INFRARED ATTRIBUTES FOR PROJECT 2851 STANDARD SIMULATOR DATA BASES

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ABSTRACT

The many phenomenological Infra-Red (IR) modeling programs currently in use require a large number of parameters to achieve a high degree of image simulation accuracy. When the parameter sets required by these programs are tabulated, the result is a large and diverse set of potential database attributes. In addition, these IR modeling programs are intended to satisfy the needs of a wide range of IR simulation users. To achieve the goals of Project 2851 in defining DoD Standard Simulator Data Bases, decisions must be made regarding which parameters should be included as attributes within the databases. The set of selected attributes must satisfy a wide variety of IR image simulation programs and users while being of reasonable size for storage in IR image generator databases.

McDonnell Douglas Training Systems assisted Project 2851 in the selection of these parameters by taking a three part approach to the task. First, current IR phenomenological models were studied and their required parameter sets were tabulated. Second, IR modeling experts and weapons systems users were surveyed to determine their needs. And third, a Quality Function Deployment analysis was performed to prioritize the parameters with respect to user needs, producing a set of IR database attributes that were recommended to Project 2851. This paper describes the results of the user survey, the evaluation process, and the recommended IR attribute set.

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INTRODUCTION AND PURPOSE

Project 2851 (P2851) has incorporated data structures and attributes for Infra-Red (IR) sensor Image Generation within its Standard Simulator Data Base (SSDB). However, P2851 expressed a further need for an improved set of IR simulation attributes satisfying training, simulation, and weapon systems user requirements.

McDonnell Douglas Training Systems (MDTS) has been conducting on-going research and development efforts to improve the fidelity and rapid generation of simulated IR imagery. These efforts have included studies in environmental IR modelling and the definition of requirements imposed by training, mission rehearsal, and weapon systems users and experts.

As a result, MDTS was contracted by P2851 to recommend an improved set of IR simulation attributes based on IR sub-system training requirements, existing target and background IR imaging models, and IR simulation attributes currently defined by P2851. The objectives of the contract were to evaluate and suggest improvements to the IR simulation attributes for IR Generic Transformed Data Bases (GTDB) and SSDB Interchange Format (SIF) to support a high level of simulation fidelity with respect to dynamic time, weather, and atmosphere-dependent IR simulations. Since attributes in the GTDB and SIF are derived from the SSDB, any IR attribute recommendations would apply to the SSDB as well as GTDB and SIF.

To meet these objectives, a systematic IR attribute evaluation and selection process was performed. The steps taken were: 1) Identify and categorize training-dependent IR image attributes; 2) Survey IR image simulation models and selected database attributes; 3) Analyze IR simulation attribute relative importance; 4) Evaluate currently defined SIF and GTDB IR simulation attributes; and 5) Select and recommended a prioritized IR simulation attribute set for SSDB use.

IR SIMULATION USER-NEEDS SURVEY

To support a user-driven approach to defining required and desirable SSDB IR attributes, selected members of the IR simulation user community were asked to identify which characteristics of IR imagery are most important to them in various training contexts. These user-prioritized IR image attributes were then related to a large set of IR database attributes obtained from a study of current IR simulation models. These relationships were combined with the user- specified priorities using MDC Quality Function Deployment (QFD) methods to derive a set of prioritized database attributes capable of supporting the simulation of the desired IR image characteristics.

User Communities

Input from a broad spectrum of IR image simulation users was solicited. The user communities that were addressed included fighter pilots, Bombardier/Navigators (B/Ns), the Automatic Target Recognition (ATR) community, and other IR simulation experts.

