of covertly pursuing nuclear weapons capabilities can be identified at an earlier stage so that necessary action can be taken on them. However, despite such unique verification mechanisms, both the IAEA and CTBTO have one common mandate: Nuclear Non Proliferation.

But, till date, there exists no continuous & uniform synergy between the verification mechanisms of these two organisations. The reasons for lack of such a synergy are political but once the positive potential of such a synergy is realised, it can significantly boost the effective capacity of both organisations for fulfilling their mandates.

This void in synergy between the two organisations is what motivated me for writing the thesis through which I will aim to assess & evaluate the existing verification technologies in the two organisations and then consider a hypothesis where possibility of such a synergy exists and then analyse and investigate as to how to achieve such a synergy between these two organisations thus seeking enhanced nuclear non-proliferation and security.

1.2 CENTRAL RESEARCH QUESTIONS & GOALS OF RESEARCH

Through this thesis, I wish to focus on and answer three critical questions:

-What does 'Verification Technologies' at the IAEA and CTBTO mean?

-What are 'Synergies' in the context of non-proliferation and nuclear security?

-Roadmap to maximum benefits of these synergies with its feasibility?

An Investigative Study to analyse and elaborate on the mandate, functioning, various contemporary detection and verification technologies existing in the IAEA and CTBTO for detecting nuclear explosions and proliferation activities by member state. It is a key step to understand these technologies from a technical perspective as only then the synergy between different technologies of the two organisations can be engineered.

This will be followed by forming the synergies depending on key common elements & compatibility in verification technologies of the two organisations. Aim is to synergise their technologies for developing an intelligent system thus studying the technicalities, hurdles and effects (political and scientific) of such a synergy for deriving an apt conclusion and assessing the feasibility and effectiveness of such a synergy regime for enhanced nuclear non-proliferation & security.

Thus, the goal of the research is to synergise and develop an intelligent dataset based system for which, this thesis shall encompass studying the mandate of the IAEA and CTBTO, analysing the verification mechanisms, synergising technologies in order to develop an intelligent system and platform via datasets which meshes information from both organisations creating an effective non-proliferation mechanism and study the feasibility effects. The goal of the research is not to criticise the current verification technologies of the IAEA and CTBTO which are undoubtedly, potent, sound and credible, but to investigate & analyse a synergy between their verification mechanisms and the potential positive effects it can have on strengthening the global non-proliferation regime.

1.3 INTERNATIONAL ATOMIC ENERGY AGENCY

The IAEA was formed in the year 1957 as a result of the deep fears and expectations emanating from the misuse and proliferation of nuclear energy for military purposes. Its work & function are uniquely aligned to this controversial technology which can be used both as a military weapon and as a useful tool for human development and amenities. The Agency's foundation idea was laid by former US President Eisenhower's 'Atoms for Peace' address to the General Assembly of the United Nations in New York on 8th December 1953. These ideas helped to form & elaborate the IAEA Statute, which 81 nations unanimously approved in October 1956. The work and scope of the agency grew in years and as of 2016, there are 168 member states of the IAEA. (IAEA 2014a)

In its statute, IAEA clearly states that it *"shall seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world. It shall ensure, so far as it is able, that assistance provided by it or at its request or under its supervision or control is not used in such a way as to further any military purpose."* (IAEA 1956)

Some of the key functions which are highlighted in the statute of the IAEA are:

- To encourage and assist the member states for research and development on practical application of nuclear energy for peaceful uses; and, if needed to do so, the agency should make provisions to act as an intermediary for the purposes of insuring the performance of services and the supplying of equipment & facilities by one member state of the Agency for another in order to perform any operation or service useful in research or development of nuclear energy for peaceful purposes including the production of electric power, with due importance & consideration to be given for the needs of the under-developed areas of the world. (IAEA 1956)

- To foster and encourage the exchange of scientific and technical information & training and capacity building of scientists and experts on peaceful uses of nuclear energy. (IAEA 1956)

- To create and administer nuclear safeguards that are designed to ensure that special fissionable and other nuclear equipment, services , information & facilities are made accessible by the Agency at its request or under its supervision and ensuring that they are not used in such a way as to further any military program and purpose; and to apply the safeguards, at the request of the other member parties, to any bilateral or multilateral arrangement of which the party is a member, or at the request of a State, to any of that State's activities, facilities and infrastructure in the field of nuclear energy. (IAEA 1956)

- To give the authority to the agency to acquire or establish any facilities and equipment which may be helpful in carrying out agency's authorized mandate & functions, whenever the facilities and equipment otherwise available to it in the area concerned are not adequate or available only on terms which the agency may deems unsatisfactory & incomplete. (IAEA 1956)

- To create and adopt in consultation and collaboration with the relevant functioning organs of the United Nations and with other recognized specialist agencies concerned with respect to the safety standards for protection of human health and minimization of danger to life and property, and to call & provide for the application of these standards to its own operations as well as to the operations making use of the services, equipment & facilities, and information made available by the Agency, at its request or under its supervision. It also calls to provide for the application of these standards, at the request of the member parties of IAEA to operations in the declared facilities under any bilateral or multilateral arrangements or at the request of another State with respect to another State's activities in the field of nuclear energy. (IAEA 1956)

There also is a code of conduct which the agency shall adhere to while carrying out its operations:

- It should conduct its activities in accordance and with the spirit of the purpose and principles of the United Nations to promote peace and international co-operation, and in abidance with policies of the United Nations encouraging the establishment of safeguarded worldwide nuclear disarmament and in conformity with any other international agreements aimed at pursuing such goals. It shall also establish authority over the use of special fissionable materials received by the Agency, in order to ensure that these materials are safeguarded and are used only for peaceful purposes. (IAEA 1956)

- Concerning its yearly activities and objectives accomplished, the agency should submit reports annually to the General Assembly of the United Nations and, when appropriate, to the United Nations Security Council, if related to its activities, should there be any questions within the competence of the Security Council, the Agency then should notify the Security Council, considering its authority and recognizing it as an organ bearing the main responsibility for the maintenance of international peace and security, and may also take the measures open to it under the Statute present under article XII. It should also submit reports to the Economic and Social Council and other organs of the United Nations on matters of relevance to these organs. (IAEA 1956)

- In carrying out its role & functions, the Agency shall not make assistance to members subject to any political, economic, military, or other conditions that may be incompatible with the provisions of the IAEA Statute. The activities of the Agency shall be carried out honouring the sovereign rights of States Subject to the provisions of the IAEA Statute and to the terms of agreements concluded between a State or a group of States and the Agency according to the provisions of the Statute. (IAEA 1956)

The statute also elaborates on nuclear safeguards with respect to any project, arrangement or activity of the IAEA where it is requested by member states for applying the safeguards the agency shall have certain responsibilities & rights which forms the core of the non-proliferation mechanism of the IAEA in article XII. Some of such key responsibilities are:

- The right to assess & analyse the design of specialized equipment and facilities related to nuclear reactors & nuclear reactors itself, to ensure that the program is not diverted to a military purpose and it complies with applicable health and safety standards as required by the agency. It also requires states to maintain and produce operating records of the facilities and the equipment to assist in nuclear accounting of the source and fissionable materials being used and also the right to call for the inspection of such reports. (IAEA 1956)

- The right to approve the methods to be applied for the chemical processing of irradiated materials mainly to ensure that this chemical process will not lead to diversion of material for usage for military purposes and will comply with the relevant safety standards of the; to require the special fissionable materials which are produced or recovered as a by-product of during use be only utilised for peaceful purposes including for research reactors and deposition of any other fissionable material recovered as a by-product in order to prevent its stockpiling provided that such materials collected by the agency should be returned to the respective member state on its request for specific use approved by the provisions of this statute. (IAEA 1956)

- The staff of inspectors shall be established by the agency and they should have the task of examining all operations being conducted by the agency itself to make sure its adhering to the required health and safety standards decreed by it for the application of projects subject to its approval and control and to ensure that appropriate measures are being taken to prevent the misuse of the source and fissionable material under its scrutiny or produced under its operations for military purposes. Following the assessments, if needed, the agency may take curative actions to correct any noncompliance. (IAEA 1956)

- To send inspectors into the territory of the member states, after its consultation with the states concerned to whom there shall be access to all data, places and persons relevant to the nuclear materials, facilities and the equipment for the purpose of safeguarding and to account for the fissionable materials and products and to determine the compliance against diversion of material for military purposes and to check compliance with the health and safety standard of the agency. And with any other conditions in agreement which exists between the inspected state/concerned state and the agency and can at the request of the inspected state be accompanied by representatives of the authorities of the state concerned given that they don't impede the inspections and assessment functions of the agency inspectors. (IAEA 1956)

- In the event a recipient state fails to comply to take the necessary required steps as mentioned by the agency for correction within the stipulated time, the IAEA has the right to suspend and terminate assistance for any equipment and material given to it by the agency or one of its other members for the advancement of a project. (IAEA 1956)

- During inspections, the staff of inspectors also have the authority and responsibility of obtaining and checking the nuclear accounting of the recipient state/states as referred to earlier and also to ascertain whether there is compliance to the undertaking mentioned in article XI of the statute and with all the other compliance conditions which have been described and elaborated in the agreement of the project between the concerned state/states and the IAEA. In case of any such noncompliance, the inspectors shall report it directly to the Director General of the agency who shall transmit the report of inspection and noncompliance to the Board of the Governors of the agency which, shall call on the recipient state for curative measures to remedy the noncompliance which has occurred from the inspection report. The noncompliance report will also be shared with all the members of the United Nations General Assembly and Security Council. (IAEA 1956)

- In the case of failure on part of the recipient state to implement the suggested corrective measures by the agency in the stipulated time, the board may take one or multiple actions like: direct suspension of any project, equipment assistance provided by either the agency or one of its other member states, return of materials & equipment which were supplied to the recipient state and the agency may even, according to article XIX of the statute, curtail or suspend the rights and privileges of agency membership of the noncomplying member. (IAEA 1956)

For this thesis, another important facet crucial for consideration is the legal aspect of the interaction of the IAEA with other agencies in context of its mandate, this has been elaborated in the article XVI of statute of the IAEA.

- Following the approval of the General Conference of the IAEA, the Board of Governors is allowed to enter and sign into agreement/agreements establishing a suitable relationship between the IAEA and the other United Nations body or any other organisation whose work is closely aligned with that of the agency. Such an agreement between the agency and the United Nations or other body should provide for the submission of reports by the agency as required and mentioned under article III of the statute. (IAEA 1956)

- IAEA’s consideration of resolutions adopted to it in the General Assembly or other councils of the United Nations which relates to its work and when requested, the submission of reports to the appropriate body of United Nations regarding the steps taken by the member states of the agency or the agency itself with respect to the statute resulting from such a consideration of cooperation with the other body. (IAEA 1956)

Before we talk about the various verification mechanisms of the IAEA, it is important to understand the functioning structure and the hierarchy of the agency. The IAEA is headed by the Director General, and under him are seven departments, the table below shows the entire hierarchy of the IAEA departments along with its sub-departments explaining the organisational structure of the organisation:

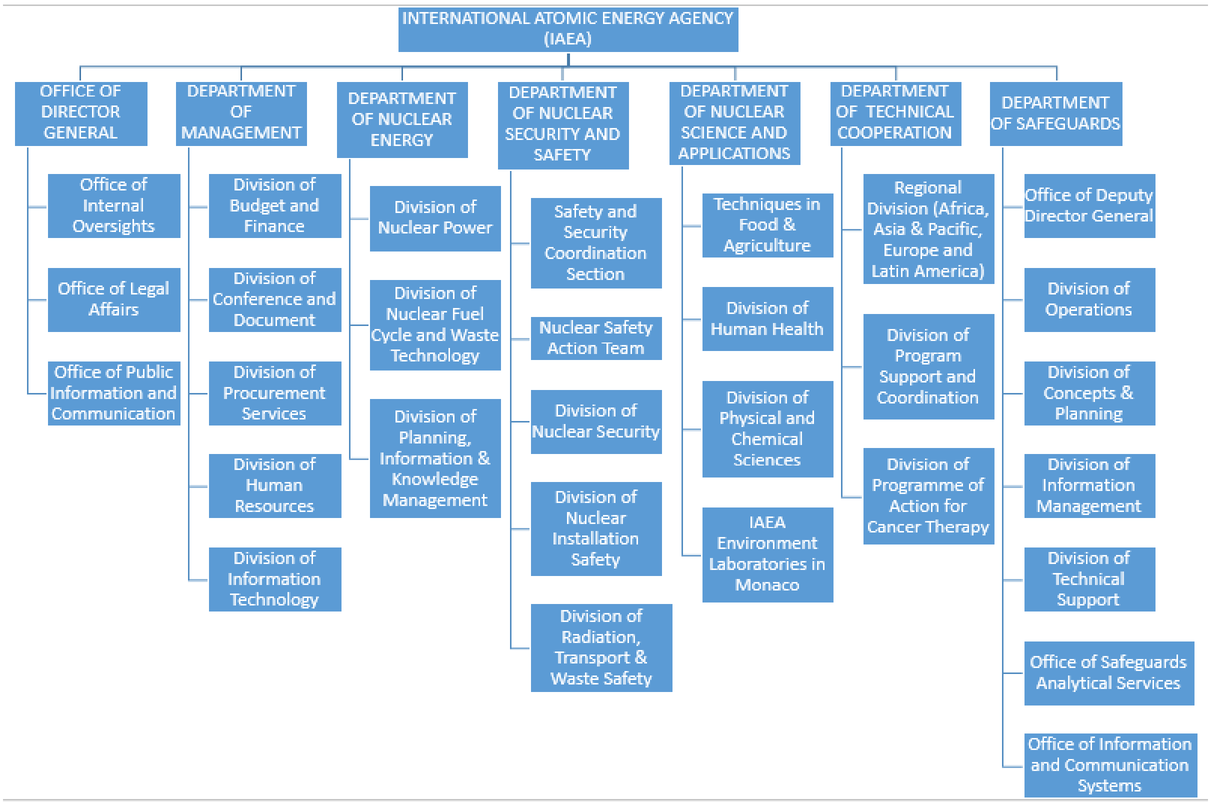

Figure 1.3.1: Organisational Structure of the IAEA with all departments

(Source: Self)

- **Director General's Office for Coordination**: This office is responsible for a number of functions crucial to support the Director General's performance of activities which includes external relations with member states and stakeholders, overall coordination of policy, coordinating activities of all the offices in Geneva and New York which arbitrate with the UN and its agencies & policy planning. The objectives of the Policy Making Secretariat is to enable the organs responsible for policy making, mainly the Board of Governors and the General Conference to perform their stated legal responsibilities and functions to ensure the all meetings are conducted efficiently. (IAEA 2014b)

- **Department of Management**: The department of management deals with the budgetary, financial, human resources, procurement and managerial services of the agency. It is further divided into six divisions: **Division of Budget and Finance** which seeks to deliver services in support of programme budgeting, payments and accounting and is responsible for management of financial information system of the agency; **Division of General Services** which provides service functions like facilities management, travel and transport support, archives and records management; **Division of Conference and Document Services** which facilitates the effective exchange and distribution of information between the agency Secretariat and Member States; **Division of Procurement Services** whose primary aim is to procure the goods and services required in support of the IAEA's mandate; **Division of Human Resources**.**; Division of Information Technology**. (IAEA 2014c)

- **Department of Nuclear Energy:** Is responsible for the advancement of efficient and safe use of nuclear power done by backing and encouraging existing and new nuclear power programmes around the world, catalysing the development of indigenous capability for energy planning & innovation in nuclear facilities and fuel cycles, analysis & dissemination of nuclear information and knowledge. It also advises member states on nuclear fuel cycles and nuclear power. It also engages in capacity building for energy planning & analysis and significantly considers the role of nuclear power for sustainable development. (IAEA 2015)

- **Department of Nuclear Safety and Security:** It develops and implements the agency's nuclear safety and security program and is further divided into five divisions: **Safety and Security Coordination Section** which aims to ensure the technical consistency and coordination between the agency's activities under radiation, transport & nuclear waste safety and security programs; **Nuclear Safety Action Team** objective is to supervise the swift implementation of the IAEA action Plan on Nuclear; **Division of Nuclear Security** which is responsible for implementing and aligning the agency's program on nuclear security for protection, detection and response to nuclear terrorism or criminal; **Division of Nuclear Installation Safety** aims to accomplish and maintain a high level of safety for the nuclear installations worldwide that are either under design, construction or in operation ;**Division of Radiation, Transport and Waste Safety** engages in formulating and maintaining radioactive waste safety, radiation protection and radioactive material transport safety standards. (IAEA 2014d)

- **Department of Nuclear Sciences and Applications:** It consists of four divisions: **Joint FAO/IAEA Division of Nuclear Techniques in Food and Agriculture** focuses on assisting member countries of the Food and Agriculture Organization (FAO) and IAEA to utilize nuclear technologies & biotechnologies for sustainable food security development; **Division of Human Health** engages in disseminating, developing and evaluating nuclear based technologies for public health application programs of the member states; **Division of Physical and Chemical Sciences** holds responsibility for implementing the activities on their needs for research and development in isotope hydrology & geochemistry and industrial applications of radiative isotopes; **IAEA Environment Laboratories in Monaco** whose main objectives are to provide assistance for proper usage of nuclear and isotopic techniques to give better understanding of marine pollution transfers and help them protecting the marine environment by improving their monitoring and assessment capability. (IAEA 2014e)

- **Department of Technical Cooperation:** It consists of three divisions and this department provides strategic direction for the agency's program of technical cooperation and with close collaboration with member states is responsible for all stages of the program from planning till implementation which is in accordance with the Medium Term Strategy of the IAEA. Section of Program Support and Coordination is responsible for improving the quality and transparency in the design, delivery and monitoring of programme via timely, accurate and effective support services. (IAEA 2014f)

- **Department of Safeguards:** Department of Safeguards is an essential component of the international security system whose primary function is the deterrence of proliferation of nuclear weapons which it does by basically two main ways: ability to detect misuse or diversion of nuclear material & technology meant for peaceful purposes through technical measures known as 'safeguards' and building international confidence by assuring that the member states are honouring the safeguards agreement and their international obligations. Its work is further divided into seven sub-divisions: **Office of the Deputy Director General:** it's accountable for the overall supervision of the operations, project implementation, planning, budget communicating with states etc.

Divisions of Operations: Divided into geographical divisions verifying safeguard agreements in those areas. **Division of Concepts and Planning:** Division is responsible for carrying out strategic planning and research coordination for developmental activities & Member State Support management. **Division of Information Management:** It is accountable for development and the operation of specialised information and data processing analysts and reception, processing and analysis of data for declarations. **Division of Technical Support:** It is accountable for technical and scientific support to Operations division which includes testing, design, and installation of equipment among others. **Office of Safeguards Analytical Services:** It is accountable for the environmental swipes and nuclear material analysis, quality control of samples & cooperation with member state institutions & sample shipping logistics. **Office of Information and Communications Systems:** It is the hub for the development and maintenance of the information and communication technology systems and managing safeguards supporting infrastructure & services. (IAEA 2014g)

1.4 COMPREHENSIVE TEST BAN TREATY ORGANISATION

The foundation of the inception of the Comprehensive Test Ban Organisation (CTBTO) is more than six decades old, starting in 1954, nine years post the world‘s first nuclear explosion in 1945. It was in this year when the efforts to ban a nuclear explosion started. A ‘Standstill Agreement’ on nuclear testing was advocated, but the testing of high-yield thermonuclear weapon in the atmosphere by United States and Soviet Union was started during the 1950’s leading to international criticism which met with success for the nuclear test ban advocates as the Partial Nuclear Test-Ban Treaty (PTBT) was signed in 1963 banning nuclear tests in the atmosphere, under water and outer space but not underground, however, despite PTBT, there was surge in underground nuclear testing. (CTBTO 2012b)

Key impetus for a treaty banning nuclear explosion was given by the adoption of the Nuclear Non-Proliferation Treaty (NPT) in 1968, which laid down the basis for a global nuclear non-proliferation and disarmament regime and a comprehensive ban on nuclear testing featured in the preamble of the NPT. Although during 1970’s, joint research into monitoring technologies and data analysis for verification methods was conducted by Group of Scientific Experts (GSE), it was only in 1994 in Geneva that the Conference on Disarmament (CD), the United Nations’ disarmament body began formal negotiations on the CTBT lasting till 1996. Swift consensus was reached on verification regime however the binding time plan was stuck in limbo, ultimately, the treat was introduced and adopted in the U.N. General Assembly on 10 September 1996. (CTBTO 2012b)

With it being open for signature in 1996, CTBT became the de-facto international norm on nuclear testing ban. Post the adoption, the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) was created, with a mandate for establishment of the verification regime of the CTBT; which stands at 337 monitoring facilities today; and promotion for signatures and ratification. The key provision of the CTBT for its entry into force is the signature and ratification of all the 44 Annex 2 states, which had nuclear power or research reactors during the time of the initial negotiations. (CTBTO 2012b)

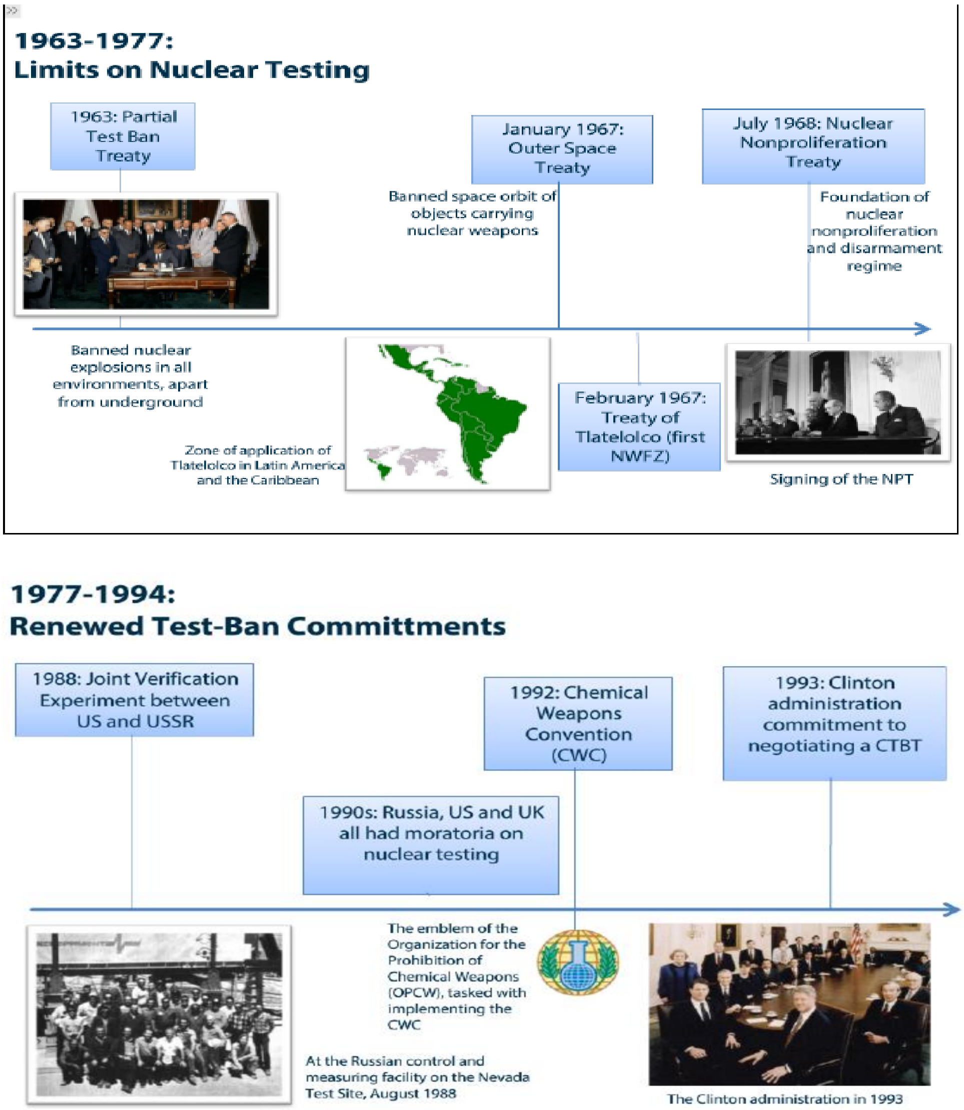

Figure 1.4.1: Timeline of the CTBT Negotiation (Source: CTBTO 2012l)

CTBT, which aims at banning all kinds of nuclear explosions in the world functions on the basis of the preamble, which contains seventeen articles, two annexes and a Protocol with two annexes. The key summarised articles are discussed below:

- Article 1: Which states the basic obligations of the treat, prohibiting state parties from carrying out and encouraging participation in any nuclear explosion. (CTBTO 2012c)
- Article 2: It furnishes the establishment of the CTBTO in Vienna for ensuring the implementation of the treaty and providing a forum for cooperation. (CTBTO 2012c)
- Article 4: It expands on the global verification regime and the framework for monitoring the compliance with the treat obligations. (CTBTO 2012c)
- Article 5: It elaborates on the redressal measures to resolve a situation which infringes on the provisions on the CTBTO in order to maintain the compliance with the treaty. (CTBTO 2012c)
- Article 15: It elaborates on the entry into force of the treaty which is scheduled to take place 180 days post the ratification of all the 44 Annex countries.
- Protocol I: It describes the functioning of the two main elements of the CTBTO verification mechanism-International Monitoring System (IMS) and the International Data Centre (IDC). (CTBTO 2012c)
- Annex 2: It is the most important element and annexure in the preamble of the CTBTO which lists the 44 countries belonging under this annexure whose signature is needed for the CTBT to come into force. (CTBTO 2012c)

As an international organisation, the Preparatory commission is financed by the CTBT States Signatories. The commission has a strong focus on technicalities and is based on cost effective and result oriented methods with more than 75% of the budget earmarked for the global verification regime establishment. (CTBTO 2012d)

Legally speaking, the CTBTO was granted a standing as an international organisation by the resolution through which it was established and was given the appropriate legal authority including the verification regime functioning and its provisional operation.

