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Common Launch Acceptability Region Approach (CLARA) Rationale Document

RATIONALE

The Technical Committee which originally created this document is no longer active.

STABILIZED NOTICE

This document has been declared "Stabilized" by the SAE AS-1B Aircraft Store Integration Committee and will no longer be subjected to periodic reviews for currency. Users are responsible for verifying references and continued suitability of technical requirements. Newer technology may exist.

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1. SCOPE

1.1 Purpose

This document was developed by the SAE AS-1B5 CLARA Task Group to explain and document background information and decisions with associated rationale made in development of the CLARA Interface Control Document (ICD), AIR5682. This rationale document is published separately to preserve information that is not required or provided in the ICD but may be important to users.

1.2 Related Documents

SAE ACE paper 2001-01-2953 titled “Common Launch Acceptability Region Task Group” (explanation of CLARA concepts and proposed approach)

SAE Aerospace Information Report AIR5788, Common Launch Acceptability Region (CLAR) Truth Data Generator Interface Control Document (ICD) for the CLAR Approach (CLARA)

SAE Aerospace Information Report AIR5682, Common Launch Acceptability Region Approach Interface Control Document (CLARA ICD)

2. REFERENCES

SAE Technical Standards Board Standard, TSB 003 as issued 1965-06 and revised 1999-05

NOAA-S/T 76-1562 U.S. Standard Atmosphere, 1976

MIL-STD-1760 Interface Standard for Aircraft/Store Electrical Interconnection System

3. CLARA RATIONALE

The following is a collection of paragraphs based on discussions and decisions made at CLARA Task Group meetings. The month and year notation at the end of most of the paragraphs indicate when each decision was reached or significantly modified.

3.1 LAR Basic Assumptions

In early deliberations, the group decided that the CLARA effort would assume a “parametric model” or “fitting algorithm” LAR, not a fly-out. The accuracy of weapon 6DOF models can be quite good, but they are computer resource intensive, and not well suited for real time applications. Airborne and mission planning systems are computer resource limited, so other mathematical models that are not as computer intensive must be used to approximate the LAR. (July 04)

The two types of models that can be used are: dynamic, and parametric. A dynamic model computes fly-out results using current data for the situation at the time. A parametric model uses fitting techniques on previously prepared fly-out data to define the LAR. The parametric model uses a set of functions that attempt to match the output of the weapon 6DOF model without actually modeling the equations of motion. An example of a parametric model is a polynomial least squares fit. Whichever model is selected for the application, dynamic or parametric, it is adjusted so its output matches the weapon 6DOF output to a predefined tolerance. Parametric models are used to avoid the computational burden of doing a fly-out model for a large number of weapons (on a bomber, for example) and to allow easy tailoring of the model to specific weapons by changing only the coefficients. (July 04)

3.2 Release Point Versus Impact Points

The question was asked, why we do not use a grid of release points instead of a grid of impact points? It seems more straightforward to use the release points because that is the LAR. The footprint requires other steps to transform it into the LAR (flip and rotate). (July 03)

The reason we do footprints instead of LAR up front is because that is the current convention and that is what a weapon flight model (e.g., 6DOF) generates. The conversion is simple, so we decided to proceed with the current convention in mind. (Oct 03)

Issues were raised as to why the Footprint Generator was called the Footprint Generator when in reality it does not produce the footprint. It merely produces the raw impact data on a grid. We decided to change the FFBD and the ICD to rename the Footprint Generator to Truth Data Generator. (July 03)

3.3 ICD Definition / Organization

Issues were raised as to why we were doing ICD's for the functional blocks (Data Space Generator, Truth Data Generator, Coefficient Generator, and Algorithm), while a typical ICD would identify the interface between the functional blocks (the arrows between the blocks). Instead of changing the current ICD, we decided to make sure the Input and the Output are covered and identified as such. (July 03)

There was an effort to convert the Truth Data Generator ICD to the beginnings of the single CLARA ICD with TBDs in place of the functional blocks yet to be defined. This was abandoned due to A. Faust's request to continue working on the pieces so that AS-1B5 will be able to submit a document and show progress. The data that go into the individual partial ICD's will go directly into an overall ICD anyway, so it is not a waste of time to complete the parts individually. (July 03)

It was further decided that parallel effort on the other ICDs is necessary to speed the pace to completion and complete each individual ICD with the benefit of check and balance from the effort on the adjacent ICDs. (Apr 04)

Drafts of the ICDs have revealed significant overlap/duplication in content. Now that one is finished and the technical content of another is well established, the group decided to start work on the final consolidated ICD and stop work on individual ICDs. There will be a section for each of the original ICD subjects, and the tables (representing interfaces between blocks) will be shared between sections. (Jan 05)

The group discussed the merits of publishing the glossary and performance specification documents separately or integrating them. We decided to include the glossary (only terms that are actually used) in the ICD. Useful content from the specification was incorporated into this rationale document. (Jan 06)

3.4 Weapon Truth Model Tool

The input/output tables in the what-is-now Truth Data Generator show the input and output to the Weapon Truth Model, which we have now clarified is just a tool used in the Truth Data Generation. We added a paragraph in the Truth Data Generator ICD to cover the output of the whole functional block – the "push" into the database (the Impact Data Set). To help clarify further, we decided to extract the database from the Truth Data Generator to show the database "pulls" by the Coefficient Generator and the Data Space Generator (for refinement of the input data). (July 03)

3.5 Inputs to Truth Model

The group agreed that truth model inputs will include aircraft horizontal and vertical velocities at time of release. It was decided that impact constraints include Impact Angle and Impact Azimuth because these constraints have a major effect on LAR size and shape.

