

Applications of the MuSES Infrared Signature Code

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ABSTRACT

MuSES (the Multi-Service Electro-optic Signature code) is the next-generation infrared (IR) signature prediction program developed by ThermoAnalytics. The implementation of several features has allowed MuSES to find increasing usage outside its primary function as a tool for designing ground vehicles. These features: MuSES batch mode, the MuSES database file library interface (“tdfio” library), transient restart facility and user routines are described along with their application to synthetic natural environments, real-time scene generators, mission planning systems and a continuously running temperature prediction system.

1.0 INTRODUCTION

MuSES (known as RadTherm/IR outside of the USA) is commonly viewed as a standalone IR signature prediction tool for designing ground vehicles. However, many applications require that MuSES temperature and/or signature predictions be used in a chain of automated analyses. Over the course of MuSES’ development, a number of features were implemented to allow other programs to modify, exercise, and query MuSES models before, during and after a simulation [Figure 1]. These features are listed here and described in greater detail in the following sections:

- **tdfio library:** MuSES stores all model information (except for weather and view factors) in a single database file known as the “Thermal Description File”, or TDF file. The cross-platform C++ tdfio library gives programmers access to much of the functionality contained in the Graphical User Interface (GUI) for building, modifying, and querying models.
- **Batch Mode:** MuSES can be run without its GUI, thus enabling scripts or other programs to spawn a MuSES executable and run a simulation that has been previously set-up. A number of command line options allow basic changes to be made to the scenario being simulated and provide several output options.

Paper presented at the RTO SCI Symposium on “Sensors and Sensor Denial by Camouflage, Concealment and Deception”, held in Brussels, Belgium, 19-20 April 2004, and published in RTO-MP-SCI-145.

Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE 01 DEC 2005	2. REPORT TYPE N/A	3. DATES COVERED -			
4. TITLE AND SUBTITLE Applications of the MuSES Infrared Signature Code		5a. CONTRACT NUMBER			
		5b. GRANT NUMBER			
		5c. PROGRAM ELEMENT NUMBER			
6. AUTHOR(S)		5d. PROJECT NUMBER			
		5e. TASK NUMBER			
		5f. WORK UNIT NUMBER			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) ThermoAnalytics, Inc. 23440 Airpark Blvd Calumet, MI 49913		8. PERFORMING ORGANIZATION REPORT NUMBER			
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)			
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)			
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES See also ADM202015, Sensors and Sensor Denial by Camouflage, Concealment and Deception (Capteurs et saturation des capteurs par camouflage, dissimulation et deception). , The original document contains color images.					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UU	18. NUMBER OF PAGES 32	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

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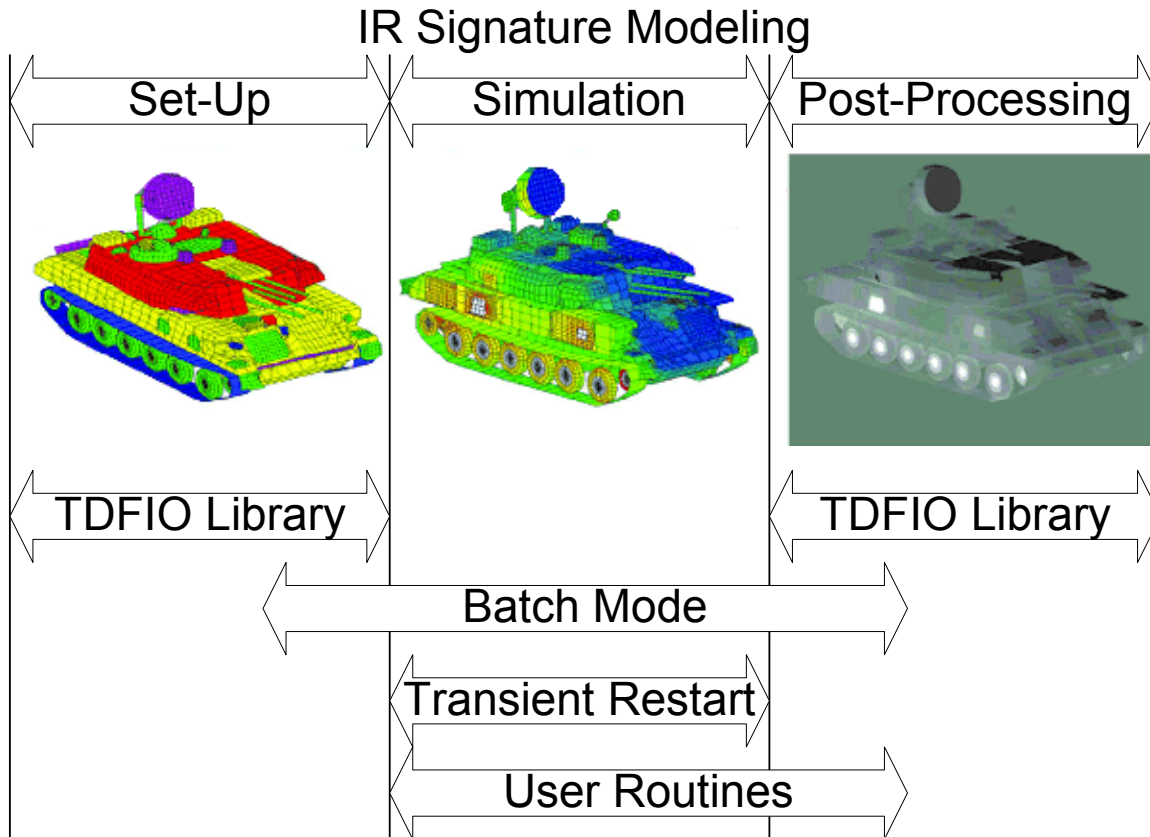


Figure 1: The features that have been developed to allow other programs or scripts to modify, simulate or query MuSES are depicted along with where they can be used in the modeling process.

- **Transient Restart:** MuSES can be instructed to save extra state information along with the thermal results to the TDF file. Subsequently, MuSES can start a new simulation where a previous simulation had left off. In between the two runs, the scenario, weather, and even the thermal model itself can be changed, thus allowing MuSES to respond to changes in operating conditions.
- **User Routines:** User supplied scripts and/or compiled libraries can be used in place of most property curves and/or called from specified points within the solution process. An Application Programmer's Interface (API) provides access to geometry, part, scenario, analysis, and weather data.

2.0 TDFIO LIBRARY

The tdfio C++ library was developed for application programmers that need access to the functionality encapsulated in the MuSES GUI – including creating, reading, querying, modifying and writing MuSES TDF files. Typically, the library is used to change modeling parameters prior to running a simulation in batch mode and to query the results after the simulation has finished. Additionally, the tdfio library contains functions that can be used for creating file converters from a user's file format to the TDF file format. Not only can simple

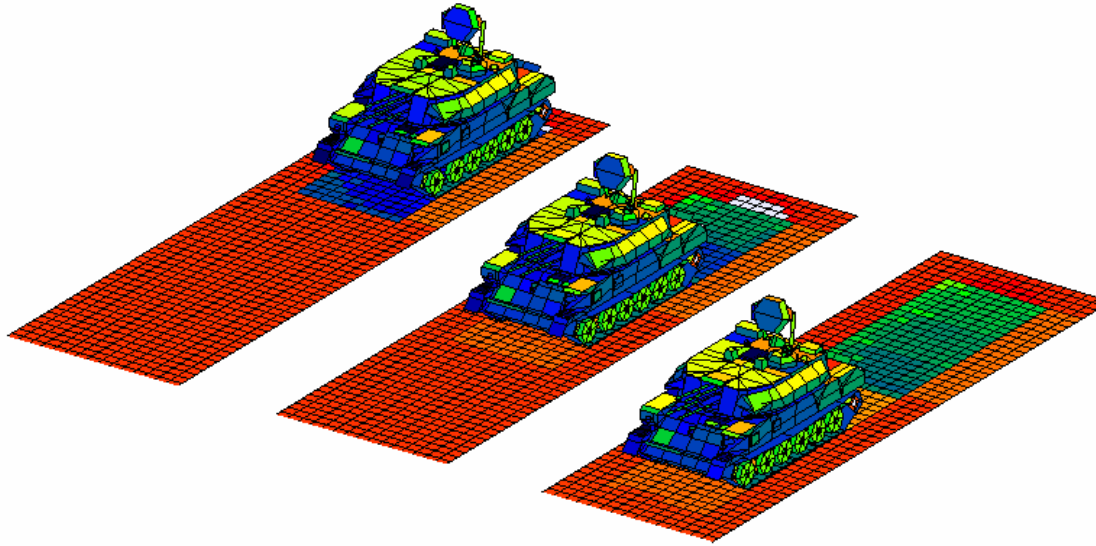


Figure 2: The Transient Restart feature can be used to simulate the movement of a vehicle within a scene. Since view factors are recalculated each time the simulation is restarted, the thermal shadows and hot spots that were due to the presence of the vehicle begin to fade as the vehicle moves away.

geometry (vertices and elements) be converted but parts (groups of elements), assemblies, material properties, surface properties, and boundary conditions can also be assigned. The tdfio library includes two features that are not directly accessible from the MuSES GUI: Retrieving view factors from the target geometry to the sky and ground and calculating and retrieving apparent areas from an arbitrary sensor position.

