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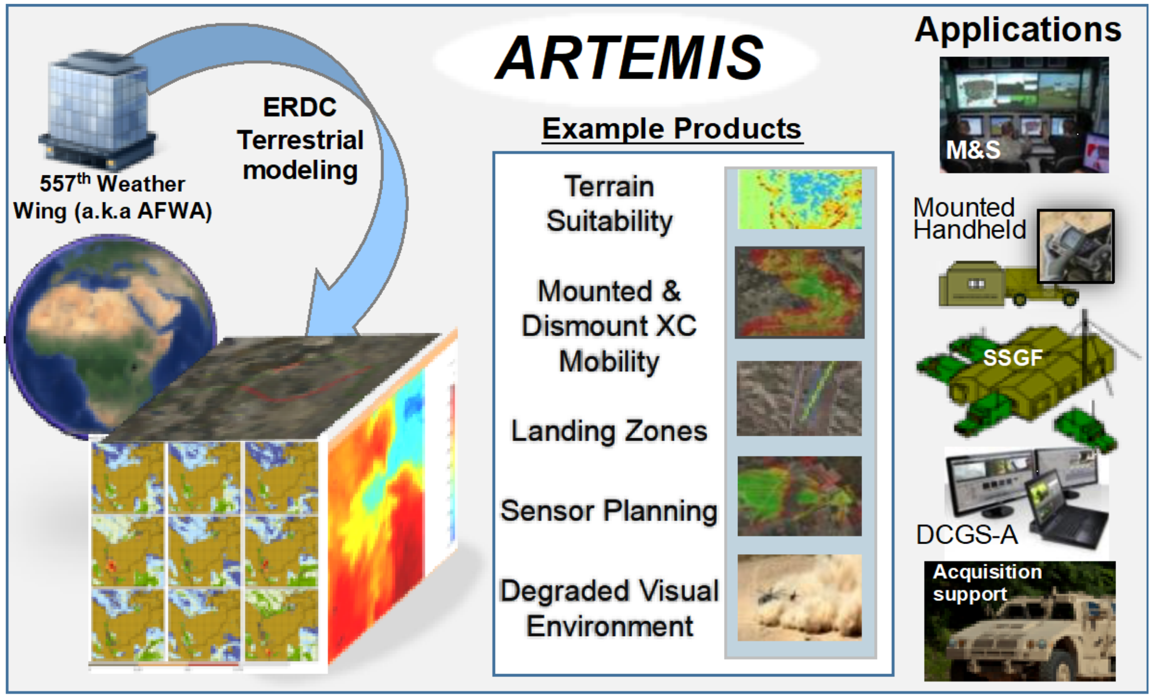
ERDC 6.2 Geospatial Research and Engineering (GRE) ARTEMIS STO-R

Army Terrestrial Environmental Modeling and Intelligence System, ARTEMIS

John Eylander, Sally Shoop, Elias Deeb, Carrie Vuyovich, Steven Peckham, Sandra LeGrand, Robyn Barbato, Theodore Letcher, D. Keith Wilson, Andmorgan Fisher, John Nedza, Dhiren Khona, Michael Paquette, Jerry Bieszczad, and Christian Borden

December 2019



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Final Report

Prepared for Assistant Secretary of the Army for Acquisitions, Logistics, and Technology
103 Army Pentagon
Washington, DC 20314-1000

Under ERDC 6.2 Geospatial Research and Engineering (GRE) Army Terrestrial-Environmental Modeling and Intelligence System Science Technology Objective–Research (ARTEMIS STO-R) under Work Item ARTEMIS CRREL T42 053HJ0, Funding Account Number U4357509

Abstract

The Army Terrestrial Modeling and Intelligence System (ARTEMIS) research program focused on developing innovative methods of fusing weather data from authoritative sources with geospatial content and services to fill a number of identified Army capability gaps. The tools developed within the ARTEMIS research program can support operations anywhere in the world, supporting Army Global Land Operation's needs. We overcame technology challenges that limited the use of gridded weather products and digital terrain products with Army tactical decision aids, providing relevancy to the impacts of weather and terrain on military operations beyond the current methods of delivering weather impacts on the battlefield via PowerPoint briefings. The project benefited from the recent availability of higher-resolution global soil texture, digital elevation models, and land use and land cover datasets provided by the National Geospatial-Intelligence Agency. Teams working on the ARTEMIS research program developed tools and capabilities that integrated weather digital products into the Army Geospatial Enterprise–compliant systems to deliver fused all-weather and all-season military decision aids (e.g., maneuver, austere entry, sensor performance, and other typical terrain analysis tasks) in a method that supports risk-based assessments.