The group decided not to include Angle of Attack and Angle of Sideslip because these are variables used to score the impacts, rather than inputs. (Oct 03), revised (Apr 04)

Pitch and Roll will not be included in Truth Model Inputs. Unlike vertical velocity (climb angle), pitch and roll at time of launch do not contribute significant energy to the weapon, therefore are not significant to the size and shape of the LAR. (Oct 03)

It was later decided that the input file format and example would not be included as part of the ICD in order to allow the user flexibility. Revised (July 04)

3.6 Evenly Spaced Input Points

A requirement for "evenly spaced input points" was discussed. Consensus was that there are good reasons for using unevenly spaced data in many cases, so evenly spaced data should not be required. (Feb 04). For example, extra data points for Mach number may be needed around Mach 1 because of the non linearities which occur there. (Apr 04). Input data elements could well be incremented in evenly spaced increments, but the number of "runs" of the 6DOF can be greatly reduced by using design-of-experiments methods to define the target grid points to be tested. For example, if grid points are flown and tested to find the edges of the LAR, there may be no need to fly all the internal points. (July 04)

3.7 Scoring

The term "score" is used to describe a process of post-generation evaluation of each single output "grid" to define points as "in" or "out" of LAR. In this process, criteria are applied that may not be universal. For instance the development specification for a weapon usually specifies a definition of an acceptable hit, but for a specific class of missions a different, more restrictive or less restrictive, definition may be operationally more meaningful. Alternatively, the development specification criteria may be most meaningful. "Scoring" is the a-posteriori evaluation of a grid of impact state information that uses the operationally applicable criteria for "in LAR" points. The operational LAR is subsequently developed using the impact points that are scored as acceptable.

3.8 Laser Data as Truth Model Input

Concern was raised that in the Truth Model inputs, we do not take into account Laser input data such as Laser Designation Time. Some believe that in some weapons, this may affect the LAR. (July 03)

Laser parameters were evaluated for inclusion in the input data set to the Truth Model. Some objected to removing them while others stated reasons why they should not be considered. The reason for removing them is that they are considered part of the model and not inputs to the model. Conclusion: Go ahead and remove them. (Oct 03)

On further discussion, there may be some types of weapons where lase time would be a key input variable (e.g., Laser guided with no GPS/INS guidance) and lase time may be added as an input variable in these cases. If the weapon were guided to a point with GPS/INS and laser is only used to refine precision in the end game, then lasing time may be assumed to be constant or may have little effect on LAR. (Apr 04)

For a system with guidance mode switches, each mode would actually generate a different LAR (analogous to a different weapon) so guidance mode is not an input variable. (Apr 04)

3.9 Coordinate Systems

Consistency with the MIL-STD-1760 coordinate system was discussed (i.e., Lat/Lon versus X/Y). The group decided that since the critical inputs to the Truth Model are downrange and cross range, this X and Y coordinate system makes more sense since .conversion from Lat/Long is not required. (July 03)

Decision on Coordinate system: The coordinate frame for the launch and target states shall be an aircraft centric local level "right hand rule" coordinate system with positive x forward, positive y right, positive z down, at the time of launch. This decision was made due to the premise that the coordinate system would be aircraft centric. The original intent was a simplification to a LAR computed with wings level at launch. This constraint has now been withdrawn. (Oct 03)

Generally, the origin of launch is the A/C reference frame with the store location's spatial offsets known. For the purposes of generating weapon truth data, since store locations are different for every A/C, the most precise origin would be the store itself without regard to the A/C. However, for LAR purposes, the difference between defining the origin at a store centered position or at an aircraft centered location is insignificant. The origin can be taken at any convenient location on the aircraft/store at launch. (Apr 04)

The coordinate system at the impact state is defined as the launch coordinate frame with the origin translated to the intended target point (the desired impact or intended aimpoint). Impact azimuth is positive from the X-axis toward the Y-axis. The impact angle is measured from the horizontal plane toward the Z-Axis in the plane that includes the velocity vector at impact. (Oct 03)

Wind data direction shall be defined as a vector (air motion "toward" the launch aircraft) in the launch coordinate frame. (Oct 03)

3.10 Wind Model

A "wind model" is used to approximate the horizontal velocity of the air mass as a function of altitude. The coefficient generation process and the aircraft LAR calculation both use a wind model to improve the accuracy of the LAR calculation. The model is generally a simple equation, such as a linear decrease in wind speed as altitude decreases. Actual wind speed at release should be input to the wind model in the aircraft LAR calculation.