3.0 BATCH MODE

The MuSES Command Line Interface or “Batch Mode” allows view factor calculation, thermal analysis, and/or signature analysis to be run from a Unix or Windows Command prompt. MuSES batch mode can also be invoked from scripts, batch files or by system calls made from compiled programs. In addition to running the thermal and/or signature solutions, the command line arguments provide a limited capability for changing simulation conditions and for automated post-processing.

The following simulation parameters may be changed directly from the command line without the need to use the GUI or the tdfio library:

- The name of the weather file
- The solution start time and end time
- Latitude, longitude and time zone
- Sea surface temperature (for use with the constant temperature water background)
- Vehicle heading

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- Vehicle speed
- The time step and waveband to be used for a signature analysis that uses a surface's Bi-directional Reflectance Distribution Function (i.e., a "BRDF analysis").

The output of the batch mode BRDF analysis are several contrast radiances that are calculated from a BRDF rendering; in the current MuSES release, the BRDF image itself can only be output by using the GUI. Performing a batch mode BRDF analysis requires an extra input file due to the large number of inputs required (e.g., MODTRAN inputs, field of view, image size, etc.).

Images containing temperature maps can be output while running in batch mode. Since only a few inputs are required, command line arguments are used to specify the viewing and scale parameters.

4.0 TRANSIENT RESTART

The Transient Restart feature in MuSES allows a new transient simulation to start where a previous simulation left off. Since two simulations are involved, this is a two-step process: First, the original simulation must be run with the option to save extra state information to the TDF file. Second, the subsequent simulation must be initialized by either the "Transient Restart" or "Initialize Transient Solution" solution initialization methods.

Transient Restart differs from Initialize Transient Solution in that it automatically sets the simulation start time, end time, etc. For this reason, the results of the previous run must be available at the time the Transient Restart option is selected. It follows that Transient Restart is used most commonly by a user who is manually starting a new simulation from the GUI and Initialize Transient Solution is used most commonly when the transient restart is being performed under program control. In either case, changes to geometry, materials, and the boundary conditions in the original simulation can be made so long as the resulting thermal model has the same number and assignment of thermal nodes. Practically speaking, this means that if a simulation is being interrupted to change operating conditions, any changes that do not involve changing a part type or adding or removing geometry either from a part or from the model itself can be made before continuing the simulation.

When a transient restart is initiated, all of the preprocessing that is normally done at the beginning of a simulation is still performed, including view factor and conductor calculations. This allows for the rigorous modeling of the effects of radiation exchange, shadowing, etc., even in the presence of relative movement and/or articulation [Figure 2].

Note that the Initialize Transient Solution option does not enforce that a new simulation begins exactly one time step after the previous simulation ended. If the user starts a new run with a start time other than one time step after the last time in the initialization file, a mismatch will occur: the initialization temperatures will not match the boundary conditions at the specified start time.

5.0 USER ROUTINES

In MuSES, geometry is grouped into parts. By definition, all of the geometry assigned to the same part has the same material and thermal properties. Most of these properties, as well as some scenario information (such as vehicle speed), can be represented in MuSES by time-varying or temperature-dependent curves. In some instances, it is desirable to model more complicated behavior. When this is the case, user-written routines, in the form of scripts or compiled code, can be used as an alternative to curves. The "user routines" are called

each time a property that would have been provided by a curve is needed in a calculation, typically once per time step (per thermal node if applicable) for time-varying properties and once per iteration per thermal node for temperature-dependent properties.

An optional string, settable by the end-user on the MuSES GUI, is passed to the user routine, along with basic state information (e.g., the simulation time, nodal temperatures, etc.) every time the user routine is called. Functions are provided for use by the author of the user routine to determine the position of the thermal node within (the thickness of) each element, the element number, the part to which the element belongs, and the spatial position of the element. From this information, different properties can be calculated for and applied to each thermal node.

In addition to being called whenever curve values are needed, designated user routines will be called from any of six different points of the solution process:

- The beginning and end of the thermal solution.
- The beginning and end of each time step.
- The beginning and end of each iteration.

An API is provided to give authors of advanced user routines access to internal data used in the simulation. The API provides 89 functions to access geometry, part, scenario, analysis, and weather information:

- Retrieve the command line arguments used to start MuSES.
- Retrieve the number of parts, elements or vertices in the model.
- Retrieve the xyz coordinates of each vertex or the element centroid.
- Retrieve the vehicle heading and speed.
- Retrieve the engine power and speed.
- Retrieve and Set the temperature, convection coefficient, fluid temperature, imposed heat, capacitance, area, emissivity, or absorptivity of a node.
- Retrieve and Set the first strike diffuse, direct or total solar flux.
- Retrieve the incoming/outgoing/net conduction, convection, radiation, or advection heat rate.
- Retrieve the convergence criteria.
- Retrieve the current time step's maximum temperature change.
- Retrieve the time step number and solution start time and duration.
- Retrieve the total/diffuse/direct solar, air temperature, air pressure, relative humidity, wind speed, wind direction, sky temperature, cloud cover, rain rate, rain temperature, and sun position.

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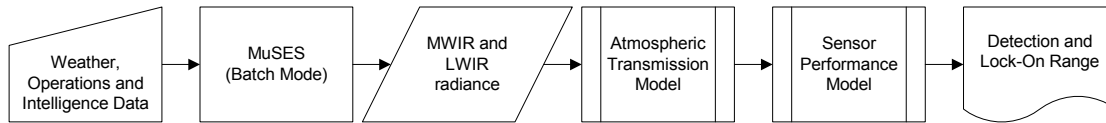


Figure 3: The TAWS simulation process.

6.0 EXAMPLES

6.1 Target Acquisition Weather Software (TAWS)

“TAWS [1] was developed for use by tactical weather teams supporting Air Force, Army, Navy, and Marine operations. Mission planners, pilots, and other tactical forces need to know if it is possible to conduct their missions under expected weather conditions using electro-optical weapon and target acquisition systems. TAWS predicts detection or lock-on range for a series of targets. For each target, calculations may be performed for a series of potential times, approach azimuths, weapons systems, and sensor elevations.”

TAWS users select targets and operating conditions through the TAWS GUI; MuSES is run in batch mode. [Figure 3] The potentially large number of scenarios places a constraint on run time, which translates to a requirement that radiation exchange factors cannot be recalculated. Since MuSES precomputes view factors¹ and solves for the (multi-bounce) net radiation exchange (in the solar and thermal bands) simultaneously with the thermal solution, TAWS users can potentially specify different paints as part of the problem definition. In other words, changing surface emissivity and absorptivity does not require a lengthy recalculation of view factors.

At the conclusion of each MuSES simulation, TAWS retrieves target radiances in MWIR and LWIR wavebands. The tdfio library also contains a function for calculating apparent areas for an arbitrary azimuth and zenith angle. TAWS then sends the target (as seen from the sensor position) and background radiance to its atmospheric and sensor performance models so that detection and lock-on ranges can be calculated.

