

WEATHER ENVIRONMENT SIMULATION TECHNOLOGY

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ABSTRACT

This paper presents the results of an internal research program at Southwest Research Institute for the development of a weather simulation and modeling approach for training and simulation applications. This weather simulation system approach, known as Weather Environment Simulation Technology (WEST), provides the means to correlate and synchronize all weather-related cues presented to the student. The approach provides for direct correlation between out-the-window visual weather scenes, weather-processing sensors and avionics displays, and vehicle handling qualities through the use of a unified meteorological database that has been reformatted specifically for real-time simulation. By ensuring dynamic weather cue correlation across all simulator subsystems, this technique enables simulator instruction in weather-related procedures to be highly transferable to mission-oriented situations. This research effort demonstrated a method for processing weather data in real time for generation of out-the-window weather imagery that correlates directly with airframe dynamic effects. The model architecture also supports sensor simulations and generation of cues on operator displays and controls. Since the weather model is driven by gridded-field, digital meteorological data, students can learn and practice weather-related skills within a realistic, synthetic weather environment as produced by a WEST-compatible simulator.

ABOUT THE AUTHOR

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INTRODUCTION

Weather plays a key role in the planning and performance of joint operations involving the tactical employment of sensors and weapon systems. Yet weapon system trainers (WSTs) and networked distributed interactive simulation (DIS)-compatible simulators are currently limited in their ability to provide a realistic portrayal of weather conditions that are applicable to these types of mission operations.

Needs and Requirements

Sources of sensed atmospheric data have expanded rapidly within the last several years, including ground-based doppler weather radars and satellite-based systems that sense and record large-scale weather conditions in the form of time-varying 3-D (space plus time) gridded-field, digital data. Although these systems are producing voluminous amounts of data for forecasting and analysis purposes, methods for applying this data effectively within simulators for training, mission planning, and mission rehearsal are needed.

Approach

The WEST approach outlines an efficient way for integrating digital weather data, structured in a gridded Cartesian format, into manned simulation systems. Both uniform and non-uniform grid formats may be accommodated. WEST provides the means for simulators to manipulate atmospheric data rapidly and transform physical weather parameters into simulator display cues that are correlatable across individual simulator subsystems. Weather data parameters accommodated within WEST include wind direction and magnitude, liquid water content, temperature, pressure, radar reflectivity, and water content type (rain, snow, ice). Digital atmospheric data sets currently supported by the approach include the Joint Airport Weather Studies (JAWS) database

from the National Center for Atmospheric Research (NCAR) and the Terminal Area Simulation System (TASS) meteorological weather model developed by the NASA Langley Research Center for windshear research.

With the WEST approach, digital atmospheric source data is reformatted and preprocessed to form a unified weather database capable of supporting each simulator subsystem. During simulator operation, a weather "generator" accesses the unified database and provides a sensor-specific formatted list of weather elements located within each subsystem's field of regard. The subsystems incorporate the weather data into sensor processing operations and transform the sensed digital weather data into simulator display cues.

Applications

WEST is designed to support weapon system training applications, mission rehearsal, flight training, and weather analysis applications. Although work to date has focused on generating visual imagery from gridded weather data sets, the approach is extensible to supporting FLIR simulations, digital radar landmass simulators (DRLMS), and other types of sensor simulations.

BACKGROUND

The atmospheric environment is a common denominator that affects virtually all military operations. Aircraft, ships, tanks, sensors, dismounted infantry, weapons, and communications system, must perform their individual tasks under a wide range of weather conditions, anywhere in the world, at any time of year. Providing the warfighter with the tools to understand, cope with, and take advantage of the weather environment and its effects on mission tasks is a pressing need within the simulation and training community.

Mission Operations Affected by Weather

Specific mission operations that are most affected by spatial and time-varying weather conditions include aircraft take-off/landing, air combat tactics, target acquisition, and weapons delivery, to name a few.

Aircraft Take-Off/Landing. Aircraft are most susceptible to the effects of windshear, heavy rain, and turbulence during the take-off and landing phases of flight. Training aircrews via simulator instruction in how to detect and avoid hazardous meteorological conditions and effects is needed *within the military and also within the commercial and general aviation sectors.* Adverse atmospheric conditions that impact flight safety include thunderstorms, microburst windshear events, gust front turbulence, wake vortices, and dynamic interface between aircraft and structures, such as those between a rotary wing aircraft and a ship superstructure.