It also has the authority to negotiate and into international agreements with other international organisations. Although it had a relationship agreement with the UN in 2000 and follows the UN system for international civil service, the CTBTO is not a part of the UN system. (CTBTO 2012d)

The relationship agreement with the UN is however advantageous as this cooperation facilitates the Commission’s duty of carrying the necessary prerequisites for effective treaty implementation including the extensive verification regime. It also allows reciprocal exchange of information, knowledge and attending meetings of each other’s organisation thus eliminating the germination of the common services like conference, translation services etc. (CTBTO 2012d)

The Secretary-General of the UN is the chief depositary of the CTBT, states ratifying the treaty need to deposit their instrument of ratification with the Secretary-General of the UN through which status of the treaty will be officially notified. Thus, the treaty is open for signature at the United Nations headquarters in New York City. Secretary General has the obligation under article XV of the CTBT to call a meeting of the ratified members of the treaty upon their request to study and decide measures needed to be taken for speeding up the process of ratification of the treaty to bring its entry into force. Apart from the United Nations, the CTBTO has completed agreements with the World Meteorological Organization (WMO), United Nations Development Programme (UNDP), and European Centre for Medium-Range Weather Forecast (ECMWF) among others for knowledge sharing and common applications. Thus, the Preparatory Commission of the CTBT has achieved the standing as an international organization and holds the power to enter into international agreements with other legal organisations. (CTBTO 2012d)

When the CTBTO being set up in Vienna, enters into force, there would be several important organisational changes like Comprehensive Nuclear-Test-Ban Treaty Organization will replace the Preparatory Commission, Director General will replace the incumbent Executive Secretary and most importantly, working and effectiveness of the organisation will be assessed every 10 years from the year of ratification through a review conference. (CTBTO 2012e)

THE CTBTO AT A GLANCE

Executive Secretary:	**Lassina Zerbo (Burkina Faso)**
Chairperson:	**HE Cristian Istrate (Romania)**
Chairperson on Administration:	**HE Aliyar Lebbe Abdul Azeez (Sri Lanka)**
Chairperson on Verification:	**Joachim Schulze (Germany)**
Chairperson, Advisory Group:	**Sir Michael Weston (United Kingdom)**
Staff:	**Some 260 multi-disciplinary professional and support staff from more than 70 State Signatories**
2016 Budget:	**US$128.120.000**
Treaty State Signatories:	**183**

Figure 1.4.2: Key details of the CTBTO as of Jan 2016 (Source: CTBTO 2012f)

To understand the various verification mechanisms used by the CTBTO, it is important to understand the hierarchy, functioning & organisation structure of the preparatory commission. Shown below is the table showing the visual illustration of the organisation structure of the CTBTO.

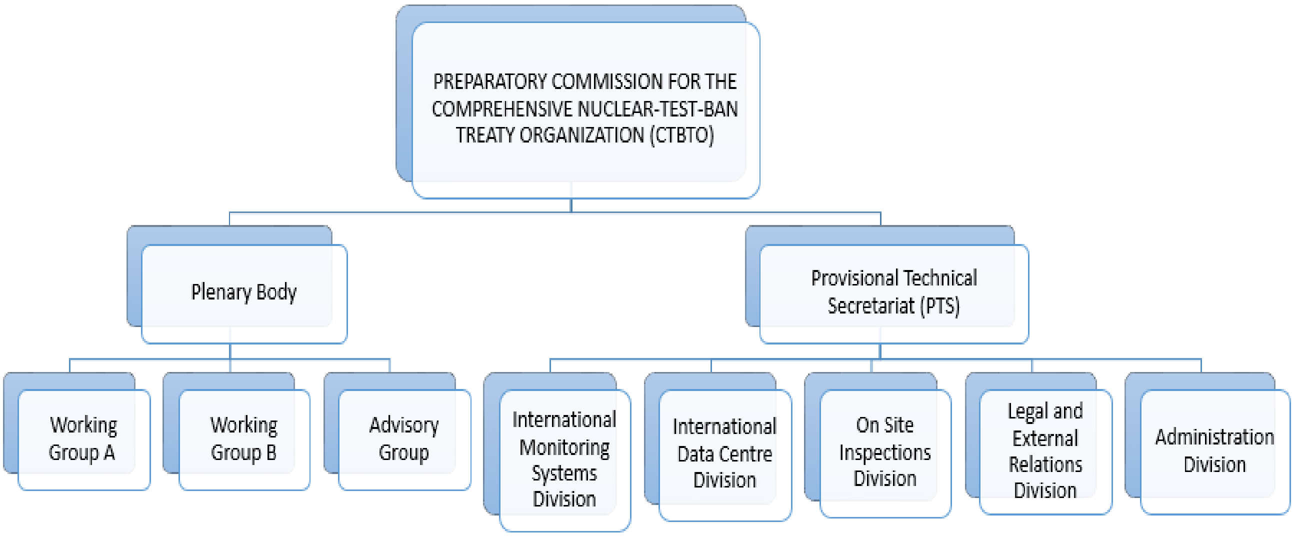

Figure 1.4.3: Organisation Structure of the Preparatory Commission (Source: Self)

The CTBTO commission consists of two main divisions: A Plenary body consisting of all the signatory member states, it is also known as Preparatory Commission, the body contains three groups which assists it for its working.

The CTBTO commission consists of two main divisions: A Plenary body consisting of all the signatory member states, it is also known as Preparatory Commission, the body contains three groups which assists it for its working.

- **Working Group A**: It concerns with administrative and budgetary issues for example the staff regulations, financial and legal rules and annual budget.
- **Working Group B**: It deals with all the matters related to the verification processes including the examination of the verification regime.
- **Advisory Group**: It proposes and advises the preparatory commission and the subordinate bodies on budgetary and administrative issues. It consists of experts belonging to the signatory states who are highly reputed and have rich experience in finance related matters at global level. (CTBTO 2012f)

The second important organ of the commission is the Provisional Technical Secretariat (PTS), assisting in implementing the duties and activities of the plenary body. The PTS is further divided into three main technical divisions:

- **International Monitoring Systems Division**: The IMS division consists of 337 monitoring facilities including seismic, infrasound, hydro acoustic and radionuclide monitoring facilities built in 89 countries worldwide in order to detect any form of nuclear explosion on Earth. (CTBTO 2012g)
- **International Data Centre**: The IDC complements the IMS by analysing and processing the incoming data from the monitoring stations worldwide to produces data bulletins that are submitted to the Member States for their evaluation and decision making (CTBTO 2012g)
- **On Site Inspection**: The final technical division of the PTS is the OSI. After the analysis of the data bulletins by member states, they make ask for an OSI to investigate whether a state has indeed conducted nuclear explosion or not. The purpose of these inspections is to ascertain the violation of the CTBT and to collect facts that can help identify the violators. It is the final stone of the verification regime and is only applicable once the treaty is in force.

The PTS contains more departments within the mentioned divisions as shown below:

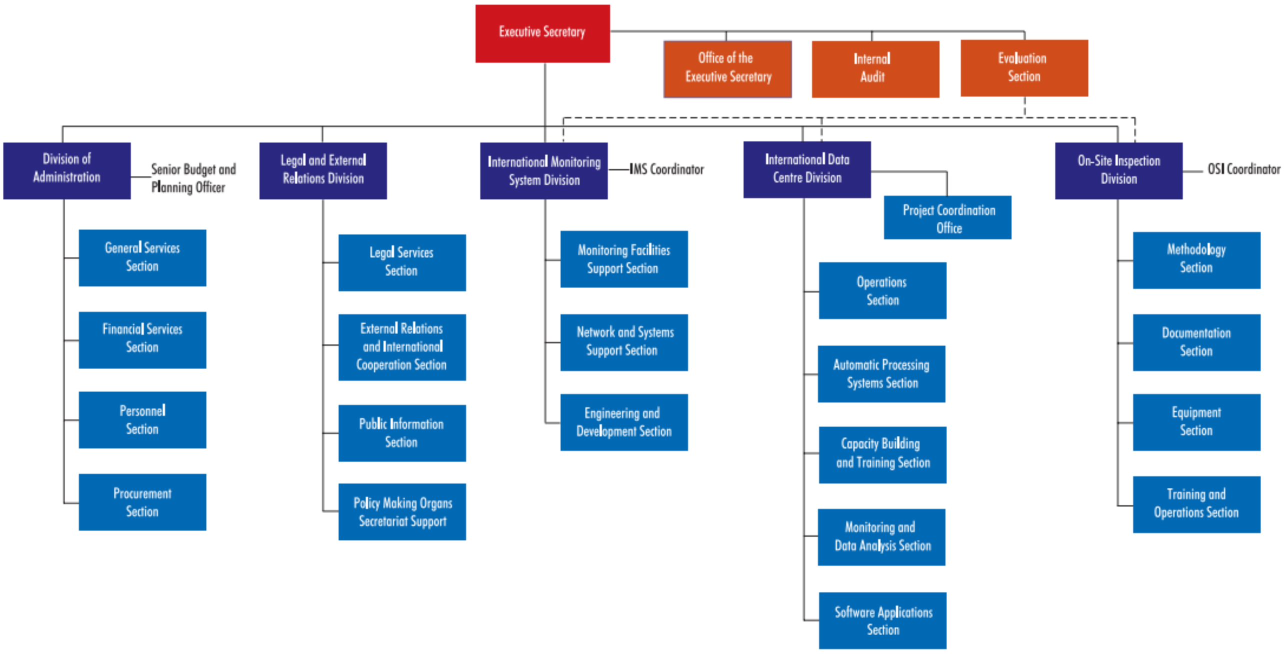

Figure 1.4.4: Elaborated structure of PTS (Source: CTBTO 2012m)

The technical divisions of the PTS mentioned above are supported by a Legal and External Relations Division and a Division of Administration. It is to be noted that CTBTO is chiefly funded by its member states, including the budget for its main verification regime. Apart from the above mentioned departments and duties of the PTS, another crucial role it plays is assisting the member states of the CTBT in special outreach activities like the ministerial meetings or the article XV conferences which aims at promoting the CTBTO's entry into force, furthermore, it also conducts number of capacity building workshops for the member states which helps in strengthening the verification regime. (CTBTO 2012f)

2. STATE OF THE ART

2.1 IAEA VERIFICATION TECHNOLOGIES FOR NON-PROLIFERATION

IAEA Safeguards are technologically approved measures that are utilized by the department of safeguards to monitor nuclear activities and materials so as to verify that the facilities are not being used for diversion from peaceful uses; it is done via safeguards agreement with the member states. Various verification technologies are used for ascertaining such facts. The fundamental process or flow of the safeguard implementation is as follows:

- Collection & Evaluation of Information
- Development of a particular safeguards approach for a member state
- Conducting in field activities and their subsequent planning and evaluation at laboratory and headquarters
- Deriving safeguards conclusions based on the analyzed facts

The processes described above vary from country to country and developed according to various parameters deemed important by the agency regarding the country for evaluation of the verification safeguards, the agency may access various sources of information including open media and third party sources for developing the safeguard approaches. Once the approach is drawn, the infield activities using the key verification technologies will be done. (IAEA 2016a)

The above processes are further illustrated in the flow diagram shown in the figure in the next page which clearly shows the process flow.

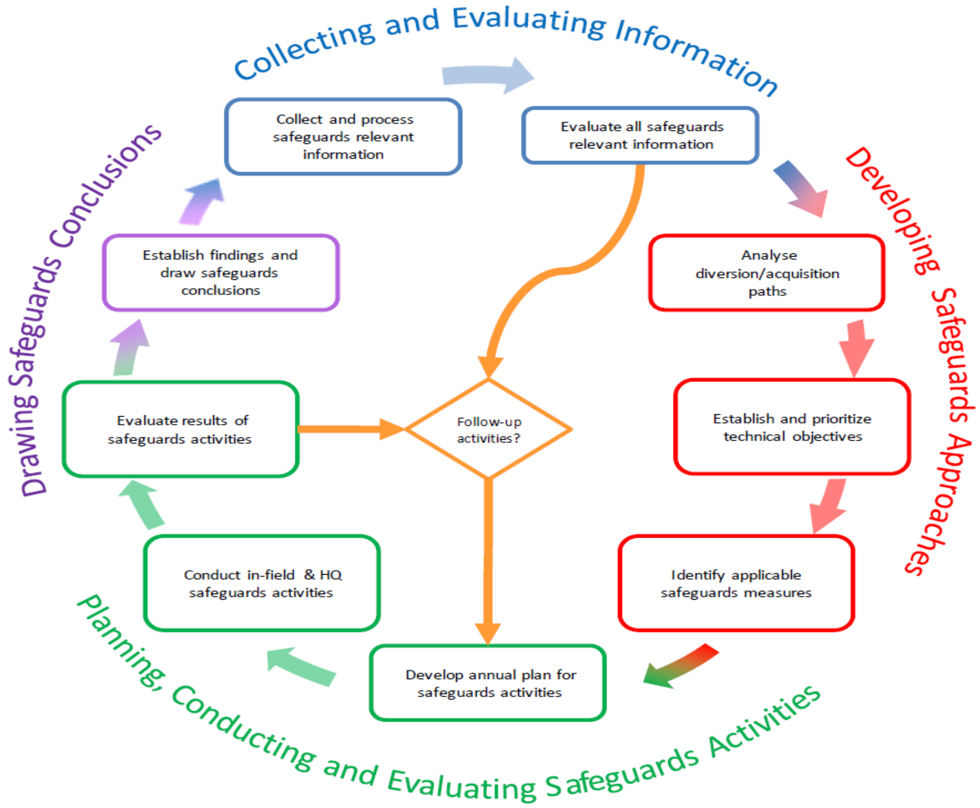

Figure 2.1.1: Main steps in IAEA Safeguards implementation (Source: IAEA 2016e)

The agency has mainly three sources for collecting and analyzing the safeguards related information about the member states: In field activities, nuclear material accounting & analysis at the headquarters of the IAEA; Open source media and third party sources of information; data and information provided by the state itself. The agency conducts such reviews for assessment of the consistency of information declared by a member state. Post such analysis, any deviations or anomalies found are identified and worked upon for correctness in a timely manner via meetings and consultations with the state. (IAEA 2016a)

A State Level safeguards approach (SLA) is created for safeguard verification for the member states on the basis of a structured & technical method to understand the logical path of acquisition of nuclear material for the use as a weapon or explosive device. On such an analysis, the technical process along with objectives and their planning is finalized which guides the process flow for verification, thus in scope of a member country's safeguard agreement, specific safeguard measures are realized. (IAEA 2016b)

In-field safeguards activities are of fundamental importance since they provide the agency with the information on the basis of which it can deduce the conclusions and determine whether the state is respecting its safeguard obligations or not particularly with respect to undeclared nuclear material and nuclear activities. It covers specific set of activities executed by the appointed agency inspectors to verify that the facilities and material declared is accounted for and is not being diverted to non-peaceful activities. Various verification activities conducted by the agency for safeguards verification along with their functioning and objectives is mentioned below in the table (IAEA 2016c)

Table 2.1.1: Verification Mechanisms for IAEA Safeguards (Source: Self)

NAME OF VERIFICATION TECHNOLOGY	FUNCTIONIONING/ WORKING PRINCIPLE	CRITICAL/DECISIVE PARAMETER
Nuclear Material Accountancy	Comparison is made between the nuclear material accounting records, books & other reports of a facility with the information that has been shared and described to the IAEA by the State beforehand, specifically concerning the presence of the declared nuclear material in the facility. It is a method of checks and balances which seeks to compare the shared information with the actual information as measured by the inspectors.	Accounting & Quality Control measurement; Characterisation and accounting for material recovered; Monitoring and evaluating nuclear material accumulation and operating losses; Physical evaluation of inventory and Material Unaccounted for (MUF)
Design Information Verification	The safeguard inspectors make the comparison of the design information which they physically observe and measure with the details of the design being submitted by the state to the agency so as to evaluate and confirm whether the information provided by the state is complete and correct to rule out the misuse of the facility for non-peaceful purposes. Laser distance tools, tape measures, drawings & sketches are used	Location, External dimensions of the facility; Configuration of essential equipment; Nuclear Material Flow Paths.

Environment Sampling Analysis (ESA)	Swipe samples are also taken for analysis for verification purposes which reveal details about the nature of nuclear activities and materials and their isotopic composition, especially for Uranium and Plutonium through analysis of trace materials.	Isotopic Concentrations of Uranium and Plutonium in nuclear materials
Nuclear Material Inventory (Non-Destructive and Destructive Analysis)	Analysis of the nuclear material inventory can be done by various non-destructive techniques like through radiation detectors, gamma spectrometry, neutron counting, weighing at the agency approved labs. It can determine the presence of nuclear material in the item and the quantity of the present material. Destructive Analysis gives accurate value of the concentration of nuclear material in the sample through procedures which destroy the sample.	Uranium-Plutonium concentrations and their ratios; Quantity of uranium/plutonium in the sample and its weight.
Open Source (Satellite Imagery)	Using the satellite images, collects, processes, analyses to provide geospatial information services and products like site plan, elevation, and vector data generating geo-spatial products for verification.	Site elevation, Vector data, coordinates of the facility, imagery based illustrations
Containment and Surveillance	Includes the usage of physical surveillance devices like monitoring cameras, seals & detectors installed at the facility which provides information and the status on the nuclear materials and facilities under safeguards by providing constant and barrier free information to the agency though remote data transmission.	Due to continuous monitoring of the data and video, consistency is the key parameter.

Out of the verification techniques mentioned above, for this thesis, the three technologies that will be studied and synergized with the verification technology at CTBTO are: Environment Sampling Analysis, Satellite Imagery Analysis and Non Destructive Analysis.

2.2 ENVIRONMENT SAMPLING ANALYIS TECHNOLOGY

As the key task of the international nuclear material safeguards is reduction of threats due to nuclear weapons proliferation, environment sampling plays an important role in contributing to this objective. The environment sampling analysis method has been implemented as a part of the IAEA safeguard verification regime since 1996 after the inspectors found the importance of swipe samples collected in Iraqi nuclear facilities in early 1990's. It serves as a key strengthening measure in detecting undeclared nuclear materials or activities in nuclear facilitates of countries which are under safeguards. Environment sampling is based on the premise that no matter how insulated and secretive a nuclear process may be, it will leave small amounts of material or particles to the environment which serves as a radioactive signature and can be detected by swipe sampling analysis. (Donohue 2010)

The environment sample analytical laboratory, is equipped with state of the art mass spectrometric equipment such as, thermal ionization mass spectrometry (TIMS), secondary ion mass spectrometry (SIMS), and inductively coupled plasma mass spectrometry (ICP-MS) creating a powerful and effective nuclear material analytical infrastructure for studying the samples collected by the inspectors from the suspected nuclear facility of the member state. These devices are deployed in the laboratories of the agency as well as in the analytical laboratories of some member states which verify the samples for its authenticity. The key main methods used by the equipment for sample analysis are: 1) The bulk analysis of U, Pu and other elements in the whole swipe sample at sensitive ultra-low levels detection and 2) the precise isotopic analysis of U or Pu containing particles from the sample which may be as small as 1 micrometre in diameter. (Donohue 2010)

Figure 2.2.1: Standard swipe sample kit used for Environmental Sampling
(Source: Penkin 2009)

Environment Sampling is now a standard process of the IAEA. The sample kit used by inspectors is prepared in the clean room of the agency's laboratory and includes The package contains two pairs of latex gloves, 6 to 10 cotton swipes, as well as additional zip lock packets for the swiped samples, once the multiple samples are taken at the nuclear facility being inspected, it is placed in an outer sealed bag until they arrive at the IAEA before being analysed at the IAEA laboratory as well as at the IAEA's network of eighteen affiliated laboratories present in eight IAEA Member States and the European Atomic Energy Community (EURATOM). (IAEA 2016d)

To maintain authenticity and confidentiality of the entire process and analysis, all the samples undergo a strict labelling system which anonymises the country and location of the samples. Then the samples undergo screening and spectrometry for radioactive signatures, elemental composition and isotopic ratios using the sophisticated equipment whose results are compared with sample results at the accredited laboratories for uniformity and high quality results. (IAEA 2016d)

Bulk Analysis: First process is the bulk analysis of the swipe samples which is carried out in two different facilities: Clean Laboratory (CL) handling the non-radioactive samples and Hot Environmental Sample Laboratory (HESL) handling the radioactive samples, these two laboratories are separated to prevent contamination. A typical bulk analysis request is for measuring the Uranium and Plutonium elemental concentration & isotopic composition present in the sample swipe. The analytical process starts with a non-destructive measurement technique like gamma spectrometric screening or X-ray fluorescence spectrometry for determining the amount of Uranium or Plutonium in the sample. Preliminary data is used to modify the analytical scheme. (Donohue 2010) Following processes described below explain the bulk analysis:

- **Chemical Treatment of Cotton and Cellulose Swipes**: It starts with ashing of the swipe material in a furnace at 600 degree Celsius followed by its dissolution in concentrated mixture of nitric acid and hydrogen peroxide, initial portion is measured through X-ray fluorescence spectrometry (TXRF) followed by inductively-coupled plasma mass spectrometry (ICP-MS) to approximate the U and Pu concentrations in the sample and other possible elements which interfere with the analysis and needs to be removed. (Donohue 2010)
  Chemical separation is then executed via anion exchange and station phase chromatography for more accurate U and Pu concentrations without the interfering elements. Due to significant presence of U-238 in the Pu isotopic concentration, mass spectrometry is unable to measure and thus alpha

spectrometry is used for getting an accurate measure as activity ratio of Pu-238 to the sum of Pu-239 and -240. (Donohue 2010)

- **Inductively-Coupled Plasma Mass Spectrometry**: The introduced sample consists of a nebulizer and a sample changer for allowing programming of samples and standards sequence to minimize cross contamination. Sensitivity of the instrument is determined first and standards are measured to verify mass resolution and scale calibration correctness. For each sample aliquot we obtain mass peaks for U-238, Pu-239, Pu-240, Pu-241 and Pu-242 are monitored including the mass spectrum regions where likely interference from other elements like lead, mercury might have occurred. (Donohue 2010)

  A correction is done when the effect on Pu isotopes exceeds 1% of the signal. Through isotopic dilution analysis (IDA) the concentration of Pu in the original swipe sample is measured by comparing the obtained signal from the sample isotope (Pu-239 or Pu-240) with that of Pu-242 which was used as a tracer, similarly, Uranium concentration is estimated by using the U-233 tracer.

  Final report shows the amount of Uranium in total and the amount of each separate Plutonium isotope with combined uncertainty. (Donohue 2010)

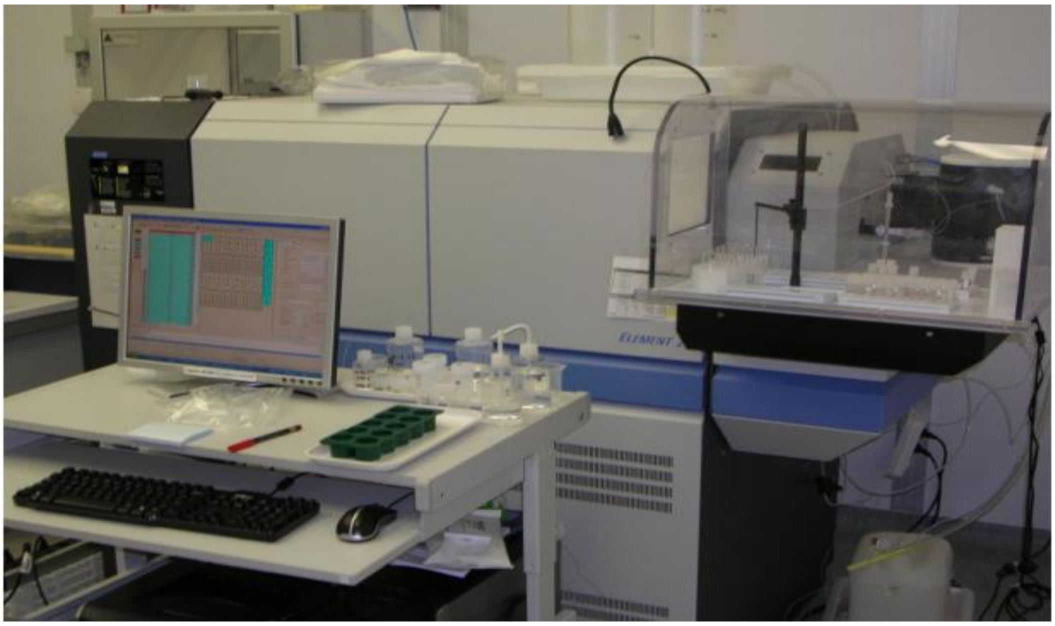

Figure 2.2.2: Inductively-coupled plasma mass spectrometer used for bulk analysis (Source: Donohue 2010)

- **Thermal Ionization Mass Spectrometry:** In order to get high accuracy of the Uranium isotopic composition in the environmental samples highlighting the presence of a small anthropogenic component like enriched Uranium from the natural uranium background, we need Thermal Ionization Mass Spectrometry (TIMS) because it gives highly accurate data. In this process, the uranium fraction is dried post chemical separation on rhenium filament and TIM's measurements are then executed through a Triton instrument and the counting detection system of TIMS collects the data. U-233, U-234, U-235, U-236 and U-238 measurements are made through peak jumping within specified patterns. Data correction is then done for effects like mass fractionation, baseline etc followed by uncertainty estimation. (Donohue 2010)

- **Alpha Spectrometry for Pu-238:** This method is used to measure quantity of Pu 238 in the sample when the total Pu is in the range of pictogram (10^{-12} g) . The un spiked portion of Pu through ICPMS mentioned above is split and a portion is precipitated with Neodymium and collected on a fine membrane filter. It is then counted in a low-level alpha spectrometer system though an implanted Silicon detector. The final result of the measurement is obtained as a ratio of Pu-238 to Pu-(239+240) which, post uncertainty estimation, is then aggregated with the data from ICPMS to get the ratio of Pu-238 to Pu-239 in the sample. (Donohue 2010)

Isotopic Particle Analysis: The environmental swipe samples taken at the nuclear facility contains the dust from the particulate matter originating from materials used in construction or natural minerals like gypsum, cement etc., but apart from the construction materials, nuclear processes like enrichment or reprocessing also produces particulate matter in the range of 0.1-10 micrometre. Due its small size, such particles are highly mobile and can travel several metres due to air or human activity making it difficult to clean up such particles from the area, due to the miniscule and mobile nature of the particles highly sensitive methods are used for locating them and to determine their elemental and isotopic composition. (Donohue 2010)

Before conducting the particle analysis, sample preparation is done using vacuum inspection replacing the older heptane method. It involves sucking the particles from the swipe and entrenching them on a sample planchet, this method ensures swift deposition without cotton fibres contamination and uniform particle deposition, electrostatic precipitation technology is being considered for future sample preparation. Multiple planchet are prepared from the sample to ensure optimum loading of particles to reduce the chance of shadowing effect and false negative findings.