An evaluation form was prepared to allow users to specify the importance of various aspects of IR imaging simulations. The survey form included sections on "Sensor Controls" and "Sensor Effects" in addition to "Background Characteristics" and "Target Characteristics". *Recipients of the survey were* asked to specify the importance of various IR image attributes in the context of three IR image simulation categories: Initial Training, Advanced Training, and Mission Rehearsal. The training categories can be described more completely as follows:

1) **Initial Training**[1] – Generally limited to a period of several weeks using highly scripted scenarios with objectives to:

- Learn operating procedures
  - Functions and applications of system features
  - Displays and controls
  - Handoffs, coordination, and timing of events
- Integrate Forward Looking Infra-Red (FLIR) operation, navigation, and weapons
  - Consolidate visual tasks (e.g., target acquisition) with systems tasks (e.g. weapons release)
  - Sequences of operations
  - Workload management

2) **Advanced Training**[1] – A broad category between "Initial Training" and "Mission Rehearsal" with objectives to:

- Upgrade skills to employ new systems or weapons
- Operate under simulated threats
- Develop and evaluate tactics for various scenarios

3) **Mission Rehearsal** – Defined here as flying a specific mission profile utilizing the full complement of on-board sensors, correlated with a highly geo-specific visual scene that displays a 3-D perspective environment in real-time. No avoidable disparity between the simulated and actual mission that would jeopardize the mission's success is permitted.

Users were specifically asked to provide input about IR image characteristics (e.g., "diurnal effects") rather than the underlying database feature attributes (e.g., "emissivity") from which the IR image could be generated. However, they were free to include their own suggestions for IR database attributes if they so desired.

Initial Training Needs

Analysis of the survey responses yielded the following observations regarding the training importance of various IR image characteristics.

First, it is clear that there is little consensus concerning the importance of specific IR image characteristics in most cases. That is, for nearly every image characteristic listed, someone believed it was very important and someone else believed that the same characteristic was minimally important. This was true of most background and target characteristics with the exception of "Accurate Relative (Background) Intensities" which was consistently considered to be "Very Important" to "Moderately Important".

Second, there was general agreement that simulation of sensor controls for initial training was very important. The simulation of sensor effects was *consistently judged to be more important than background* or target characteristics, but less important than sensor controls.

Perhaps the most useful overall observation to be made in the context of "Initial Training Needs" is that learning the sensor controls and observing basic sensor effects are more important than the accuracy of background and target intensities. This *is not surprising since the geographic areas and* targets being observed can often be generic for this level of training.

Advanced Training Needs

The observations made for the Initial Training category also apply here with the following modifications. First, although there was still no strong consensus concerning the importance of specific IR image characteristics, the number rated as "Minimally Important" dropped dramatically. There was general agreement on the importance of "Accurate Relative (Background) Intensities" with most users considering this aspect of an IR simulation to be "Very Important".

Mission Rehearsal Needs

Mission rehearsal needs represent (excluding ATR applications) the most demanding set of IR simulation requirements to be addressed by the SSDB. Observations made for the Advanced Training category also apply here but with increased importance ratings for all image characteristics and sensor effects.

The accurate simulation of sensor controls remained of highest importance for mission rehearsal scenarios. Although the accurate simulation of IR targets increased in importance, accurate IR background simulations continue to be viewed as more important than either IR target appearance or sensor effects.

Another fact of particular significance is that "Diurnal Effects" and "Weather/Environmental Effects" are considered more important than any other background effects in a mission rehearsal scenario. This is expected as the training becomes increasingly focused on specific geographic areas, particular targets, and expected environmental conditions.

IR SIMULATION MODELS

A brief review of the methods and needs of current IR modelling systems may help the reader better understand the constraints leading to the final list of recommended IR attributes.

Conventional IR Modelling Methods

Conventional IR simulation models divide their complete predictive model either explicitly or implicitly into a "Physical (World) Model" component and a "Sensor Model" component as shown in Figure 1.