Mission Tactics. Tactical exploitation of area weather conditions can provide an extra edge over an opposing force when planning and performing mission operations. The liquid water content within convective weather masses provides a freely available means for attenuating and masking platform observables (visual, radar, infrared) when the weather mass is placed between the aircraft and the observing sensor. By introducing timely, geospecific gridded weather data into a mission rehearsal or mission planning system, various routes and sensor profiles can be examined beforehand to identify the optimal movement and placement of forces for a given operation. Routing a strike package around the upwind side of a thunderstorm to hide its presence from search radars would be one example of how local weather conditions can be exploited to provide a tactical advantage.

Target Acquisition. The ability of target acquisition sensors such as radars, imaging infrared (IIR) sensors, and electro-optical sensors to discriminate targets is greatly complicated by intervening weather. A similar problem is presented by battlefield smoke. The spatial distribution of water and particulates within the volume of air over the area of operations causes varying amounts of signal attenuation and clutter across each spectral band, making targets and

cultural features difficult to distinguish and *designate on operator displays.* In addition to reducing situational awareness, intervening convective weather and smoke obscuration conditions also can cause seekers/trackers to break lock. This is more of a problem for longer-range sensors and weapons in which clouds or smoke plumes may come into the sensor's field of view while target tracking.

Weapons Delivery. Weapon flyout and delivery accuracy is also affected by adverse weather conditions. Atmospheric wind and density variation have a direct impact on the way in which weapons fly to the target. *Both wind variability and density variation affect the aerodynamic forces acting on the weapon, which in turn affect the weapon's flight path.*

Current Practice Limitations

Current practices for modeling four-dimensional (space plus time) weather effects for simulator-based training do not yet provide the necessary cues, cue correlation, system performance, or environmental modeling features that are required for truly transferable training to the weapon system for weather-affected operations. Most WSTs in the field today feature separate weather modeling approaches on a per-subsystem basis. Simulator subsystems that model the sensing of weather conditions include digital radar landmass simulators (DRLMS), visual systems, FLIR image generation systems, and airframe/vehicle simulation systems.

Digital Radar Landmass Simulators. State-of-the-art approaches for modeling weather within DRLMS systems involve the use of simple geometric objects (e.g., cylinders, cubes) or digitized two-dimensional (2-D) weather maps for the DRLMS weather database. On systems that use maps as a database source, 2-D map elements are assigned top and bottom altitudes to provide 3-D weather slices. The individual slices are then translated, rotated, and expanded to provide a time-varying radar weather environment. Correlation with other subsystems is attempted by providing the spatial position of active slices back to the host simulation during simulator operations.

Visual Systems. Out-the-window image generators commonly present spatial weather conditions through the use of traditional 3-D

computer graphics techniques that are optimized for real-time image generation involving solid surfaces and/or textured surfaces.

Solid Surfaces. Early flight simulator visual systems used solid-surface polygonal objects to represent cloud formations. These visual cloud representations were created manually using a database modeling system. With the solid-surface approach, clouds are constructed by stretching a tri-mesh-type polygonal surface around the exterior of a cloud. The surface is then colored, shaded, and in some cases assigned a transparency value or material code to provide the cloud's visual appearance. Cloud objects are then grouped together to form weather formations.

The main limitations of solid surfaces for visualizing weather are limited visual realism and the difficulty of correlating visual appearance with digital atmospheric source data. Creating realistic weather effects with solid surfaces requires a lot of hands-on work at the database modeler's station by a highly skilled designer. A mathematical model of weather pattern dynamics must also be developed so that during simulation the individual cloud objects can be dynamically sized, oriented, and positioned. Other significant limitations are that varying resolution models must be developed to accommodate viewing under both far and near distances, and that special visual effects are required to accommodate reduced visibility inside cloud boundaries.