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Preface

This study was conducted for the Assistant Secretary of the Army for Acquisition, Logistics, and Technology under the U.S. Army Engineer Research and Development Center (ERDC) 6.2 Geospatial Research and Engineering (GRE) Applied Research Program's Army Terrestrial-Environmental Modeling and Intelligence System Science Technology Objective–Research (ARTEMIS STO-R), Work Item ARTEMIS CRREL T42 053HJ0, Funding Account Number U4357509, "ARTEMIS Army Terrestrial Environmental Mode."

The work was performed by the Force Projection and Sustainment Branch (CEERD-RRH), the Terrestrial and Cryospheric Sciences Branch (CEERD-RRG), and the Signature Physics Branch (CEERD-RRD) of the Research and Engineering Division (CEERD-RR) and the Lidar and Wetlands Group and the Terrain and Ice Engineering Group of the Remote Sensing/GIS Center of Expertise (CEERD-RS), ERDC Cold Regions Research and Engineering Laboratory (CRREL), and the Data Signature and Analysis Branch (CEERD-TRS), the Data Representation Branch (CEERD-TRR), and the Information Generation and Management Branch (CEERD-TRG) of the Topography, Imagery, and Geospatial Research Division (CEERD-TR), ERDC Geospatial Research Laboratory (GRL). At the time of publication, Mr. Justin Putnam was Acting Chief, CEERD-RRH; Dr. John Weatherly was Chief, CEERD-RRG; Dr. Andrew Niccolai was Chief, CEERD-RRD; Mr. J. D. Horne was Chief, CEERD-RR; Dr. Elias Deeb was lead for the Lidar and Wetlands Group; Mr. Stephen Newnan was lead for the Terrain and Ice Engineering Group; Mr. David Finnegan was Chief, CEERD-RS; Ms. Jennifer Smith was Chief, CEERD-TRS; Mr. Vineet Gupta was Chief, CEERD-TRR; Mr. Jeffrey Murphy was Chief, CEERD-TRG; and Ms. Martha Kiene was Chief, CEERD-TR. The Deputy Director of ERDC-CRREL was Mr. David B. Ringelberg, and the Director was Dr. Joseph L. Corriveau. The Deputy Director of GRL was Ms. Valerie Carney, and the Director was Mr. Gary Blohm.

We would like to thank the research staff at the Jornada Experiment Range, specifically Dr. Nicholas Webb and Mr. Brad Cooper, for site access. We would also like to thank Ms. Ashley Mossell, CRREL, for soils analysis support.

COL Teresa A. Schlosser was the Commander of ERDC, and Dr. David W. Pittman was the Director.

Acronyms and Abbreviations

3-D	Three Dimensional
AFWA	Air Force Weather Agency
ARTEMIS	Army Terrestrial Environmental Modeling and Intelligence System
CFS	Climate Forecast System
CFSR	Climate Forecast System Reanalysis
CRREL	Cold Regions Research and Engineering Laboratory
DMRT-ML	Dense Media Radiative Transfer for Multi Layers
DoD	Department of Defense
DRTSPORE	Dynamic Representation of Terrestrial Soil Predictions of Organisms' Response to the Environment
DSRC	Distributed Supercomputing Resource Center
DUST-CLOUD	Dynamic Undisturbed Soils Testbed to Characterize Local Origins and Uncertainties of Dust
EASEE	Environmental Awareness for Sensor and Emitter Employment
EDC	Environmental Data Cube
EHF	Extremely High Frequency
ERDC	U.S. Army Engineer Research and Development Center
EWS	EASEE Web Services
FY	Fiscal Year
GALWEM	Global Air-Land Weather Exploitation Model
GEAR	Geocentric Environment for Analysis and Reasoning
GeoWATCH	Geospatial Weather Affected Terrain Conditions and Hazards
GIS	Geographical Information System

GPU	Graphics Processing Unit
GRAIL	Geospatial Remote Assessment for Ingress Locations
GRE	Geospatial Research and Engineering
GRL	Geospatial Research Laboratory
GWX	Geospatial Weather Services
HPC	High Performance Computing
ITL	Information Technology Laboratory
KML	Keyhole Markup Language
KNEE	KNEE is not EASEE in its Entirety
KNL	Knights Landing
LIS	Land Information System
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NRMM	NATO Reference Mobility Model
RF	Radio Frequency
SAGE	Situational-Awareness Geospatially Enabled
SCAN	Soil Climate Analysis Network
SHF	Superhigh Frequency
SIPRNet	Secret Internet Protocol Router Network
SNODAS	Snow Data Assimilation System
SNOTEL	Snow Telemetry