- **Scanning Electron Microscopy Combined with X-Ray Spectrometry**: It is equipped with Oxford INCA Energy 350 and wave 700 spectrometers and the tungsten filament provides an electron source of high current density for sensitive X ray detection minimising spatial resolution loss. The software with the instrument provides for automated searching depending on heavy particle detection through backscattered electron signal followed by X-ray spectrum accumulation. (Donohue 2010)

  Exact location of particles can be determined through optical microscope or via secondary ion mass spectrometry which can lead to the determination of the approximate origin of particles during the particular process nuclear process in the facility. Time for search is dependent on how heavy particles are found , from the obtained data, U and Pu signals are sorted from the spectrum and details about size and elemental composition can be determined using wavelength dispersive spectrometers. (Donohue 2010)

  The image below shows the sample containing uranium particles in a silica matrix in the backscattered electron image mode. The brightest particles represent Uranium which can be manipulated for location information using tungsten needle. (Donohue 2010)

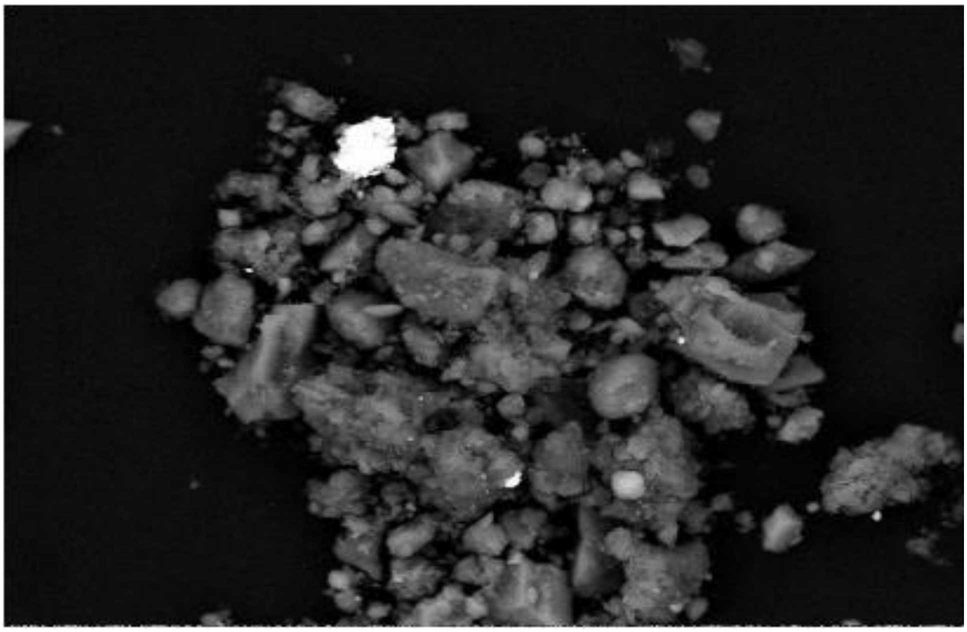

Figure 2.2.3: SEM image of U particles in matrix (Source: Donohue 2010)

- **Secondary Ion Mass Spectrometry**: Operation of SIMS is based on the principle of producing a micro focussed beam of positive O_2 ions which entrenches on the sample and splatters the material away as neutral and positive ions out of which positive ions are the characteristic of sample composition which is fed to the mass spectrometer and detected through a anode encoder or single channel electron multiplier ion counter, raster scanning over a surface area generates an image giving the spatial map of isotopes present which, using a special software, locates the Uranium containing particles. (Donohue 2010)
  Ionisation Mass Spectrometry measures the U-235/U-238 ratio especially of pure compounds like UO_2 or UO_2F_2 for low amount of interfering elements, however, the large geometry secondary ion mass spectrometer has higher sensitivity and mass resolution for better accuracy which gives the ability to filter the interfering elements effects. Depending in the particles size measured, the uncertainty of measuring U-235/U-238 ratios will better than 1% relatively. (Donohue 2010)

- **Chemical Analysis of Particles:** Apart from spectrometry analysis, amount of plutonium can be measured from the swipe samples from hot cells of the facility, isotopic composition of such plutonium particles can provide crucial information on the reactor conditions and to confirm whether chemical purification of Pu took place or not. The Pu particles are initially located through SEM and their elemental ratio is calculated following which particles undergo chemical processing leading to eventual measurement of Pu by ICPMS spectrometry, thus for Pu particles, depending on the size, composition etc., the age can be determined whether it's of recent origin (within 5 years) or of historical production (more than 10 years). (Donohue 2010)

From the above described particle and bulk analysis, various isotopic compositions & ratios can be deduced. This data when represented on graphs can show relative presence and composition of isotopes of Uranium and Plutonium. Comparing data to predictive calculations leads to determination of: Enrichment activities, Plutonium production and separation techniques being used in the facility, the age of the identified nuclear material or the isotopes, reactor type based on the particles generated and the irradiation history of the facility. (Donohue 2010)

Thus, spectrometry essentially provides isotopic fingerprinting mechanism for safeguard verification.

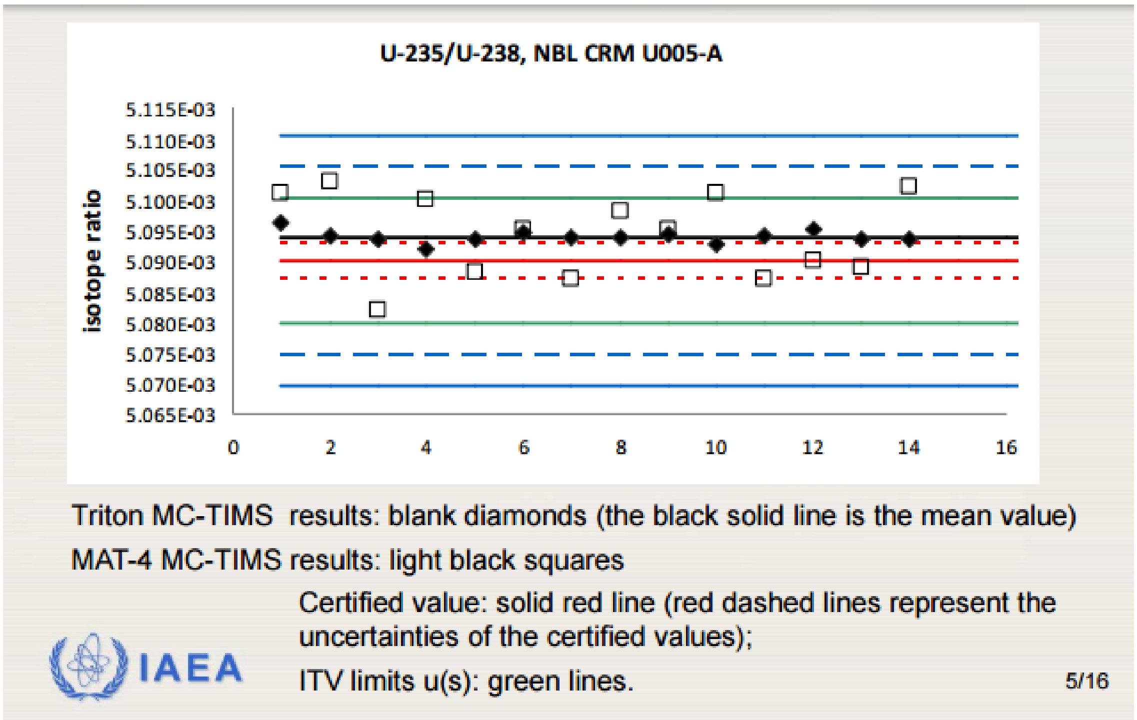

Figure 2.2.4: TIMS Spectrometry data for U-235/U-238 (Source: Boulya et al. 2014)

TABLE 2.2.1: Results of Bulk Analysis through spectrometry methods (Donohue 2010)

Element/Isotope Ratio	Amount	Uncertainty	Method
U-238	6.90 ng	0.1 ng	IDA – ICP-MS
Pu-239	3.03 pg	0.10 pg	IDA– ICP-MS
Pu-240	0.173 pg	0.005 pg	IDA – ICP-MS
Pu-241	0.0018 pg	0.0003 pg	IDA – ICP-MS
U-234/U-238	0.000107	0.000007	TIMS
U-235/U-238	0.01111	0.00015	TIMS
U-236/U-238	0.00022	0.00002	TIMS
Pu-238/Pu-239	0.00147	0.00046	AS

The above tables show how the data from the bulk analysis gives information on Uranium and Plutonium isotopic concentration. It is this data which will be key for synergising with the verification technology of CTBTO for obtaining a concrete conclusion for safeguards implementation.

2.3 SATELLITE IMAGERY ANALYSIS TECHNOLOGY

The IAEA has been involved in various programs in recent years to improve the efficiency and the effectiveness of the safeguards verification regime, one of the measures that was recognized for improved information and data investigation was though satellite imagery analysis established on the recommendation of the group of outside experts of the IAEA in 1994 to obtain satellite imagery via commercial sources for assessment. A work plan consisting of potential applications related to safeguards, policy & legal issues was developed by the department of safeguards for including such an assessment method for safeguards verification. Following suggestions and discussions with the member states and various pilot study programs and workshops led to the foundation and integration of IAEA'S Satellite Imagery Analysis Laboratory for image analysis in the verification regime with full operational capability in the year 2001. (Chitumbo et al. 2002, 23)

The Satellite imagery analysis unit has various tasks and roles that are assigned to it, the main ones being:

- To provide analytical services for image interpretation for safeguards inspection and verification activities associated with the leveraging of the satellite imagery.
- Providing the complete image cycle data to the safeguards including collecting, processing, analysing and distributing the satellite imagery derived information to the relevant safeguards division.
- Furnishing essential geospatial information identifying the features of the object and its location on the surface of Earth.
- Monitoring nuclear sites and their activities by observing their baseline updates, detecting changes in site plan via satellite imagery monitoring
- Using the imagery analysis unit data to verify important safeguard facets like Additional Protocol declarations, verifying design information & verifying undeclared activities by the member state. (IAEA 2009)

Satellite Imagery analysis has proven to be extremely useful for cross checking the member state given information. For instance, Ground Sampling Distance panchromatic 4 metre multispectral imagery can identify crucial physical features of a nuclear site like security fencing, power lines, cooling towers, construction & dismantling activities and combining them with data analysis obtained from sensors using the thermal bands can give information on the operational status of the facilities. The technology can be further harnessed by using different optical resolution satellites. (Chitumbo et al. 2002, 25)

Imagery Analysis: The core component of the satellite imagery verification technique is the analysis of the data and images. Image analysis means the derivation of useful information from the captured satellite images obtained from the commercial operators, it is the one of the methods of assessing raw data which when merged with other relevant safeguard data creates a logical data fusion which can produce and provide more concrete and specific results. It's thus a value addition to the existing verification technologies for the IAEA, adding additional relevant content to an existing dataset of information about an activity, facility or an event. It provides answer to the location, specifications, methods used in a suspected activity or facility underscoring its significance in a reliable manner. Along with satellite imagery, the availability of geospatial tools like virtual globes (Google Maps), social networks, and Meta search engines has facilitated the safeguard verification mechanism. (Pabian 2012)

Before understanding the details of imagery analysis, it is essential to briefly decipher the features of the captured image that aids interpretation:

- Size: It gives a good approximation of the relative and true size of the captured object when converted to the required scale.
- Shape: The physical appearance of the objects can help in distinguishing whether they are manmade or of natural by studying their characteristics.
- Shadows: It's an important feature as it gives an idea of the orientation of the object by studying its silhouette.
- Shade: By comparing the brightness and contrast variations of the observed object, differences can be elaborated considering the surroundings to understand the setting.
- Signatures: The common functional characteristics which are observed and picked by the satellite imagery and comparing their relevance to the nuclear fuel cycle can give an idea of the kind of activity being pursued. However, analysis needs to be done considering the possibility of signature suppression. Hence, enhanced 3d model analysis is needed from the 2d captured images.
- Time: By studying the satellite images taken at different intervals, one can determine the construction history, operations and the level of activity
- Aggregating data from geospatial sources facilitates in better understanding of the observations being made by the image analysis.

For deciphering the above mentioned features it is important to know all the stages and the components of the complete nuclear fuel cycle so that accurate and relevant observations can be made with minimum discrepancies. (Pabian 2012)

The Satellite Imagery Analysis Unit sources the images from commercial satellite operators on a contract basis. The satellites are sourced from different operators and have different resolutions depending on the application and the cost. This practice enhances the ability of the department to assess the status and extent of activities in the facility of the member state and also insures integrity and authenticity of the satellite imagery without any bias. The table below shows various types of commercial imaging systems being used by the department and their utility and disadvantages.

Table 2.3.1: Comparison of various Imaging Systems (Source: Pabian 2012)

Imagery Type	Advantages	Disadvantages
Optical/Electro-Optical:	Very high resolution possible. Near-infrared is optimal because it can penetrate haze and can be merged with true color for more natural appearance as an aid to interpretation.	Acquisition restricted by cloud cover and limited to daylight hours.
Multi-spectral: (Incl. Hyper-spectral)* Includes both visual bands and non-visual bands	Provide the means to view sites in a more natural, true color setting. May also provide a means for determining material/chemical composition and material transfer, and for detecting camouflage and concealment activities	Slightly lower resolution (i.e., currently 2.5-meters).
Thermal infrared	Provides a quantifiable measure of heat transfer as a basis for determining site status such as reactor power operations. When correlated with optical could determine heat flow, both qualitatively and quantitatively, from waste ponds, steam lines, vents, stacks, cooling towers, etc.	Generally of too low resolution for anything other than facility activity monitoring (currently no better than about 20 to 90 meters)#.
Radar:	Provides 24-hour monitoring capability, can penetrate clouds, and is a useful complement to optical imagery.** Resolution improved greatly in 2007 with successful launch of the 1-meter capable German built *TerraSAR-X* .	Processing and interpretation of imagery is much more difficult.

Table 2.3.2: Resolution for Nuclear Fuel Cycle in metres (Pabian 2012)

Facility of Interest	Detection	General Facility Identification & Site Layout	General Functional Building Description	Precise Building Identification	Technical Analysis & OMV
Uranium mining, processing & feed materials	5 to 10	1 to 5	1	0.2 to 0.5	.5 for mines and processing, limited other
EMIS Enrichment Facilities	2 to 5	1 to 3	1	0.2 to 0.5	Limited to none at any resolution
Gas Centrifuge Facilities	N/A	1 to 3	0.5	0.2	Limited to none at any resolution
Heavy Water Plants	5	1-3	0.5	0.2	0.2
Research Reactors	2 to 5	1 to 3	1	0.5	Limited to none at any resolution
Plutonium Production Reactors	2 to 10	1 to 5	1	0.5 to 1	0.5 to 1
Nuclear Weapons R&D (i.e., High Explosives Testing)	1 to 2	0.5 to 1	0.5	0.5	0.1 to 0.5
Nuclear Weapons Mfg.	1 to 2	1	0.5	.1 to .5	Limited to none at any resolution
Test Site	10	1 to 3	1 to 2	.5 to 1	0.5 to 1

While Table 2.3.1 gives a comparison of various commercial imaging systems and their pros and cons, Table 2.3.2 provides information regarding the minimum overhead imagery resolution needed for various processes in the nuclear fuel cycle, depending on the process to be specifically monitored, the corresponding resolution is checked and then the satellite or imagery type providing the required resolution is selected considering the financial costs.

As of 2012, following were the available high resolution commercial sensors.

Figure 2.3.1: List of available high resolution commercial sensors (Source: IAEA 2009)

Just to illustrate the difference between the choices of the type of satellite being used for a particular purpose, when using a Synthetic Aperture Radar Satellite (SAR) which creates the images of landscapes or objects near the facility through Motion of a radar antenna over the area being targeted for better resolution, one gets Acces to 24 hours montoring capability as well as complimentary and additional information. It can also penetrate the clouds for the capture, can work in all weather day and night situation and is also sensitive to metallic objects, however processing and the interpreation of the obtained imagery is quite difficult.

While, while using an optical imagery system one can obtain a very high resolution and even near infrared is optimal and possible since it has the capacity to penetrate haze and it can be meshed with the original colour of the surroundings for better and clearer interpretation. However, the disadvantage is that the image acquisition is limited and confined by the cloud cover and restricted sunshine hours as it cannot function in the night. Below, are the images underlining the differences between these two systems.

Figure 2.3.2: Satellite image of a site through a SAR based imagery system

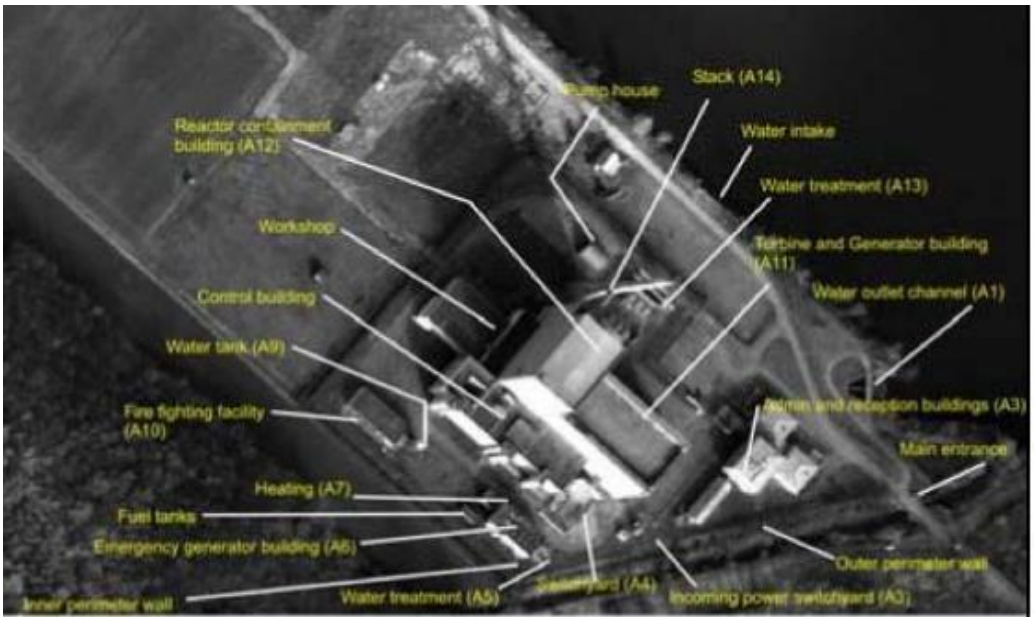

Figure 2.3.3: Satellite image of a site through an optical imagery based system

(Source: IAEA 2009)

IAEA satellite imagery analysis unit uses the parameters mentioned in the section previously like signature, shape, size, time etc. to understand and decipher the satellite images, since satellite images being provided are essentially two dimensional and thus can give limited information, therefore the agency uses software's through which when one enters key parameters like coordinates, size, shape, signature, elevation and other crucial observations from the 2d satellite image, the software generates a three dimensional model of the facility and the location which further helps in understanding the previous complexities, giving further information on the facility and the kind of activity being pursued.

Figure 2.3.4: Annotated 2D satellite image of a facility (Source: Pabian 2012)

Figure shown above was taken in January 2006 of an uranium enrichment complex, the picture is annotated to describe the miniscule findings which were observed by the IAEA, the picture clearly shows the location of the pilot fuel enrichment plant and also the location of the centrifuge cascade halls for enrichment with underground entrance facilitates and near these enrichment facilities are the newly constructed facilities having a hidden entrance. The facility was designed to hold certain number of centrifuges installed in a specific modules and cascade halls while the new construction adds to the doubt of the purpose which is to be investigated. (Pabian 2012)

Figure 2.3.5: 3 D visualisation of a sample site (Source: Pabian 2012)

3 D visualization as shown above gives a clearer and more elaborate image of the facility, its facilities and the components which then can be highlighted and studies based on the detail, the facility can be studied with other sources of media like the intelligence agencies, pictures available on the internet etc. for accuracy and calibration.

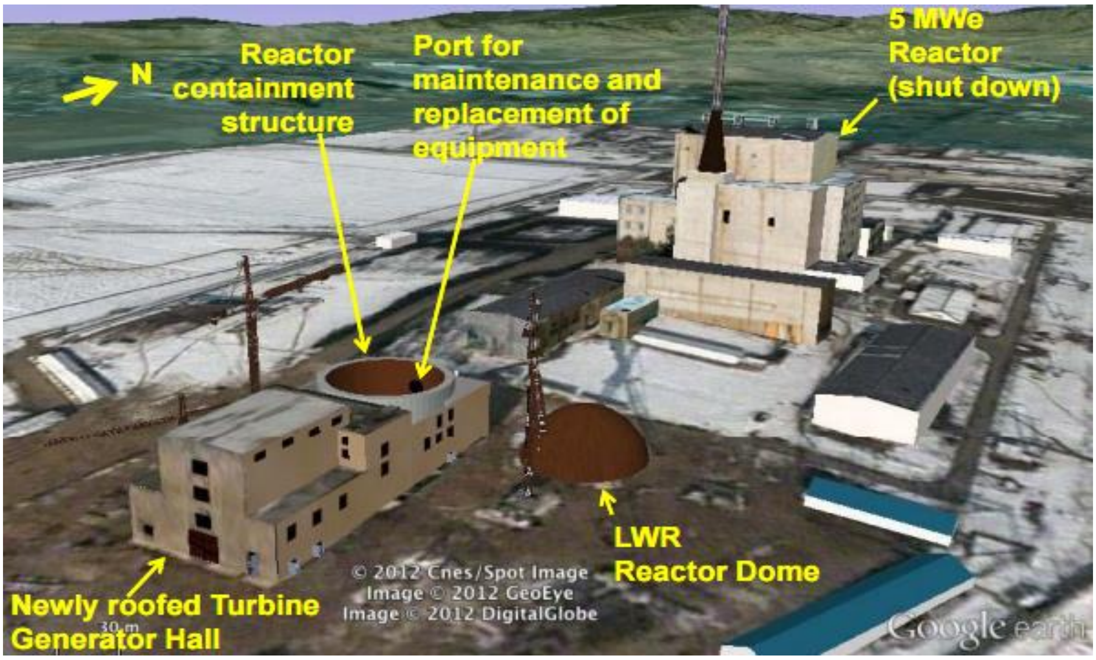

Figure 2.3.6: 3d model of an experimental light water reactor (Source: Pabian 2012)

From the above two 3d images renditions, once the details of the facility and the site are known, the details including the coordinates are the key points which if shared with the CTBTO can be of immense utility and creating a positive non-proliferation synergy.

2.4 NON DESTRUCTIVE ANALYSIS

As the IAEA has been tasked with the responsibility of ensuring that the states which have entered in safeguards agreements with the agency are bound by it and are continuously meeting their obligations, it essentially implies that any diversion of material for military purposes would be detected and that all nuclear materials possessed by the states is declared with the agency. This is crucial in order to provide credible assurances to the international community regarding the safety and sanctity of nuclear materials being used only for peaceful purposes. Thus, *timely detection* of diversion of *significant quantities* of nuclear material from peaceful to military purposes & deterrence of a diversion form the foundation stone for a strong and reliable safeguards verification regime. (IAEA 2011)

To satisfy the above commitments, the Non Destructive Analysis (NDA) along with Material Accountancy measures form the fundamental and key methods in the safeguards verification regime and is thus of fundamental importance. In applying NDA and material accountancy methods, the inspectors perform measurements aimed at quantitatively verifying the amount of nuclear material and cross checking it with the documented amount in the account of the member state. When, discrepancies and gross defects are detected, the next level of verification begins which aims to determine whether portion of the amount declared is missing and involves weighing of the items using effective NDA methods like gamma ray spectrometry and neutron counting.