Textured Surfaces. Current-generation flight simulator visual systems use texture to produce photorealistic weather effects. These "texture maps" allow scanned photographic images to be mapped onto polygon surfaces to provide visual weather conditions. The most common practice is to apply photographs of clouds to very large single-polygon "billboards" that are oriented either horizontally (parallel to the ground) or vertically (perpendicular to the ground) to provide the appearance of cloud tops/bottoms or weather formations on the horizon.

FLIR Image Generators. Imaging infrared simulation systems rely upon look-up tables (LUTs) to determine the effect of atmospheric conditions upon the thermo-sensed scene. LUTs are defined for both standard and non-standard day conditions. These tables provide parametric data for altering the color and intensity of scene objects as a

function of ambient atmospheric conditions such as temperature and humidity. FLIR simulations do not yet provide the capability to introduce spatial and temporal weather effects into the scene generation process.

Airframe/Vehicle Simulations. Most flight simulators already use some form of gridded-field data structure to model geographically varying pressure, wind, and temperature within the atmosphere on a large scale. This database is accessed during simulator operation by the aircraft equations-of-motion model and the flight instruments simulation. The grid resolution of the pressure, wind, temperature database is on the order of several kilometers, and liquid water content is not included as a database parameter. For these reasons, the pressure, wind, and temperature database used by the host flight simulation is not directly applicable to other simulator subsystems.

Weather Simulation Requirements

An ideal approach for overcoming the limitations of current techniques for modeling weather is to derive simulator cues directly from a unified digital weather database. This provides a much better alternative to the practice of manually creating separate subsystem specific databases (visual, radar, flight) and then attempting to correlate weather cues by "tuning" the individual databases to meet specific training requirements. The WEST approach solves this problem by using a modified simulator architecture that includes additional subsystem interfaces for handling dynamic weather data. Figure 1 illustrates the main idea of the WEST concept for correlating weather cues across individual simulator subsystems.

With the WEST approach, environmental correlation between simulators and simulator subsystems is achievable by sharing a common numerical description of weather conditions over the gaming area (the unified weather database). Just as terrain data is shared between simulators in a common generic format (Project 2851), the WEST approach provides a similar technique for sharing weather data. The primary difference is that terrain data is static (excepting dynamic terrain), while weather data is time-varying and subject to dramatic change. This characteristic calls for a different way of thinking about how weather data should be accessed and processed