The "World Model", as depicted in Figure 2, calculates the amount of reflected, transmitted, and emitted IR energy present by solving equations based on conservation of energy principles and energy transfer rates constrained by the objects and environmental conditions. Inputs to the world model include static feature attributes such as reflectance and dynamic environmental attributes such as cloud cover. Dynamic environmental attributes including humidity, haze, smoke, and dust levels are used to simulate atmospheric effects, primarily further attenuation of the input IR (generally solar) energy. Attenuation of the output IR energy on its way to the sensor can be predicted using the same dynamic IR attributes plus knowledge of the sensor's position.

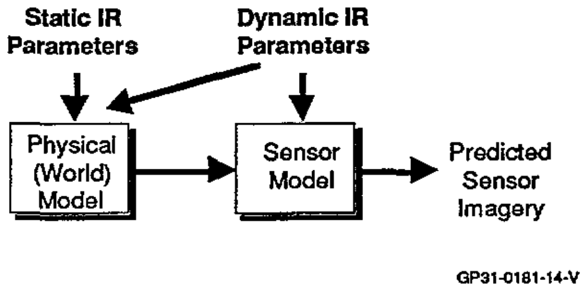

Figure 1. IR Model Components

The "Sensor Model" is responsible for determining what portion of that energy is in the sensor's field-of-view and adding sensor-specific effects such as noise, AC coupling (swathing/striping), and blooming. These sensor effects can be influenced by the settings of sensor controls including gain and level. Inputs to the sensor model are the output from the world model and any dynamic attributes that may affect the sensor's operation.

IR Model Attribute Survey

An extensive survey of existing IR image simulation models produced a comprehensive set of database attributes potentially useful for accurate, model-based, image generation.[2] As an initial step in the selection process, the database attributes for each model were separated into dynamic and static attribute sets.

Static attributes include properties such as thermal mass or emissivity which generally remain constant

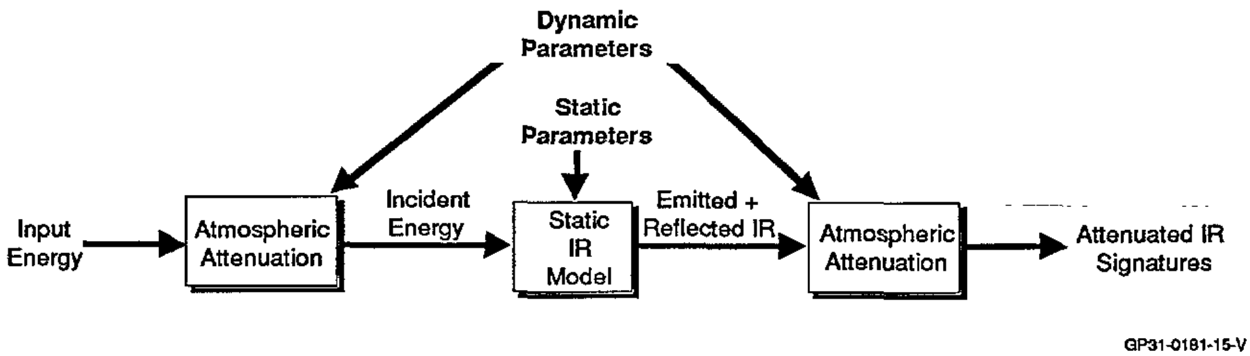

Figure 2. World Model

for an object and are natural feature and model descriptors to be included in the SSDB. Dynamic attributes such as cloud cover, air temperature, humidity, time-of-day, snow cover, haze/smoke/dust levels, and other environmental attributes are important inputs to IR sensor simulations, but are usually initialized by a user at simulation run-time and are therefore not appropriate for inclusion in the static IR attribute set of the SSDB.

This study focused on the static attribute set used to describe terrain and objects. The recommended database attributes set consists of the union of those IR attributes already in the SSDB with a selected subset of the large, comprehensive, static attributes set derived from the IR simulation model survey.[2]

RELATIVE IMPORTANCE OF IR ATTRIBUTES

The IR attribute set recommended here represents a necessary compromise among several competing factors including generality, redundancy, convenience of use, availability of values, and database size. These constraints were balanced with the overriding need to satisfy a variety of IR simulation users and models.