In summary, TAWS:

- Makes TDFIO library calls to:
 - Set simulation parameters.
 - Apply different paints to targets.
- Runs MuSES in batch mode to calculate diffuse target radiances.
- Makes TDFIO library calls to:
 - Retrieve target and background radiances.
 - Calculate element apparent areas (and from that the target radiance) as seen from multiple sensor positions.

¹ A view factor is the amount of radiation emitted from one surface and absorbed at a second surface assuming all surfaces are black; view factors depend only on geometry.

6.2 Cameo-Sim

Cameo-Sim (CS) is a broadband scene simulation software system that produces high quality synthetic imagery of natural terrestrial scenes. [Figure 4] Static and moving objects and observers can be accommodated, and although CS does have a real-time capability, it is not considered in this discussion. [2] Unlike in the previous example, CS makes its own radiance calculations as part of its rendering process. For this reason, it uses MuSES only for its thermal solution. However, in order to ensure consistency between the rendered image and the thermal results, CS requires access to the surface properties that have been assigned to a MuSES target.

Once a MuSES target has been placed within a scene, CS, at rendering time, creates a MuSES weather file from the CS atmospheric definition and then uses the tdfio library to read in and modify a baseline TDF file. The modifications include a reference to weather file, simulation start time, end time, global position, orientation, speed, etc. CS then runs MuSES in batch mode. Upon completion of the simulation, CS reads the target geometry, material properties and predicted temperatures and converts it to its own file format for use within the CS renderer.



Figure 4: CameoSim MWIR Image

In summary, CS:

- Makes TDFIO library calls to set simulation parameters.
- Runs MuSES in batch mode to calculate target temperatures.
- Makes TDFIO library calls to extract target geometry, surface properties, and temperatures.

6.3 Pavement Thermal Model (PTM)

This example illustrates the transient restart feature of MuSES, which in this case is used to run a simulation continuously while making use of updated weather forecasts as they become available. The same technique could also be used to produce simulations that combine (near) real-time weather measurements with weather forecasts resulting in predicted temperatures that are more accurate than when using only forecast weather.

In an effort to make road and weather information more readily available to travelers and maintenance personnel, the State of Montana (USA) Department of Transportation has implemented the Greater Yellowstone Regional Traveler and Weather Information System (GYRTWIS). As part of this program, the Western Transportation Institute/Montana State University (WTI/MSU) developed the Pavement Thermal Model (PTM). The PTM computer model receives forecasted weather conditions and generates a location-specific prediction of pavement conditions. [3] The PTM uses a commercial variant of MuSES known as RadTherm/RT; the pavement thermal model in RadTherm/RT was originally developed as a background for MuSES targets.

In the actual operation of the PTM, new forecast weather becomes available every 12 hours; the forecast is for the next 12 hour period. In this case, the use of the transient restart feature is fairly straightforward: Set up a

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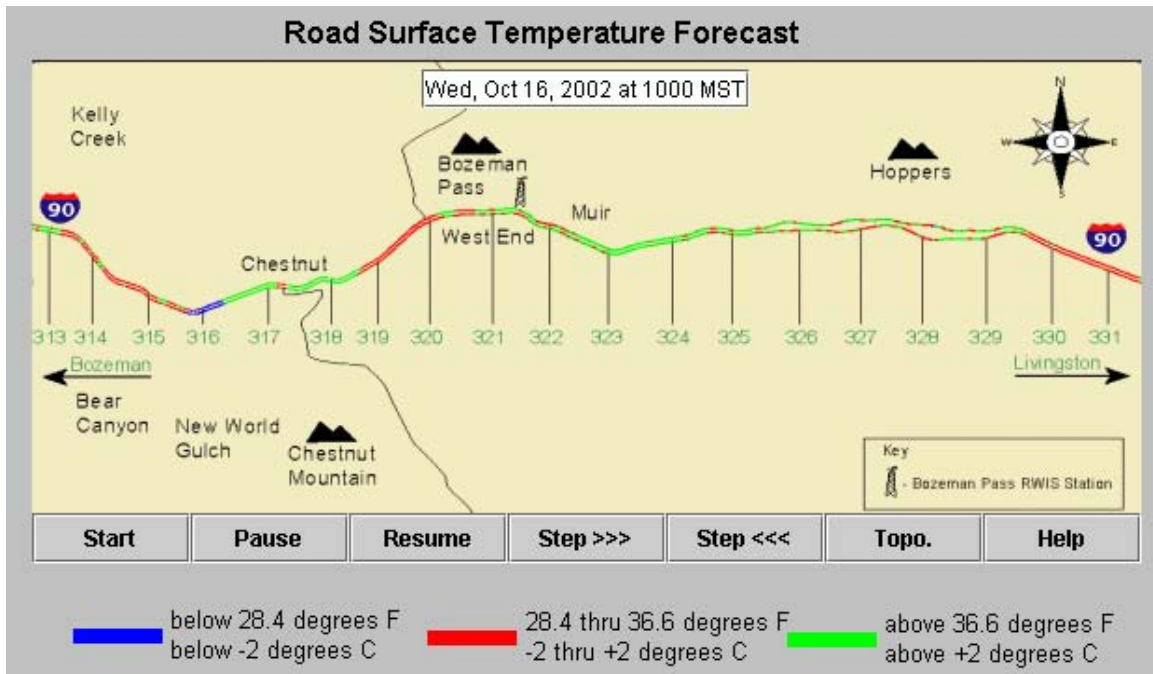


Figure 5: The variation in road surface temperature predicted by the PTM is due largely to changing weather conditions and shadowing of the road as it passes through a mountainous region.

RadTherm/RT model to run for 12 hours with the initial weather data. Twelve hours later (long after the RadTherm/RT simulation has finished) when a new weather forecast becomes available, modify the TDF file to run a simulation for the next 12 hour period using the newly available forecast. This process is then repeated indefinitely.

The use of the transient restart feature would be only a little more complicated if a new 12 hour weather forecast were available every hour. Since a transient restart can only be performed at the end of a previous simulation, two transient restarts are required each time new forecast weather becomes available: First, an hours worth of simulation is run and a copy of the resulting TDF file is saved. A transient restart is performed to provide the remaining 11 hours worth of forecast pavement temperature. Second, one hour (of real-time) later when a new weather forecast becomes available, a second transient restart is performed using the copy of the TDF file and the new weather data. [Figure 6]

In summary, the PTM:

- Makes tdfio library calls to set simulation parameters.
- Runs RadTherm/RT in batch mode to calculate terrain temperatures.
- Makes TDFIO library calls to extract terrain temperatures.
- Performs a transient restart (in batch mode) to continue a new simulation where the old one left off.

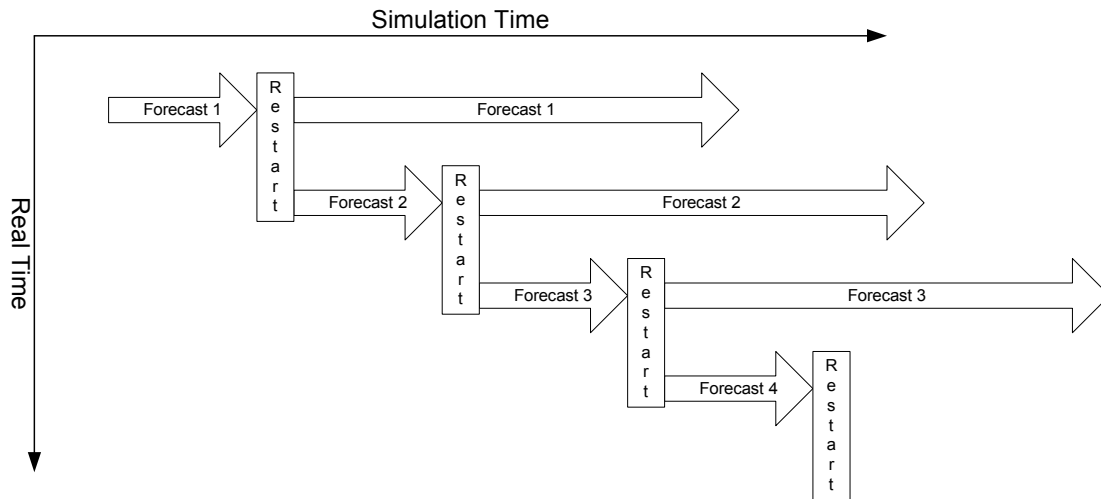


Figure 6: A weather forecast is usually updated before the previous forecast has expired. Providing temperature predictions based on the most recent forecast requires two transient restarts from the same point: First with the original forecast and again when the next forecast becomes available.