These are some of the numerous methods used by the IAEA, since the agency utilizes more than 100 NDA methods for verification and monitoring of nuclear materials without altering the chemical and physical characteristics of the equipment or material being tested. The equipment varies both in terms of complexity and size from portable hand held devices during on spite inspection to large in situ NDA techniques for uninterrupted and unattended in plant use for monitoring purposes. The most commonly employed NDA methods depend on the detection of nuclear radiation from the material usually in form of gamma rays or neutrons, instruments measuring physical characteristics like heat, weight, volume, emission & absorption are also used to provide additional information. (IAEA 2011)

Special standards have to be met for the non-destructive remote monitoring devices for the data security. Such installations which are scrutinized by the IAEA inspectors periodically transmit data between different systems and the IAEA headquarters, thus the data needs to be verified & encrypted to ensure authenticity and to avoid disclosure of information ensuring confidentiality of the information from the state. (IAEA 2011)

Two key definitions which form the main crux of the NDA technologies are:

- **Timely Detection**: It is defined as time required to convert nuclear material of different forms to the components or constituents of a nuclear device.
- **Significant Quantity (SQ)**: It is defined as the minimum approximate quantity of nuclear material, considering the conversion process involved, through which the chances of fabricating a nuclear explosive device cannot be excluded. In simple words, amount of specific nuclear material needed for manufacturing a nuclear explosive device. (Chichester 2011)

The figure below gives a good overview of the various technologies involved in the NDA technologies being used by the agency.

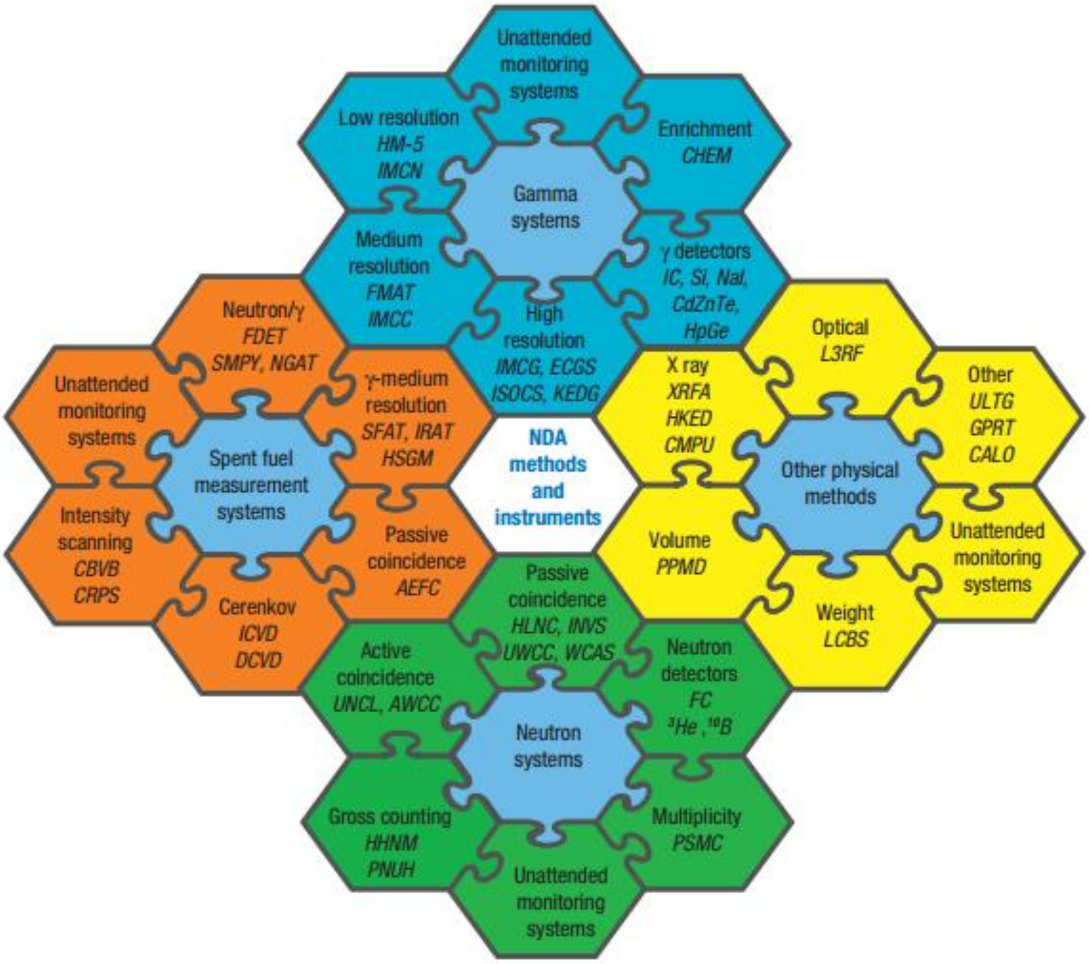

Figure 2.4.1: Overview of various NDA technologies (Source: IAEA 2011)

As shown in the figure, the key NDA technologies are centred on Spent Fuel Management Systems, Gamma Systems, Neutron Systems and other physical methods. Of these core technologies, gamma systems and neutron systems will be elaborated and considered for synergy with CTBTO verification system.

Gamma Systems: Gamma rays is emitted by most of the nuclear materials under the IAEA safeguards which is leveraged for inspection through NDA techniques. The logic for their working is based on the fact that gamma rays, according to the isotopes emitting them, have defined energies. Thus identification of the gamma ray energies with relative intensities suffices in identifying the corresponding isotopic composition. When this is combined with the measurement of absolute intensities, we can get quantitative information on amount of material present, for instance, with the alpha decay of U-235 fuel, it has a strong gamma ray energy of 185 keV, thus the level of U-235 enrichment can be measured by measuring the energy intensity of the emitted gamma ray.

By measuring the relative intensity of the gamma rays related with nuclear fission and activation product, the approximate date of an irradiated fuel discharge from a reactor can be determined. For the detection of gamma rays, the emitted radiation should interact with the detector so as to pass on all or fraction of the photon energy. The working principle of all spectroscopic gamma ray detectors is the accumulation of this emitted electrical charge which produces a voltage pulse giving an amplitude proportional to energy given by a gamma ray to the detector. Sorting of these voltage pluses are then done according to their amplitude and calculated through electronic instruments like a multichannel analyser, in which, gamma rays of different energy intensities can be plotted to produce a gamma ray spectrum providing elaborate information on the nuclear material being measured. (IAEA 2011)

- **Inspector 2000 Multichannel Analyser (IMCA 2000):** This instrument has been in use since 2001 and has its basis on digital signal processing technology, its combined with other types of detectors like high purity germanium, cadmium zinc telluride for inspection purposes permitting high, medium and low resolution spectrometry, it gives an unexceeded count rate and resolution performance in a a compact package due to reduction in use of analog circuitry, its high performance is gained from the digitization of preamplifier signals in the beginning of the processing cycle. This configuration gives the device high stability, accuracy and data duplicability improving the overall signal attainment performance. (IAEA 2011)

- **The Miniature Multichannel Analyser (MMCA)**: It's a miniaturized spectrometry system supporting various detectors used by the agency. Its portable use is permitted by a battery lasting when paired with CdZnTe or a NaI detector. When merged with a palmtop computer, it becomes a versatile and effective system making it extremely handy for inspection activities. (IAEA 2011)

The gamma ray detectors which are mainly used for inspection of nuclear materials are either scintillators like activated NaI crystals or solid state semiconductors like CdZnTe or even gas filled detectors like xenon detectors, all of these detectors have different working conditions, resolutions and application for measuring different parts of nuclear fuel cycle, a summary of the detectors is shown below in the table.

Table 2.4.1: Summary of Gamma Ray Detectors with applications (Source: IAEA 2011)

Code	Equipment	Primary application
CHEM	Cascade header enrichment monitor, uses a special collimated HPGe detector, X ray fluorescence source	Verification of U enrichment of UF_6 gas in header pipes
FMAT	Fresh MOX attribute tester, uses a shielded and collimated CdZnTe detector	Verification of characteristics of fresh MOX (distinguishes between the γ rays of ^{235}U (186 keV) and ^{241}Pu (208 keV))
HM-5	Hand held assay probe	Search for and identification of nearby materials and isotopes Determination of active length Verification of U enrichment
ECGS	Electrically cooled germanium system	Verification of U enrichment and Pu isotopic composition in non-laboratory environments
KEDG	K-edge densitometer, uses a high resolution Ge detector with $^{57}Se/^{57}Co$ sources	Verification of Pu concentration in solutions
IMCN, IMCC, IMCG	InSpector 2000® multichannel analyser (IMCA) paired with either a NaI (IMCN), CdZnTe (IMCC) or HPGe (IMCG) detector	Verification of U enrichment, spent fuel and Pu isotopic composition
ISOCS	In Situ Object Counting System, uses a well characterized HPGe detector	Verification of U contained in hold-up and waste
MMCN, MMCC, MMCG	Miniature multichannel analyser (MMCA) paired with either a NaI (MMCN), CdZnTe (MMCC) or HPGe (MMCG) detector	Verification of U enrichment and spent fuel

Depending on the application, the gamma ray detectors are chosen. Important considerations are the working conditions of the detector and the sensitivity for detection of the gamma rays from nuclear material.

Low and Medium Resolution Gamma Spectrometry: It uses different configurations and is used for safeguard verification for the presence of nuclear material, especially like quantitative verification of enrichment levels & detection of plutonium and uranium in fresh and spent fuel.

- **MMCN**: This technique is obtained when MMCA is paired with a NaI detector. It is mostly used to verify uranium enrichment in pure, homogenous powder and pellet form. The level of enrichment is determined through the gamma ray intensity of U-235, the count rate of photons at energy level 186KeV is proportional to the abundance of U-235. (IAEA 2011)
- **MMCC**: This method involves the pairing of MMCA analyser with CdZnTe detector and is mainly used for verification of fresh fuel, the probe of the analyser can be inserted into the guide tube of the fuel assemblies, thereby making it an in situ process with minimal interference from radiation from neighbouring fuel assemblies. (IAEA 2011)
- **FMAT**: It stands for fresh MOX attribute tester and consists of a cylinder housing with CdZnTe detector and a preamplifier. It has the ability to distinguish between gamma rays emitted by U-235 and Pu-241 and through the measurement of plutonium gamma rays it measures that the nuclear material has fresh mixed U-Pu oxide characteristics. (IAEA 2011)

High Resolution Gamma Spectrometry: High resolution gamma spectrometer is obtained by the coupling of germanium detector with MMCA. It's primarily used for determination of U-235 enrichment of UF6 in the cylinders used for shipping, it also requires determination of the cylinder wall thickness for adjustments for gamma ray attenuation, in some cases software like The Multi-Group Analysis for Uranium (MGAU) can also be used to speed up the measurement and analysis of high resolution uranium spectra. Furthermore, high resolution gamma spectrometry is also used to determine isotopic composition of Plutonium, as it emits a wide range of X ray and gamma ray spectrum, it is interpreted using software which take advantage of the high energy resolution spectrum ad HPGe detector to assess different plutonium isotopes. Isotopic determination of plutonium is essential for checking the nature of material and as an input parameter for neutron measurements. (IAEA 2011)

- **ECGS**: It stands for the electrically cooled germanium system and consists of a germanium detector, multichannel analyser, computer and an electrically cooled system and is battery powered system. It is used for UF6 cylinder assay and cascade uranium enrichment assay.

- **ISOCS**: The In Situ Object Counting System incorporates an HPGe detector and is used to verify uranium contained in hold up waste, it takes into consideration all physical parameters elaborating the geometry. (IAEA 2011)

- **CHEM**: The Cascade Header Enrichment Monitor employs an HPGe detector and x ray source for measuring UF6 gas enrichment in a pipe to confirm the absence of highly enriched uranium in cascade header pipes of the plants. The x ray fluorescence measurement gives the amount of uranium in UF6 gas. The enrichment level of uranium in the pipe is counted independently of the deposit present on the inside of the pipe. (IAEA 2011)

- **KEDG**: The K edge densitometer is an instrument used by the agency to calculate the plutonium concentration in solutions. It consists of a high resolution germanium detector, a multichannel analyser and a portable computer which measures the photon transmission at two energies bracketing the K absorption edge energy of the material being measured. The amount of the radiation being absorbed gives a very accurate measure of the plutonium concentration present in the sample. Measurements can be provided on highly radioactive samples owing to the strong photon strength of the x ray tube. This method is one of the most accurate NDA technologies and is best used for relatively concentrated plutonium in the solution being measured. (IAEA 2011)

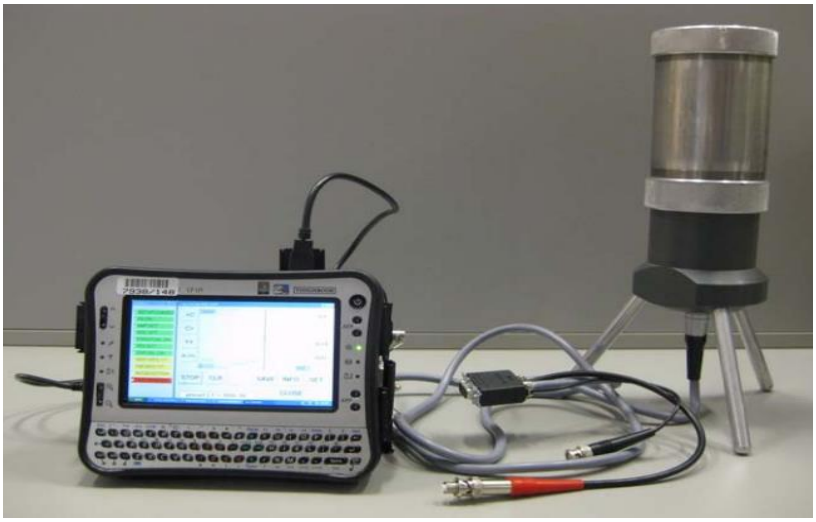

Figure 2.4.2: Miniature Multi Channel Analyser with NaI Detector (Source: IAEA 2011)

Neutron Counting: From a non-irradiated nuclear fuel, neutrons are mainly emitted in three ways for the counting:

- From spontaneous fission of uranium and plutonium primarily in the even isotopes of plutonium.
- Through induced fission from uranium and plutonium fissile isotopes from neutrons coming from other external sources.
- Through reactions brought on by alpha particles involving lighter elements like fluorine and oxygen.

The main purpose of neutron counting is to differentiate between the neutrons given out from a single fission event from the neutrons that are formed other secondary fission events or other processes. The scientific principle is that alpha particles are emitted by almost all the isotopes of uranium, plutonium and other transuranic elements, and these alpha particles on interaction with lighter elements in the compounds like oxides and fluorides or impurities in material like boron or lithium form neutrons creating an undesirable neutron background which is distinguished by neutron coincidence counting. This is primarily achieved by time tracking of neutron detection since same fission event neutrons are identified close to each other while neutrons from non-fission processes are arbitrarily spread in time. (IAEA 2011)

Mass of plutonium based on spontaneous fission is determined by the passive coincidence system especially in even numbered plutonium isotopes, high resolution gamma spectrometry makes the isotopic abundance known, and using which Pu-240 mass from the neutron count rates can be determined and converted into total plutonium mass of the sample. Also, induced fission of sample of natural uranium by low energy neutrons contributes negligibly to the measured coincident neutron count rate even when the fuel maybe be slightly enriched (U-235 enrichment). (IAEA 2011)

Neutrons detectors basically use different neutron capture reactions in order to generate pulses. One of the most commonly used neutron detector is the Helium 33 gas detector whose principle is based on the reaction between 3He(n,p)3H reaction which produces a proton and a triton with combined recoil energy of 764 keV ionizing the surrounding gas thus generating an electronic signal. As their absorption capacity decreases with their increased energy, hence moderation of neutrons is needed for a fair efficiency of detection of the counting system. When the thin layer of U-235 on the inner wall of the gas filled chamber undergoes fission caused by neutrons, high energy fission fragments cause ionisation of the stopping gas and transforming it into an electronic signal which can be noted. (IAEA 2011)

- **Gross Neutron Counting**: It refers to the sum of all the detected neutrons. The presence of significant number of neutrons is usually an ample indication that there is a presence of fissile material due to the fission reactions. Hand held neutron monitor (HHNM) has 3 He proportional neutron counters and is a portable device focalizing neutron radiation sources, after background measurements, if there is surpassing of a predetermined threshold value, an alarm is set off giving the relevant information. A Portable neutron uranium hold up (PNUH) system has 3 He neutron tubes to determine the uranium hold up quantity measuring the total neutron signals at the locations prescribed. (IAEA 2011)

- **Neutron Coincidence Counting**: Neutron coincidence counting due to its reliable pulse processing capability even over a large range of input count rates has developed into a very stable and accurate method for determination of plutonium and U-235 content in the sample material. Stability is achieved by reducing noise interference by well-placed amplifiers. The electronic boards, amplify and shape the pulses removing gamma noise feeding a narrow and useful pulse to external processor. Analysis software is used to remove the accidental data to find out the real coincidences. It includes passive detector systems like The High Level Neutron Coincidence Counter (HLNC), employed for measuring non-irradiated plutonium materials; The Inventory Sample (INVS) used for measuring low small plutonium samples, lower than those measured by HLNC but with double neutron detection efficiency; The Underwater Coincidence Counter (UWCC) used for measuring fresh MOX fuel stored under water; The Waste Crate Assay System (WCAS) which determines the plutonium content for large waste containers for both high and low activity. The active coincidence detector system employs neutron sources to interrogate the U-235 present in a sample. The Active Well Coincidence Counter (AWCC) which is used for producing high accuracy checks on the U-235 content; The Uranium Neutron Coincidence Collar (UNCL) is used for determination of the linear mass density of uranium in fresh fuel assemblies. (IAEA 2011)

- **Multiplicity coincidence counting**: When at least three coincident neutrons are detected per fission, this method uses the surplus information from the events though measured multiplicity distribution, thus allowing for three unknowns namely, effective Pu-240 mass, multiplication and the neutron rate. Since detected triple rate is proportional to the cube of the efficiency, multiplicity counting requires higher efficiency. The plutonium scrap multiplicity counter (PSMC) system measures the impure plutonium oxide standards and plutonium scrap standards with an average operator-inspector difference of 0.3 % and 0.6% respectively. (IAEA 2011)

Thus, gamma and neutron counting systems are very efficient method to determine the quantity and type of isotope in the nuclear material being examined. The data analysis from this information when synergised with information from the verification technology of the CTBTO can give us concrete evidence of the kind of nuclear proliferation.

2.5 CTBTO VERIFICATION TECHNOLOGIES FOR DISARMAMENT

The CTBTO verification regime aims to detect and ban any underground, underwater or atmospheric nuclear explosion which is conducted on earth by a country. Verification regime seeks to monitor the compliance of the member state countries with the treaty so as to ensure banning of nuclear explosions. The Preparatory commission is keen on ensuring the full functionality of verification regime once the treaty enters into force. The verification regime of the CTBTO is multi-faceted and utilises different technologies for detection (CTBTO 2012g). It has following main elements:

- **International Monitoring System**: IMS consists of the 337 facilities around the world, out of which 321 are monitoring stations and 16 are laboratories which aim at detecting any nuclear explosion. They form the core of the verification regime.
- **International Data Centre**: IDC is the key data analysis element of the regime as it processes data from the 337 monitoring facilities of the IMS stations and provides the analysis results in form of bulletins and reports for the member states, based on which, member states decides and judges the ambiguous event being reported. All the data bulletins from the IDC are archived in the computer centre for possible future usage and reference.
- **Global Communications Infrastructure**: GCI has dual purpose of transmitting the data which is recorded at different IMS stations to the IDC for data analysis and processing & transmitting data bulletins from the IDC to the member states. This process is done through a network of six satellites ensuring global coverage and data is sent via terrestrial links to the IDC. (CTBTO 2012g)
- **Consultation and Clarification:** After receiving and studying the data bulletins sent by the IDC, if the member state feels that the data recorded implies a nuclear explosion as the event, then a process of consultation and clarification can be set about from a member state directly to either to a particular member state or to

the executive council for clarification and in some cases can approach the Director General to seek information, state being questioned in this process has usually 48 hours to clarify the event being questioned. (CTBTO 2012g)

- **On-Site Inspection**: OSI is the ultimate verification measure requiring physical presence on the field, irrespective of the result of the consultation and clarification process, member states have the right to request an OSI. Such physical inspections are carried out by experts on the field of the suspected country in order to determine whether violation of treaty by conducting a nuclear explosion has occurred or not and it can be invoked only when treaty is in force.
- **Confidence-building measures**: CBM is a voluntary step taken by the member states to notify the CTBTO technical secretariat about any TNT equivalent based chemical explosion of 300 tonnes or more occurring in their territory since it may lead to misinterpretation from the data from IMS facilities, which if clarified is resolved and secondly it assists in the improved calibration of the measuring equipment. (CTBTO 2012g)

Amongst the above mentioned elements, Radionuclide Monitoring, Atmospheric Transport Modelling and IDC are crucial for synergy with IAEA, others are in table below.

Table 2.5.1: Seismic Monitoring Technologies of the IMS (Source: Self)

NAME OF VERIFICATION TECHNOLOGY	FUNCTIONIONING/ WORKING PRINCIPLE	CRITICAL/DECISIVE PARAMETER
Seismic Monitoring	Seismic stations are equipped with seismic sensors for measuring waves generated by earthquakes or explosion through A Richter Scale. Sensors used are either seismic arrays or three component stations aimed at locating and detecting underground nuclear explosions violating the treaty obligations. Data is then sent through the GIC to the IDC.	Magnitude of seismic activity as measured on the Richter scale, Measurement of surface and body waves including 'P' and 'S' body waves for locating source.
Hydroacoustic Monitoring	It measures the changes in the water pressure due to sound waves, information obtained from this device can be analysed to locate the nuclear explosion underwater, close to ocean or even on the coastline. Hydrophone sensors are used underwater while T phase stations are located on steep slopes. Highly sensitive owing to efficient transmission of sound through water.	Measuring electrical signals generated by conversion of water pressure change by sound waves from the hydrophones
Infrasound Monitoring	Infrasound waves being acoustic waves with very low frequencies generated by atmospheric or shallow underground nuclear explosions can be detected by network of infrasound array systems by intake of the waves through port and using a micro barometer to measure the change in air's micro pressure giving signals post wind generated noise reduction.	Measurement of the change in air's micro pressure recorded by the micro barometer, Recorded data from central recording facility

2.6 RADIONUCLIDE MONITORING

The radionuclide technology of the CTBTO is one of the monitoring methods of the IMS stations which is complementary to the three other waveform technologies namely seismic, infrasound and hydroacoustic technologies of the IMS, due to its nature, it's also the one which can confirm whether the explosion was nuclear or not due to the parameters which it seeks to measure are radioactive in nature. Radionuclide technology measures the quantity of radioactive particulates and noble gases which are present in the air. Since a radionuclide is an isotope having an unstable nuclei losing excess energy as it emits radiation in form of particles or electromagnetic waves in a process called radioactive decay. (CTBTO 2012h)

Noble gases are chemically inert elements and occurs in nature in different isotopes including unstable nuclei emitting radiation. However, their special property is that some radionuclides which are radioactive noble gas isotopes are not found naturally but are formed from nuclear reactions, and considering their properties, four isotopes of Xenon- ^{131m}Xe, ^{133}Xe , ^{133m}Xe and ^{135}Xe are relevant to nuclear explosions detection.

Radionuclide Formation: When a nuclear explosion occurs, majority of the explosive energy being released is converted into heat energy and shockwaves which is lost. Only a small fraction of the released energy is in form initial radiation, however, with time, residual radiation energy is released through the radioactive decay of the fission products formed during the explosion. These fission products which are obtained from the chain reaction in the nuclear explosion have isotopes and maybe solid or liquid in state, they maybe stable or unstable depending on the characteristics, those which are unstable undergo decay. (CTBTO 2012h)

Since, the radioactive fission products formed are small, they get attached to the dust particles thus having the propensity to get carried away through wind currents over long distances. Even underwater nuclear tests produces radioactive fission products and particles which form radioactive debris and are detectable, but when radioactive particles are formed during an underground nuclear test, they get trapped and thus can't be carried away by wind currents. (CTBTO 2012h)

However certain radioactive isotopes like Xenon which are formed during the explosion are inert in nature and are not attracted to the dust particles, instead they retain their gaseous state, thus managing to seep through the underground rocks through which they can be carried by the air and measured by the noble gas monitoring stations of the IMS. This is the basic principle of how radioactive particles/gas is available for detection at the facility. (CTBTO 2012h)

Detection at Facility: Basic components of a radionuclide station includes detection equipment, a high volume air sampler and a satellite antenna. Detection equipment chiefly comprises of a gamma ray detector, compressed filter, and decay chamber.