The same wind model must be used throughout the process. It must be the same in the LAR coefficient generation, in the onboard aircraft LAR calculation, (and weapon LAR calculations in cases where the weapon calculates LAR), in mission planning LAR calculation, and in LAR tool validation. (Oct 03). This is important because differences in these models create greater errors. Revised (Apr 04)

The "bomber wind model" has been recommended. The "B-52 bomber wind model" was also suggested. A sensitivity study was suggested to determine the differences in various models. A need to determine the "best" wind model was expressed. (Feb 04). This was reconsidered and it was decided that the model used by the weapon builder (or entity developing the LAR truth data base) becomes the standard for each weapon type, and it does not matter that different weapon types use different models. What does matter is that, whatever model is chosen, it is used consistently by all consumers. (Apr 04)

This was reconsidered in (July 04) and the group decided to standardize on a single wind model and describe that model in the ICD rather than referring to another source. Many different models *can* be used, however different models produce different results. All wind models are an approximation and will never perfectly represent the actual wind during the real flyout. A wind model is desired over no wind model since the variance in trajectories due to differences in models is smaller than not using a wind model at all. Selection of a common wind model will also avoid the discrepancies that occur when different models are used.

Several models including one described as "28 knots in all directions" were considered. The "Bomber Model" was the consensus choice. (July 04)

3.11 Units

Units shall be in metric conforming to SAE TSB 003. (Oct 03)

A desire to use degrees instead of radians was stated. TSB 003 allows either to be used, based on the conventions used in the relevant industry. Radian was the final choice to remain consistent with the metric system. (July 04)

3.12 Weapon Type Applicability

The initial focus of CLARA is on short-range, direct-attack munitions. Powered waypoint flyers as well as air-to-air may be considered in the future. (Oct 03)

The applicability of CLARA to weapon types is not determined by store “mission class”. The modeling used in CLARA is applicable to all stores where the kinetic energy plus gravitational potential energy at time of launch is an important factor in determining range. CLARA is not appropriate where energy from fuel provides most of the range capability (e.g., a cruise missile). Users and weapon developers can determine from first principles if their weapon is suitable for LAR development using CLARA methodology. (Apr 04)

3.13 Flat Earth Assumption

The issue of “round-earth” versus “flat-earth” assumptions was discussed. The earth’s curvature at 60 miles results in a relatively small horizontal error of about 0.016% over that of a flat earth. Therefore, a LAR calculated with flat earth assumptions is sufficiently accurate over the ranges of interest. Note that both aircraft and weapon navigation systems typically use round earth (actually ellipsoidal or “geoids”) calculations. The weapon impact accuracy is not affected by the simplifying assumptions used in the LAR calculations. (Feb 04)

3.14 Joint Common Missile Interface (JCMI)

The SAE CLARA Task Group believes that current direct-fire phase of the Joint Common Missile is largely a fire control problem that has many driving factors that are inherently different from our current focus, which is to provide navigation cues to support successful drops of guided, unpowered weapons on fixed targets. The CLARA Task Group may share approach, and process, support periodic technical interchanges, and regularly re-evaluate applicability as respective efforts develop. (Oct 03)

The JCMI was discussed again. It was decided that the CLAR approach is applicable to any bomb-on-coordinate GPS/INS direct attack weapon. The CLAR process in development is directly applicable to JCM, contrary to prior assertion. (Feb 04) ('See Weapon Type Applicability topic (section 3.12 of this AIR) for the general applicability of CLARA methodology)

3.15 Discussion on ICD Versus Another Name

Several times the use of the term “ICD” as the correct document name for the information about the CLARA process was questioned. CLARA decided to continue to call these documents ICDs. These documents will specify the interfaces for each functional block and contain descriptions thereof. (Oct 03)

3.16 Altitude References

There were extensive discussions concerning which reference system for “zero altitude” should be used in the LAR generation processes. The initial work of the group had assumed MSL as the altitude reference. It was pointed out that the GPS navigational frame in which the aircraft and the store have their most accurate (or even only) position information is referenced to the GPS ellipsoid. There is also an Air Force memorandum instructing that positional information for targeting will use the ellipsoid. (Jan 04)

The variables that control the range capability of a store (and therefore LAR) are those that relate to lift, drag, kinetic and potential energy of the store at launch. Potential energy available to the store is the difference between the geopotential at the launch point and the geopotential at the target. For determining potential energy the “correct” altitude references are the heights above the geoid (i.e. MSL). However, there is an issue that there are many models for the geoid, several of which are “standard”. (Jan 04)

Lift and drag acting on the store through its flight path are dependent upon air density. However the required use of the MIL-STD-3013 Standard Atmosphere “Geometric Altitude” model results in the density altitude of the launch aircraft equaling the MSL altitude. (The Standard Atmosphere is referenced to the geoid with a choice of either Geometric or Geopotential Altitudes. The use of a constant gravity value for LAR dictates the use of Geometric altitude in the atmosphere model.) (Jan 04)

