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Overview of Deployed EDS Technologies

H. E. Martz, C. Crawford

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Overview of Deployed EDS Technologies

Harry E. Martz, Jr.[1] and Carl Crawford[2]

[1]Lawrence Livermore National Laboratory
Livermore, CA

[2]Explosives Division, Science & Technology Directorate
US Department of Homeland Security
Washington, DC

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Overview[1]

The term explosive detection system (EDS) is used by the TSA to describe equipment that is certified to detect explosives in checked bags. The EDS, as certified, by the TSL must consist of device for interrogating a bag and an automated detection algorithm (ATD) for evaluating the results of the interrogation. We only consider CT as the interrogation device in this report. A schematic drawing of a CT-based EDS is shown in Figure 2[2].

The output of the ATD is the binary decision of alarm or non-alarm. Alarms may true- or false-positives. Non-alarms may be true- or false-negatives. False positives are also denoted false alarms. The true detection means that the ATD reports an alarm when a threat is present in the scanned bag. The probability of detecting a threat given that a threat is present is denoted the probability of detection (PD). The probability of false alarm (PFA) is the case when an alarm is reported when a threat is not present in a bag. Certification in this context means passing tests for PD and PFA at the TSL.

The results of the EDS include CT cross-sectional images of the bag and specifics about the alarmed objects generated by ATD. These results are presented on a display so that a person may override the decision of ATD and declare the alarm to be a non-alarm. This process is denoted clearing.

Bags that are not cleared by the person are sent to a secondary inspection process. Here the bags may be opened or assessed with explosive trace detection (ETD) in order to clear the bags. Bags that are not cleared at this point are evaluated by an ordinance disposal team.

The CT scanner along with ATD is denoted Level 1 screening. The process of clearing on a display is denoted Level 2 screening. Secondary inspection is denoted Level 3 screening. Vendors of the deployed EDSs supply the TSA with equipment for all three levels. Therefore, the term EDS may include the equipment provided for Levels 1, 2 and 3.

A schematic diagram of an EDS and the levels of screening are shown in Figure 7. The decision processes used as a bag is scanned and cleared is shown in Figure 8. Shield alarms and exceptions are discussed below. Since most alarms are false alarms, the probability of alarm is oftentimes denoted the probability of a false alarm. The expenses associated with clearing false alarms occur in Levels 2 and 3.

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[1] A table with acronyms and their definitions can be found at the end of this document.
[2] Figures can be found at the end of this document. The figures are numbered out of order because this report was derived from multiple other documents.

TSA Requirement Specifications

The TSA specifications that are relevant to the false alarm problem are discussed in this section. Some of the details are omitted because they are SSI or Classified.

An EDS must detect a number of categories of explosives. The PD for each category has to be greater than the threshold x. The average of the PDs for all the categories has to be greater than the threshold y, where $y > x$. The PFA for the EDS has to less than the threshold z. *Detection* must be performed automatically with a system denoted ATD. The humans that participate in Levels 2 and Level 3 are not tested as part of these requirement specifications.

The throughput of EDS must be at least 450 bags per hour. Multiple scanners may be configured in parallel to achieve this requirement. This throughout is measured without consideration of the TSO resolving false alarms. This condition is known as the *human is not in the loop*.

The EDS must report that exceptions occurred. The exceptions include cut bags, shield alarms, ATD time-outs, bag jams and scanner failures. Shield alarms are the largest source of exceptions; there is no requirement specification for shield alarms.

An EDS is also required to record data about the bags being scanned, the threats found by ATD, and the results of Level 2 and Level 3 screening. The data is collected by the FDRS.

Certification Testing

EDSs are certified to meet the above requirements at the TSL using tests that have been described in detail elsewhere [Management-Plan][3]. A summary of the tests is as follows.

Two sets of bags were created, one with one threat per bag and one with no threats per bag. The bags are preserved so that all vendors are tested with the same sets of bags. The bags are not representative of bags in the field because fragile, perishable and valuable items are not included. These test sets are not moved from the TSL so that testing could be performed at the factories of the vendors or on fielded systems.

The bags with threats are run through the EDS and the PD per category and the average of the PDs per category are calculated by summing the binary decision reported by ATD. The bags without threats are scanned and the decision reported by ATD is summed to report PFA. Throughput is measured on the set without threats.

[3] The notation [XXX] indicates a citation to an entry in the bibliography below.

The EDS that passes certification is denoted the certified system. Subsequent tests are designed to assure that all manufactured and deployed scanners match the performance of the certified system.