In a facility, air is forced through the air sampler via filter retaining 85% of the particles. The filter with the trapped particles is first cooled for 24 hours following which it is measured in the detection device for 24 hours at the station. The gamma ray spectrum which is obtained of the particles along with meteorological data is sent to the IDC via satellite transfer from GIC for further analysis and information. It also send a state of the health information of the monitoring station to IDC describing the operational ability of that particular station. (CTBTO 2012h)

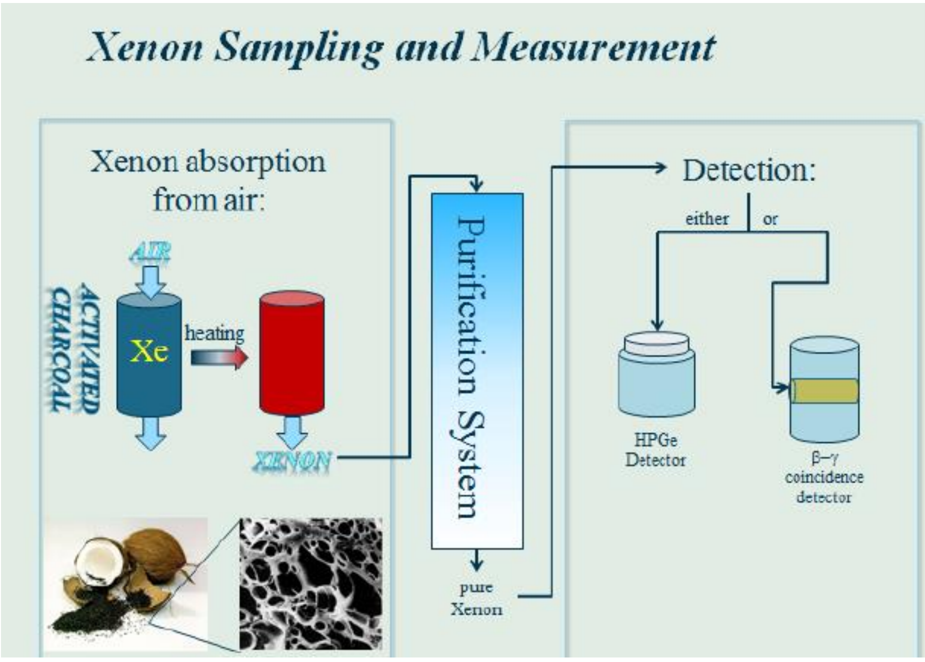

Figure 2.6.1: Schematic explaining Xenon Sampling (Source: Auer 2014)

There are 80 radionuclide stations worldwide in the four regions namely the Americas, Europe and Eurasia, Asia and Oceania, and the Mediterranean and Africa, out of the 80 stations, half of them are equipped with noble gas monitoring technology called International Noble Gas Experiment (INGE). In working principle of INGE, the incoming air is pumped into a charcoal laden purification device for separating and isolating the noble gas xenon while removing dust, water vapour and other impurities. The xenon rich air is then measured for its radioactivity and the spectrum obtained from the measurement is then sent to IDC in Vienna. The working is explained above in Fig 2.5.1. Apart from the from the monitoring stations, there are 16 radionuclide laboratories conducting sampling analysis when necessary and they conduct routine analyses of the samples for quality control of the monitoring stations samplers. (CTBTO 2012h)

The detection facility or stations should be built near the equator since the global wind fields are favourable and stations have a higher probability of detection in a less time. For the air sampling, is better to have a good mixing of upper layers of air with the surface air, windy sites are preferred so that there is higher chance of the air containing the particles or gases hitting the sampler which collects the particles/gases. Particulate sample collection efficiency is directly proportional to the air volume. (CTBTO 2012h)

Table 2.6.1 below shows the characteristics and minimum requirements for the monitoring stations, specifically xenon measuring IGNE stations.

Table 2.6.1: Monitoring System Requirements of RN Stations (Source: Auer 2014)

Characteristics	Minimum requirements
Air flow	$0.4\ m^3\ h^{-1}$
Total volume of sample	$10\ m^3$
Collection time	≤ 24 h
Measurement time	≤ 24 h
Time before reporting	≤ 48 h
Reporting frequency	Daily
Isotopes measured	^{131m}Xe, ^{133m}Xe, ^{133}Xe, ^{135}Xe
Measurement mode	beta - gamma coincidence or high resolution gamma spectrometry
Minimum Detectable Concentration	$1\ mBq/m^3$ for ^{133}Xe
State - of - Health	status data transmitted to IDC
Communication	two - way
Data availability	95%
Down time	≤ 7 consecutive days ≤ 15 days annually

Ultimately, the objective of the radionuclide monitoring network of CTBTO is to provide the 'nuclear forensic proof' for detecting residual radiation from particles or noble gas. By collecting and analysing the sample, radionuclide technology is the only IMS technology which can confirm that an event was nuclear in nature. Thus, due to its strong evidence, it is one of the CTBTO's verification technology which can be synergised with IAEA technology for enhanced nuclear non-proliferation.

2.7 ATMOSPHERIC TRANSPORT MODELLING

Although waveform signals generated from the seismic monitoring stations can assist in differentiating between natural event and an explosion and in locating the explosion, it can't determine whether the event was nuclear in nature or not. The final proof of the nuclear nature can only be confirmed by detection of radionuclides, hence to fill this void and to support the verification regime, the PTS has developed Atmospheric Transport Modelling software (ATM). ATM sets up a relationship between the radioactive air constituent measurements like radionuclide particulates and noble gases at receptor stations to their originating sources respectively. There are two kinds of modelling that can be done through ATM depending on the location. (Wotawa and Becker 2007)

- Forward Modelling: It is preferred when the radioactive originating sources are either known or when their possible number/measurement is small compared to the number of receptor locations. In this case, strength and timing of the original release needs to be determined. Methods used are: Source Receptor Sensitivity (SRS) or Transfer Coefficient Matrix (TCM) based bulk estimates; inverse modelling.
- Backward Modelling: It is preferred when the originating source of the radioactive release is unsure and possible release locations shall be identified. The methods used are: Source Correlation Method; Source Receptor Matrix Method.

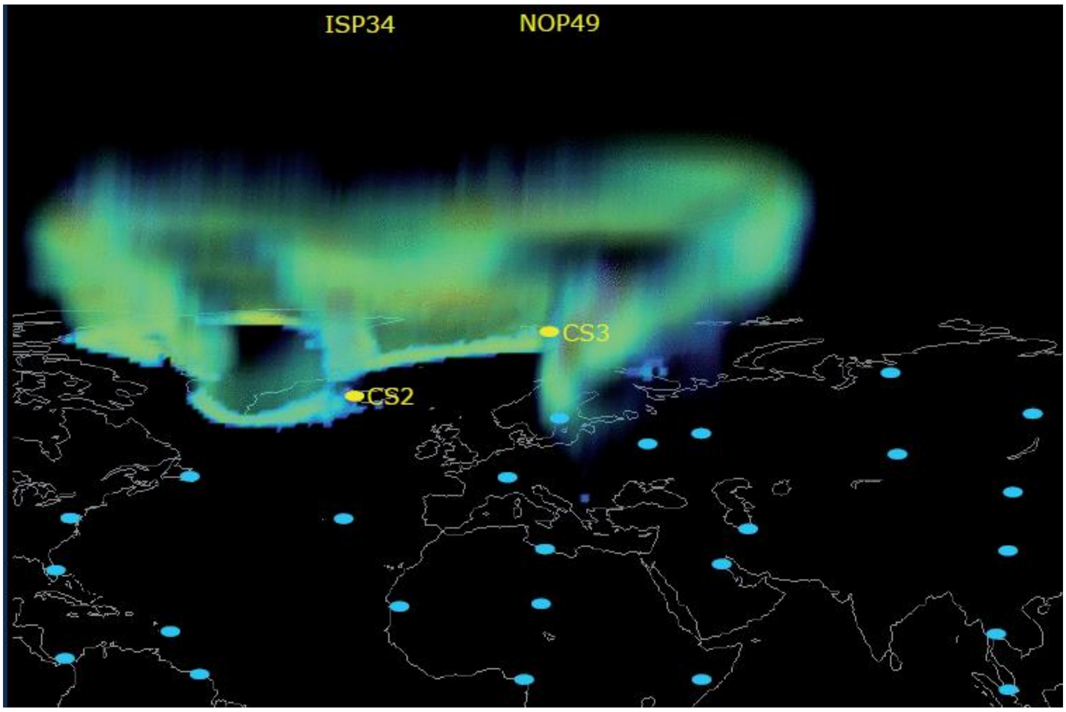

Figure 2.7.1: Illustration of 3D radioactive plume from nuclear debris through ATM (Source: Chen and Hogue 2012)

Working of the Modelling Software: For successful use of ATM technology, there is a need of high quality meteorological data having good accuracy to be merged with the software. By incorporating the meteorological data, it is possible for tracing the various 3D travel paths taken by the radionuclides from the receptor station where they were received back to their point/source of origin, thus giving the approximate source location. This process, termed as Source Region Attribution, aims at producing the best possible approximate source area of the radionuclide or the noble gas. This is the basic principle. (Wotawa and Becker 2007)

Firstly, the software receives first input, which is the high quality & high resolution weather and meteorological analysis report from two globally leading agencies- European Centre for Medium Range Weather Forecasts and the US Centre for Environmental Protection. The Provisional Technical Secretariat then calculates the source receptor sensitivity (SRS) fields for the entire samples obtained from different radionuclide and noble gas monitoring stations, 14 days backward in time. (Wotawa and Becker 2007)

The Lagrangian particle diffusion model FLEXPART is used as the transport code simulating diffusion and transport through backtracking. The adjoint tracer is then released from the monitoring location from end to start time of sampling, being repeated after three hours, fourteen days backwards. The resultant fields are saved in database. If there is an event which qualifies the possibilities for explosion, then SRS fields from all Regional Specialized Meteorological Centres of World Meteorological Organisation (WMO) is demanded, CTBTO and WMO have an agreement for collaboration and sharing of data to reduce uncertainties. (Wotawa and Becker 2007)

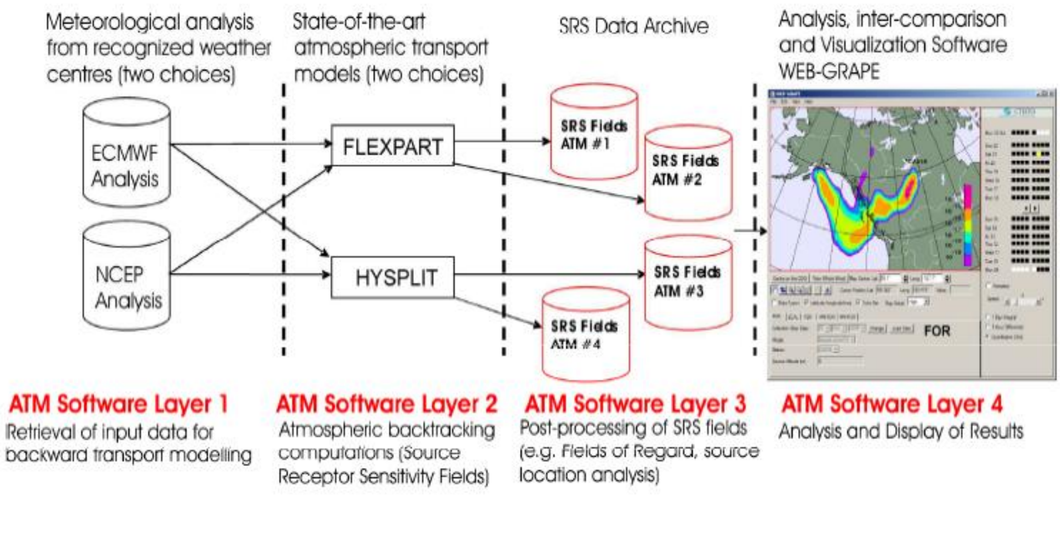

Figure 2.7.2: Schematic of Four Layer ATM System (Source: Wotawa and Becker 2007)

Depending on the pre computed SRS fields, post processing software Web Connected Graphics Engine (WebGrape) has been developed, WebGrape correlates measurement scenarios being input with resulting signals in order to identify consistent source locations of radionuclides being detected. The information of the approximate source is then overlaid with the waveform data from seismic IMS technologies, this is called Data Fusion, it is used to relate the waveform analysis with radionuclide measurement, considering the source located by ATM. Furthermore, SRS concept allows post processing analysis, providing excellent means to verify, validate and adapt the data produces with other technologies. (Wotawa and Becker 2007)

For example, a highly effective post processing tool which also displays the ATM results is beta testing, it produces the results with the event locations and error eclipses from seismic bulletins. The main need of the ATM technology arises considering the fact that seismic technology cannot confirm the nuclear nature of event and the radionuclide technology cannot confirm the location of the source, thus ATM fills this void by backtracking modelling and data fusion. (Wotawa and Becker 2007)

The results of the ATM observations, bulletins and findings are made available to the member states, additionally, they also have the access to the GRAPE software allowing them to generate their customized ATM and data fusion results depending on their information. The CTBTO is only provides the data to the states, it’s their prerogative to make the assessments leading to decisions. This unique backtracking modelling of the ATM makes it attractive for a synergy with IAEA for enhanced nuclear non-proliferation.

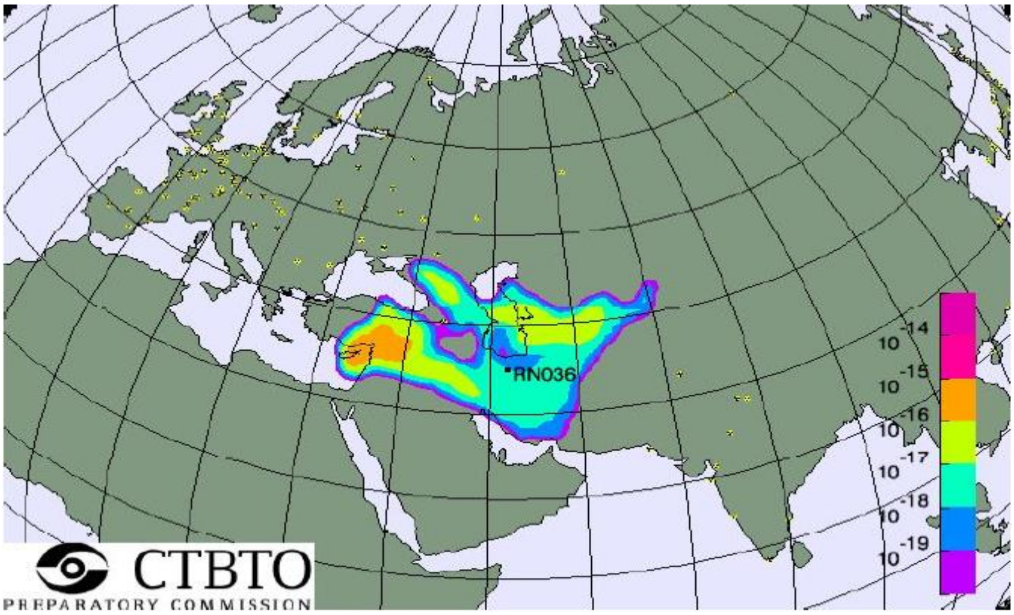

Figure 2.7.3: RN detection intensity from RN36 monitoring station in Tehran.
(Source: Wotawa and Becker 2007)

2.8 INTERNATIONAL DATA CENTER

The International Data Center (IDC) is the key element in the verification mechanism of the CTBTO as its role is to collect, process and analyses the data sent to it from 337 monitoring stations of four kinds around the world via satellites. After processing and analysis, the analysis is presented in form of data bulletin and sent to the member states, which, based on their interpretation of the received data, make their judgements about the nature of the event being ambiguous or not. The IDC started routine data analysis and distribution in February from CTBTO headquarters in Vienna, it archives all data and bulletins in its sophisticated state of the art computer center. Ultimately, IDC processes all the data which makes it the core component of the mechanism as the decision for further action by member states rests on the data analyses given to them. IDC itself has several subdivisions which are explained below:

Waveform Data Processing and Analysis: Seismic, Hydroacoustic and Infrasound technologies form the waveform technologies of the IMS as thy monitor and record the energy generated by events in form of waves. Thus the data being sent by them to the IDC needs to be specifically processed and analysed by the IDC so that it provides the states with crucial information about the event location, intensity, characteristics, and its manmade or natural cause so that they can make appropriate judgements. Data from these 3 waveform technologies is called waveform data, usually, waveform data is displayed as moving traces with x and y axis describing the movement of medium which is being monitored like water, ground etc. on a computer screen. (CTBTO 2012i) Some crucial processing steps in waveform analysis are:

- **Station Processing**: Once the data from each station reaches the IDC, it undergoes intensive automatic analysis detecting signals originating from seismic or acoustic disturbances. On detection of a disturbance, various characteristics of the signals are measured and recorded like time, size and azimuth. It also determines the accuracy and reliability of each parameter. (CTBTO 2012i)

- **Network Processing**: There is always a possibility of recording of the same event by multiple monitoring stations, hence, network processing sorts outs the signals from different stations which originate from the same event. It is a complex task but leads to an estimation of the location of the event, which is essential to determine the size of the event as the signal size is inversely proportional to the distance of the event source. (CTBTO 2012i)

- **Standard Event Lists**: From the completed processing, automatic list of events and bulletins for member states are created. First is the Standard Event List 1 (SEL1) which comprises of events recorded from seismic and hydroacoustic stations as infrasound data takes time for recording due to its slower signal travel through atmosphere. Post, SE1, request are sent for additional data to the auxiliary seismic stations, which when received and combined with the infrasound data leads to a more comprehensive list of events called SEL2. Post SEL2, additional data from late signals is incorporated leading to creation of SEL3, it is the most refined and accurate list of events which is sent to states. (CTBTO 2012i)

- **Analysed and Reviewed Event Bulletin**: Even after the results of SEL3, its important for a human analytical review to provide accurate and reliable information to the member states. Analysts at IDC review every single event of SEL3 eliminating events which are not real, adding missing signals, location correction of the real events. Important feature is to separate out mixed event where two event are fused together automatically and merge the split event, where one event has been processed as two separate events. The analysed event bulletin is called Reviewed Event Bulletin (REB). (CTBTO 2012i)

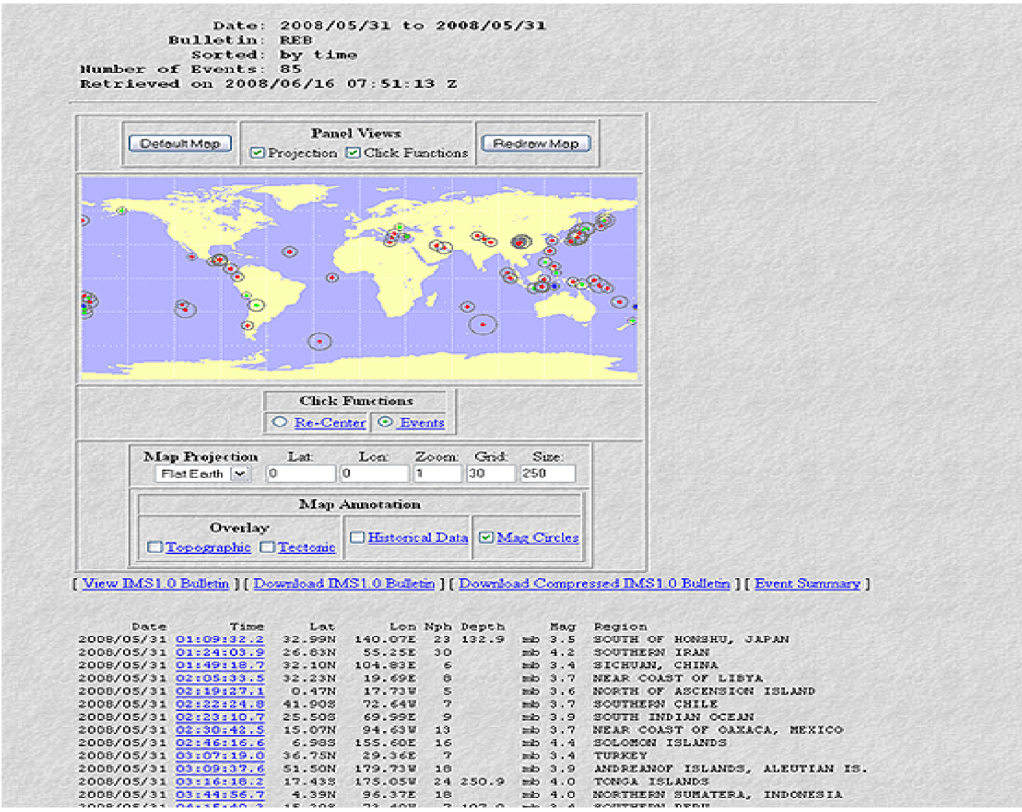

Figure 2.8.1: Reviewed Event Bulletin Listed Events (Source: CTBTO 2012i)

- **Automatic Waveform Event Screening**: This process aims to identify the natural events being listed in the Reviewed Event Bulletin by analysing the characteristics of the events. Through this criteria of characterisation, events can be distinguished as natural and manmade. Pattern of the seismic waves of the event provides information on the nature of the event. There are two kinds of seismic waves, surface waves which travel along earth's surface and body waves that travel through earth's interior. Two kinds of body waves are examined: P-waves & S-Waves, natural events generates smaller P and larger S waves, whereas manmade explosions generate larger P and small S waves. P waves travel faster than S waves noticeable in the seismograms. (CTBTO 2012i)

  Another key criteria for distinction is the magnitude ratio of body waves to surface waves, this ratio is larger for manmade events and less large for natural events. Information on depth of an event can also aid in distinction as due to technology constraints, manmade explosions cannot be conducted in great depths.

  Apart from seismic, even hydroacoustic properties can show the distinction between manmade and natural events. Soundwaves recorded by hydroacoustic sensors can be either H-phase, T-phase or N-phase in which T phase is usually generated from distant earthquakes, H phase from underwater explosions or volcanic eruptions and N phase being noise signals from variety of physical sources like airgun surveys, whale song etc. Eventually, only those events which are distinguished as manmade or where screening provided unclear answers are saved and listed as suspicious events in Standard Screened Event Bulletin (SSEB). (CTBTO 2012i)

Radionuclide Data Processing and Analysis: As we know that although waveform analysis helps in identifying the location of event, it doesn't provide any information as to whether the event is nuclear in nature or nor, for the nuclear nature, the only reliable and accurate technique is analysis of the radioactive particulates or noble gas generated post the event. Every radionuclide monitoring station sends one gamma spectrum, which is a 2D plot of the collected sample with the quantity of observed radionuclides every day. The principle is that since gamma radiation energy for all isotope's decay process is known, the measured gamma radiation energy from spectrometry can lead to determination of the present isotopes in the sample spectrum. This information is shown in a graph where x-axis is the energy of gamma ray emission of the radionuclides identified in sample and y-axis shows the count rate, which determines the quantity of each radioactive substance in the sample. (CTBTO 2012j)

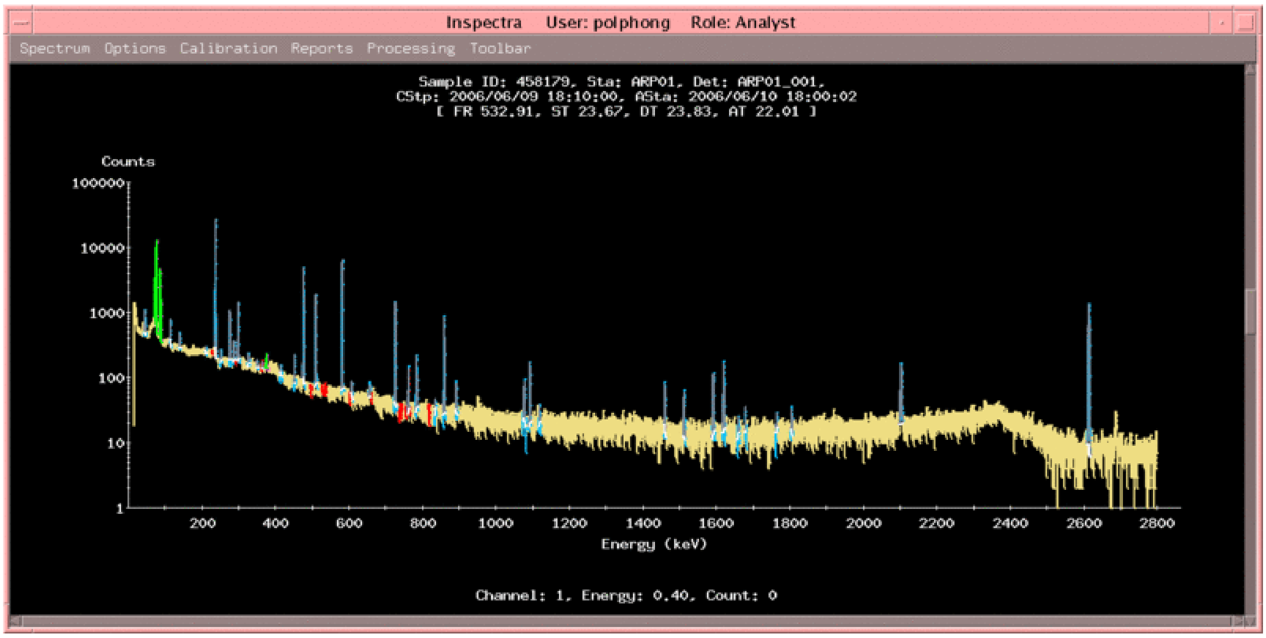

Figure 2.8.2: Gamma ray spectrum from RN monitoring station (Source: CTBTO 2012j)

It is a fully automated process and the results are listed in Automatic Radionuclide Report (ARR) which are reviewed by analysts in the IDC for corrective measures leading to a Reviewed Radionuclide Report (RRR). RRR is followed by automatic radionuclide event screening which uses the existing knowledge of distinction of natural and manmade radionuclides and the quantities and the ratio of elements produced during manmade explosions through the radiation spectra. For ease of inference, using this knowledge, samples are categorized into five groups of radionuclides. Group 1 and 2 belong to natural source radionuclides, Group 3 includes manmade isotopes from civilian power plants and nuclear medicine. It's Group 4 and 5 that are carefully analysed for nuclear explosions, especially Group 5 since it contains specific radionuclides formed from a nuclear explosion. (CTBTO 2012j)

Relevant radionuclides consists of those radionuclides which are formed from nuclear fission in an explosion and those resulting from the interaction of neutrons with surrounding particles. The information regarding the relative quantities of various isotopes detected can provide knowledge of the time of explosion and the environment in which it was conducted. These important findings are then presented in the Standard Screened Radionuclide Event Bulletin (SSREB), which, along with raw data and other bulletins is made available to member states to make their judgements. (CTBTO 2012j)

Operations Centre and Computer Centre: This department of the IDC is tasked with monitoring all the data traffic including incoming data through satellites, automatic data processing and the data bulletins being sent to member states. Its responsibilities are to assure data quality and timely availability. It shows the progress of automatic processing of seismic monitoring technologies with signals signifying data arrival, masking and missing data. There is mutual communication and coordination between the IMS and Operations Centre for clarification of data, Operation centre is the focal point for station operators. It plays a crucial role in assuring high quality and reliable processed data products. (CTBTO 2012k)

Time elapsed between occurrence of an event and its detection by CTBTO is of core importance for the working of the regime. The automatic processing of waveform data and the Standard Event Lists 1,2 & 3 are produced one, four and six hours after the event respectively. The Standard Screened Event Bulletin is completed in two days including the screening out of natural events, thus states have within 48 hours analysed and processed data at their disposal from IMS networks and IDC. (CTBTO 2012k)

However, processed radionuclide data takes time as sample collection depends on global and regional wind patterns, once collected, sample measurement, measurement and transmission takes two days and the Reviewed Radionuclide Report is available in 3 days. A National Data Centre (NDC) is beneficial to facilitate technical interaction between the member state and CTBTO and it also aids member states to obtain, examine and analyse the information sent by IDC which they deem necessary. (CTBTO 2012k)

Due to the importance of the waveform and radionuclide analysis & processing of raw data done by the IDC, it output is reliable, accurate and thus if merged and synergised with an IAEA verification technology, it could prove to be a potent deterrent against nuclear proliferation.