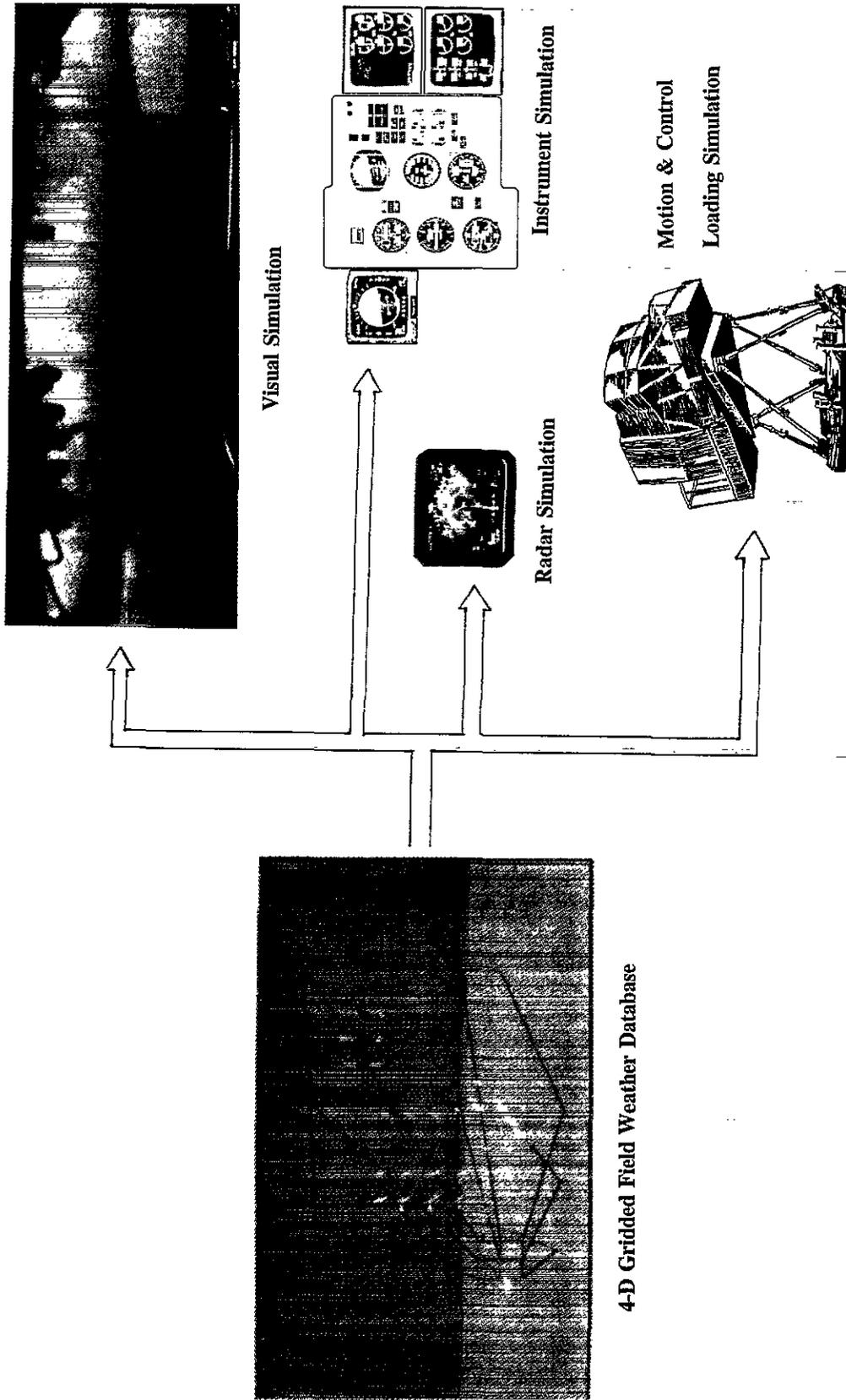


Figure 1 WEST Unified Weather Simulation

during simulator operation. With the WEST approach, each simulator subsystem is provided with only the necessary data required for immediate processing by the subsystem, the intent being to minimize the computational timing and sizing impact on subsystems for incorporating dynamic weather data. The other benefit is that with this architecture, simulators can accommodate "just in time" weather feeds for integrated live/virtual training in addition to accommodating predefined, canned weather scenarios.

Digital atmospheric data is becoming increasingly available in the form of time-varying 3-D gridded data sets. Essential simulation capabilities for generating simulator cues from gridded data sets have been outlined by the author^{1,2} and include 3-D gridded-field data handling, position-independent viewing/sensing, and fly-through viewing.

Digital Data Handling Capability. In order to drive simulator subsystems directly from digital atmospheric data, the weather simulation technique must be capable of manipulating and processing 3-D gridded data very rapidly to support real-time scene update rates (typically 30Hz). The data handling technique must accommodate paging between spatial weather data subdivisions or tiles as well as continuous interpolation between adjacent time-stamped data files. This capability is essential for handling very large spatial and temporal data sets.

Position Independent Viewpoint Capability. A key requirement is that the ideal digital weather simulation technique must support totally independent viewpoint capability for sensor scan processing of the gridded weather data set. This means that the data must be sensed and formatted from any position, orientation, or relative motion with respect to the data set. This capability is essential for simulator applications where the platform is almost always maneuvering within the boundaries of the 3-D gridded field. In many circumstances for high-altitude weather viewing, the entire data set may be located within the platform's visual field of view.

Fly-Through Viewing Capability. In addition to supporting unconstrained platform motion, the optimal simulation technique for 4-D weather must also support seamless fly-through visual viewing of

the data. The student should be presented with perspective-correct imagery under all viewing conditions. The visual appearance of the weather effects should automatically compensate for viewing aspect, lighting conditions, and relative motion of the eyepoint and dynamic weather effects data.

WEST DESCRIPTION

Advances in computer image-generation (CIG) processing power, coupled with the increasing availability of gridded field weather data, now make realistic weather modeling practical for use in manned simulators. During the WEST research effort, attention was focused on the visual simulation of weather. Several weather imagery techniques were evaluated on high-capacity graphics workstations to determine the best method for simulator application. An approach using continuous-level-of-detail graphics primitives was selected as the best method, and a frame-based image-generation transform function was developed for constructing and rendering scene primitives from weather database parameters in real time.