The following vendors have certified systems: GE[4] (and its predecessor InVision), L-3 Communications, Analogic and Reveal. The majority of the 1500 systems deployed after 9/11 are produced by GE, L-3 Communication and Reveal. All of the 1500 systems are based on CT.

GE has also certified systems based on XRD. However, the throughput of these scanners is too low to be deployed. Therefore, systems based on XRD are not discussed in this section.

Other Testing

Other tests are performed at the TSL in addition to certification. CRT and pre-cert are run to qualify a system before certification. After certification, a post-certification test is run to assure that there are certain configurations and locations of explosives that are not detected. The acceptance criteria for these tests are subjective. The basis for this additional testing appears to be based on the following statement from TSA's requirements: "The detection must not be dependent on the shape, position, or orientation of the explosive, or the configuration of an improvised explosive device (IED)" [Management-Plan].

EDSs are tested in a factory using a factory acceptance test (FAT) and when they are installed at a site using a site acceptance test (SAT). It is not known who controls FAT and SAT. FAT and SAT are run to assure that all systems match the certified system. However, the committee did not hear evidence to show that PD in the field matches the PD obtained during certification.

The vendors scan test phantoms (also known as test bags) periodically to assure that the scanners in the field are performing per specification. It is not known who controls the requirements for frequency of these scans. It is known that the acceptance criteria are set by the vendors.

Deployment

EDSs are deployed in a number of configurations. In-line means that the EDS given bags by the BHS. Stand-alone means that bags are fed manually. Stand-along systems can be in front or begin the check in counter.

[4] Since this report was initially written, GE has changed its name to Morpho Detection

An in-line deployment is shown in Figure 9 and depicted in Figure 1. The blocks in this figure are now described. The process that is followed in the field is denoted SOP.

An EDS consists of the following components: (1) **CT scanner**; (2) **automated threat detection (ATD)** algorithm; (3) **baggage viewing station (BVS)** and (4) **control computer (CC)**. The EDS is integrated with the following other components: (5) **baggage handling system (BHS)**; (6) **baggage inspection room (BIR)** and (7) **ordinance disposal team (ODT)**.

The **CT scanner** produces cross-sectional images of the bags. The images are either a set of contiguous slices, known as 3D or volumetric data, or a variable number of slices at varying slice spacing, known is selective slices. The CT scanner may be combined with an x-ray line scanner, which also denoted a digital radiography (DR) projection scanner. The images from the DR are used to determine where to acquire the selective slices.

The **ATD** processes the images produced by the CT scanner to locate threats. Zero or more threats may be found per bag. The output of the ATD includes descriptions of the threats including their locations within in a bag. Cleared bags (bags with no threats found by the ATD) are sent to the airplane. The performance of an ATD is characterized by its PD and PFA. PD is less than 100% and PFA is greater than 0%. ATD may run on computers in the CT portion of the EDS or on the BVS.

The **ATD** also analyzes the images of the bags and determines if a threat could be shielded from the x-rays used in the EDS. If shielded regions are found in the bag, the bag and its images are sent directly to the BIR.

The **BVS** displays images of bags that contain threats. A TSO may clear the decision of ATD using a protocol known as OSR or OSARP. The procedure used by the TSO during OSR is SSI. Bags cleared by the TSO per OSR are sent to the airplane. If ATD finds multiple threats, the TSO may clear some or all of the threats. The BVS is also known as a PVS. The use of the BVS is also denoted Level 2 screening.

The **BIR** receives bags that have not been cleared by the TSO using OSR on the BVS**.** TSOs visually inspect the threats or apply explosive trace detection (ETD) to attempt to clear threats. If the TSO clears the threats, the bag is sent to the airplane. Bags with remaining threats are transferred to an ordinance disposal team (ODT). The processing in the BIR is known as Level 3 screening. There may be a workstation, denoted the SVS, in the BIR, where the TSO examines the CT slices and the outputs of ATD. It may be possible that the threat, as found by ATD, is not found by the TSO or another item is mistaken for the threat.

The **BHS** consists of a set of conveyor belts, diverting mechanisms and a tracking system. The conveyor belts move bags in and out of the EDS, to the BIR and to the airplane. The diverting mechanisms move the bags between the different sections of the conveyor belts. There are a number of exceptions, in addition to shield alarms, that may cause a bag and its images to be sent directly to the BIR. The exceptions include shield alarms, mis-tracking, operator time-out errors, bag jams in the scanner, and scanner failures.