QFD Evaluation Method

Quality Function Deployment (QFD) methods were used to convert the user- specified IR image attribute rankings into a set of prioritized IR database attributes[3,4]. The format of the QFD matrix for IR database attribute evaluation is shown in Figure 3.

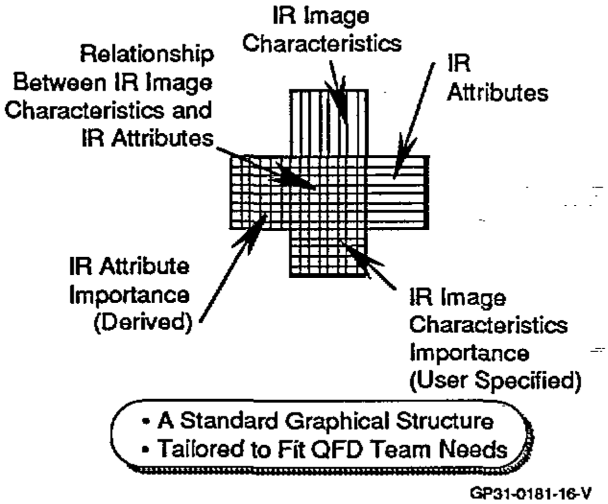

Figure 3. IR QFD Matrix Format

Input to the QFD matrix consisted of the Mean importance values for "Accurate Relative Intensities" and "Diurnal Effects" of IR backgrounds, and the "Infrared Signatures" of targets. Relationships between the IR image characteristics and the IR database attributes required to simulate them were defined as strong, medium, or weak.

The static IR database attributes were ranked in importance by the QFD evaluation function based on the user-specified IR image characteristic importances and the image-to-database attribute relationships[3,4]. The completed "Infrared Attribute Importance" QFD matrix is shown in Figure 4. It includes IR database attribute rankings for Initial Training, Advanced Training, and Mission Rehearsal. Note that the importance of the IR image attributes increases, as expected, when moving from Initial Training through Advanced Training to Mission Rehearsal. However, as described in the following sections, the relative ranking of the IR database attributes does not change significantly.

Reduced IR Attribute Set

The first step in the process of producing a reasonably sized set of IR attributes was to eliminate redundancies in the IR attribute superset derived from the IR models surveyed. This required the identification of attributes that were shared between IR simulation models, even if called by different names or using slightly different units. It is important to note here that "redundancy" is not the same as "dependency". Some dependencies among attributes were allowed to remain in order to simplify the usage of the SSDB. For example, although "heat capacity" is theoretically derivable from the other IR attributes and a geometric model, the task is not trivial. It is better to pre-compute the value and store it in the SSDB.

The second step was to separate the "static" feature and model attributes from "dynamic" (generally environmental) attributes. The static attributes include properties such as thermal mass or emissivity which generally remain constant for an object and are natural feature and model descriptors to be included in the SSDB. Dynamic attributes such as air temperature, cloud cover, humidity, wind speed, time-of-day, time-of-year, and other environmental attributes are important inputs to IR sensor simulations, but they are usually initialized or modified at simulation run-time.