The WEST approach is specifically designed to support real-time visual simulation requirements associated with rendering 4-D weather imagery directly from digital source data. The WEST prototype³ executes on a Silicon Graphics Crimson Reality Engine with two Raster Managers. Figure 2 illustrates the architecture and functional elements of the WEST approach. Major elements include the digital weather source database, a visual preprocessor component, a data handling component, a simulation interface component, a visual weather database, and an image-generation component.

Digital Weather Source Database

WEST is designed to process large-scale gridded data sets containing digital atmospheric data parameters that may be produced from sensor observations, or from numerical models. Digital atmospheric physics models such as TASS and Doppler radar-derived atmospheric observations such as JAWS data sets are examples of the types of gridded field data sets available that provide quantitative, time-varying descriptions of aviation weather conditions.

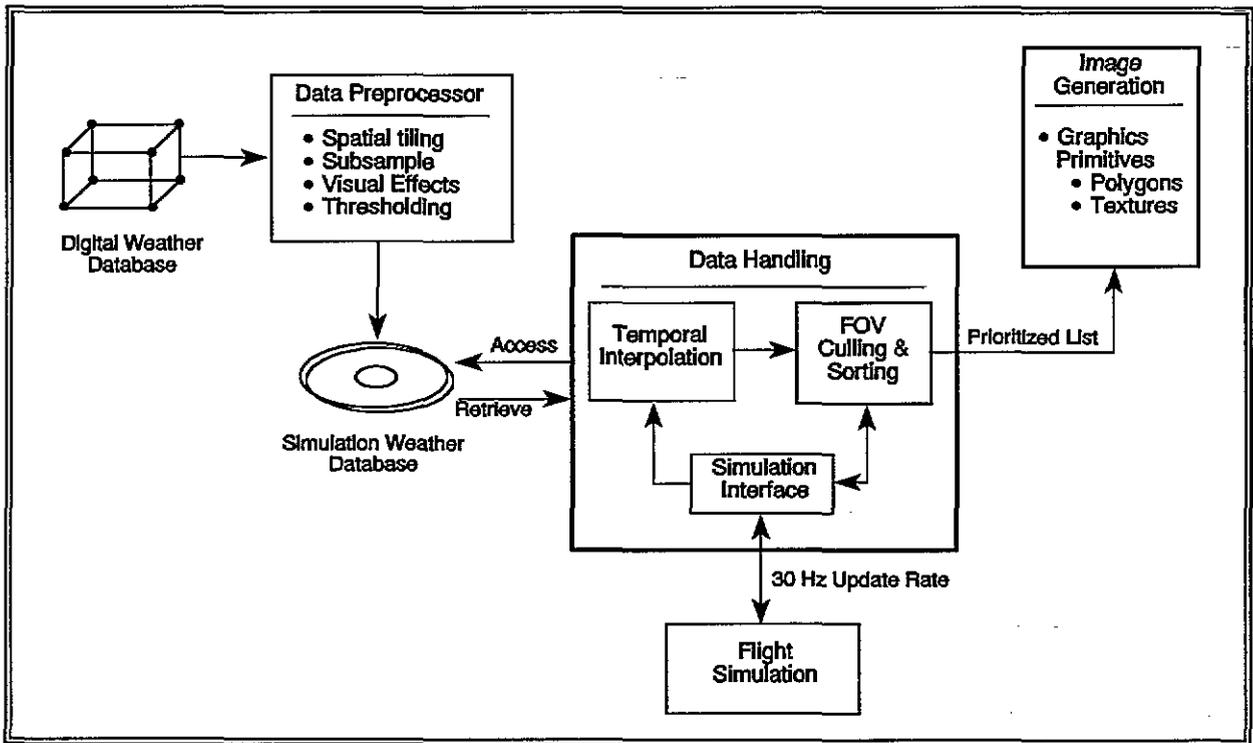


Figure 2 WEST Visual Simulation Approach

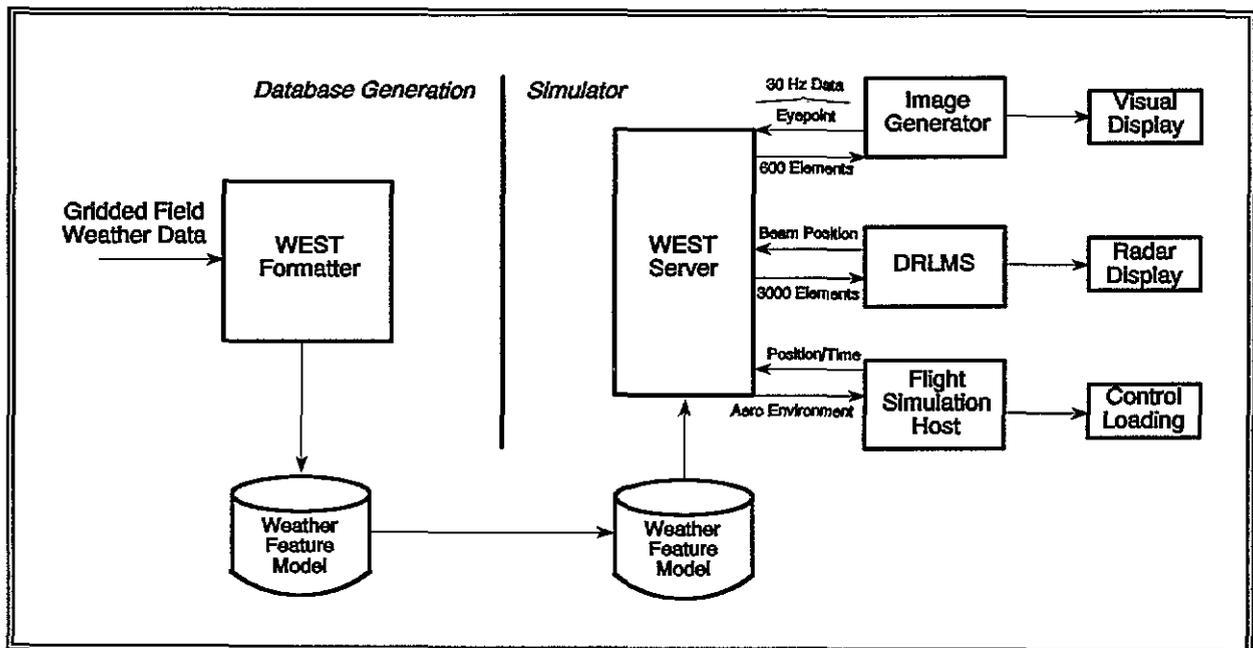


Figure 3 Simulator Integration

For the TASS model, each grid point within the model domain contains 11 atmospheric parameters describing the state of the air mass volume for that spatial location at a given point in time. These parameters include north, east, down wind speed, pressure, temperature, liquid water content, ice content, precipitation rate, snowfall, and hail fall. Grid spacing for the microscale TASS model varies between a maximum of 200 meters down to 40 meters within a typical domain size of 500 cubic miles (10mi × 10mi × 5mi).