SOAP	Simple Object Access Protocol
SPRUCE	Signal Physics Representation in Uncertain and Complex Environments
STNDMOB	Standard Mobility
STO-R	Science Technology Objective—Research
SWE	Snow Water Equivalent
TDR	Time Domain Reflectometry
TerraPAC	Terrain Phenomenology and Data Collection
TERRASIM	Terrestrial-Environment Rapidly Relocatable Simulation
TRADOC	Training and Doctrine Command
TRL	Technical Readiness Level
UHF	Ultrahigh Frequency
USAF	U.S. Air Force
UTA	Urban and Terrain Analysis
VHF	Very High Frequency
VIIRS	Visible and Infrared Imaging Radiometer Suite
WRF	Weather Research and Forecasting
XML	eXtensible Markup Language

Executive Summary

What was the problem?

The military decision-making process is dependent on accurate and complete geospatial characterization of the battlespace, with relevant data and information presented appropriately to enable risk-based decisions across a broad range of operations, from small unit decisions to phase-zero preparations and humanitarian missions. Therefore, at the commencement of this project, the Army Terrestrial Environmental Modeling and Intelligence System (ARTEMIS), we analyzed U.S. Army Training and Doctrine Command (TRADOC)–documented capability gaps and Joint Capabilities Integration and Development System documents from the centers of excellence that referenced weather and climate impacts on the operational environment. From these, we developed a prioritized list of products and services that we would develop on the project. The focus for the first couple of years was oriented toward those we believed had the highest probability of successful development given the resources and technological advancements and those that would have the largest impact on improving operational support.

This project overcame a number of challenges to bridge gaps between weather and impact, linking weather with Army tactical decision algorithms and models and enabling product delivery through Army Geospatial Enterprise–compliant geospatial systems by using teams of interdisciplinary scientists and engineers collaborating to deliver new technologies to bridge the gaps. There were also scale-dependent challenges for us to bridge. “Weather-scale” data is time dependent and available either on a “point” basis or available in gridded (raster) form that is relevant on the order of tens of kilometers horizontally. The data require large-capacity data storage devices due to the hundreds of gigabytes of gridded analysis and forecast products generated several times per day. At “Army scale,” sometimes referred to as “field-scale” or “microscale,” data is relevant at resolutions on the order of meters to a few kilometers. Application of weather data is challenging, especially regarding weather impacts on land surface fields, like soil moisture and temperature, for mobility/maneuver operations due to the highly varying characteristics of the terrain and the amount of physical computations and data required to generate those physical calculations. However, newer web-based, rapid physical models together with higher-resolution terrain characteristic provided the opportunity to bridge the scale gaps and demonstrate weather-impacts down to Army scale.

Weather and terrain impact Army operations in many ways, including but not limited to military maneuver, fires (targeting, air and missile defense), austere entry, water security, concealment and confinement, flight operations, intelligence, surveillance, and reconnaissance. The impacts could be immediate, requiring knowledge about current and future weather conditions over the next 2–3 days for a small domain, or be more broadscale, requiring conditional assessments that rely on an understanding of typical range of weather conditions in an operating area many months in advance. Regardless of the operation, blending integrated, physics-based land-atmosphere models and algorithms to apply weather-scale data to Army-scale problems provides an opportunity to deliver advanced situational awareness, to improve the speed at which Army commanders are able to understand the environment and make decisions, and for the Army to understand how capable its tools are in a number of environments.

We used a number of approved requirements documents to support the goals of this project, including the Meteorological and Oceanographic and Net-Enabled Mission Command Initial Capability Documents and the Distributed Common Ground System–Army Capability Development Document. Many of the unfulfilled requirements include weather-impacted mobility, line-of-sight prediction, austere entry, precision air drop and opportune airfield, and weather/climate products supporting advance planning of potential engagement zones for humanitarian assistance. We also referenced a requirements memorandum signed by Army G3/5/7 in 2011 and sent to the U.S. Air Force (USAF) A3W (Weather) components outlining important Army weather parameters along with accuracy metrics.

What barriers did we overcome to solve this problem?

We overcame barriers that limited the use of weather data in Army applications by acquiring higher-resolution digital elevation model data, land use maps, and soils maps that were available from a number of Department of Defense (DoD) and non-DoD sources and blending the data with coarser-resolution weather data using new “downscaling” algorithms to increase resolutions toward those needed for Army support. The new global terrain datasets were available at horizontal resolutions of at least 30 m (higher in many instances) and were available globally, enabling our applications to work anywhere in the world supporting global land operations. We developed efficient and flexible software to enable lightweight computing in a “cloud” environment, enabling web-based data services.