6.4 Real-Time Scene Generation

Real-time scene generators, such as Multigen-Paradigm’s Vega Prime IR Scene and Amherst Systems’ RISS, currently use MuSES in a manner similar to Pavement Thermal Model. For the same reasons as Cameo-Sim, these scene generators use MuSES to predict physical temperatures rather than radiances. For real-time operation, a transient restart may be done as often as every time-step so that vehicle operating conditions can be updated in near real-time. However, the large amount of file i/o that occurs as:

- MuSES writes out its TDF file every time temperatures are needed,
- The application reads the TDF file in order to extract the temperatures, and
- MuSES reads the TDF file in order to perform a transient restart

can impose limits on model and/or time-step sizes.

MuSES 7.1 can execute user-supplied code from various points in the simulation. From an IR signature analyst’s point of view, the primary utility of user routines is the ability to add customized code to simulate the thermal behavior of engines and other complex objects. However, user routines will also provide for a more straightforward and efficient integration of MuSES into real-time scene generators.

Both types of user routines, those that provide replacements for curve data (e.g., to set the vehicle heading as the real time simulation proceeds) and those that are called from specific points in the solver (e.g., to write target temperatures to shared memory at the end of each simulation time step), will be applicable to real-time scene generators. Since control is turned over to the user routine when it is called, synchronization between the real-time application and MuSES can easily be accomplished. [Figure 7]

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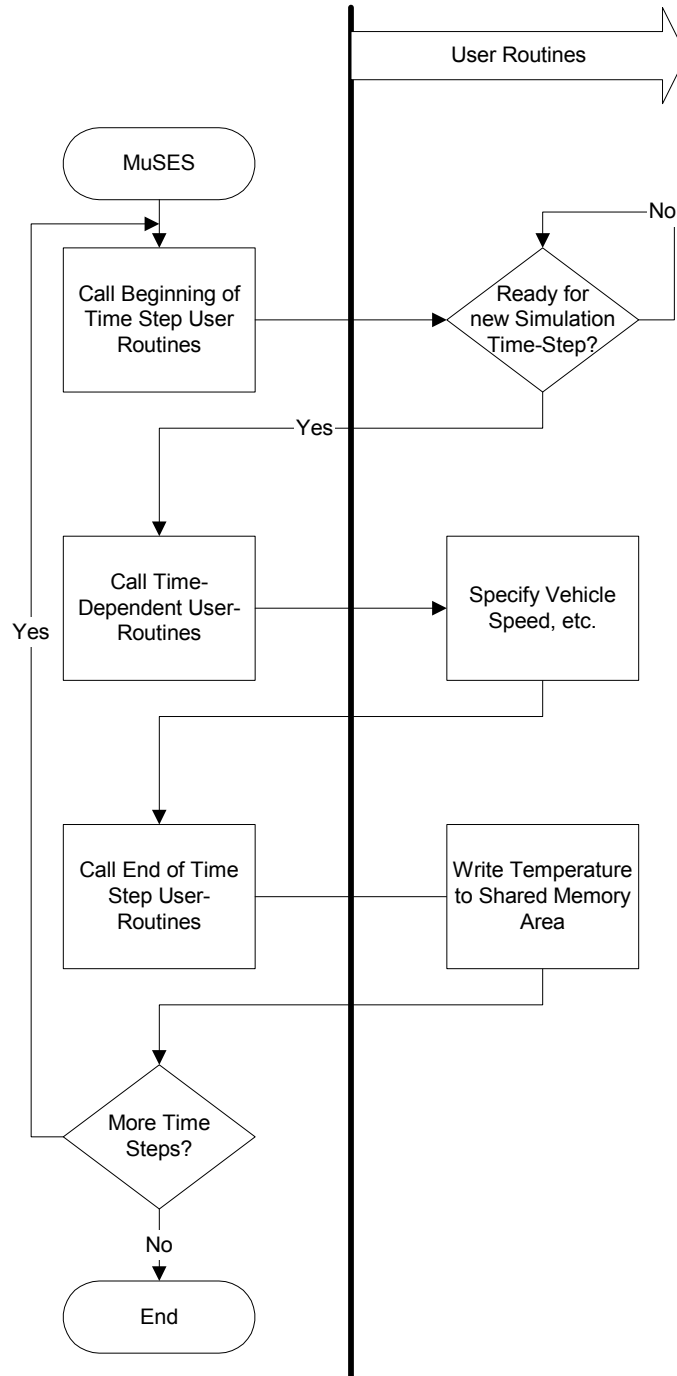


Figure 7: An example of how MuSES' user routines might provide synchronization to and data exchange with real-time applications.

In this example, temperatures are written to shared memory so that they can be displayed in real-time. Similarly, non real-time applications can save temperatures, heat fluxes, etc., to disk for post-processing outside of MuSES.

In summary, real-time scene generators will:

- Run MuSES in batch mode.
- Use MuSES user routines to:
 - Provide synchronization between real-time and MuSES simulation time.
 - Set scenario information such as vehicle speed, heading, orientation, etc.
 - Write temperatures to a shared memory area.

7.0 SUMMARY

The development of the tdfio library, MuSES batch mode, the transient restart facility and the run-time linking of user routines into the Muses executable make it possible to run MuSES as part of an automated analysis. MuSES' batch mode is essential for any application or script that needs to run a MuSES simulation. The tdfio library provides the means by which MuSES models and/or simulation scenario parameters can be modified under program control. Some application programmers may find that the batch mode command line arguments are a suitable alternative to the tdfio library. The transient restart facility provides a simple mechanism for restarting a simulation that has been suspended to make use of updated operating conditions. Beginning with MuSES 7.1, user routines will allow applications to modify and extract data from a MuSES simulation *while it is running*.

8.0 REFERENCES

- [1] Gouveia, M. J. et al, TAWS and Nows: Software Products for Operations Weather Support, *Battlespace Atmospheric and Cloud Impacts on Military Operations Conference 2000, Fort Collins, Colorado, USA, April 24-27, 2000*.
- [2] Gonda, T. G., et al, An Exploration of Vehicle-Terrain Interaction in IR Synthetic Scenes, *SPIE Defense & Security Symposium, April 13-15, 2004*.
- [3] Final Evaluation Report for the Greater Yellowstone Regional Traveler and Weather Information System (GYRTWIS), *Department of Transportation Task 9826, December 30, 2003*.



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Introduction

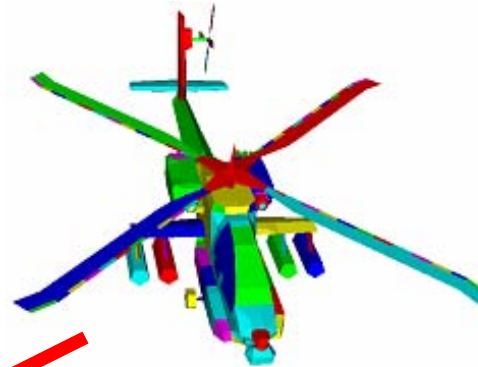
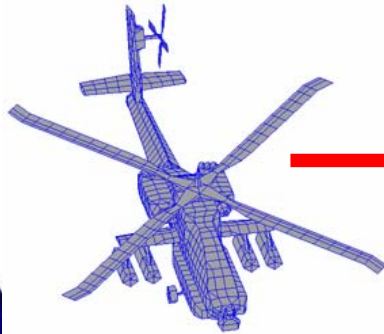
- MuSES (== RadTherm/IR) is commonly viewed as a standalone IR signature prediction tool
- Many Applications need to run MuSES under program control
- Objective: Describe features that allow other programs to modify, exercise, and query MuSES models.