The NCAR database contains gridded parametric data for wind speed and direction, radar reflectivity, and derived liquid water content at 200-meter grid intervals within a 16km by 16km volume of airspace. Additional types of sensor-derived data sets are typically mesoscale-oriented and contain grid spacing on the order of 500 to 1000 meters, and cover thousands of cubic miles of atmosphere. Grid domains for these data sets can extend to 2048 × 2048 × 15 elements. Weather parameters typically supported include temperature, wind speed, pressure, water content, and water type.

Visual Preprocessor Component

Preprocessing methods were implemented within WEST for reading in gridded weather database files and reformatting the data for real-time simulation. Data reformatting includes tiling the data into spatial subdivisions known as cells, and preprocessing/compressing the source data to support simulator subsystem simulations. Preprocessing operations currently implemented include spatial subsampling, data thresholding, coordinate transformation into north-east-down coordinates, liquid water content calculation, texture/primitive assignment, apparent lighting calculation, and spatial dithering. Graphic primitives are assigned to weather data elements according to a parametric data look-up table to support out-the-window scene generation. These primitives are stored in a library format and include textures as well as polygon primitives. Lighting effects are precomputed based on sun position as determined by a time-of-day, day-of-year look-up table. A graphical user interface allows the user to interactively control preprocessing functions for tailoring and evaluating the visual appearance of the resulting visual weather database.