CT Scanner Hardware

CT scanners collect projections from different angular positions. The projections are inverted using the step denoted reconstruction to produce cross-sectional images. The images provide estimates of the object's linear attenuation coefficient, which is closely related to physical density, and optionally the atomic number. The images are contiguous, resulting in a 3D volume, or selective 2D slices, known as selective-slice. ATD follows reconstruction. A picture of the inside of a CT scanner is shown in Figure 3. The components of the CT scanner are now described.

A typical CT scanner is described in this section. Variations are noted in the text and after the description. CT scanners have five key subsystems: HVPS, x-ray source, detector, gantry, data acquisition system, and reconstruction algorithm.

The HVPS produces high-voltages required to drive the x-ray tube. The average potential of the HVPS is in the range 140 – 180 kV. Some systems use a DC waveform. Other systems add an AC component in order to collect high and low voltage information, as described below. The power of the HVPS is the range 500 – 5000 W.

The x-ray tube produces a Bremsstrahlung spectrum of x-rays from 0 keV to the peak potential of the HVPS.

The bag is transported through the EDS on a conveyor belt. The bag and the conveyor are not shown in Figure 3.

The detector detects x-rays that pass through a bag under inspection. The detector converts the x-ray photons to light. Photodiodes, which are mounted behind the detector, convert the light to electrical charge. There are one or more rows of detectors, where each row forms a fan-beam with x-ray tube as the vertex of the fan. The collection of detector rows forms a cone-beam.

The output of the detector is digitized by the DAS. The outputs of the DAS are either fan-beam or cone-beam projections. These projections are related to the line-integrals of the x-ray attenuation coefficient of the bag along the paths from the x-ray tube to the detectors.

The x-ray tube, HVPS, detector and the DAS are mounted on a gantry. The gantry rotates at approximately 0.5 seconds per rotation. The DAS is sampled at approximately a 1 kHz so that projections are obtained at various angular positions around the bag.

The conveyor belt may or may not be stationary when the gantry rotates around the bag. The scanner is considered to be a step-and-shoot variety if the conveyor is stationary. The scanner is considered to be a helical or spiral scanner if the conveyor is moving.

The outputs of the DAS are sent to a reconstruction computer to reconstruct cross-sectional images. The cross-sectional images are sent to another computer on which ATD is performed. The reconstruction and ATD computers are not shown in Figure 3.

Some EDSs combine CT with a DR scanner. The images from the DR are used to determine where selective cross-sectional images should be acquired. The deployed GE scanners use this combination.

The GE (InVision) scanners combine DR with a step-and-shoot CT scanner. Reveal and L-3 only use volumetric CT scanners. GE (InVision) and L-3 are single energy systems and therefore only produce measurements of the linear attenuation coefficient. The Reveal system obtains dual energy measurements and therefore can produce estimates of the atomic number.

Reconstruction

Most scanners use a process denoted filtered-back-projection (FBP) to reconstruct the cross-sectional images [Kak-Slaney]. The output of the DAS is corrected in order to generate the line-integral data required by FBP. The steps of reconstruction are shown schematically in Figure 4.

If the steps in correction cannot completely reverse the underlying physical effects, images will be degraded leading to inaccurate measurements of the linear attenuation coefficient, density and atomic number. The following operations may be performed during the correction step.

Step	Synopsis
Offset	The electronics (photodiode and amplifiers in the DAS) have dark currents. The dark currents are measured with the x-ray tube off and then subtracted. Temperature drift of the offset has to be considered.
Reference	The current supplied by the HVPS to the x-ray tube may vary. A reference detector measures the incident x-ray flux.
Beam hardening	The x-ray tube produces a polychromatic spectrum. The x-ray attenuation coefficient is a function of the photon energy, with lower energy photons being preferentially removed. A polynomial correction is applied. Unfortunately the different materials use different polynomials so artifacts will remain.
Spectral	Each detector has its own spectral response to polychromatic x-rays. This response is known as the detector’s transfer function. The difference of the transfer function for each detector with respect the mean of the functions for all the detectors is corrected in order to prevent the insertion of concentric rings an bands in images.
Afterglow	The detector and DAS have finite impulse responses leading to a temporal blur of the projections. The impulse responses may be de-convolved.