Note that the truth data is derived using Height Above Ellipsoid (HAE) and the specified Atmosphere Model. However, the real-time solution computed at launch time can be improved by correcting launch HAE for observed air temperature and pressure and applying the same delta-altitude to the target HAE. (Jan 04)

The Task Group noted that weapon LAR is not sensitive to the assumption of a particular reference coordinate system; especially since the LAR depends on altitude difference much more than on the value of altitude. (Jan 04)

After extensive deliberation the Task Group selected the HAE because of its more standard use by modern weapons systems equipped with GPS. Thus, the aircraft launch altitude should be HAE, the truth model air density should be determined from MIL-STD-3013 Standard Atmosphere model, and target altitude should be expressed as HAE. (Jan 04)

WGS-84 is used in our LAR documents as the standard definition of the ellipsoid. We also realized that the precise altitude is not nearly as important for LAR calculation as it is for the actual target coordinates and guidance. (Apr 04)

3.17 LAR Geometric Shape

Two separate parts of the "LAR Algorithm" are: the geometric shape of the LAR that is used onboard the aircraft; and the functional form of the equation relating each dependent variable (parameters of the geometric shape) and the independent variables (the variables describing the state of the aircraft and target at launch, as well as the values of any constraints). (Jan 04)

It was proposed, in (Jan 04), that the CLARA group adopt a standard for the geometric shape, and that the proposed geometric shape is a polygon of n-vertices where n is specified in the data set and is equal to at least five. (Jan 04)

The definitions of the variables defining the polygon are as follows:

- The reference coordinate system is "stationary" (Earth-fixed). The origin is aircraft centered at the instant of launch and has the x-axis positive in the direction of the horizontal component of the aircraft velocity. The y-axis is normal to the x-axis and is positive to the right in the horizontal plane. The footprint is a geometric shape in this coordinate system translated into the ground plane. The LAR is a geometric shape in the x-y plane of this coordinate system.

- The "reference point" of the polygon is located at coordinates "x" and "y" in the specified coordinate system.

- The number of vertices is N.

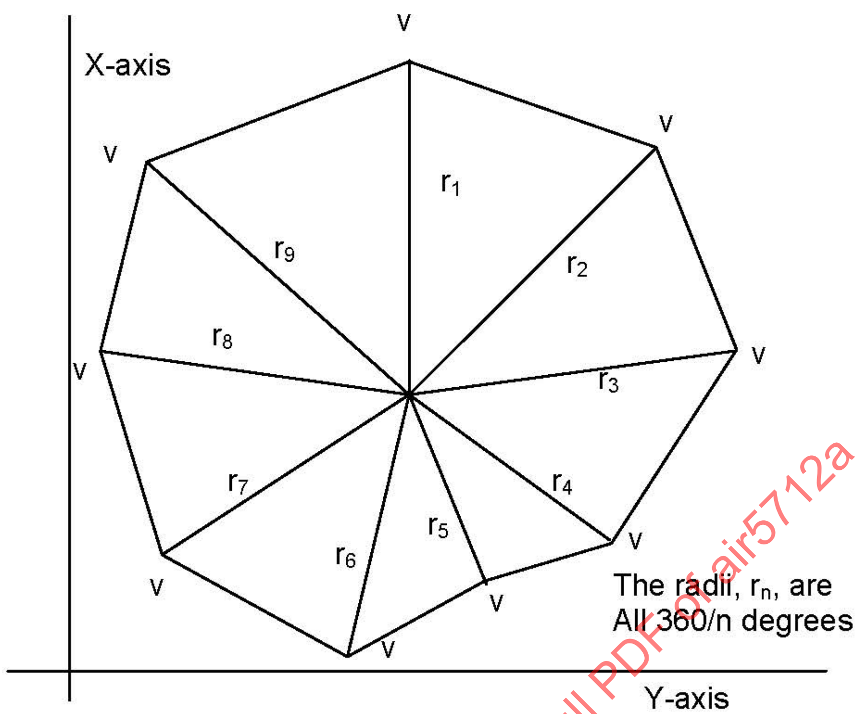

FIGURE 1 - LAR GEOMETRIC SHAPE

- The first vertex of the polygon, v_1, is located on a line through (x,y) parallel to the x-axis at a distance of r_1 in the positive "x" direction.

- Vertices are numbered clockwise from the first vertex and are located at equal angular increments of 360/N degrees.

- Each of the n-vertices is located from the reference point by its angle relative to the positive x axis and a radius to the vertex, r_n.