Unified Weather Database. The unified weather database is the run time database that has been reformatted, tiled, and compressed to support real-time simulation. The run time database is a series of time tagged files that describe volumetric weather data for a given geographic location. Each weather data element within the database contains a parameter list that describes the physical characteristics of the air mass parcel located at that element's spatial position in the atmosphere. Weather parameters maintained within the run time database on a per-element basis include wind vector, water content, spatial extent, texture assignment, color, illumination, and transparency. The unified database consists of spatial and temporal linked files that are retrieved from disk and then loaded into memory as needed during simulator operation.

Data Handling Component (Weather Generator)

The weather-generation component performs the operations necessary to process and format the volumetric weather data within a sensor's instantaneous field of view. The weather generation component is scheduled by a frame-based executive to assure periodic weather data update rates and synchronization with the flight simulation and image-generation functions. The weather-generation component controls the management and distribution of weather data to simulator subsystems. For visual systems, the weather generator controls the building of the weather display list that is converted to immediate mode display data by the image generator hardware. Weather data handling operations include data retrieval and temporal interpolation, field-of-view (FOV) culling, sorting, and prioritizing of in-FOV weather data, and formatting/distribution of active weather elements to the image-generation component. In a weapon system trainer application, this component would also format and distribute weather data within a sensor's scanning field of regard or instantaneous field of view.

Image-Generation Component

The image-generation component processes the visible weather element display list that was produced by the weather generator and transforms these weather elements into a hierarchical list of weather "objects" consisting of polygon vertices

and graphic library-specific parameters for immediate mode rendering on the image generator's graphics pipeline. The weather objects represent the visual depictions of air mass parcels containing liquid water that are assembled and blended to provide a composite weather scene. Targets and special effects (e.g., weapon impacts, smoke plumes) are inserted within the integrated and prioritized weather/terrain display list at the appropriate time to provide weather occulting and obscuration effects on visible objects.

Flight Simulation Interface Component

The flight simulation interface component receives instantaneous aerodynamic environment parameters as a function of viewing platform (aircraft) position. Weather data elements surrounding the viewpoint position are interpolated tri-linearly to determine the instantaneous atmospheric environment including the net aerodynamic effects acting on the viewing platform. These effects include north, east, down wind speed components, time rate of change of these components, and ambient temperature and pressure at the aircraft. The simulation interface component receives the viewpoint and viewing orientation from the flight simulation host computer and provides this data synchronously to the image-generation component. This capability allows WEST to be applied *within flight simulators* to assure direct correlation between visual weather imagery and aircraft dynamic modeling functions.

WEST APPLICATIONS

Weapon System Trainers

The WEST method for processing digital atmospheric data in real time is ideally suited for weapon system training applications. With the WEST approach, a weather generator may be integrated within the simulator configuration to process and distribute dynamic digital weather data to each atmosphere-sensing simulator subsystem, as shown in Figure 3. The number of active weather elements that are provided by the server to each subsystem is a function of the subsystem's field of regard and resolution. For visual systems, the field of regard is defined by visibility range and field of view. For DRLMS systems, the field of regard and resolution is defined by the antenna beam width, pulse repetition frequency, azimuth scan limits, and radar

range scale. Weather elements from a unified digital database are distributed to each subsystem (visual, radar, flight) as a function of subsystem viewing parameters (position, orientation, field of regard). Each subsystem then performs the required function for transforming digital weather elements to display cues. The visual system transforms the weather data elements into scene primitives (as demonstrated by WEST), and the radar simulation subsystem incorporates the weather data elements into range bin processing for calculating attenuation and backscatter radar effects.

Figures 4 and 5 illustrate the visual realism available with the WEST technique. Figure 4 is an example of synthetic optical imagery generated directly from NCAR gridded-field weather data by WEST. Figure 5 shows the individual weather elements (rendered as vectors) that serve as the basis for Figure 4.