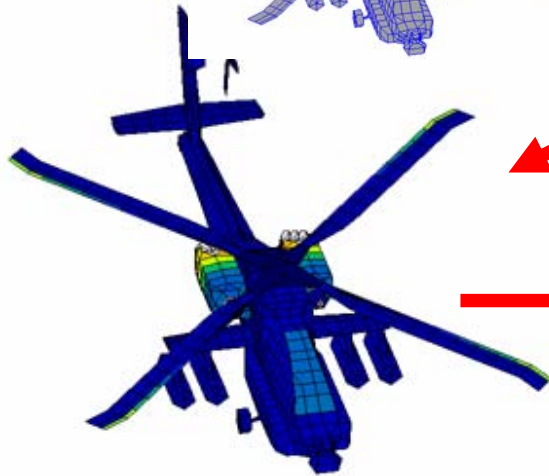
Modeling with MuSES



Meshed
Surface
Geometry



Mesh elements
grouped into
Parts;
Properties
assigned to
Parts



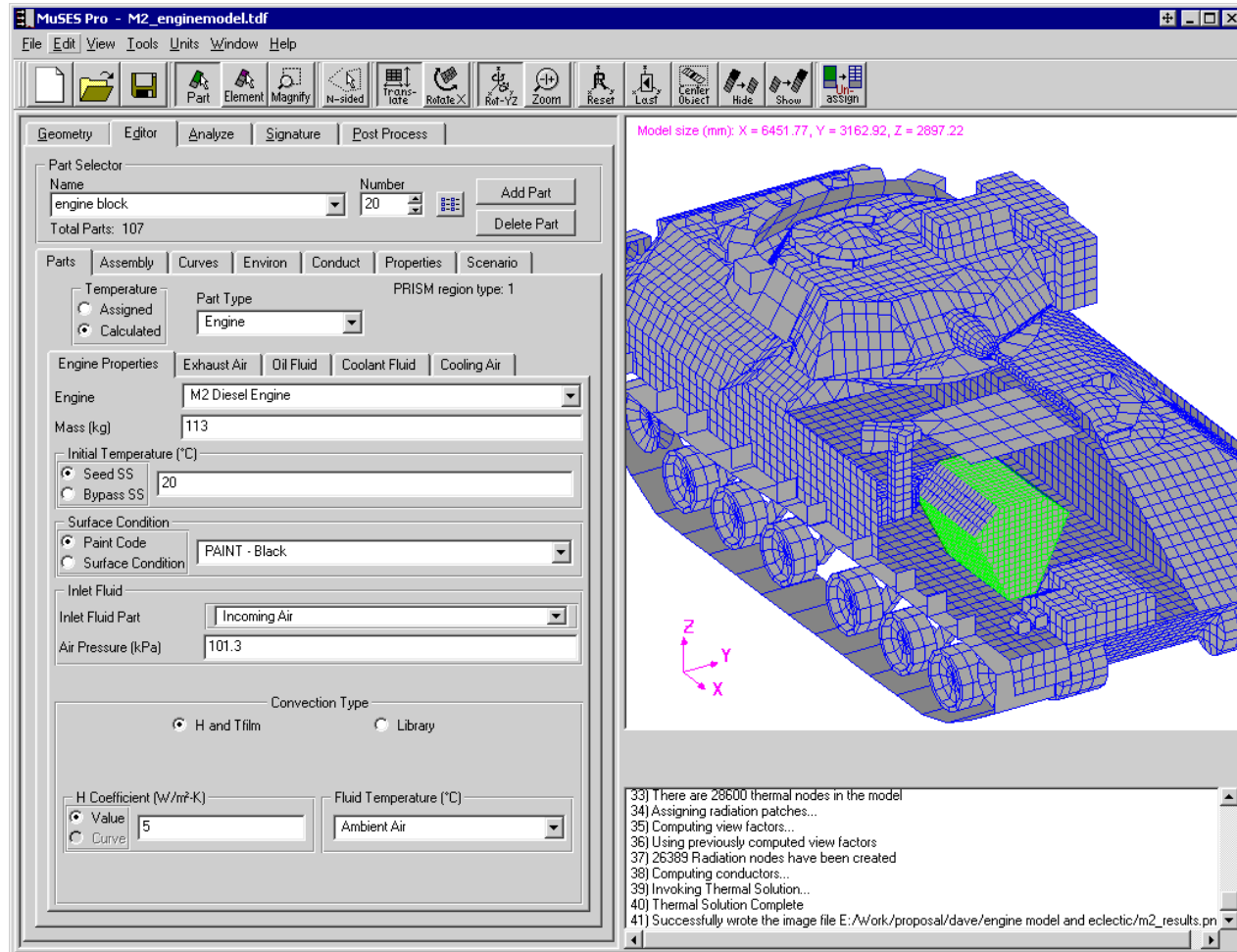
Temperature Prediction



Infrared Signature Prediction



Modeling with MuSES



The modeling process is often done entirely within MuSES' Graphical User Interface (GUI)



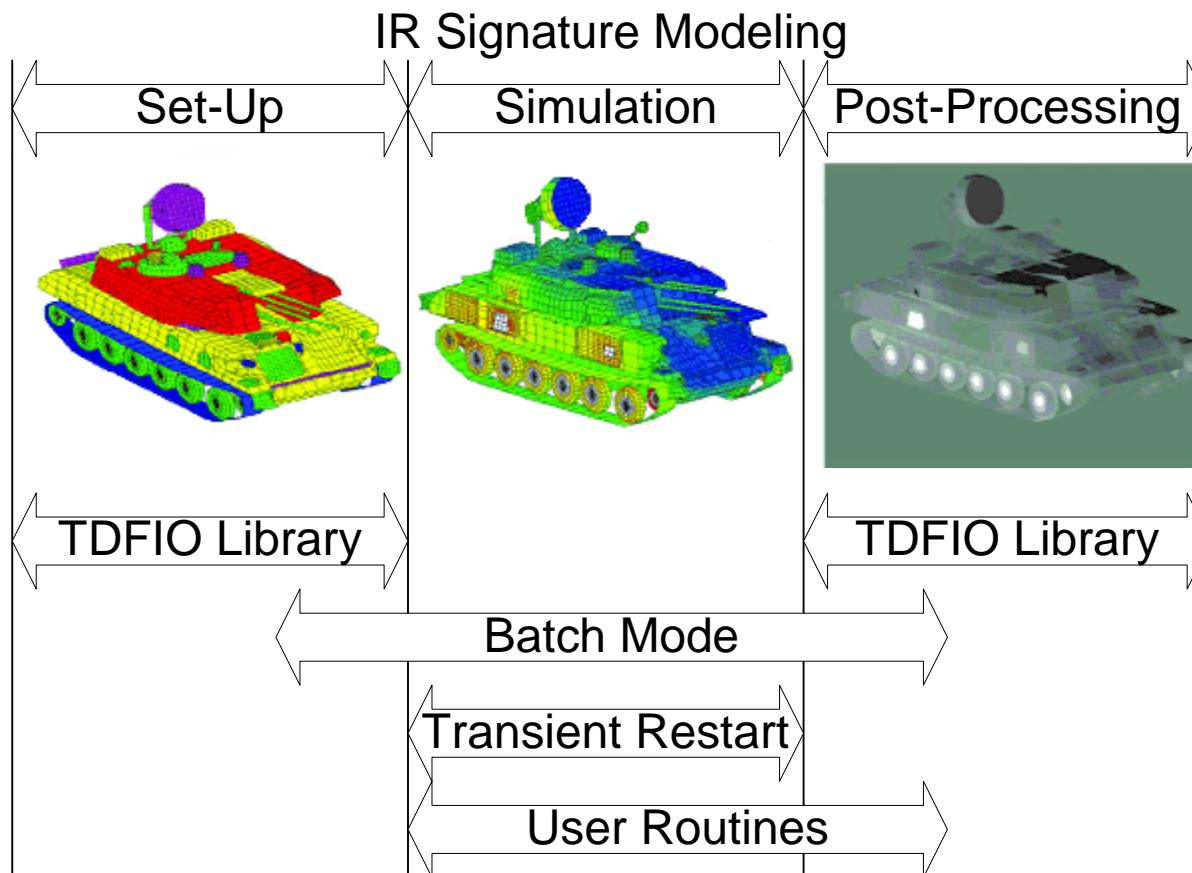
MuSES Application Interface



- Many applications require that MuSES temperatures and/or radiance output be used in a chain of automated analyses
- MuSES Application Interface
 - tdfio Library
 - Batch Mode
 - Transient Restart Facility
 - User Routines