3. RESEARCH AND METHODOLOGY

After listing various nuclear verification technologies being used for the IAEA and the CTBTO, three technologies from each organization were elaborated in detail, the reason for this being the fact that each verification technology highlighted has certain unique characteristics, signatures based on their working principle which makes it suitable for synergizing with another such technology from the other organization. The three synergies which will be discussed in this chapter have been derived considering the common characteristics and parameters of measurement which are found and extended in the synergizing technologies. Hence, we can now make the synergy between technologies discussed in detail in the previous sections of this thesis. Each synergy will lead to an important inference which will be crucial in deriving a combined conclusion.

3.1 SYNERGY 1: RADIONUCLIDE MONITORING (CTBTO) & ENVIRONMENT SAMPLING ANALYSIS (IAEA)

The first synergy is between the Radionuclide Monitoring Division of the CTBTO and the Environment Sampling Division of the IAEA. As described in the section 2.2, environment sampling chiefly consists of bulk and isotopic particle analysis which through spectrometry measures the uranium and plutonium elemental concentration & isotopic composition in the sample.

Inductively coupled plasma mass spectrometry elaborates on the mass peaks for U-238, Pu-239 & Pu-241; Secondary Ion Mass Spectrometry determines the U-235/U-238 ratio; Chemical analysis of particles determines amount pf plutonium, its isotopic composition and the particle age thus, giving information on the reactor conditions.

Synergy Need for ESA: Although the ESA techniques for composition and concentration measurement are sophisticated and accurate, the key drawback is that although it can prove through the Uranium and Plutonium isotopic ratios and concentrations that a state is on the path of a weapons program, it cannot conclusively prove that it has conducted a nuclear explosion since it does not have the ability of measuring radionuclide particulates and noble gases originating due to a nuclear explosion. Its verifications are only done on site.

Thus, sharing the data of the isotopic concentrations and the composition ratios with Radionuclide monitoring stations of CTBTO will strengthen the credibility of the net conclusion drawn regarding a country’s possible violation of the NPT and CTBT.

Synergy Need for Radionuclide Monitoring Stations: Radionuclide Monitoring stations of the CTBTO measures the residual radioactivity and the energy of the particles formed from the fission products of the nuclear explosion. However, the key constraint is in the fact that this monitoring technology heavily depends on the wind patterns putting limitations on its detection, also of special concern are the four isotopes of noble gas Xenon, ^{131m}Xe, ^{133}Xe , ^{133m}Xe and ^{135}Xe which are formed only during a nuclear reaction.

However, xenon isotopes are also formed from production of medical isotopes especially Technetium-99m which is a decay product of Molybdenum -99 and breaking of spent fuel. This can cause confusion as to the source of Xenon. Thus, when radionuclide and noble gas data is synergised with the Uranium and Plutonium concentration & isotopic composition of the ESA technology of the IAEA, concrete evidence of a nuclear explosion can be given. Since, radionuclide samples can only be obtained after a state has conducted a nuclear event, hence ESA data from the IAEA can actually help in understanding the location of the event (due to its data collection prior to the event) and thus calibrating the equipment and correction factor for the wind flow pattern verifying that the Xenon & radionuclide source is same as that of the ESA analysis.

Graphical Analysis of the Isotopic Ratios and Concentration from ESA methods

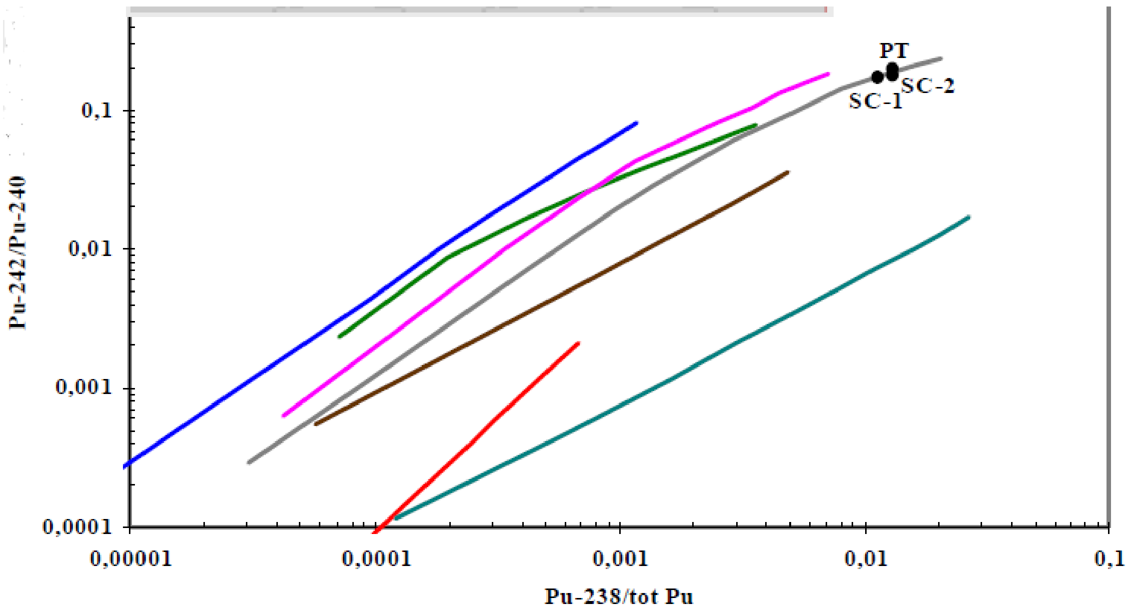

Figure 3.1.1: Graph between Plutonium isotopic ratios (Source: Penkin 2009)

The above graph shows the Pu-238/Total Pu ratio on x axis and Pu-242/Pu-240 ratio on the y axis. It is plotted for different reactor conditions giving information on the use of reactor and enrichment level of Uranium 235.

The graph gives us two important conclusions- firstly, higher abundance of Plutonium-238 is a result of higher initial enrichment of Uranium-235 & secondly, higher Pu-242/Pu-240 ratio result in a softer neutron spectrum which implies high burn up of the reactor as Pu-242 is formed by neutron absorption by Pu-239, Pu-240 & Pu-241 in high burn up conditions.

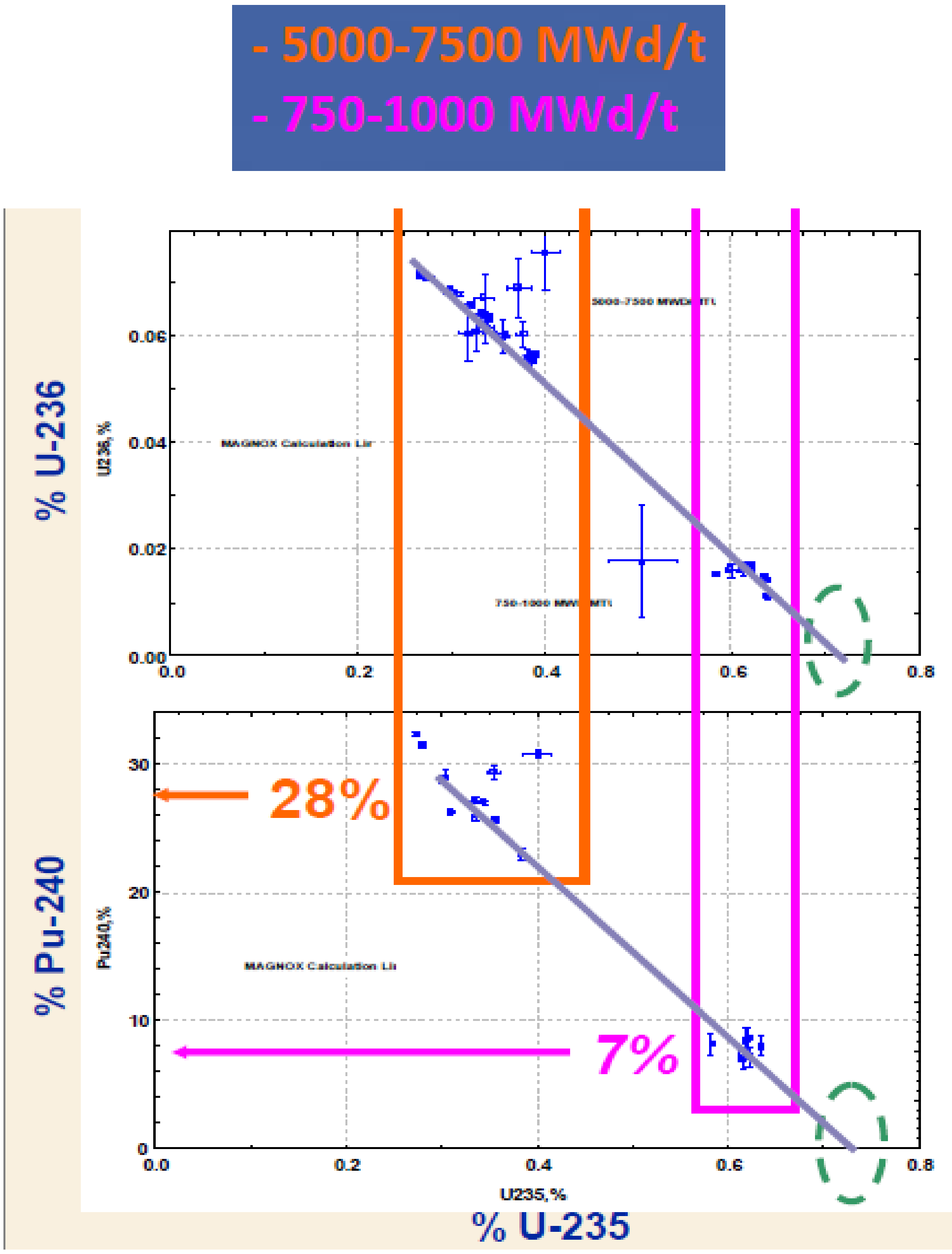

Figure 3.1.2: Graph between U-235% with Pu-240 & U-236 for different irradiation periods (Source: Penkin 2009)

The above graph shows the different levels of U-236 and Pu-240 obtained with respect to U-235 concentrations by varying the irradiation period, that is, the time for which the material is allowed to undergo fission in the reactor core. This eventually indicates the level of burnup in the reactor which basically indicates the fraction of heavy fuel atoms that underwent fission or the energy released per mass of fuel. Burn up is crucial as low burn up is an important condition for production of weapons grade Plutonium comprising over 93% of Pu-239, the most fissile isotope, with the rest comprising of Pu-240 & Pu-242. For production of weapons grade Plutonium, the concentration of Pu-239 has to be greater than or equal to 93%. This stated fact coincides with the sample analysis by IAEA as shown in graph in Fig 3.1.2 where low irradiated fuel at 750-1000 MWd/tonne led to the production of 4-7% of Pu-240 meaning that the concentration of Pu-239 is 96-93%, making it extremely suitable for weapons grade plutonium and thus demanding and warranting further investigation and subsequent action as per the safeguard regime.

Hence, the key parameters for the Environment Sampling Analysis are: U-235/U-238 ratio, Concentration of Pu-239 and Pu-240 and irradiation time (burn up) of the fuel.

Graphical Analysis of Radionuclides from RN Monitoring Stations

Radionuclide testing is apt for able detection of underground or underwater nuclear tests especially through measurement of noble gas Xenon isotopes ^{131m}Xe, ^{133}Xe, ^{133m}Xe and ^{135}Xe as they are among the noble gas isotopes with highest yield during fission of Uranium and Plutonium fuel, making its detection possible due to its long half-life and high measuring sensitivity. The 2013 nuclear test by Democratic People's Republic of Korea (DPRK) was detected by the RN stations through Xenon isotopic ratios.

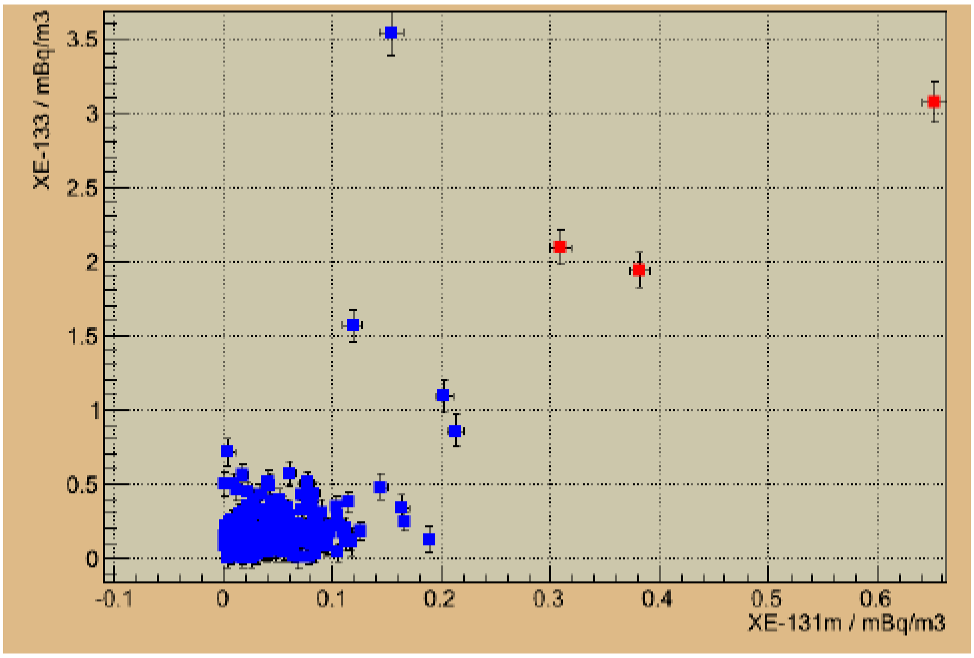

Figure 3.1.3: RN detection of 2013 DPRK nuclear test by Takasaki station, Japan (Source: Auer 2014)

Figure 3.1.3 shows how the DPRK nuclear explosion in 2013 was detected by a noble gas monitoring at a RN station in Japan based on the distinguishing the Xe-133 and Xe-131m concentrations. The high levels of Xe-131m concentrations were atypical for the station as shown in the figure by red dots on the graph, this indicated a nuclear event. It shows how the isotopic ratio and Xe-131m concentration can detect a nuclear explosion. However, as mentioned earlier, Xe isotopes are also released in the atmosphere by production of medical radioisotopes and civilian production of nuclear power, however the levels are different and the events are distinguishable as shown in the graph below.

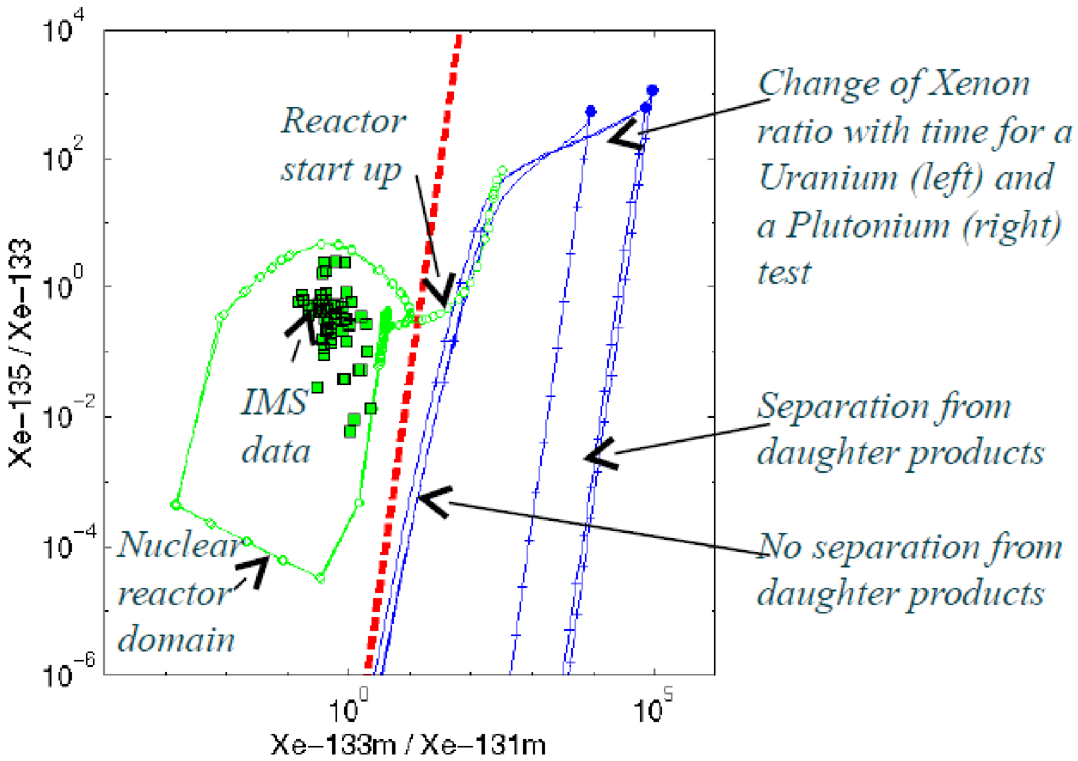

Figure 3.1.4: Graph distinguishing civilian radio xenon emission from military emission (Source: Auer 2014)

From the figure 3.1.4, it is clear that radio xenon isotopes and the ratios are in a different set range for civilian purposes and the red dotted line shows the distinction between the changes in the xenon ratios in case of a uranium or plutonium based nuclear test and the separation of daughter products also differs.

However, considering the fluctuating wind patterns and meteorological parameters, it is crucial to synergise the key parameter of RN technology, i.e., radio xenon isotopic concentrations with uranium and plutonium isotopic concentration and composition to get a strong and credible conclusion regarding the nature of the material used, the reactor conditions and material age.

Synergising Graphical Analysis Results of ESA and RN Monitoring Technology

We assume a hypothetical situation where an NPT signatory member state has gone rogue and is planning to conduct or has conducted a nuclear explosion. In that situation, there are two cases of information exchange possible between the IAEA and the CTBTO for the synergy.

Case 1: **Assuming that the explosion or suspicious event has not happened**, the IAEA through its open sources and information analysis department will inform the Environment Sampling Analysis Division regarding possible violation of safeguards based on multiple sources of information including intelligence agencies, drones, independent satellite information, investigative media etc. The ESA after analysing the information sources provided will ask member state for ESA verification analysis in the suspected facilities and sites, which when complied, will lead to the verification of facilities generating the data for the parameters of Uranium and Plutonium as mentioned above. This data, once collected, will be shared with the RN monitoring division of the CTBTO for enhancing the accuracy and for complementing its measurements. Once the explosion does happen, the RN and noble gas data is collected, a combined inference can be drawn for the conclusion by merging the values of key parameters.

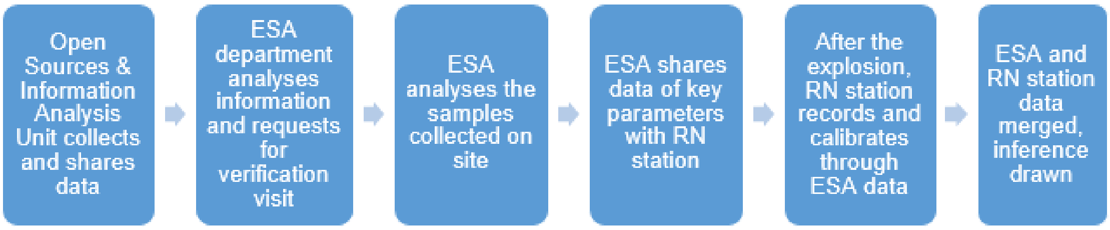

Figure 3.1.5: Flow Chart for Information and Data flow for Synergy under Case 1 (Self)

Case 2: **Assuming that the explosion or suspicious event has happened**, in this case, since, IAEA has no automatic monitoring stations, the data will first be collected by the CTBTO RN stations which will record the atypical radio Xenon ratios, which when shared with the IAEA, will prompt an ESA verification on site of the concerned member state, data collected by ESA techniques will then be synergised for credibility & inference.

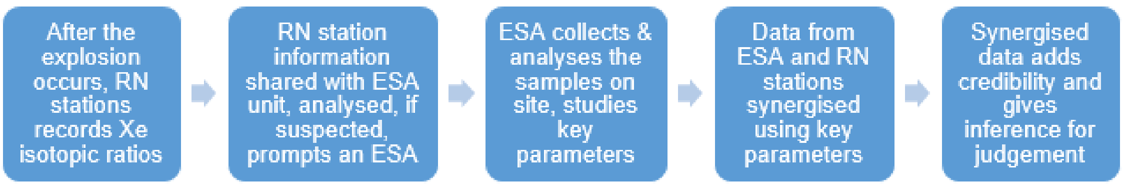

Figure 3.1.6: Flow Chart for Information and Data flow for Synergy under Case 2 (Self)

Depending in the above cases, a matrix consisting of the key parameters values can be formulated and then for different dataset values, the possible reactor condition and nature of the event can be inferred and discussed for further action. One such fundamental matrix table analysing the synergised data from assumed values are shown below deriving the knowledge from previously monitored data.

Table 3.1.1: Matrix Analysis of Synergised ESA & RN station parameters (Source: Self)

Parameters / Scenario	U-235/U-238 Ratio (%)	Pu-240 % concentration	Pu-239 % concentration	Xe-131m mBq/m^3	Irradiation Period MWd/tonne	Nature of Event
Scenario 1	**>90%**	**10-25%**	**75-90%**	**0.3-0.6**	**>5000**	**Strongly suspicious activity with highly enriched uranium, no weapons grade Plutonium, possible medical radioisotopes**
Scenario 2	**<20%**	**<7%**	**>93%**	**0.3-0.6**	**<750**	**High possibility for weapons grade Plutonium, irradiation time very low**
Scenario 3	**20-90%**	**10-15%**	**85-90%**	**0.2-0.4**	**>4000**	**No immediate strong threat, but high Pu-239 and U-235 concentration questionable**
Scenario 4	**<10%**	**20-30%**	**70-80%**	**0-0.2**	**>7500**	**Normal civilian usage, with spent fuel reprocessing, no proliferation concern**

When the matrix above is analysed and compared to predictive calculation, determination of enrichment activities, age of particles, reactor type and irradiation history can be determined. This synergy is crucial especially for CTBTO as it adds credibility to its data with the IAEA data taken onsite, creating a solid verification scheme.

3.2 SYNERGY 2: ATMOSPHERIC TRANSPORT MODELLING (CTBTO) & SATELLITE IMAGERY ANALYSIS (IAEA)

The second synergy is between the satellite imagery analysis (SIA) unit of the IAEA and the Atmospheric Transport Modelling (ATM) division of the IDC of CTBTO. The reason for creating this synergy is as both the technologies aim at detecting the geographical location source for suspicious nuclear related activities having a military dimension.