IR Image Characteristics vs. **IR Attributes**

IR Attributes	BACKGROUND CHARACTERISTICS: Accurate Relative Intensities	Diurnal Effects	TARGET/OBJECT CHARACTERISTICS: Infrared Signature	Column Total	CALCULATED IMPORTANCE - INITIAL TRAINING	RANK	CALCULATED IMPORTANCE - ADVANCED TRAINING	RANK	CALCULATED IMPORTANCE - MISSION REHEARSAL	RANK
Emissivity	●	●	●	91.71	1.58	1	2.07	1	2.26	1
Absorptivity	●			33.39	0.46	9	0.54	9	0.57	9
Transmissivity	○	▷		13.92	0.21	12	0.27	12	0.29	12
Total Reflectance	●	●	●	91.71	1.58	1	2.07	1	2.26	1
Specular Reflectance	●	▷	○	47.25	0.71	7	0.87	7	0.93	7
Directivity	○	▷	○	24.99	0.41	11	0.51	11	0.55	11
Surface Normal Vector	○	○	●	52.71	0.92	4	1.17	4	1.27	4
Heat Capacity	●			33.39	0.46	9	0.54	9	0.57	9
Thermal Conductivity	○	○	○	30.57	0.53	8	0.69	8	0.75	8
Thermal Mass	●	●	●	91.71	1.58	1	2.07	1	2.26	1
Self - Generated Power	○	▷	●	47.13	0.80	5	0.99	5	1.06	5
Exposure Index	○	●	▷	39.93	0.75	6	1.07	6	1.19	6
Convection Coefficient	▷	▷	▷	10.19	0.18	13	0.23	13	0.25	13
Density										
Object Volume										
Radiant Exitance										
Specific Heat										
Surface Material Category										
Surface Material Subtype										
Material Thickness										
Internal Material Category										
Internal Material Volume										
Terrain Roughness										
Initial Training	3.71	2.79	3.69							
Advanced Training	4.36	4.21	4.59							
Mission Rehearsal	4.64	4.79	4.79							

- CALCULATED IMPORTANCE - INITIAL TRAINING: Maximum Value = 1.6, Minimum Value = 0.2
- CALCULATED IMPORTANCE - ADVANCED TRAINING: Maximum Value = 2.1, Minimum Value = 0.2
- CALCULATED IMPORTANCE - MISSION REHEARSAL: Maximum Value = 2.3, Minimum Value = 0.3

WHATs vs. HOWs Legend		
Strong	●	9
Moderate	○	3
Weak	▷	1

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Figure 4. IR Attribute Importance QFD Matrix

The third step was to judiciously remove specific attributes that were extremely limited in scope, especially if they could be derived from the remaining set. The "derivability" criterion was not strictly enforced if other considerations prevailed. For example, although absorptivity and transmissivity have a complementary relationship, both are defined in the current SSDB and both are retained.

The reduced attribute list is:

Absorptivity
Convection Coefficient
Density
Directivity
Emissivity
Exposure Index
Heat Capacity
Internal Material Category
Internal Material Volume
Material Thickness
Object Volume
Radiant Exitance
Self-Generated Power
Specific Heat
Specular Reflectance
Surface Material Category
Surface Material Subtype
Surface Normal Vector
Terrain Roughness
Thermal Conductivity
Thermal Mass
Total Reflectance
Transmissivity

Emissivity, absorptivity, transmissivity, total reflectance, specular reflectance, and radiant exitance are wavelength dependent and should have separate values for visible (0.4 - 0.7 um), midwave IR (3.0 - 5.0 um), and longwave IR (8.0 - 12.0 um) wavebands.

Table 1 provides definitions and units for these attributes. The most common units used by the IR models have been retained wherever possible.

Prioritized IR Attribute Sets

QFD analysis was performed on the reduced attribute set using weighting factors corresponding to user inputs for the three training categories described earlier; Initial Training, Advanced Training, and Mission Rehearsal. The resulting ranked attribute lists are described below.

Initial Training - The ranked list of IR database attributes for Initial Training is:

1. Emissivity*
2. Total Reflectance*
3. Thermal Mass
4. Surface Normal Vector
5. Self-Generated Power
6. Exposure Index
7. Specular Reflectance*
8. Thermal Conductivity
9. Absorptivity*
10. Heat Capacity
11. Directivity
12. Transmissivity*
13. Convection Coefficient
14. Radiant Exitance*
15. Surface Material Category
16. Surface Material Subtype
17. Terrain Roughness
18. Specific Heat
19. Density
20. Object Volume
21. Material Thickness
22. Internal Material Category
23. Internal Material Volume

(* denotes wavelength dependence)

Attributes 14-23 are a reordered version of the attributes that are not given explicit rankings in the QFD matrix of Figure 4. This ordering emphasizes the remaining attributes that are most commonly used (e.g. Exitance) and/or are descriptive of backgrounds (e.g. Surface Material). The latter decision is based on the high importance of accurate IR background simulations consistently specified by the user community.