MuSES Application Interface





tdfio Library



The screenshot shows a Microsoft Internet Explorer browser window titled 'Annotated Index - Microsoft Internet Explorer'. The address bar shows a search for 'Y! Bookmarks ... attempting to connect to Yahoo!'. The main content area displays a navigation menu with links: [Class Hierarchy](#), [Compound List](#), [File List](#), [Compound Members](#), [File Members](#), and [Examples](#). Below the menu is a large black-bordered box containing the title 'ThermoAnalytics TDF I/O Library Compound List'. Underneath the title, the text reads: 'Here are the classes, structs and unions with brief descriptions:'. A bulleted list follows, detailing various data classes and their functions, such as **TdfCurve** (Data class for curve data), **TdfElement** (Data class for setting/retrieving element data from TDF file), **TdfEnvironment** (Data class for the model environment parameters), **TdfIO** (Main class for creating, modifying, and accessing a TDF file.), **TdfMaterial** (Data class for material data), **TdfPaint** (Data class for spectral paint data), **TdfPart** (Data class for part data), **TdfPatchParam** (Data class for exporting patch setup data with the TDF library), **TdfScenario** (Data class for exporting scenario data with the TDF library), **TdfSigSolutionParam** (Data class for signature solution parameters), **TdfSolutionParameters** (Data class for thermal solution parameters), **TdfSurfaceCondition** (Data class for surface condition data), and **TdfTerrain** (Data class for export terrain data with the TDF library).

- Cross-Platform C++ library gives application programmers the same functionality as the Graphical User Interface (GUI)



Batch Mode



```
D:\RadTherm\Work\Auto>type radtherm-run.bat
radtherm -run exhaust-frame.tdf -nostop
radtherm -run exhaust-frame2.tdf -nostop
radtherm -run exhaust-frame3.tdf -nostop
radtherm -run underbody.tdf -nostop
radtherm -run engine.tdf -nostop
radtherm -run truck.tdf
```

Command Line Arguments

- Scenario Changes
- Output Options

- MuSES can be run without the GUI

Automated calculation
by scripts and other
programs

- View Factors
- Thermal Analysis
- Signature Analysis

```
There are 2755 thermal nodes in the model
Assigning radiation patches...
Time spent assigning radiation patches (sec): 0
Computing view factors...
Using previously computed view factors
1781 Radiation nodes have been created
Computing conductors...
Time spent computing conductors (sec): 0.05
Invoking Thermal Solution...

Time      Iteration  Tolerance (C)  Residual (W)
00:30:00  13         0.00901337     0.025312
Thermal Solution Complete
The Thermal Solution successfully completed.

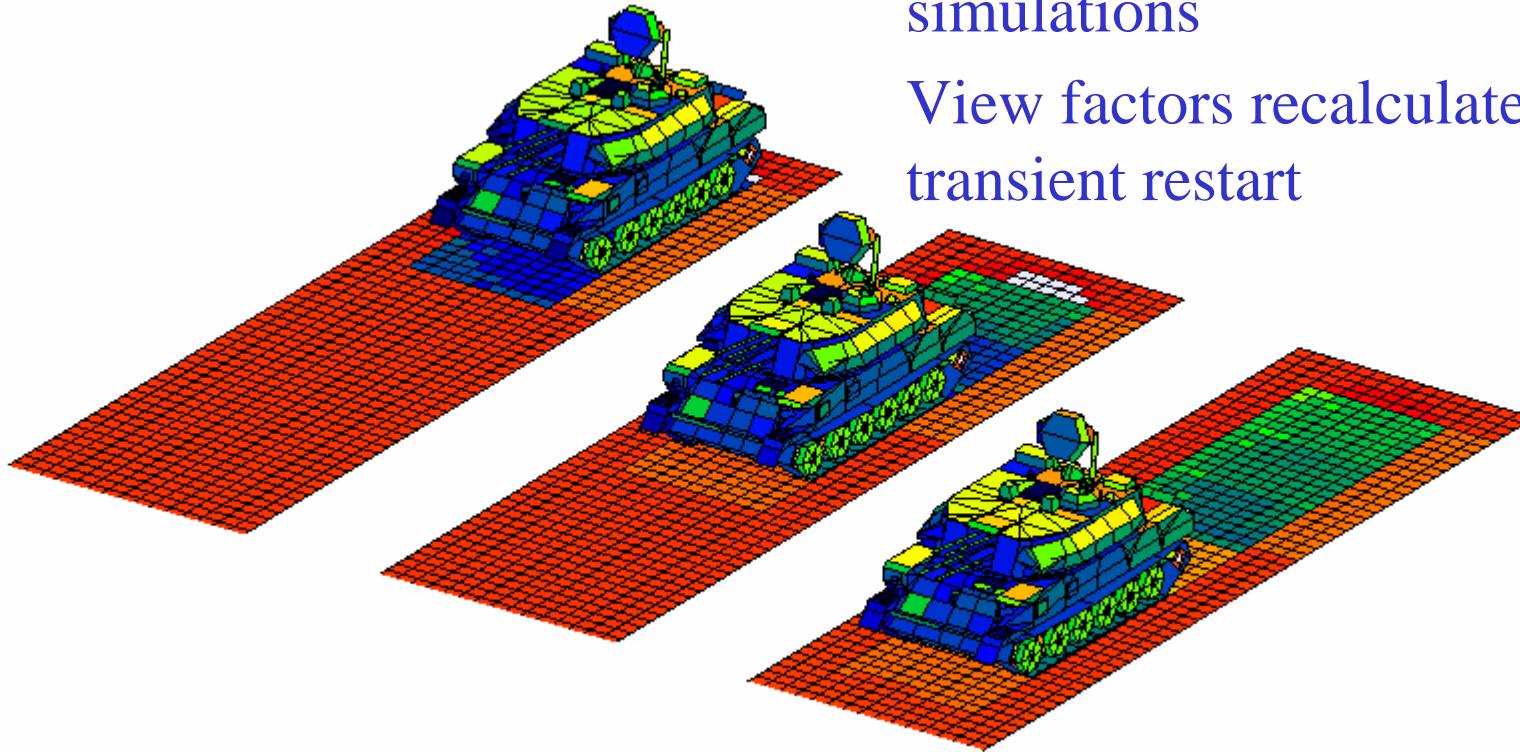
Press a key to dismiss the console.
```



Transient Restart

Geometry translated between simulations

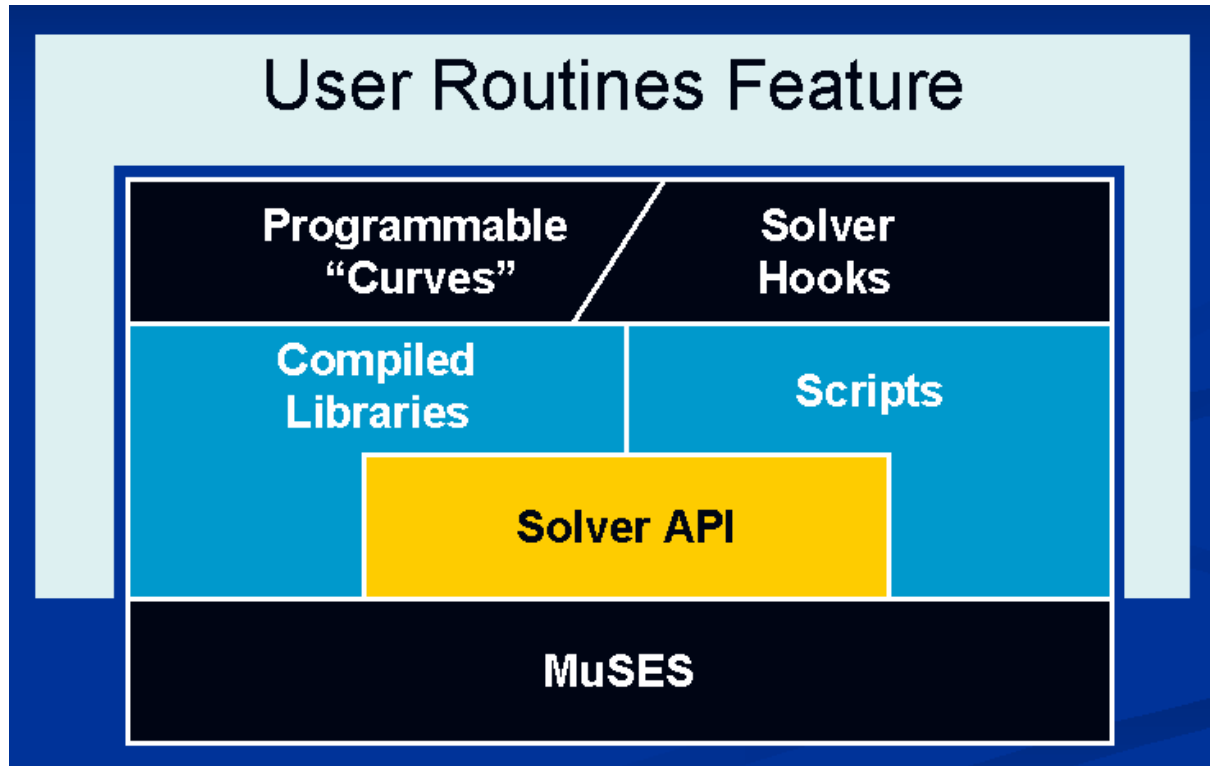
View factors recalculated upon transient restart