Scatter	Scattered x-ray photons may reach the detector. Some scattered photons may be eliminated with anti-scatter plates placed in the septa between detectors. Additional algorithmic correction can be used to remove scatter based on measurements from auxiliary detectors or using the projections themselves.
Clamping	The DAS has a finite dynamic range, which is determined in part by the electronic noise in the DAS. The number of x-ray photons reaching the detector may be on the level of the electronic noise. The number of photons is clamped to a positive number. However, artifacts will still be generated in images when this condition occurs.
Gain	Each detector has its own gain. The gain is measured by scanning only air. The values of the air readings are used to scale the readings through a bag. The gains may be a function of the angular position of the gantry,
Logarithm	The DAS/detector combination integrates energy. In order to generate the line integrals required by FBP, the natural logarithm of the readings has to be taken.
Re-binning	The cone-beam projections are processed to form fan-beam or parallel-beam projections. If the projections were acquired using helical scanning, then the movement of the bag during data acquisition is removed using interpolation.

Reconstruction may also be performed using direct Fourier methods or iterative methods [Kak-Slaney]. The iterative methods are not generally used because of their computational expense relative to FBP.

Dual Energy Decomposition

The x-ray attenuation at the energies used for explosive detection is mainly determined by the Photoelectric effect and Compton Scatter. If two different readings are taken for each path from the x-ray source to the detector, each reading with a different x-ray spectral, then line integrals of the Photoelectric and Compton contributions can be found solving two nonlinear equations. These integrals can be reconstructed using FBP to produce images of the Photoelectric and Compton contributions. It is then possible to solve for the physical density and the effective atomic number on a voxel-by-voxel basis.

Different x-ray spectra may be generated by modulating the HVPS with an AC component or two sets of detectors can be stacked on top of each other so that one detector attenuates the photons seen by the second detector. The stacked configuration is known as sandwich detectors. The EDSs produced by Reveal are the only deployed scanners that use dual energy and they use sandwich detectors.

A detailed review of the use of dual energy for explosive detection can be found elsewhere [Ying].

Dual energy may be useful to separate threats from non-threats when only density is used by ATD.

Automated Threat Detection

A schematic diagram of ATD is shown in Figure 5. The purpose of ATD is to segment (find) objects in the cross-sectional images and then to classify if the object is a threat or a non-threat. Additional steps in ATD include compensation for imperfect correction in the CT reconstruction step and extraction of features such as density, atomic number and mass.

The density and atomic number of objects are compared to the values of known explosives. If these values are in the desired range and the mass sufficient, then the object is declared a threat. Vendors may use other features in their classification step, but these features are proprietary. CT is not specific to the chemical and molecular composition of explosives. False alarms occur when non-threats are share the same density and atomic number of threats.

Some vendors may also use the projection data and the images from the DR in their ATD algorithm. ATD may use different methods, denoted paths, for finding sheet and bulk explosives.

False Alarm Problem

False alarms will be generated if non-threats have the same density and atomic number as threats. This is shown in Figure 6 for density. The use of atomic number may be used to reduce the overlap in 2D space.

The correction step in CT reconstruction attempts to correct for imperfections in the projection data acquired during scanning. However, if the corrections are not perfect, then artifacts will be generated in images leading to imprecise measurements of object characteristics. This will require a broadening of the acceptance criteria on object characteristics in ATD leading to an increase in false alarms. Significant sources of errors in the correction step include scatter, beam hardening and the dynamic range of the DAS. These problems occur mainly when large, cluttered bags are scanned.

Because of the finite resolution of the scanner, physical objects may be fused together in the segmentation step of ATD. The characteristics of these fused objects may not be representative of the constitute objects. Artifacts caused by imperfect correction may cause the segmentation step to split objects into multiple smaller objects. The smaller objects may have masses under the mass limit. In order to detect these smaller objects, the mass threshold may have to be lowered, leading to the admission of additional non-threats.

Citations

[Management-Plan] *Management Plan for Explosives Detection System Certification Testing*, DOT/FAA/AR-01/19.

[Kak-Slaney] Kak, A. C., and Slaney, M., *Principles of Computerized Tomographic Imaging*, IEEE Press, 1988.

[Ying] Ying, Z., Naidu, R., and Crawford, C., "Dual Energy Computed Tomography for Explosive Detection," *Journal of X-ray Science and Technology*, vol. 14, 2006, pp. 235-256.