Advanced Training – The ranked list of IR database attributes for Advanced Training is the same as the previous list for Initial Training except that attributes 5 and 6, Self-Generated Power and Exposure Index, are reversed in priority. Although the absolute importance of all attributes increased with the overall importance of IR image accuracy, their relative importance remained essentially the same.

Mission Rehearsal – The ranked list of IR database attributes for Mission Rehearsal was identical to that for Advanced Training. Although the absolute importance of all attributes continued to increase with the overall importance of IR image accuracy, their relative importance remained the same. A closer look at the user-specified importance ratings of various image characteristics shows that Advanced Training and Mission Rehearsal are viewed as more similar to each other than either one is to the Initial Training Category. This is probably due to the heavy emphasis on the basic operation of IR sensor controls during Initial Training and the increased emphasis on image interpretation during Advanced Training and Mission Rehearsal.

Table 1. IR Attribute Definitions

Absorptivity	Ratio of energy absorbed to the energy incident.
Convection Coefficient	Convective heat transfer rate (W/cm^2/deg C).
Density	Mass per unit volume (gm/cm^3).
Directivity	Indicator of shape of the planar response curve of a feature or model for infrared. Three values: Omni-Directional, Bi-Directional, Uni-Directional.
Emissivity	Ratio of the rate of radiation from a feature as a consequence of its temperature only, to the corresponding rate of emission from a blackbody at the same temperature.
Exposure Index	The fraction of the surface of a material that is exposed to the sun, sky, wind and precipitation.
Heat Capacity	The amount of heat required to raise the temperature of a body by one degree, either at constant pressure or at constant volume and without inducing chemical changes or change of phase (cal/g/deg K).
Internal Material Category	Category code for Category material internal to an object (DMA codes).
Internal Material Volume	Amount of material inside an object (liters).
Material Thickness	Thickness of a material (cm).
Object Volume	Total internal volume of an object (liters).
Radiant Exitance	Rate of flow of radiation from an object per unit of surface area (W/cm^2).
Self Generated Power	Heat generated or removed from an object by other than radiation, conduction or convection (W/cm^2). Has positive value if object is emitting heat; negative value if object is absorbing heat (e.g. the cold side of a heat pump).
Specific Heat	The ratio of material's heat capacity to that of water.
Specular Reflectance	The ratio of incident to reflected energy normal to the surface.
Surface Material Category	Material code for the predominant material(s) making up the surface of a feature (DMA codes).
Surface Material Subtype	Subtype of Material Category.
Surface Normal Vector	The normalized vector perpendicular to a surface. The corresponding P2851 definitions are Vertex Normal and Polygon Normal.
Terrain Roughness	Roughness measurement for terrain.
Thermal Conductivity	*Ability of a substance to conduct heat (W/cm/deg C).*
Thermal Mass	A measure of the resistance of a material to changes in its thermal environment. A summary measure of the responsiveness of an object to heat (=Density * Heat Capacity * Material Thickness).
Total Reflectance	Ratio of total energy reflected by an object to the amount incident upon it.
Transmissivity	Ratio of energy transmitted by a feature or model to the amount of energy incident upon it.

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RECOMMENDED CONTENTS OF SSDB FOR IR SIMULATION

As a result of the QFD analysis and other user inputs, the following recommendations were made regarding the desired contents of the SSDB to support IR simulation. Since the attributes in GTDB and SIF are derived from SSDB, these recommendations also apply to GTDB and SIF.