- MuSES can start a new simulation (with changes in the scenario, weather, geometry, etc.) where a previous one left off



User Routines



- User Routines: User written scripts and compiled code can be called from MuSES

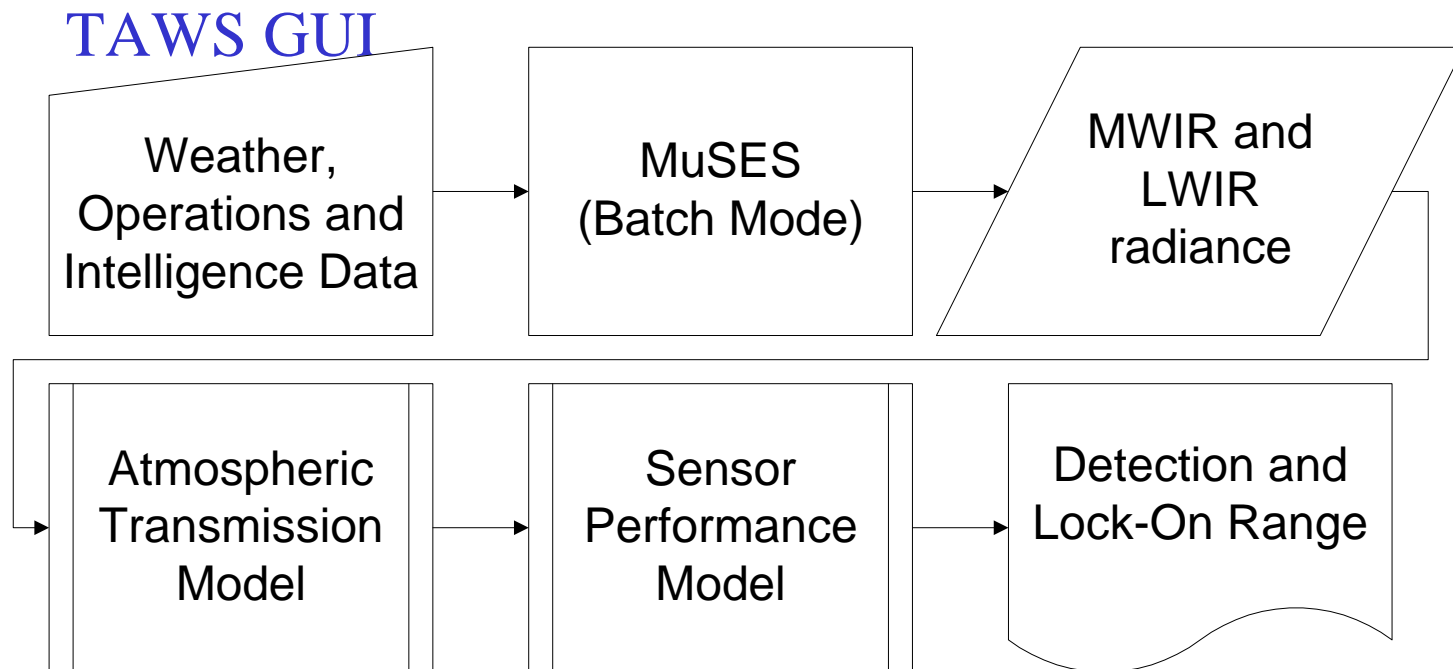


Example: Mission Planning System

- Target Acquisition Weather Software (TAWS)
 - Used by Tactical weather teams supporting Air Force, Army, Navy and Marine operations
 - Predicts if possible to conduct missions under expected weather conditions using electro-optical weapon and target acquisition systems
 - Calculations performed for a series of times and approaches



TAWS



- The TAWS simulation process



TAWS



- Makes tdfio library calls to
 - Set simulation parameters
 - Apply different paints to targets
- Runs MuSES in batch mode to calculate diffuse target radiances
- Makes tdfio library calls to
 - Retrieve target and background radiances
 - Calculate element apparent areas as seen from multiple sensor positions



Example: Synthetic Natural Environment



- Cameo-Sim
 - Broadband scene simulation
 - High Quality Synthetic Imagery
 - Runs MuSES and Imports Target Temperatures and Surface Properties



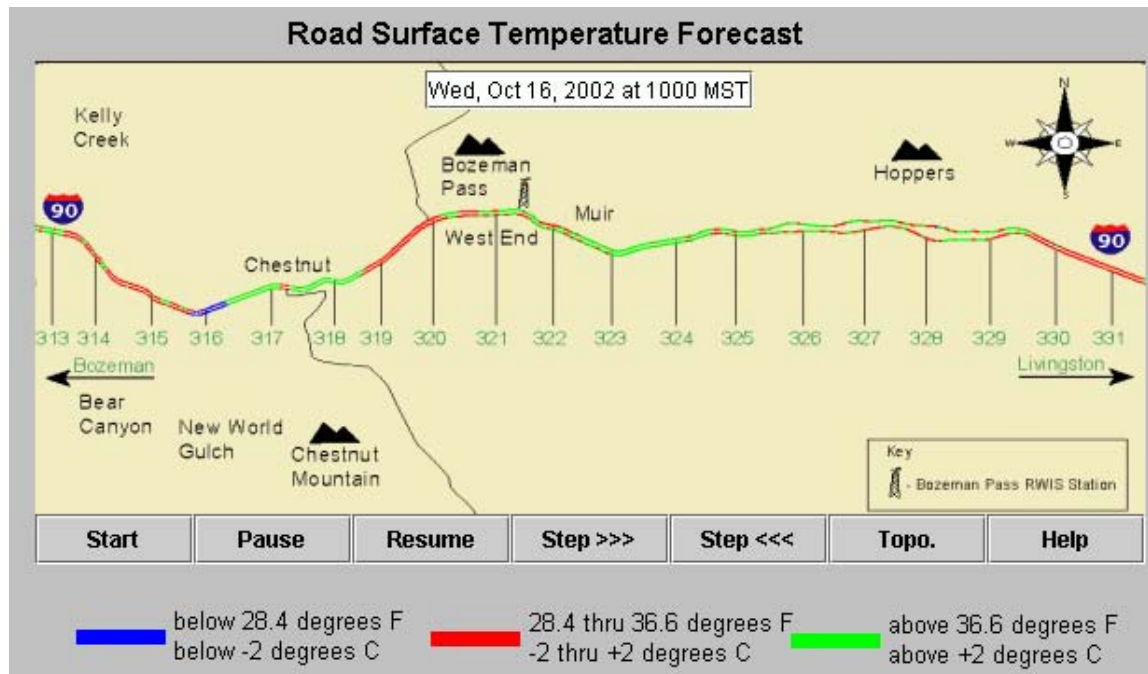
Cameo-Sim



- Creates MuSES weather file
- Makes tdfio calls to set simulation parameters
- Runs MuSES in batch Mode to calculate target temperatures
- Makes tdfio calls to retrieve target geometry, surface properties, and temperatures