The IAEA has access to commercial satellite technology which it leases from companies giving uninhibited access to the agency for monitoring the key physical parameters for image interpretation. On the other hand, ATM uses data from WMO and other concerned meteorological organizations as input to the sophisticated software WebGrape for forward or backward modelling when an explosion or suspicious event has occurred. Both these technologies can gain from one another through a synergy.

Synergy Need for SIA: The Satellite Imagery Analysis is a unit in the IAEA which provides analytical services for image interpretation for safeguards inspection. It furnishes geospatial information by identifying features and location on earth and by monitoring suspicious nuclear facilities and activities of the member state, detecting change in site plan & construction history. All the images captured for analysis by the IAEA have some common features which are looked into for detailed information. These key features include size, shape, shadows, shade and signatures. Different sensors used for different monitoring scenarios and purposes are already elaborated in Table 2.3.1 and Table 2.3.2.

Even though the data received from image analysis is very informative, it cannot confirm the chemical presence of a nuclear explosion since satellites don’t have any radionuclide or noble gas monitoring systems. Furthermore, Satellite imagery cannot give strong evidence in case of an underground nuclear explosion or preparation. For these reasons, synergy with ATM of the CTBTO can give apt information to the agency post an explosion about the traces of radionuclides and noble gas from nuclear fission process originating from the approximate geographical radius through backtracking, and this information can then be used to monitor activities in the suspicious area to get details about the site facility, activity and site plan for further safeguard actions.

Synergy Need for ATM: The Atmospheric Transport Modeling department of the IDC of CTBTO aims at locating the source of the radionuclides generated from fission by setting up a relationship between the radioactive air constituent measurements particulates and noble gases at receptor stations to their originating sources respectively.

The approximate location is generated by considering wind patterns and meteorological data from WMO, the data is then input in the software by WebGrape to get the approximate source of the nuclear event. ATM assists the RN stations of the CTBTO in determining the source. However, despite its sophisticated technology, it lacks high accuracy due to its dependency on wind patterns and also due to the background detection of medical radioisotopes which release similar radio Xenon isotopes. Hence, it is not very efficient in distinguishing an explosion from a civilian release of radio Xenon. Furthermore, unlike SIA, it cannot take satellite pictures of the identified source area for image analysis and understanding the cause and the activity for the release of radiation.

Hence, a synergy of ATM with SIA would compliment and benefit both the technologies by providing the chemical evidence of radiation release and giving the approximate location via ATM and on receiving this data, SIA can focus satellite imagery on the coordinates received from ATM data for monitoring facilities and suspected activities which may demand further intervention according to the safeguard regime.

Case Study of Satellite Imagery Analysis

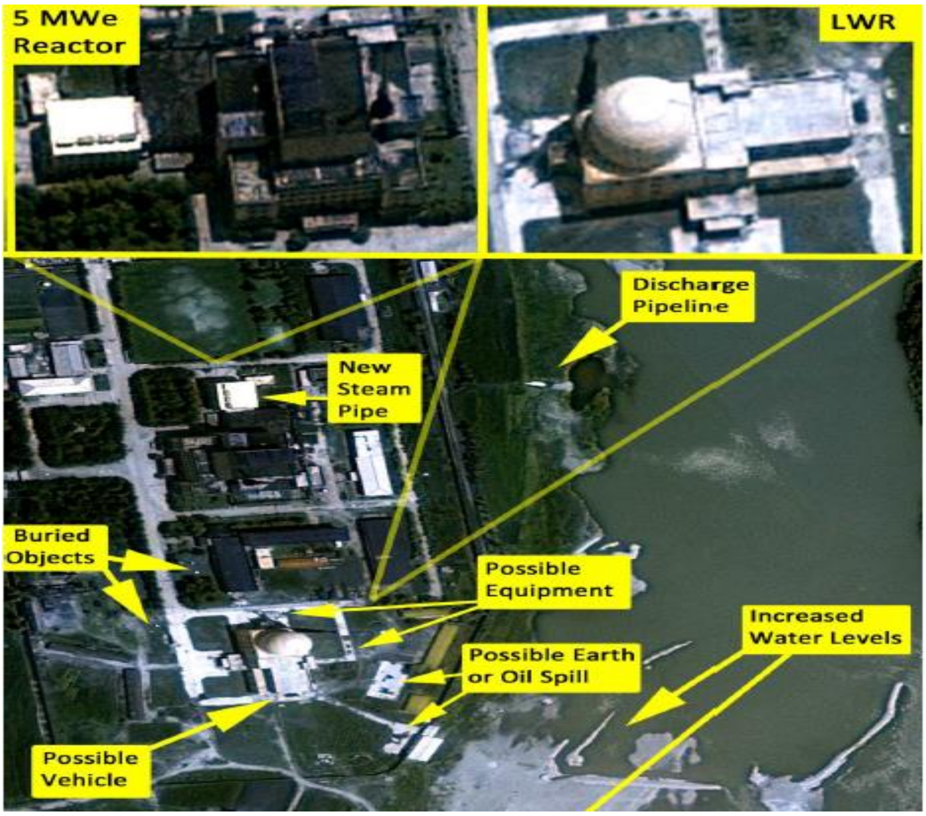

Fig 3.2.1: Satellite Imagery of DPRK'S Yongbyon plant (Source: Albright et al. 2014)

The figure above shows the satellite imagery capturing the developments and activities of the 5 MW electric reactor and Light Water Reactor (LWR) of DPRK's Yongbyon site.

The image was taken on June 30, 2014 and asses the key developments observed. It was observed that DPRK's 5 MW plant shown in the figure 3.2.1 is operational as the water was observed to be discharged to a river near the reactor through a buried pipeline, part of the secondary cooling system of the plant, the imagery also showed that North Korea is renovating and remodelling the cooling system and the steam pipelining of the plant for enhanced plutonium production. Several other renovations were detected the centrifuge complex and the fuel fabrication unit in the southern part of the site. From the site, it seemed that the renovation of the 5 MW plant was being done to make weapons grade plutonium while expanding the centrifuge plant indicating its desire to produce highly enriched uranium for its military nuclear program. (Albright et al. 2014)

Furthermore, construction activities were also detected at the new Light Water Reactor (LWR), objects and large containers are being seen moving on the road connecting to the reactor, cylindrical objects are observed which are seen as toxic waste tanks, also the increased water levels observed from the site suggests the modification of the structure of then bank showing increased construction of the LWR reactor. Thus, the conclusion of the imagery analysis was swift construction and installation of a LWR.

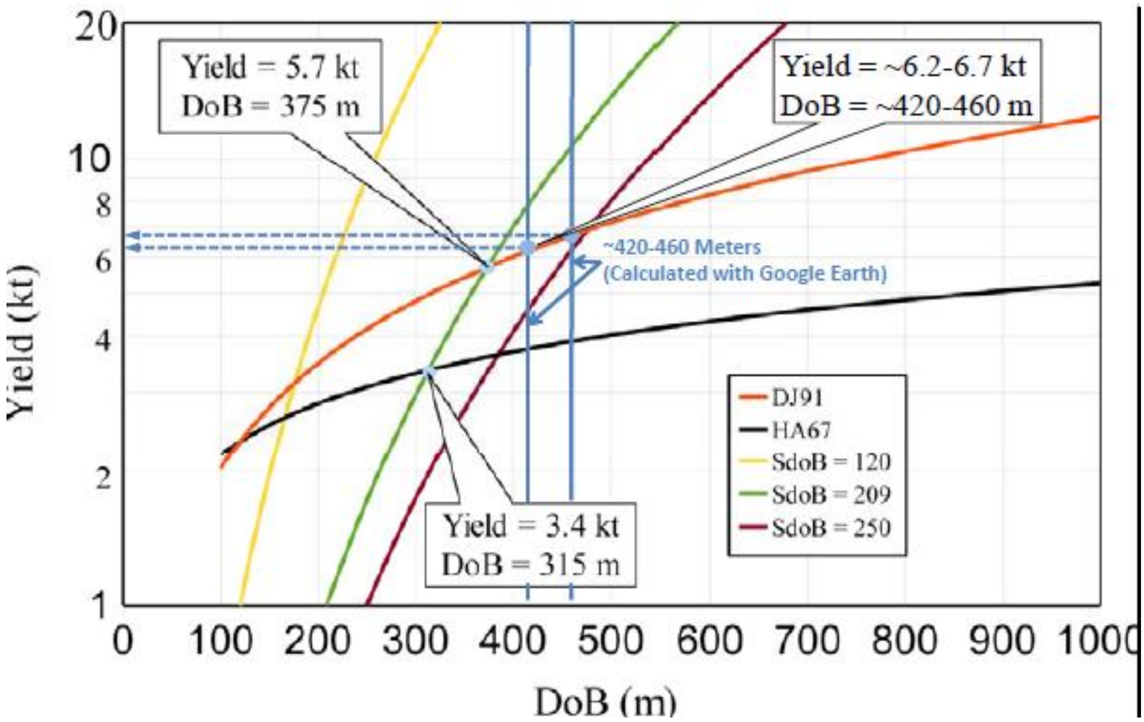

Figure 3.2.2: Nuclear yield estimation for 2009 DPRK test via SIA (Source: Pabian 2012)

Figure 3.2.2 above shows how the satellite imagery analysis and the inference drawn can help in further calculations and details of the explosion. The satellite imagery detected the 2009 DPRK tests and based on the depth of burial (DOB) derived from the topographic elevation data.

The graph describes the explosion by considering two parameters: the yield in kilotons on the y axis and the DOB on the x-axis. It plots various estimated yields for different DOB's based on different scaling models for depth of burial (SDOB's). The different trade off curves are established on the basis of the cavity radius being generated by the explosion and then relating it to the approximate yield by using scaling models developed by different researchers like Denny and Johnson in 1991 (DJ 91). This data was then compared with satellite images recorded during the 2009 DPRK test which compared the approximated yield to the free surface disturbance from the explosion as observed by the satellite imagery. Thus, surface disturbance and topography elevation data combined with the trade of curves gives us an estimate of the approximate generated yield and DOB of the explosion.

Case Study of Atmospheric Transport Modelling

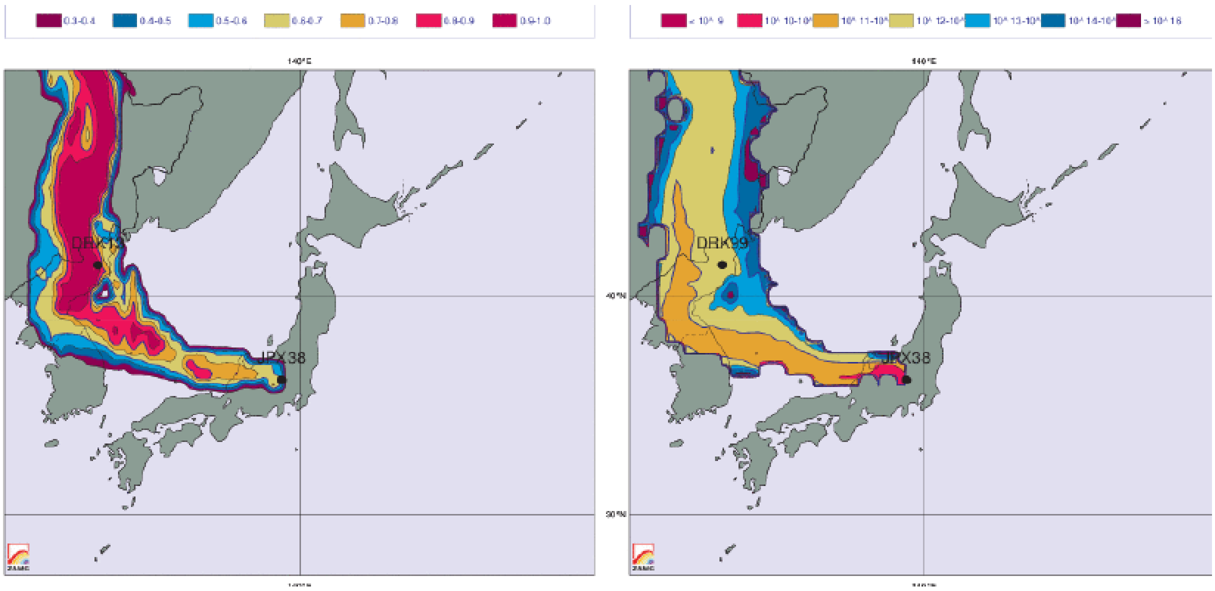

Figure 3.2.3: Source Correlation detecting 2013 DPRK test (Source: Wotowa 2014)

In February 2013, DPRK announced conducting a nuclear test. Post the announcement, about 7 weeks later, CTBTO's RN station 38 in Taksaki, Japan detected an unusually high 131mXe/133Xe ratio. The station was located around 1000 kilometres from the suspected DPRK test site, lower levels of ratio Xenon were also picked up at a RN station in Ussuriysk, Russia. Detection of Xenon 131m and Xenon 133, confirmed the nuclear nature of the event. However, the main question and doubt was whether this release of Xenon was from a civilian or medical nuclear facility or a delayed release from 2011 Fukushima Daichii accident.

To clarify this doubt, source correlation technique of the Atmospheric Transport Modelling was used, calculating the three-dimensional travel path of airborne radioactivity using WMO data which, through backtracking, gave an approximate radius of the possible originating source of the radiation. ATM technology pointed DPRK as the possible origin source. This matched the source strength of 1013 Bq which is line with a 7 week reception of the radiation. Thus, through ATM technology other possible sources were ruled out and DPRK nuclear test site was confirmed as the origin source.

From the above two case studies of SIA and ATM, we have seen how through imagery and location analysis more information of a suspicious event can be determined. Some parameters involved will be fixed while others will change depending on the each activity. Parameters can be defined for the SIA which along with their values can be shared with RN stations for possible ATM measurements in case of an explosion in the future or vice versa. This lays strong foundation for this synergy.

Synergising SIA and ATM Parameters

For this synergy to function, satellite imagery can collect the data both pre and post explosion, however, ATM can only function once radionuclides are detected by RN stations post explosion. Therefore, the synergy and cooperation between Satellite Imagery Analysis of IAEA and Atmospheric Transport Modelling of CTBTO can happen for both proactive (before the explosion) and reactive (after the explosion) scenarios from SIA's perspective, but we consider only the proactive scenario as it would create a more stringent non-proliferation environment. Thus, we assume a proactive information flow.

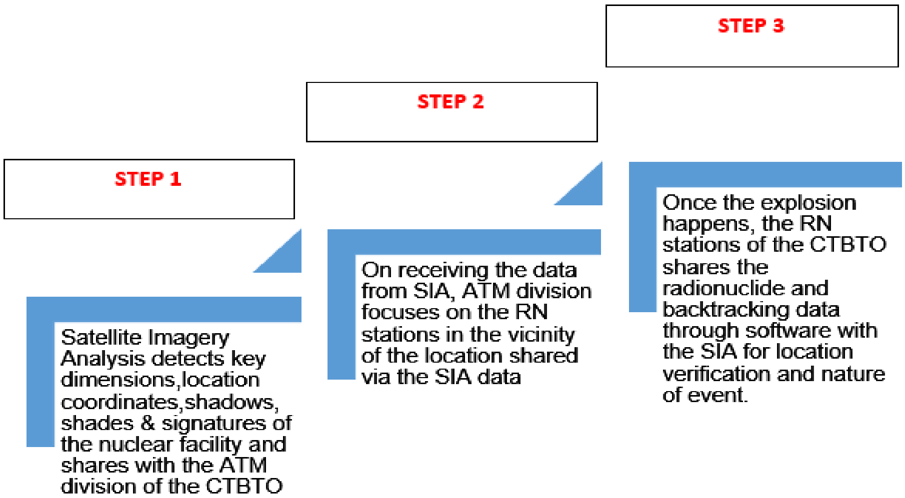

Figure 3.2.4: Information flow for Proactive Synergy Approach (Source: Self)

Figure 3.2.4 shows the information flow in proactive approach. In reactive approach, flow of information reverses, from ATM data to SIA analysis confirming location coordinates.

Irrespective of the information flow, for a more detailed synergy analysis of both the monitoring technologies, we need to understand the core parameters being monitored and shared with each other on a common platform. The satellite imagery analysis is far more extensive in terms of the number of parameters monitored. For specific and elaborate analysis, I consider crucial parameters of the nuclear fuel cycle elements which will be monitored by the SIA department. These steps include: Uranium Mining; Conversion to fuel rods/assemblies or reconversion post enrichment; Enrichment of nuclear fuel; Reactor Type & Construction; Reprocessing of spent fuel. For ATM, key parameters are the $^{131m}Xe/^{133}Xe$ ratio and activity concentration formula which defines source-receptor relationships and aids in the source receptor sensitivity, formula is given by $\mathbf{c_k = \Sigma\, SRS_{ijkn} \cdot S_{ijn}}$ (where c_k is the activity concentration measured in sample k, SRS_{ijnk} is the gridded SRS field pertaining to sample k and S_{ijn} the gridded source field. The sum is taken over all grid cells (i,j) and in the time intervals n prior to the end of the sampling time. This formula is for back modelling for proactive information flow.

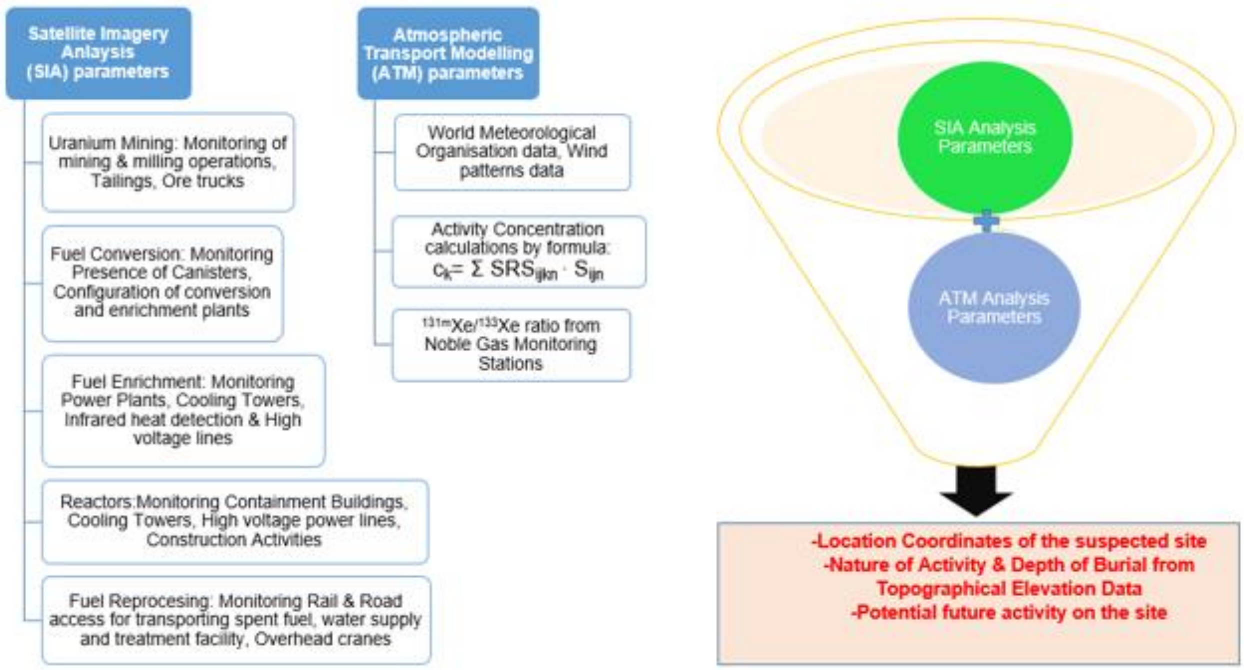

Figure 3.2.5: Synergised Flow of SIA and ATM parameters (Source: Self)

From the figure 3.2.5, it's clear how the parameters of the two technologies are merged for an accurate conclusion of location coordinates of the suspected site. Since, CTBTO makes conclusion via members, it gains the most, as synergised data adds credibility.

3.3 SYNERGY 3: INTERNATIONAL DATA CENTER (CTBTO) & NON DESTRUCTIVE ANALYSIS (IAEA)

The third synergy is between the Non-destructive analysis (NDA) methods of the IAEA and the International Data Center (IDC) of the CTBTO. The main focus of the NDA technologies is quantitatively verifying the amount of nuclear material and weighing of the items to account for any discrepancy without altering the chemical and physical characteristics of the equipment or material being tested.

Whereas, IDC, processes and analyses the data sent to it from all kinds of IMS of CTBTO. It receives and computes carious information after consecutive stages of data processing of waveform and radionuclide to publish standard event lists bulletins for the member states containing crucial information about the event location, intensity, characteristics, and its manmade or natural cause so that they can make appropriate judgements.

This synergy is created so as to relate the data obtained from NDA regarding the quantity of nuclear material and the corresponding waveform and radionuclide processing data of the event through IDC analysis. This synergy and correlation can be beneficial to elaborate on the intensity of the event conducted.

Synergy need for NDA: NDA technologies aims at quantitative measurement of nuclear material with their composition. Main technologies used are gamma spectrometry systems for verification of the enrichment levels and Uranium and Plutonium detection in irradiated and spent fuel & to measure enrichment levels of U-235 and isotopic composition of Pu. Whereas, neutron systems uses the neutron counting mechanism differentiates between the neutrons given out from a single fission event from the neutrons that are formed other secondary fission events or other processes thereby detecting nuclear material quantity and its composition. It also uses other modern techniques like design information verification and laser surface profiling.

Although NDA does provide us with the key physical and quantitative parameters, it is conducted on site and may not give accurately, size of a nuclear explosion, it acts on information from open sources for conducting inspections. It can happen both before and after a suspected nuclear explosion. However, it does not measure the vital parameters of an actual explosion. It measures the material which may be/or was used for an explosion. Hence, a synergy with the IDC of CTBTO will compliment the quantitative data on nuclear material and will shed more light on the intensity of event warranting action.

Synergy need for IDC: IDC is tasked with processing and analysing the raw data which is fed into its systems from CTBTO's worldwide network of monitoring stations. The data is differentiated between waveform data from the seismic based monitoring technologies and radionuclide data from the RN and noble gas monitoring stations. After multiple processing and screening events, data bulletins are prepared in an accurate way filtering the natural seismic and nuclear events from manmade ones, aiding states in making their own judgements.

However, IDC and the CTBTO verification technologies as a whole are reactive technologies, that is, they can detect a nuclear explosion only after it occurs, thus, and synergising the waveform and radionuclide data with quantitative data from NDA technologies will help in better interpretation of the raw data from IMS and enhanced accuracy of the natural event filtering system as characteristics of the explosions of known quantity of nuclear material can be determined.

Case Study of NDA Technologies

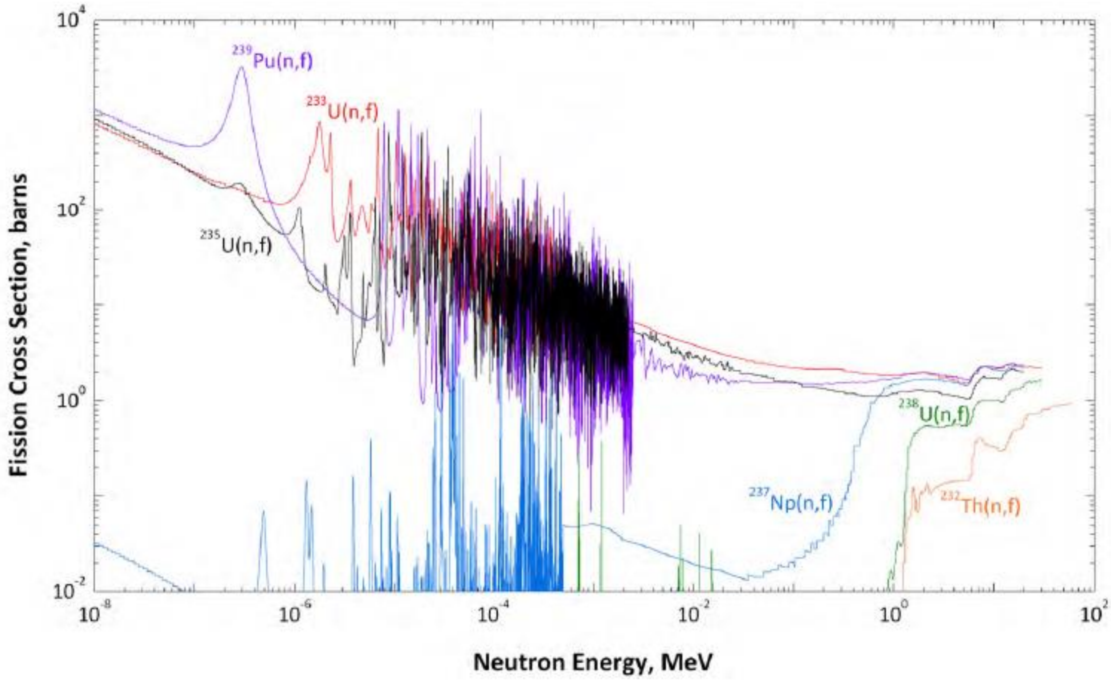

Figure 3.3.1: Neutron Fission Cross Section of various radioactive isotopes (Source: Chichester 2011)

An example of the neutron measurement system used to detect the radioactive materials and isotopes in a sample is the Neutron Fission Cross Section method. This method expresses the probability of interaction between incident neutrons and nucleus of the respective radioactive isotope. For isotopes that undergo fission when bombarded by a neutron undergo a fission cross section, larger the neutron fission cross section, more will be the chances of it undergoing fission reaction at a particular energy of the neutron. Figure 3.3.1, the experiment clearly demonstrates that for the sample being tested for fission cross section, certain highly fissile isotopes like Pu-239 and U-235 have a high fission cross section at low neutron energy range of less than 10^{-5} Mev. And as the neutron energy increases along the x=axis, the fission cross section for Pu-239 and U-235 decreases significantly. Whereas, for U-238, fission cross increase with the increase in neutron energy. Thus, this difference in intensity of nuclear fission cross section for varying neutron energy can help distinguish the different isotopes present in the sample.