Acronyms/Definitions

2D	Two-dimensional
3D	Three-dimensional
AC	Alternating current
Alarm	A portion of a bag that is a potential threat as determined by the ATD
ATD	Automated threat detection
Bag	Item scanned by the EDS. This usually is a piece of luggage. But it could be items in bins or small pieces of cargo.
BHS	Baggage handling system
BIR	Baggage inspection room
BVS	Baggage viewing station
CC	Control computer
Clearing	The process of ATD saying that a threat is not present in a bag or that the decision of ATD is overridden by secondary inspection.
CRT	Certification readiness testing
CT	Computerized tomography
DAS	Data acquisition system
DC	Direct current
DOT	Department of Transportation
EDS	Explosive detection system. The EDS is composed of a CT scanner, ATD, a workstation, and a control computer.
ETD	Explosive trace detection
FAA	Federal Aviation Administration
FAT	Factory acceptance test
FBP	Filtered back-projection
HVPS	High voltage power supply
ID	Identification or identifier
IED	Improvised explosive device
Mis-track	A bag that cannot be tracked by the BHS
ODT	Ordinance disposal team
OSARP	On-screen alarm resolution protocol
OSR	On-screen resolution
PD	Probability of detection
PFA	Probability of false alarm
SAT	Site acceptance test
Shield	The condition when the EDS cannot view a portion of a bag because the x-ray beam is extinguished of the presence of clutter.
SOP	Standard operating procedure
SSI	Sensitive security information
Threat	A portion of a bag that is a potential threat as determined by the ATD
DR	Digital radiology line scanner
TSL	Transportation Security Laboratory, Atlantic City, NJ
TSO	Transportation security officer: operator of the BVS and worked in the

	BIR
XRD	X-ray diffraction
PVS	Primary viewing station
SVS	Secondary viewing station
FDRS	Field data reporting system

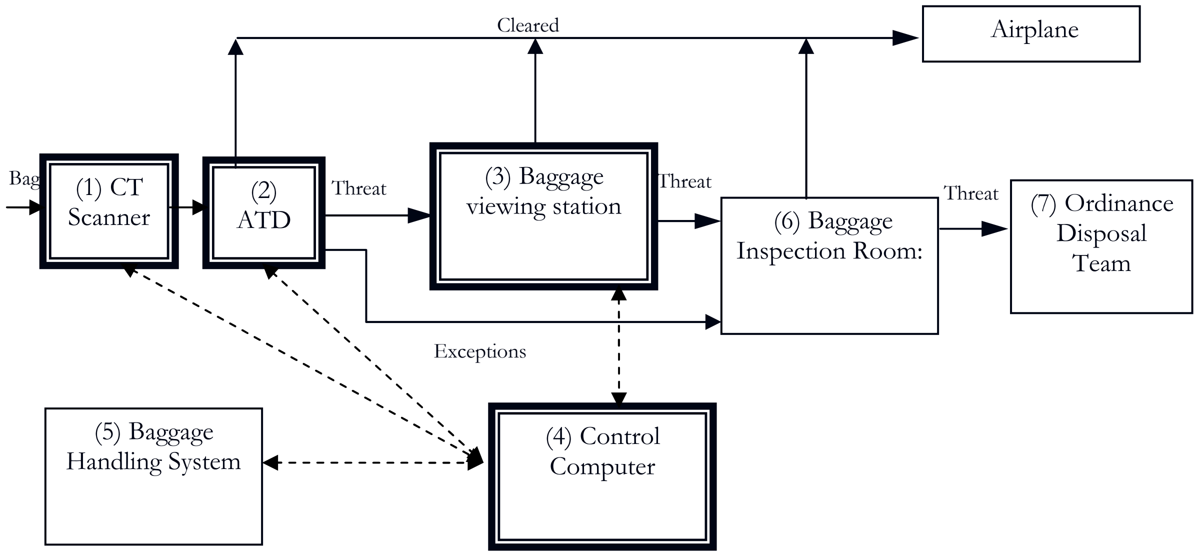

Figure 1. Schematic diagram of an in-line EDS. Wide-lined boxes are components of EDS. Narrow-lined boxes are sub-systems used in conjunction with the EDS. Solid connecting lines show flow of bags and/or images of the bags. Dashed connecting lines show the flow of control and information.