The polygon in Figure 1 is an arbitrary example to show what a nine-vertices LAR might look like. The polygon is an area at the aircraft (launch) altitude. All launch points within the polygon are members of the set of points from which the store is able to reach the target, subject to constraints and with terminal conditions that meet the externally imposed criteria to be scored as a "hit". (Jan 04)

The consequence of adopting this geometric form is that the geometric shape parameters are the dependent variables of the functions that will be selected as the "math form" of the "LAR Algorithm". (Jan 04)

The independent variables include:

V = the velocity of the aircraft
Alt = the altitude of the aircraft (above Ellipsoid)
Ht = the altitude of the target (ref. To Ellipsoid)
North and East components of wind at the launch altitude
Additional variables arising out of constraints (weapon dependent); such as angles specifying the terminal attack vector

The generic representation of the algorithm will then be the set of equations: (Jan 04)

$x = F_1(V, Alt., Ht, ...)$
$y = F_2(V, Alt., Ht, ...)$
$r_1 = F_3(V, Alt., Ht, ...)$
.
.
$r_n = F_n(V, Alt., Ht, ...)$
.
.
$r_N = F_N(V, Alt, Ht, ...)$

Notionally, each function, F_n, will consist of a summation of m-terms each having coefficients (C_{n1}, C_{n2}, ...C_{nm}). This coefficient matrix is the "verified LAR coefficients" (plus header information required to properly unblock it). (Jan 04)

Rationale for choice of this, or some other shape, will be added when it is available. (Jan 04)

There was a consensus agreement to use the n-sided polygon in all CLAR discussions. (Oct 05)

3.18 AOA and Sideslip References

Angle of Attack (AOA or alpha) and Angle of Sideslip (AOSS or beta) at time of impact are two parameters included in each set of weapon truth data. We determined that these must refer to inertial AOA and inertial sideslip, i.e., body angles relative to the line of flight at impact, since these are the angles that are important in penetration effects. In contrast, alpha and beta refer to body or wing chord angles relative to the air mass in most aerodynamics work. The inertial values are different than the air mass values if there is any wind. (Jan 04)

3.19 Tab Delimited ASCII

The group discussed various file formats for distribution of the Truth Database. We initially chose tab delimited ASCII because it is adequate for the task and can be generated and read by everyone. (Jan 04)

Delivery of CLAR data base files in binary form (as opposed to ASCII text) was discussed. Advantages of binary are smaller file size and faster computer manipulation of the data. However, definition of the binary file tends to depend on the type of processor and software being used, making it undesirable as a standard. (Feb 04)

This was assessed again, as there was serious concern about file sizes and processing time becoming unmanageable with ASCII files as large numbers of footprints are generated. We decided to allow use of other formats, with the following restrictions: Data must be available for delivery in tab-delimited ASCII. If data is delivered in any file format other than ASCII, it shall be delivered with a file specification. We discussed requiring delivery of a translator that would allow users of the data to translate to ASCII, but decided that this would not be useful in most cases. (Apr 04)

3.20 Same LAR for Mission Planning, Training, Aircraft and Weapon (if applicable)

The premise that the same LAR algorithm should be used on mission support stations, in training systems, in the aircraft, and in Weapons which calculate LAR, was discussed. It was clarified that it does absolutely no good to use a more precise algorithm for mission planning, since the crew should not deliver weapons outside the LAR displayed in the aircraft. (Feb 04)

Concern was expressed that a weapon vendor may want to provide a more accurate LAR to prove that his weapon meets all specification requirements. This may occur, but it should not be used to plan missions because it will not agree with what is displayed in the aircraft. (Apr 04)

The size of the LAR greatly depends on the allowed probability of false positives chosen by the user. Therefore, different aircraft could have different size LARs for the same weapon based on the user's trade-offs between maximizing LAR size and minimizing probability of false positives. These LAR sizes can be different than those used to verify weapon specification performance. (Apr 04)

3.21 Common Coefficients (or not)

A goal was to have LAR coefficients that are common across aircraft types (for a given weapon). Although this is a goal, and is expected to occur in some cases, it is not an essential feature. If a particular airplane has a reason to use unique coefficients (tailored for their delivery altitude, or designed for a different LAR algorithm, for example), this can be done. The time and cost of developing unique coefficients (from an existing common Truth Data Base) can be traded against other integration costs, so if such tweaking will improve performance, it should be allowed. (Feb 04), revised (Apr 04)

3.22 Minimum Range/Safe Escape

A member suggested including minimum range or minimum safe escape criteria in the LAR. The group decided that this is not appropriate. This is handled by mission planning, not the LAR process, because safe escape involves additional inputs and produces a different set of constraints. For example, weapon explosive yield would be an input to a safe escape model, and would produce release altitude or distance from target constraints. (Apr 04)

3.23 Holes in LARs

We discussed the need to display LARS with holes or other unusual shapes. Gaps or holes in a LAR imply that performance of the store in that area is not consistent or assured. Therefore, conservatism applied to the LAR would prevent delivering weapons to an area of the LAR near a hole. Also, dealing with holes in LAR calculations and generation of LAR graphics showing holes would add significant complexity to the airborne software, contrary to the goal of keeping CLARA compatible with limited processing resources. The consensus was that the design of CLARA will not attempt to accommodate holes. (Apr 04)

3.24 Standard Atmosphere and Hot Day

The group had agreed previously to require use of the NOAA-S/T 76-1562 US Standard Atmosphere model 1976, with "standard day" as the default.