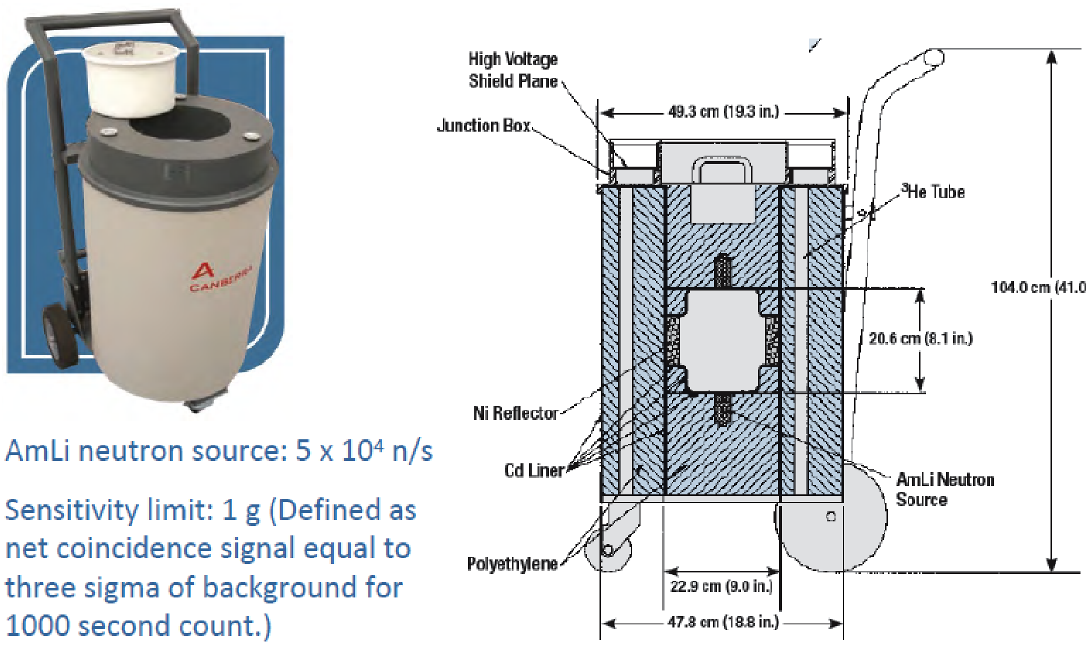

Figure 3.3.2: Active Well Coincidence Counter for U & Pu measurement (Source: Chichester 2011)

An Active well counter is a transportable neutron counter which measures the amount of plutonium and uranium present in a sample with high efficiency. Each counter has a maximum measuring capacity. It consists of americium-Lithium sources which produce the neutrons once the sample to be examined is placed in the chamber, the coincidence counter analyser measures the rate of coincidence counting based on the neutrons being produced by the fission reaction being induced by uranium or plutonium isotopes present in the sample which leads to the determination of its mass based on electronic signals being generated. Low enriched Uranium is measured using the thermal active mode, while fast active mode measures highly enriched uranium samples, fuel pellets and thorium fuel. In passive mode, the well functions as neutron coincidence counter or a neutron multiplicity counter measuring the amount of Plutonium. (IAEA 2011)

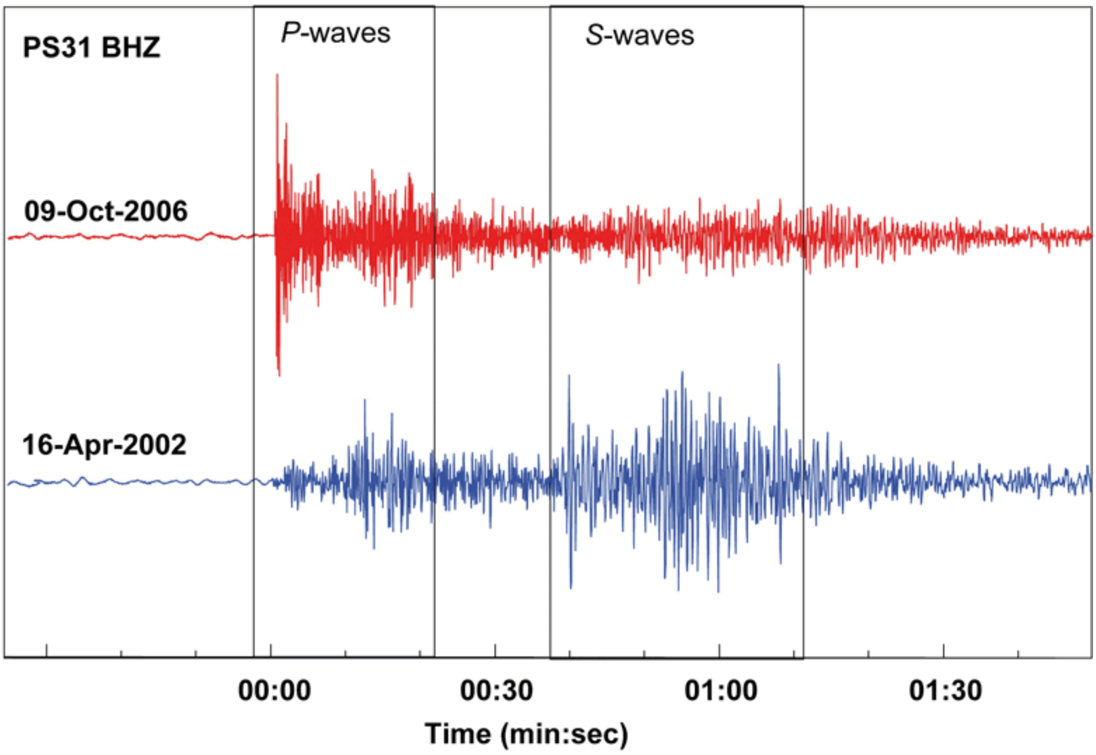

Figure 3.3.3: Comparison of measurements for earthquake and nuclear test
(Source: CTBTO 2012i)

We have studied that there are two kinds of seismic waves, surface waves which travel along earth's surface and body waves that travel through earth's interior. Two kinds of body waves are examined: P- waves & S-Waves, natural events generates smaller P and larger S waves, whereas manmade explosions generate larger P and small S waves. P waves travel faster than S waves noticeable in the seismograms. Shown above in figure 3.3.3, in the red seismogram reading is the measurement of the 2006 nuclear explosion by DPRK and in the blue seismogram is the measurement of a 2002 earthquake in the same region.

We can clearly see from the figure that for the 2006 DPRK test, the magnitude of the P waves generated is much larger than the S waves and in case of earthquake (a natural event) smaller P waves and larger S waves are observed. Also, P waves are measured first in both cases than S waves as P waves travel faster. Hence, the theory mentioned above was proven from this case study.

Another important ratio to be considered for distinction between natural and manmade explosions is the magnitude ratio of body waves to surface waves, for which, the ratio is larger for manmade events and less large for natural events.

Synergising NDA and IDC Analytical Parameters

Like Synergy 1, the synergy between the NDA and IDC will also have two flows of information on two assumptions, assumption one refers to the case when the explosion or suspicious event has not happened, and assumption two refers to the case when the explosion or suspicious event has already happened. In both cases, the flow of information and the subsequent process flow is different.

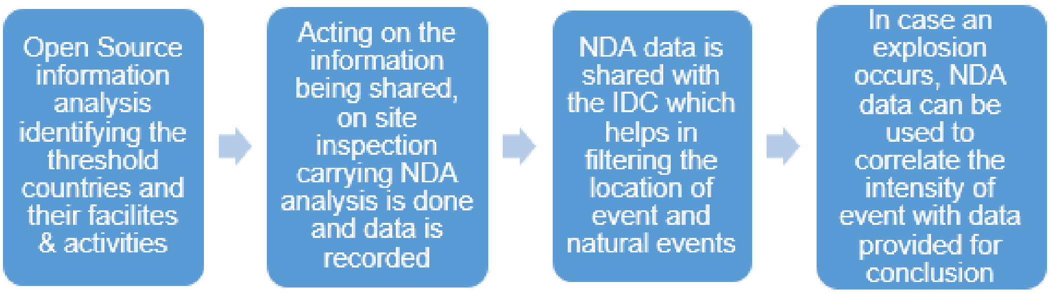

Figure 3.3.4: Flow of information in Assumption 1 (Source: Self)

In Assumption 1, the open source information analysis identifies the 'threshold countries', that is, the countries which are suspected to possesses the significant quantity of fissile Plutonium and Uranium which in the respective conversion time can be manufactured for a nuclear explosive device. This information and the key data from NDA analysis like mass of the nuclear components present, elemental composition is noted and shared with IDC. When the explosion occurs, the IDC filters the nature and location of the event by correlating the measured values from IMS stations with NDA data. Thus, the conclusion from the synergised data between NDA and IDC can add credibility making it easier for states and IAEA to make judgements for further action.

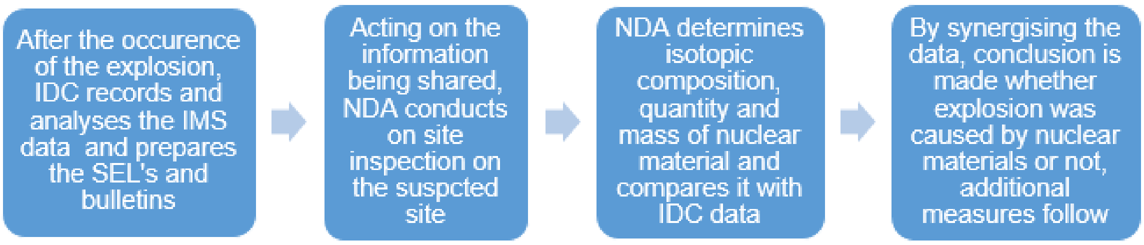

Figure 3.3.5: Flow of information in Assumption 2 (Source: Self)

In Assumption 2, since the explosion has occurred, the IDC records the seismic and radionuclide activity which is shared with the NDA, which compares the IDC data with the measured quantitative values of nuclear isotopes it has determined. This can lead to a conclusion confirming the nature of the event and the intensity of explosion. From this synergy inference, additional measures on the violating state can be taken.

Before synergising data, it is essential to understand the parameters of the NDA and IDC defined by IAEA and CTBTO respectively, through which synergy can be made.

Parameters for IDC: P/S Amplitude Ratio; Body Wave/Surface Wave Amplitude Ratio, Weight of event based on time, size, azimuth & slowness

Parameters for NDA: Significant Quantity of Nuclear Material, Conversion Time

Table 3.3.1: Matrix Analysis of NDA & IDC Parameters (Source: Self)

Parameters / Case	Significant Qty. in Kg	Conversion Time	P/S Ratio (Amplitude)	Body/Surface Wave ratio (Amplitude)	Cumulative Weight of IDC event	Probability by SQ and Conversion Time
Case 1	8 Kgs of Pu-238 (<80%)	7-10 days (metallic Pu)	>1	>1	4.0	0.98
Case 2	8 Kgs for U-233	1-3 weeks	=1	>1	3.50	0.6
Case 3	25 Kgs for HEU	7-10 days (Metallic Uranium)	>>1	>>1	4.8	1
Case 4	75 Kgs for LEU	1 year	<1	=1	3.0	0.25

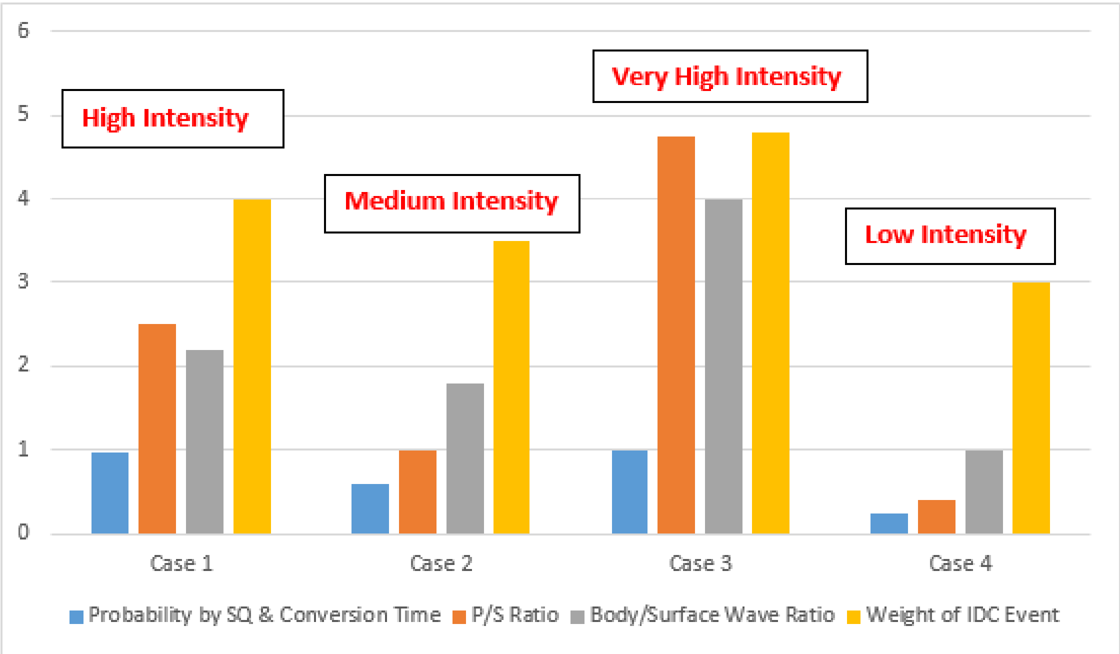

Figure 3.3.6: Characterisation of Explosion Intensity based on NDA & IDC parameters (Source: Self)

4. CONCLUSION AND RECOMMENDATIONS

Overall analysis of thesis considering current research in the field: This master thesis aims to provide a common platform for data sharing and collaboration between two existing organizations, that is, the IAEA and CTBTO under the assumption that the CTBTO has been ratified by all the concerned parties for its entry into force. It builds up on foundations laid by both the organizations in the realm of nuclear non-proliferation and security. Also, considering the current political setbacks for creation of such a synergy as discussed in the introduction, the thesis assumes a more collaborative global political structure essential for the functioning and potency of such synergies. All the synergies were formed and designed considering the common parameters involved between the technologies of both the organizations and also to bridge the weak links and constraints existing in each of these technologies individually. Thus, the primary objective was to synergize the technical resources of the organisations for developing a more uniform database of information mutually important to both IAEA and CTBTO.

The need for such synergies naturally entailed understanding the fundamental principles and working mechanisms of the contemporary verification technologies of both IAEA and the CTBTO. Synergies were specifically designed for the existing technologies for a more practical and pragmatic approach towards its realization.

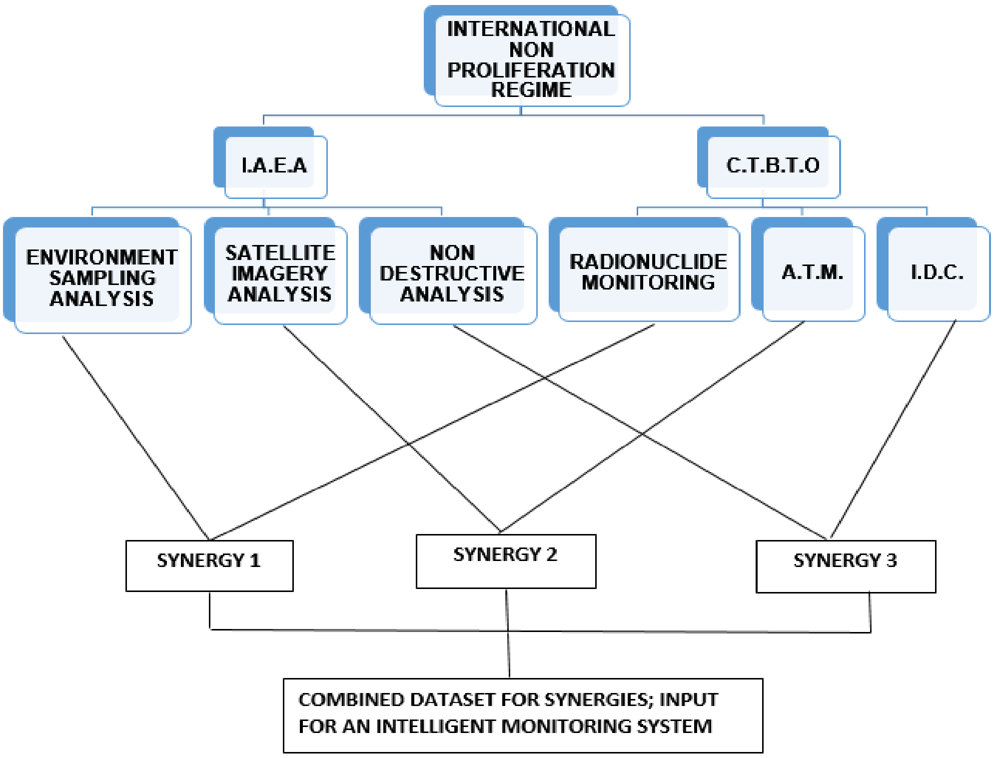

Figure 4.1: Hierarchical Representation of Thesis Research (Source: Self)

Figure 4.1 on the previous page shows the hierarchical structure of the thesis illustrating the synergetic flow of information from different departments of each organisation. To conclude the goals and hypothesis of the thesis, the integration of current technologies into a synergetic platform was done successfully after studying the organisations mandate, fundamental working principles and common parameters.

Overall Significance and Contribution Thesis Research: The significance and contribution documented in the thesis considering the synergies is not only substantial but also exclusive as such synergies have not been designed and studied before. Hence, it provides an additional opportunity for strengthening of the global non-proliferation regime with depicted models containing analysis and inference from authentic data taken from the official IAEA and CTBTO sources. Thus, if the research is continued on these synergies, then the potential contribution they can have for both organisations in general is very high. Some of the key results in brief are shown in Table 4.1 below:

Table 4.1: Key Results & Methodologies used in Synergy Research (Source: Self)

Synergy Number	Technologies Synergised	Type of Analysis	Results
Synergy 1	ESA (IAEA) & RN Stations (CTBTO)	Graphical Analysis with Information Matrix	Nature of Radioactive Material & Isotopic Composition
Synergy 2	SIA (IAEA) & ATM (CTBTO)	Imagery Analysis with dataset meshing	Location Coordinates of the site, Type of Activity being pursued.
Synergy 3	NDA (IAEA) & IDC (CTBTO)	Numerical Analysis with Information Matrix	Intensity of Explosion, Quantity of Radioactive Material

The above table shows the various analysis used for each respective synergy and the key results obtained from each of them. For understanding the significance of the synergies and its Net impact, we need to consider two scales, one weighing **the credibility of the synergised data**, which basically relates to the strength of synergised data considering the efficiency and accuracy of contemporary technologies; secondly, a scale weighing **the probability of the two technologies being synergised** realistically considering the mutual compatibility of the technologies based on common parameters.

The weighing scale for credibility of data has been taken between 0-1, with 1 being most credible, this has been taken considering past successes of the technologies in detection. Similarly, for probability, the scale is also 0-1, with 1 being most probable. Ultimately the impact is calculated as the multiplication of both the scales for each synergy respectively which can be analysed for future developments.

Table 4.2: Simplified Empirical Calculations via weighing factors (Source: Self)

Synergy	Credibility of Data	Probability of Synergy	Net Impact
Synergy 1	0.85	0.8	0.68
Synergy 2	0.75	0.95	0.7125
Synergy 3	0.9	0.75	0.675

From the above data, I have developed a 3-D graph correlating the respective synergy with its net impact highlighting the credibility of data and probability of synergy being considered.

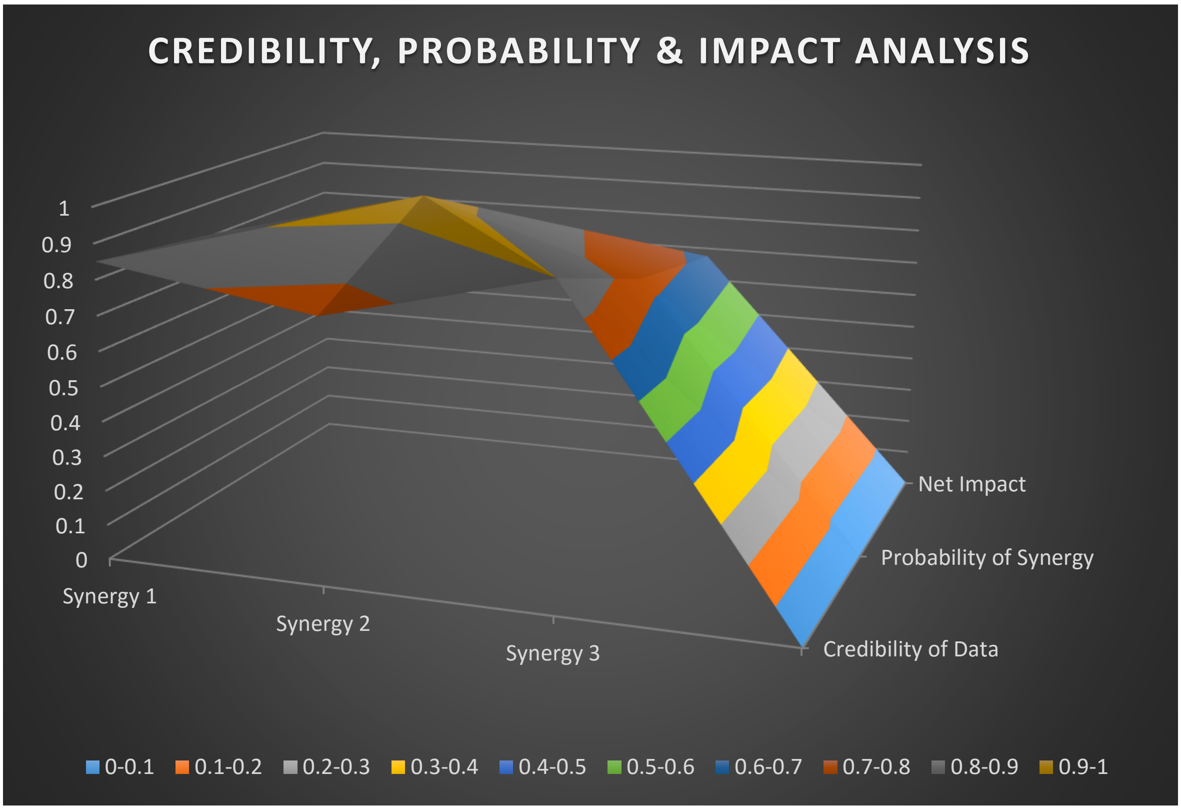

Figure 4.2: 3-D graph measuring the Net Impact of Synergies (Source: Self)

Strengths and Limitations of Research: Like any other academic study, this thesis too has strengths and weaknesses. Key strengths as elaborated earlier includes:

- Elaborated and detailed information regarding vital signs of a facility through synergies; increased confidence level of conclusion.
- Significant financial savings due to synergetic use of channelized resources
- Common platform for data sharing as a confidence building measure resulting in a stronger global non-proliferation verification regime.

While working on the thesis, key limitations identified in this study are as follows:

- Significant political opposition due to the nature and consequences of synergies.
- Possible need for modification of technologies due to certain unnecessary overlapping of information being generated by their measurements.
- Investing in the development and maintenance of a highly sophisticated, confidential and seamless data sharing system between the two organisations.
- Need for scientifically and mathematically derived data for Table 4.2

In spite of these limitations, once further research is conducted in this field, there is a strong chance for the member states to back this technological proposal and it will eventually provide a higher benefit to cost ratio.

Future Research Direction Recommendations: This thesis has highlighted and attempted at analysing the verification synergies. However, significant contribution can be made in various steps taken by the global research community, some key future research directions identified are:

- Development of a mathematical model based on summation, integral calculus and standard deviation of the synergised data which will be input into it. Emphasis on mathematical formula for accurate 'Net Impact' calculation. Use of such a model for quantitative and qualitative analysis for measuring the confidence level of the data vis-à-vis a country's nuclear program in ensuring the safeguards verification mechanism.
- Perhaps, once the model is developed, development of a software which takes in the values of the synergised parameters for assisting the organisation in determining a state's commitment to the non-proliferation regime.
- Continuous research in strengthening the contemporary technologies and development of new verification technologies for possible development of new, enhanced and accurate synergies for non-proliferation monitoring.

Lastly, it is worth reiterating that this thesis does not criticize or object to the functioning of current verification technologies of both the IAEA and CTBTO and recognizes the tremendous contribution made by them to the strengthening of nuclear non-proliferation regime. Instead, this thesis aims at investigating a method, which if researched into properly, can provide a more efficient and accurate system for further strengthening of the non-proliferation regime, as, historically, innovation and development of the contemporary technologies for the safety of humanity is what we strive for.

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