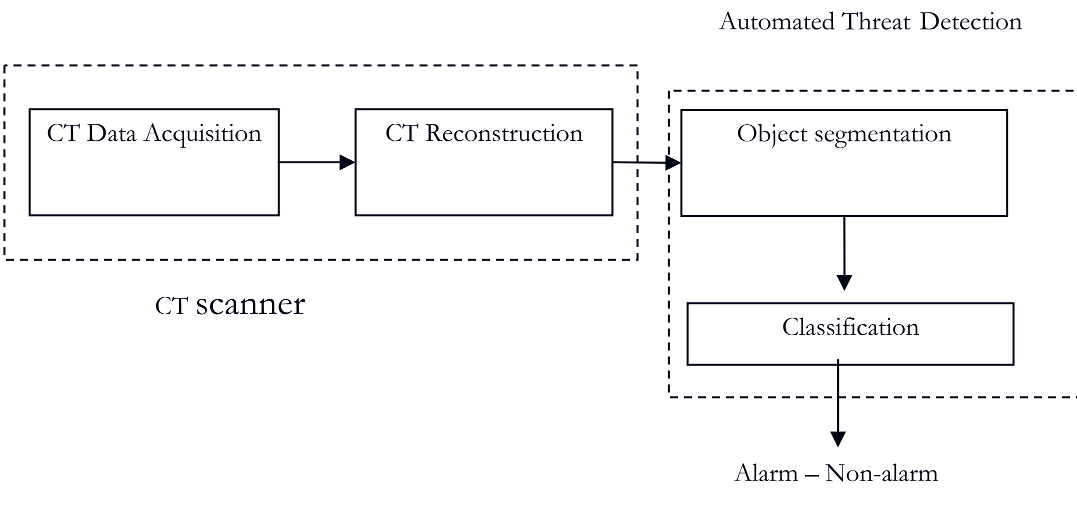

Figure 2. Schematic diagram of a CT-based EDS including ATD.

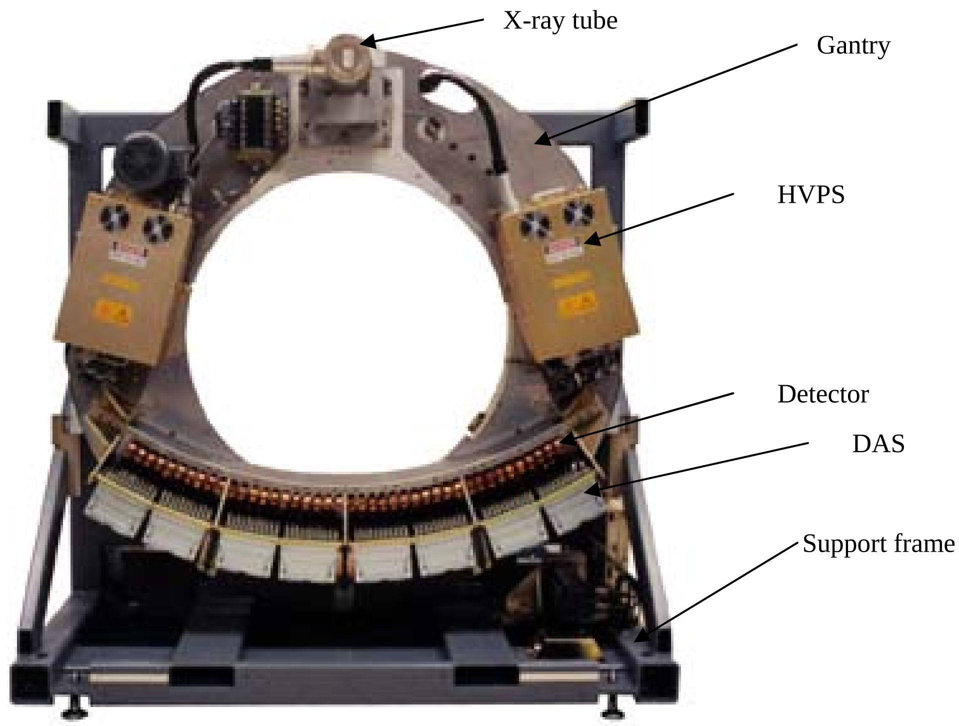

Figure 3. Picture of the inside of a L-3 eXaminer 6000. The annotated portions show the components of the x-ray beam line. [Permission granted from Analogic to reprint this figure.]

Figure 4. A schematic diagram of the CT reconstruction process.