A member stated that the resolution of typical LAR models implemented in aircraft is worse than the variance caused by different atmosphere conditions; therefore having hot and cold day models is not of much value. On the other hand, some users insist on having "hot" and "cold" day LARs, therefore we must deal with this situation. A member recommended that atmosphere model Hot, Cold and Standard day conditions be an input variable instead of merely a comment. If coefficients are calculated based on a cold day, standard day, and hot day (for example), this would result in three times the data; this approach has been taken on at least one existing system. The group decided to define atmospheric model day type as an input variable, and add it to ICD Table 1. (July 04)

3.25 Input and Output Tables

Input and output tables and examples were added to the Truth Data Generator ICD and changed several times. Some argued that Tables 1 and 2, which list the input and output data elements, with units and ranges, are all that is needed as the requirement. Others wanted to include detailed input and output file formats, standardizing to a specific file format to make the files machine-readable without interpretation. Various approaches to implement a position-based file structure or a label-based file structure were reviewed. It was finally decided to leave the input file structure unconstrained and define a specific output file structure in Table 3. One member stated that the standard output file structure is necessary because this file is used in several places (specifically, in the data space generator and in the coefficient generator). (July 04)

3.26 Terminology – Store Versus Weapon

The terms “store” and “weapon” were used interchangeably in earlier drafts. It was agreed that “weapon” is the appropriate term for this CLARA activity, since most of the other stores covered by 1760 are not launched against targets. This is not to say that LARs cannot be used for other stores besides weapons. Stores can be launched to arrive at a targeted location yet not have a weapon function. An example would be a store with a logistics or ISR pack that must go to a precise fixed location. The CLAR ICD’s primary focus is weapons, even though it can be applied to other store types. (July 04)

3.27 Data Space Generator Process(s)

At least four techniques for determining which truth data points should be analyzed to develop an adequate truth data base have been used or proposed. Each of these will be explained in the following sections. This rationale section was developed in January 2005, based on a decision to take detailed process descriptions out of the ICD and cover the process in the Rationale document.

Full Grid (sometimes called full factorial or brute force)
Sobol Method
Response Surface Design (RSD)
Boundary Search

3.28 Full Grid

Some suggested that the cost of computer time and storage has decreased to the point that the effort required to optimally choose truth data points will cost more than simply testing all points over the range of interest. The grid would consist of small increments over the full range of all the variables (e.g., altitude from 0 to 80 000 ft, airspeed from 0 to mach 2, etc). When the number of increments in each variable is multiplied out, it results in an astronomical number of runs (e.g., 10^{14}), so this approach was considered unacceptable.

3.29 Sobol Method

The goal is to generate test data samples (‘truth footprints’) across the entire weapon launch envelope by sampling each independent variable (HAT, Mach, vertical velocity, etc.) according to an independent quasi-pseudo random sequence. A so called Sobol sequence is one example of such a sequence.

Sequences of n-tuples that fill n-space more uniformly than uncorrelated random points are called quasi-random sequences. That term is somewhat of a misnomer, since there is nothing random about quasi-random sequences: They are cleverly crafted to be, in fact, sub-random. The sample points in a quasi-random sequence are, in a precise sense, maximally avoiding each other.

The following excerpt from a paper by Dariusz Golda, Karl Iagnemma and Steven Duibowsky of MIT provides some insight to the method:

The Sobol method decomposes output variance into components based on Sobol’s functional description. Parameter sensitivity is then computed from the partial variances. Total sensitivity indices are computed to estimate individual parameter sensitivity including nonlinear and interaction terms. The Sobol method employs Monte Carlo methods to estimate these terms with a relatively small set of model evaluations. Specifically, the total number of model evaluations N needed to estimate the total sensitivity indices using this method is N = n(k +1), where n is the number of samples used to estimate an integral and k is the number of model parameters. By contrast, for a brute force approach with r levels the number of model evaluations is N = r k. For good accuracy with the Sobol method approximately n = 1000 samples should be used. With a brute force approach a minimum of r = 3 levels should be used. For k = 11 model parameters, the total number of model evaluations for each method is (NSobol = 12000, Nfactorial = 177147). Thus the Sobol method is substantially more efficient in estimating nonlinear and interaction effects than the full-factorial approach for large parameter sets, and makes the analysis computationally feasible. (Oct 05)

3.30 Response Surface Design Technique

A Data Space Generator can create the Training and Verification sets by using Response Surface Design (RSD) modeling. The word response means the output or the dependent variable in a process. The RSD technique or process and available software would generate RSD polynomial models through the outputs from the CLAR Truth Data Generator. These outputs are miss distance, impact angle, and impact azimuth.