Example: Continuous Temperature Prediction System

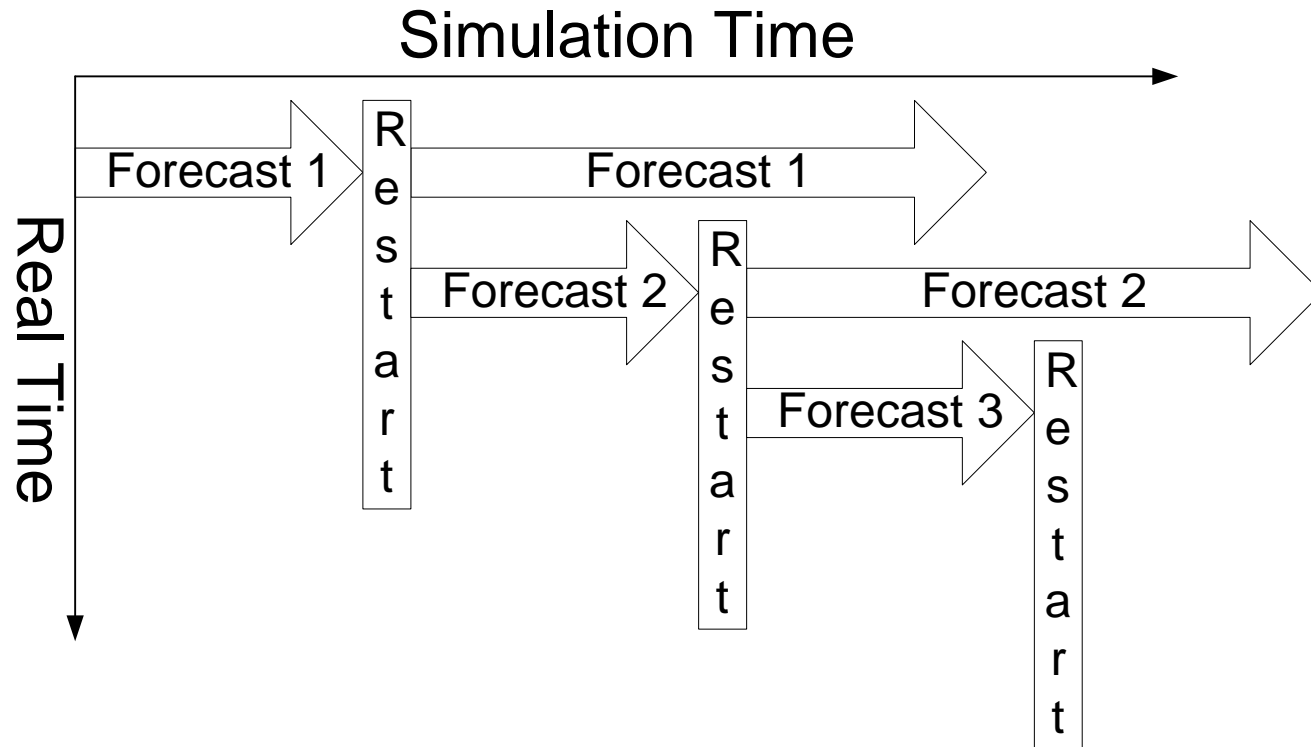


Variation in pavement temperature due to variable weather conditions and the shadowing of the road as it passes through a mountainous region.

- Pavement Thermal Model (PTM)
 - Runs Continuously (weather forecast updated periodically)
 - RadTherm/RT (commercial variant of MuSES) pavement model originally a “background” for MuSES’ targets



Pavement Thermal Model



- Temperature predictions based on the most recent forecast requires two transient restarts from the same point
 - Once with the original forecast
 - Once again when the next forecast becomes available



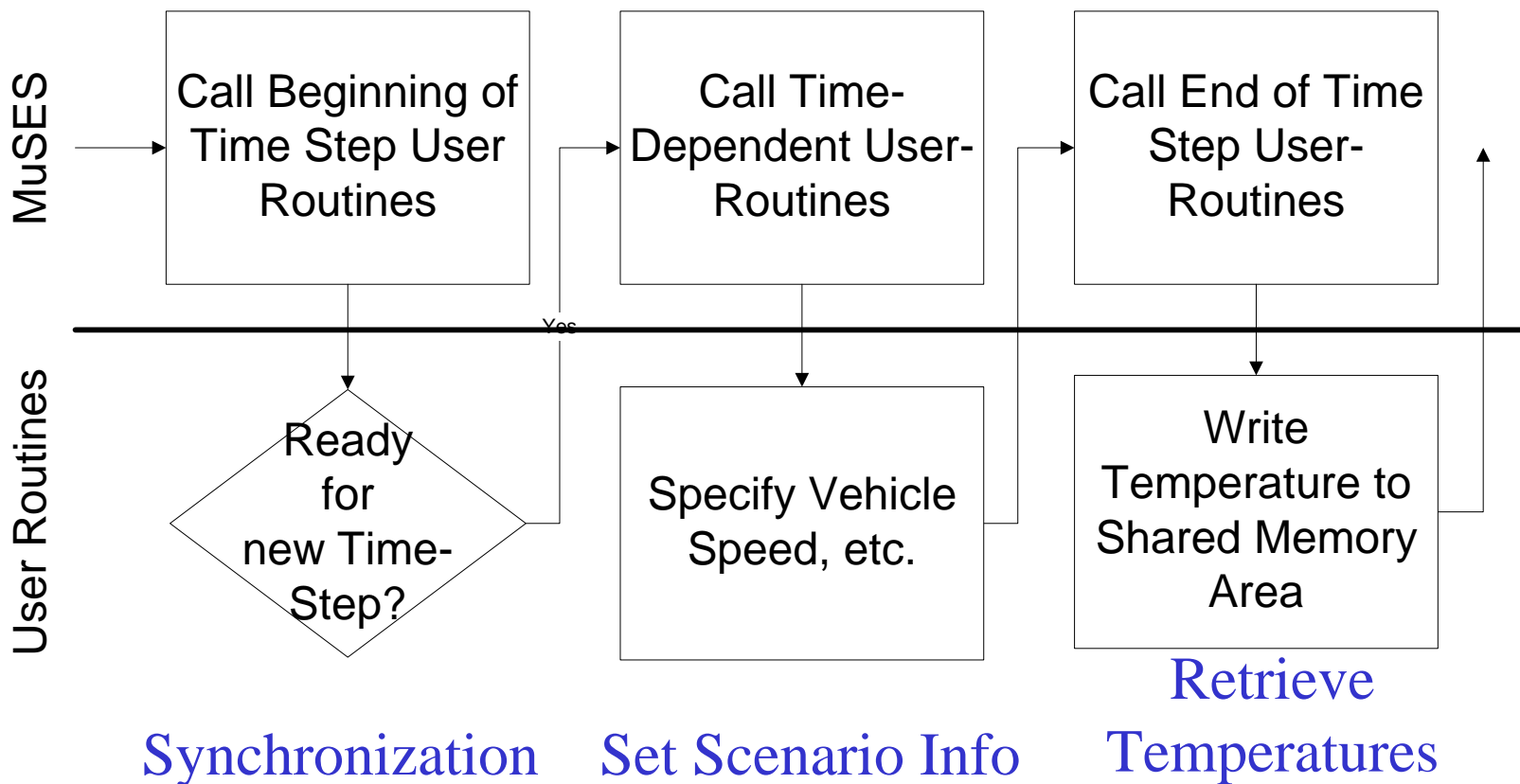
Pavement Thermal Model



- Makes tdfio calls to set simulation parameters
- Runs MuSES in batch mode to calculate terrain temperatures
- Makes tdfio calls to extract terrain temperatures
- Performs a transient restart to continue the simulation using updated weather



Example: Real-Time Scene Generators



- Starting with MuSES 7.1, Real-Time Scene Generators can use User Routines instead of the Transient Restart Facility



Summary

- MuSES can be run as part of an automated analysis
- Batch Mode is essential
- tdfio library provides an alternative to the GUI
- Batch mode command line arguments are a (limited) alternative to the tdfio library
- Transient Restart provides a simple mechanism for restarting a simulation with updated operating conditions
- User Routines allow applications to extract and modify data from a *running* MuSES simulation