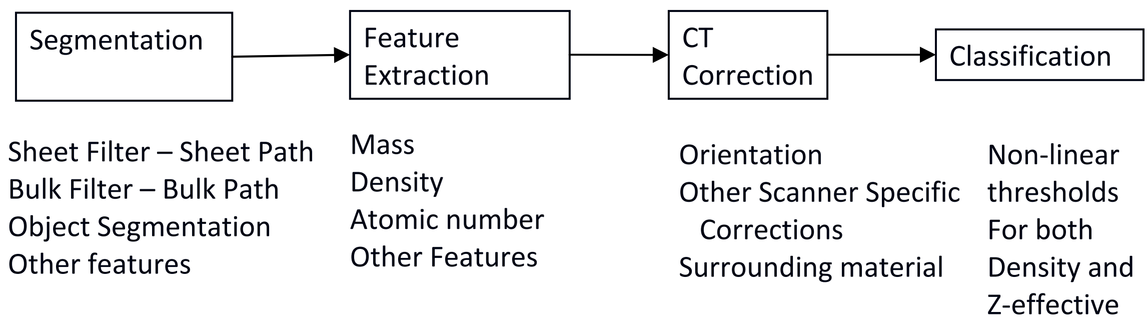

Figure 5. Simplified schematic diagram of one possible version of ATD.

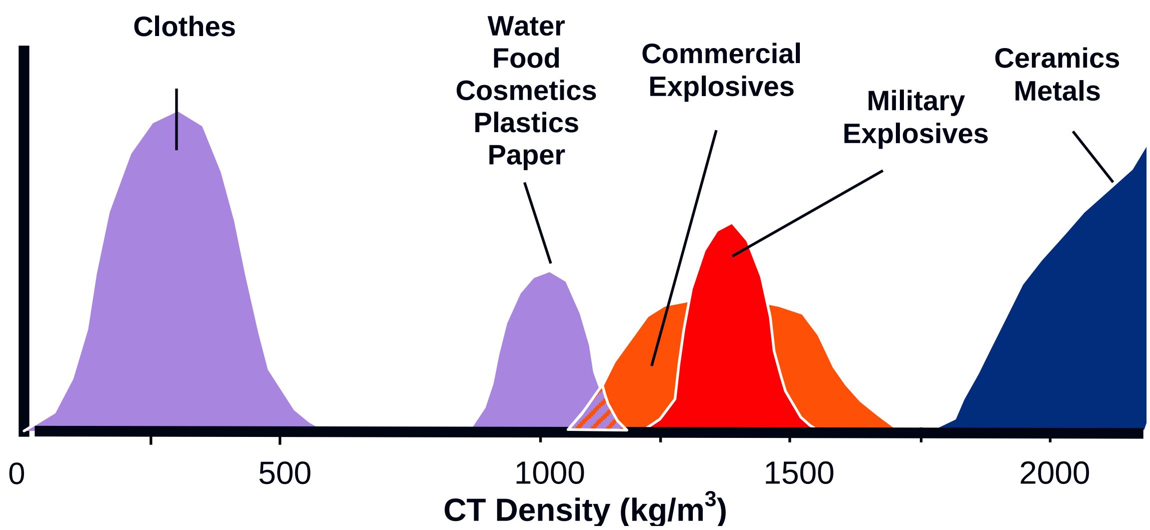

Figure 6. Overlap of threats and non-threats using in CT density space.

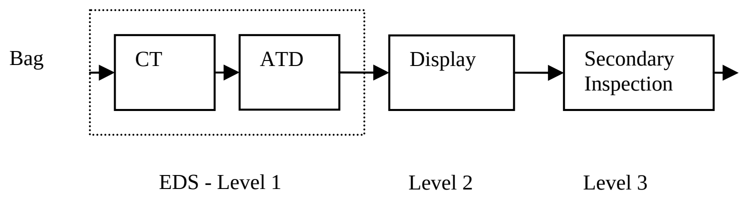

Figure 7: Schematic of an EDS and additional levels of screening used to resolve alarms from the ATD.