RSD is a Design of Experiments technique that is most effective when there are less than five factors. Factors are the independent variables or in this application, some of the inputs to the CLAR Truth Data Generator. While five factors vary, other variables will be held fixed. RSD uses at least three levels, which are the variations in an input parameter, for every factor in the design. Table 1 contains the partitioning of the outputs from the CLAR Data Space Generator into variables that are held static and RSD factors.

TABLE 1 - CLAR DATA SPACE GENERATOR STATIC VARIABLES AND RSD FACTORS

Variables That Are Static While the RSD Factors Vary	RSD Factors
Impact Angle	X-axis distance from aircraft to target point
Impact Azimuth	Y-axis distance from aircraft to target point
Aircraft Vx (inertial)	Z-axis distance from aircraft to target point
Aircraft Vy (inertial)	X-axis speed at launch
Altitude (HAE)	Y-axis speed at launch
Wind Vx	
Wind Vy	
Atmosphere model	

Users of RSD often employ quadratic models to fit a polynomial through the responses. If we denote the quadratic expressions with the letter f, then the process of controlling the truth data generation is characterized by

$$\begin{bmatrix} f_1(\text{targetPosition},\text{targetVelocity}) \\ f_2(\text{targetPosition},\text{targetVelocity}) \\ f_3(\text{targetPosition},\text{targetVelocity}) \end{bmatrix} = \begin{bmatrix} \text{missDistance} \\ \text{impactAngle} \\ \text{impactAzimuth} \end{bmatrix}$$

If the data is sufficient for RSD to generate a good polynomial fit for miss distance, impact angle, and impact azimuth, then the implication is that the overall CLAR generation process can be characterized by performing the inverse operation that finds the footprint as a function of miss distance, impact angle, impact azimuth.

$$F(\text{missDistance},\text{impactAngle},\text{impactAzimuth},\text{targetVelocity}) = \text{targetPosition}$$

The parameters that are held constant as the RSD factor are varied are set at discrete settings. Examples of the increments for these settings are shown in Table 2.

TABLE 2 - CLAR DATA SPACE GENERATOR RSD CONSTANT INCREMENTS

Parameter	Increment	Number of runs
Aircraft Altitude (HAE)	300 m	TBD
Aircraft Vx (inertial)	20 m/s	TBD
Aircraft Vz (inertial)	20 m/s	TBD
Impact angle	$\pi/20$	10
Impact Azimuth	$\pi/20$	40
Wind Vx	20 m/s	TBD
Wind Vy	20 m/s	TBD

Three different quadratic polynomials model the three responses. The form of the polynomials is

y = b0 +b1 *x1 +...+b5 *x5 + b12 *x1 *x2 +b13 *x1 *x3 +...+b45 *x4 *x5 + b11 *x1² +...+b55*x5²

This model fits the observed values of the responses, y (miss distance, impact angle, impact azimuth), to (1) main effects, which are the linear terms x_1 , ..., x_5, (2) their interactions (x_1*x_2, x_1*x_3, ... ,x_4*x_5), and (3) their quadratic components (x_1^2, ..., x_5^2). No assumptions are made concerning the levels of the factors, and the CLAR Data Space Generator can analyze any set of continuous values for the factors. One set of continuous values is used for the Training set and one set of values is used for the Verification Set. Table 3 contains the CLARA Data Space Generator definitions for the variables in the quadratic model

TABLE 3 - MODEL VARIABLES AND CLAR DATA SPACE GENERATOR RSD FACTORS

Generic Model	RSD Factors
x_1	X-axis distance from aircraft to Target
x_2	Y-axis distance from aircraft to Target
x_3	Z-axis distance from aircraft to Target
x_4	X-axis speed at launch
x_5	Y-axis speed at launch
x_1x_2	interaction between X-axis and Y-axis distance from aircraft to Target
x_1x_3	interaction between X-axis and Z-axis distance from aircraft to Target
x_1x_4	interaction between X-axis distance from aircraft to Target and X-axis speed at launch
x_1x_5	interaction between X-axis distance from aircraft to Target and Y-axis speed at launch
x_2x_3	interaction between Y-axis and Z-axis distance from aircraft to Target
x_2x_4	interaction between Y-axis distance from aircraft to Target and X-axis speed at launch
x_2x_5	interaction between Y-axis distance from aircraft to Target and Y-axis speed at launch
x_3x_4	interaction between Z-axis distance from aircraft to Target and X-axis speed at launch
x_3x_5	interaction between X-axis distance from aircraft to Target and Y-axis speed at launch
x_4x_5	interaction between X-axis and Y-axis speed at launch
x_1^2	quadratic effect of the X-axis distance from the aircraft to the Target
x_2^2	quadratic effect of the Y-axis distance from the aircraft to the Target
x_3^2	quadratic effect of the Z-axis distance from the aircraft to the Target
x_4^2	quadratic effect of the X-axis speed at launch
x_5^2	quadratic effect of the Y-axis speed at launch

The manner in which the CLAR Data Space Generator picks the levels of the RSD factors is decided by the weapon contractor as well as the resulting goodness of fit of the response models. Ultimately, the goal of selecting the levels of the RSD factors is to ensure success for the CLAR Coefficient Generator. To accomplish this goal, the RSD should consider resolution, rotatability, and orthogonality.