How did we overcome those barriers?

The ARTEMIS research team used a cross-discipline, integrated plan aimed at performing research and conducting experiments collaboratively, educating each other on the challenges unique to the many disciplines supported on the project, to explore multidisciplinary solutions. This enabled rapid technical achievement rather than focusing on stovepiped, single-discipline solutions. However, the team incorporated existing single-discipline solutions that were well suited for further advancement to accomplish our goals. Some of these tools included the Situational-Awareness Geospatially Enabled (SAGE) toolkit, developed by the Geospatial Research Laboratory and available as a download into the Army Geospatial Enterprise version of Esri ArcMap; the NATO (North Atlantic Treaty Organization) Reference Mobility Model (NRMM) (Ahlvin et al. 1992) and Standard Mobility (STNDMOB) (Baylot et al. 2005) application; and the Weather Research and Forecasting (WRF) (Skamarock et al. 2008) and Land Information System (LIS) (Kumar et al. 2006) weather and terrain modeling software systems. Utilizing each system, some of which were more mature from a systems-development perspective, enabled us to focus on the interdisciplinary challenges of developing integrated products rather than focusing on developing new capabilities from the ground up. This also supports a more rapid technology prototype demonstration and technology transition since many of the independent software systems were already accredited DoD applications independently but were never used to support the capabilities developed within this project. The capabilities developed using this approach greatly advance situational awareness opportunities, increase military functionality around adverse conditions, and provide new predictive geospatial content that supports gains in technical overmatch while reducing documented capability gaps.

We focused our new technical development in areas where suitable applications were either not available or not mature enough to support our development goals. Digital output from the LIS and WRF modeling systems was used as input to a new soil-moisture downscaling algorithm, Geospatial Weather Affected Terrain Conditions and Hazards (GeoWATCH) (Ueckermann 2018), developed under a Small Business Innovative Research award to Creare LLC as part of this project, delivered to the ARTEMIS team and further linked to a new Python version of STNDMOB using techniques developed by the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL). The downscaled soil-moisture, strength, and mobility products also supported new ingress/egress technologies. Output from both efforts were demonstrated within the SAGE application.

There were barriers to making the products we developed applicable to the Army intelligence community. To address these, we had to first better understanding those needs by interacting with the Army Intelligence Center of Excellence and then to develop new technical approaches to solve those problems. The Army intelligence community is focused on longer time ranges, generally months to years ahead of operations, and requires long-range advance planning tools to support their decision-making. To support this longer-range planning cycle, we linked our mobility and sensor-performance tools with an archive of gridded weather forecasts created by NOAA (National Oceanic and Atmospheric Administration) in what is informally termed a “Weather Data Cube.” The USAF hosts a similar system as a weather program of record titled “the Environmental Data Cube Support System” that uses both archived, gridded historical weather and 30-year global climate reanalyses from the NOAA Climate Forecast System. This essentially enables the use of digital climate information or historical weather-event scenarios as a way of understanding weather risk on various military planning processes. We demonstrated a sensor-performance and acoustic-planning capability within the Environmental Awareness for Sensor and Emitter Employment (EASEE) tool, which combines historical weather-scenario capabilities with acoustic and infrared predictions for the intelligence community. A user now has the ability to better understand the range of impacts that the “typical weather of the day” for any day of the year, and any location on earth, has on sensor or platform signatures through the EASEE tool. We also developed an ability to use archived gridded weather products to support mobility decision support. This capability supports longer-range, uncertainty-based estimates for a number of processes by using the range of weather conditions experienced on a day, or span of days, to assess impacts on military planning for sensor placement, ingress/egress, maneuver, and other decision-support scenarios.

What are the capabilities we developed?

We developed many capabilities on this project:

- GeoWATCH soil-moisture downscaling tool
- Cross-country vehicle speed analysis/prediction tool with dynamic weather/terrain impacts
- Ingress/egress geospatial analysis tool
- EASEE Web Services application
- Geospatial Weather Services four-dimensional Weather Cube support to mobility/sensor performance
- Improved visibility analysis and prediction tools

This project addressed Intelligence Warfighting Function Functional Needs Assessment Gap 11 (weather), TRADOC Army Vision Force 2025 and Beyond, and TRADOC G-2 Operational Environments to 2028: The Strategic Environment for Unified Land Operations.