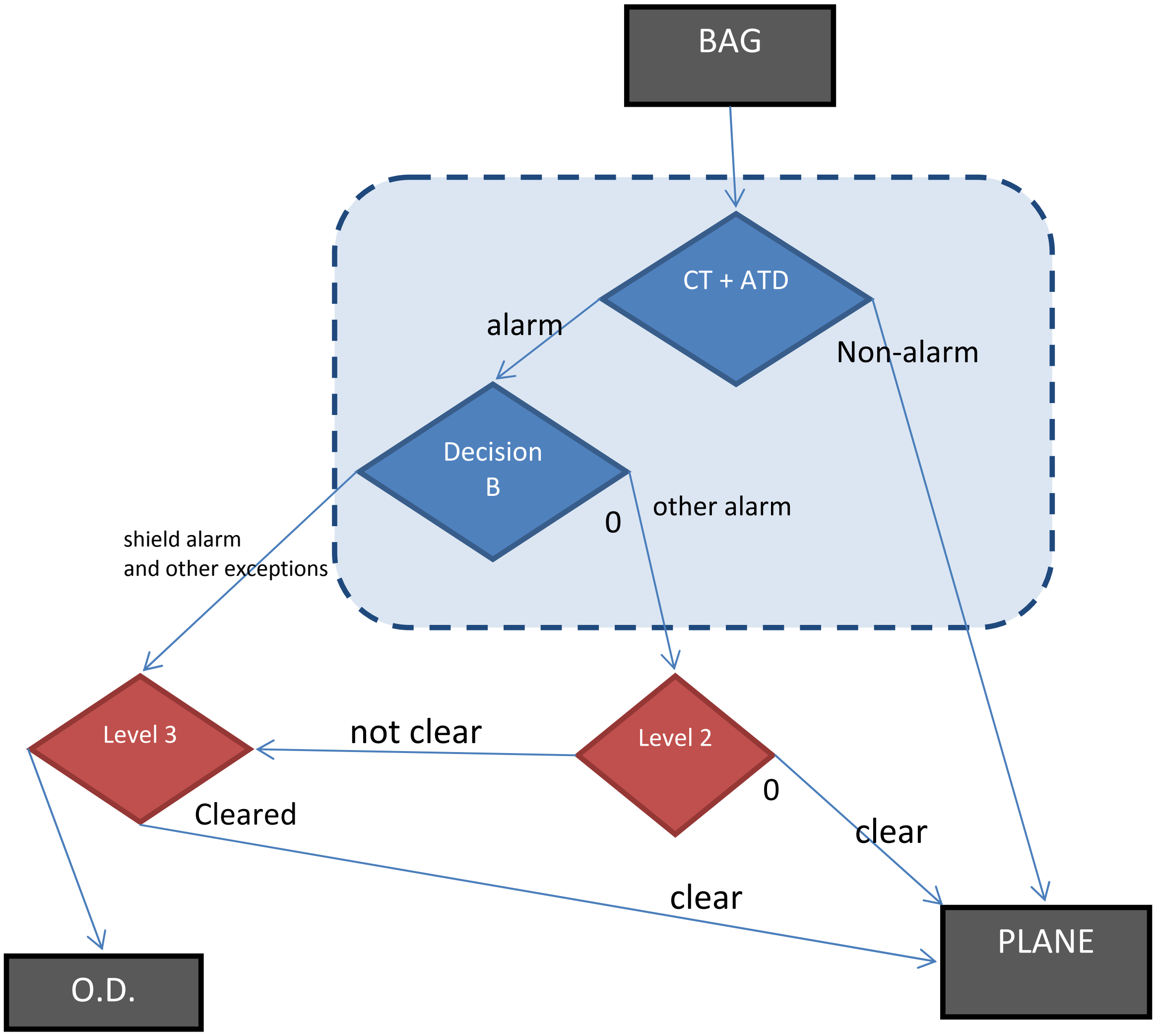

Figure 8: Schematic diagram of the decision process.

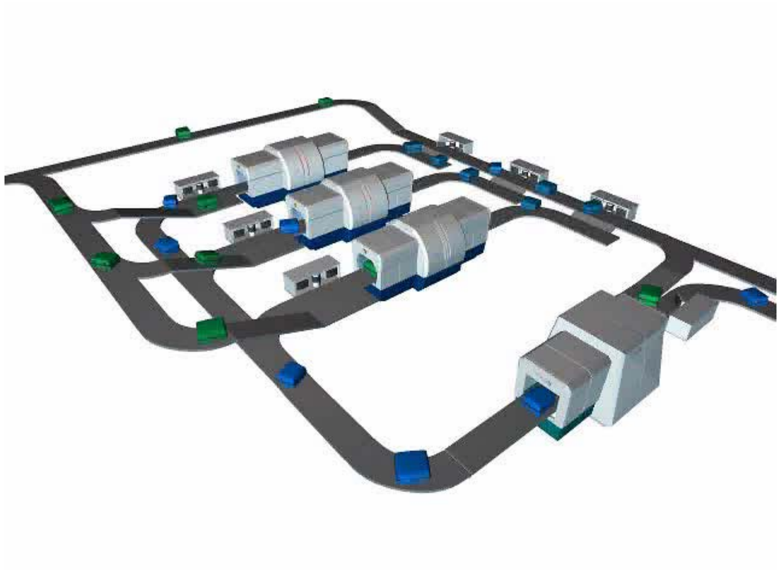

Figure 9. A schematic diagram of four EDSs deployed in an inline configuration.