Resolution describes the degree to which estimated main effects (the linear terms) are aliased (or confounded) with 2-level interactions, 3-level interactions, etc. In general, the resolution of a design is one more than the smallest order interaction that is aliased with a main effect. If a main effect is confounded with 2-level interactions, the resolution is 3. A resolution 5 design is excellent. To achieve resolution 5 (or higher), the design should consist of as many of the combinations of the extremes for each RSD factor as possible and maintain rotatability and orthogonality.

A design is rotatable if the variance of the predicted response at any point depends only on point's distance from the design center point. To measure variability, the CLAR Data Space Generator must have several repeated trials of runs with the same input settings to measure the variability in the responses. Rotatability is related to how best to extract the maximum amount of (unbiased) information from the design, or specifically, from the experimental region of interest and leave the least amount of uncertainty in the prediction of other values.

Two vectors of the same length are orthogonal if the sum of the products of their corresponding elements is 0. Intuitively, one can extract the maximum amount of information regarding a response from the experimental region (the region defined by the settings of the factor levels), if all factors are orthogonal to each other.

The selection of the levels for the five RSD factors is the weapon contractor's decision. However, Table 4 offers methods for selecting the optimal design.

TABLE 4 - CLAR DATA SPACE GENERATOR SELECTION OF THE RSD LEVELS

Method	Features	Comments
Sequential or Dykstra method	Fastest, but often fails to find optimal input conditions	Starting point for remaining designs
Simple exchange (Wynn-Mitchell) method	Adds and drops points from the design until no further improvement is reached	Iterative
DETMAX algorithm (exchange with excursions).	Will add or drop more than one point at a time	Best known and most widely used
Modified Fedorov (simultaneous switching)	Add or drop points from the design	Unlike the simple exchange, the exchanges are not sequential
Fedorov (simultaneous switching)	Only a single exchange is made	Somewhat slow

The CLAR Data Space Generator recommends using the modified Fedorov to generate the training sets while the DETMAX algorithm could be used to generate the validation training sets.

Table 5 is an example RSD. The minimum values of each of the five variables are coded as -1 while the maximum value is coded as +1. For instance, if the minimum X-axis downrange is 10 000 meters, then 10 000 are coded as -1. If the maximum X-axis downrange is 40 000 meters, then 40 000 are coded as +1. The midpoints of the range are then coded as zero. In addition to the sample design, a partial check of the orthogonality condition is provided in the last four columns. For each entry in the X-axis distance column, multiply it by the entry in another column. Add the products and the sum should be zero. This exercise of forming products and adding should continue for the remainder of the factors.

Note that not all combinations of extremes are included. For example, all 1's corresponding to all five factors at maximum value is not in the design, nor is all -1's. The all midpoint cases (all zeros are included). Star points should be added to the design to support the rotatability concern. There are many opinions as to how to add points and increase the number of levels for each factor (see earlier discussion on optimal design methods).

3.31 Boundary Search

A technique known as boundary search has been used in the various vendors' weapon footprint tools. This is actually used to find a LAR, rather than as a data space generator.

All weapon footprint tools ultimately employ a weapon flyout or trajectory model (i.e., 3-DOF, 5-DOF, 6-DOF) which determines (based upon assumed launch condition, atmosphere / wind profile, intended target location and commanded / desired end-game constraint / state where the weapon lands relative to the intended target, as well as its end-game state relative to that commanded or assumed. To search for the LAR boundary, the flyout or trajectory model is run repeated times for the same launch condition, end-game scenario and atmosphere / wind profile while perturbing the target location relative to the aircraft launch point. In each case, the model is called by the footprint tool, much like a subroutine, to perform the trajectory calculations which provide endpoint data needed to compare to success criteria in determining if a prospective target is located within the weapon's capability, relative to the aircraft, to accurately reach it. There are two footprint boundary search methodologies that have been employed in the footprint tools provided by weapon vendors.

The first method involves a radial search about a point contained within the footprint. The tool initially performs a coarse search along the aircraft track to determine if a capability exists there. If not, the tool will perturb the lateral displacement of the prospective target in the direction of the commanded azimuth, relative to the assumed aircraft track at launch. Once again it searches along the new track established, parallel to the assumed aircraft track at launch, in an attempt to find a target the weapon can hit while satisfying all commanded and desired end-game constraints / states. It repeats this until a footprint heel and toe are found. Once found, the tool will perform a refined boundary search on the footprint heel and toe. Then the footprint tool begins a radial search, at fixed angles, about a point located halfway between the footprint heel and toe. The search is performed in a coarse manner along each radial until a boundary point is found. Then, once the location of that point is found, it is further refined with a smaller search increment. This is done until all radials about the heel / toe midpoint are searched.