Features and Models

All but two of the attributes in Table 1 should be in the SSDB attribute sets for features and models. Since the Terrain Roughness can be calculated from data already stored in the SSDB, it should not be stored separately. Also, since the Normal Vector can be calculated for existing polygons but may be variable for Constructive Solid Geometry (CSG) quantities, its calculation should be deferred until GTDB or SIF files are produced, or left up to the user.

Internal Consistency

When radiation is incident upon an object, the Total Power Law states that[5]:

Absorptivity + Total Reflectance + Transmissivity = 1

If all three values are specified for any IR range, the total power law should be obeyed.

The Thermal Mass is a function of density, heat capacity, and surface thickness. If all four values are specified, the following equation should be obeyed:

Thermal Mass = Density * Heat Capacity * Surface Thickness

Environmental Attributes

Environmental attributes including cloud cover, air temperature, humidity, time-of-day, snow cover, haze/smoke/dust levels, and other dynamic attributes are important inputs to IR sensor simulations, but they are usually initialized or modified at simulation run-time, and are not recommended for inclusion in the core attribute set of the SSDB. Instead, the existing ability to define "Microdescriptors" describing weather and other environmental conditions can be used to store a set of initial values for these dynamic attributes, if so desired.

Inter-Feature Attributes

Some IR simulation models rely heavily on knowledge of the physical interfaces between adjacent features of an object to calculate heat flow across boundaries. Attributes required to support this approach include relationships such as inter-feature conduction, area of contact, and path length.

Such inter-feature relationships are not readily describable in the SSDB and deriving them from accurate geometric models, even when feasible, can be a formidable task. On the other hand, including such information explicitly in the SSDB for all related features of an object could demand a prohibitive amount of space. For this reason it is recommended that such inter-feature attributes be specified, when needed, in user-defined FACS fields.

SUMMARY AND CONCLUSION

In summary, in addition to the recommended set of 23 IR-related attributes, we have drawn the following conclusions from the user-survey and subsequent QFD analysis:

User Needs – The order of importance of IR simulation capabilities needed for most training applications are:

1) Sensor Controls Operation;
2) Accurate IR Backgrounds;
3) Accurate IR Target Signatures;
4) Other Sensor Effects.

Wavelength Dependence – Emissivity, absorptivity, transmissivity, total reflectance, specular reflectance, and radiant exitance are wavelength dependent and should have values stored for the visible (0.4 to 0.7 um), mid-wave IR (3.0 to 5.0 um), and long-wave IR (8.0 to 12.0 um) bands.

Environmental Attributes – Cloud cover, air temperature, humidity, and haze/smoke/dust levels are important inputs to IR sensor simulations, but are usually initialized at simulation run-time and are not recommended for inclusion in the core attribute set of the SSDB.

Inter-Feature Relationships – Some IR simulation models rely on knowledge of the physical interfaces between adjacent features of an object to calculate heat flow. Such inter-feature relationships are not readily describable in the SSDB, and could require a prohibitive amount of space.

ATR Applications – Although the ATR community represents a very important group of IR simulation users, it is unclear whether the SSDB can or should be expected to serve their very demanding needs. The requirements for extreme accuracy and completeness of IR predictions to test ATR algorithms and sensors under all conceivable conditions probably places the needs of the ATR community beyond the scope of P2851.

Availability of Attribute Values – Unfortunately, the difficulty of obtaining an IR attribute value appears to vary directly with its usefulness for predicting an IR image. In other words, the most useful "fundamental" attributes (e.g. emissivity, absorptivity) are often the most difficult to obtain, while the more easily determined "superficial" attributes (e.g. radiant exitance, surface material category) are less robust. To support high-fidelity IR simulations over large gaming areas and/or to rapidly update P2851 IR simulation databases, it is essential that methods be developed to automatically extract values for these attributes from available data sources such as Multi-Spectral Imagery (MSI).

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