Mission Planning and Mission Rehearsal

Mission planning and mission rehearsal training could become more effective and transferable to operations through the application of the WEST approach for simulating weather conditions that are expected or forecast for a given mission. Weather environment effects on weapon system employment and combat tactics procedures could be simulated and evaluated by integrating real-world weather conditions into the synthetic mission environment provided for mission planning systems and tactical preview systems. Given the gridded-field data handling capability of the WEST approach, it is conceivable that satellite-derived weather conditions could be formatted to produce a geospecific, synthetic weather environment for mission rehearsal training. Incorporating satellite weather data for simulator training is an area of continuing research and development.

SUMMARY

This paper has presented an overview of the WEST weather simulation approach. This approach is capable of integrating real-world weather into manned simulators in such a way that display cues may be automatically correlated across simulator subsystems. This capability is achievable due to the unified format of the weather database, and simulator architecture modifications that accommodate dynamic data handling with minimum



Figure 4 WEST Computer-generated Weather Scene From Gridded-Field Data

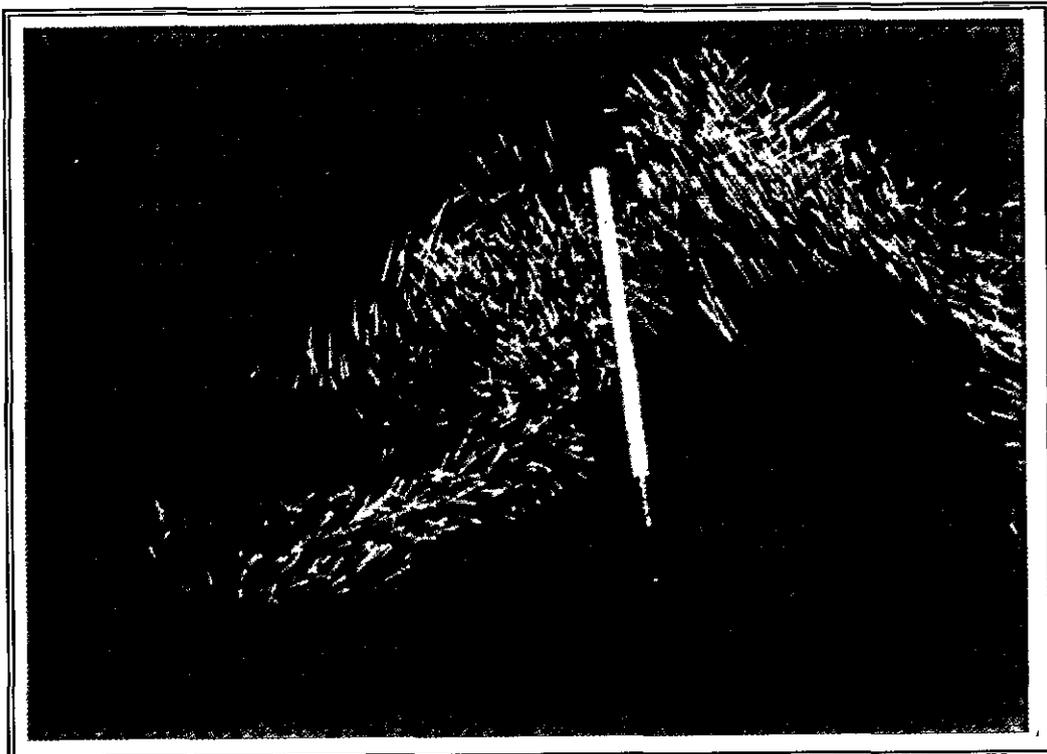


Figure 5 WEST Active Weather Elements Within Gridded Field

impact to simulator subsystems. The approach as demonstrated is extensible to accommodate the special needs of simulator subsystems, including DRLMS, FLIR, and weapon system simulations.

Although the WEST approach was developed in response to a need to improve the way in which atmospheric effects are modeled for flight training, the simulation techniques implemented within WEST are directed at solving weather-related simulation problems pertaining to sensor simulation modeling, geospecific mission rehearsal applications, and multi-force distributed network training applications.

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