Quantitative metrics

The table below lists the metrics established at the beginning of the project using Army G3/5/7 stated metrics for soil moisture, soil temperature and snow depth. The project achieved all the resolution and product development goals stated in the proposal, with real-time demonstrations delivering significant advances over current capabilities. An automated, predictive, weather-impacted maneuver capability was largely nonexistent before the project, with mobility forecasts created only by analysts that manually combined coarse-resolution weather knowledge into geospatial tools by using documented field manual guidance as a method to predict mobility. ARTEMIS now delivers domain knowledge of future vehicle-class mobility as a guidance product for military mission planners. We developed a remote assessment of weather- and climate-impacted socio-cultural stability largely not available from an analyst-produced assessment prior to the project. We integrated higher-resolution weather products with the sensor-performance tool to deliver improved acoustic predictions in variable terrain and delivered improved snow characterization algorithms supporting Army movement and maneuver.

Metrics of the Technical Readiness Levels (TRLs) and pre- and post-ARTEMIS metrics achieved during the 4-year span of the project.

Measure	Pre-ARTEMIS	Project Objective	Army Objective	Results	TRL
Soil moisture for mobility, landing zone, sensing	Daily values; 4 incremental values of climatological soil wetness (wet, average-dry) based on user input of the surface condition	Volumetric soil moisture in 5% increments, 10% error; at 1-hour intervals; 30 m resolution	5% error at 1-hour increments; resolutions less than 1 km	Relative and Volumetric soil moisture at 1% increments for 2 m soil profile at 3-hour increments, soil-strength products, and vehicle speed analysis products all available hourly at 30 m resolutions for any location worldwide, also producing forecasts for each parameter out to 144 hours	5
Snow Depth for mobility, landing zone, sensing, etc.	Daily values, >30% error	<1 in. error at 6 hour increments; 1 km resolution products	1 in. error at 6 hour increments; resolutions less than 1 km	Daily snow depth and snow-cover products at 1 km resolution, with some decrease in error over pre-ARTEMIS products	5
Soil Temperature	User input	1°C accuracy; hourly products; 1 km resolution	1°C accuracy; hourly products; <1 km resolution	Hourly products at 1 km resolution; relative error is approximately 10%	5

Transitions

This project included transitions to Project Manager–Terrestrial Sensor prior to the milestone B phase of the Integrated Ground Security Surveillance Response–Capability program of record. Towards the end of the project, the Distributed Common Ground System–Army program of record leadership requested a Knowledge Transition Agreement during the last quarter of fiscal year 18. Additionally, using Army Regulation 115-10 (jointly published as Air Force Instruction 15-157), we transitioned to the USAF's 557th Weather Wing technology improving the remote sensing of snow depth, snow cover, and snow water equivalent and transitioned CRREL-developed products that better link snow depth and snow water equivalent to military decision making. We received USAF Life Cycle Management Center Configuration Change Request approval to transition the GeoWATCH application into production. The EASEE Toolkit was transitioned and is available for use on the Joint Worldwide Intelligence Communication System by intelligence analysts.

Teams and laboratories

The ARTEMIS research program included participants from two U.S. Army Engineer Research and Development Center laboratories: CRREL and the Geospatial Research Laboratory (GRL). Additionally, the Army Research Laboratory Battlefield Environment Division was an active participant in this program for the entire four years. This project also includes contributors from four other Engineer Research and Development Center laboratories, the Geotechnical and Structures Laboratory, the Coastal and Hydraulics Laboratory, the Environmental Laboratory, and the Construction Engineering Research Laboratory, and from the National Aeronautics and Space Administration's Goddard Space Flight Center and USAF's 16th Weather Squadron.

The ARTEMIS project was split into seven teams. There were four teams at CRREL and three teams at GRL. The four teams at CRREL included the Terrestrial-Environment Rapidly Relocatable Simulation (TERRASIM) team; the Dynamic Representation of Terrestrial Soil Predictions of Organisms' Response to the Environment (DRTSPORE) team; the Terrestrial Geospatial Remote Assessment for Ingress Locations (Terrestrial GRAIL) team; and the Signal Physics Representation in Uncertain and Complex Environments (SPRUCE) team, which was responsible for EASEE research and development. The three teams at GRL included the Terrain Phenomenology and Characterization (TerraPAC) team; the Geocentric Environment for Analysis and Reasoning (GEAR) team; and the Urban and Terrain Analysis (UTA) team, which developed the SAGE application. The Army Research Laboratory Battlespace Environment Division, the NASA Goddard Space Flight Center, and the USAF 16th Weather Squadron contributed to the development of models and applications developed by the TERRASIM team.

1 Introduction

1.1 Background

The military decision-making process is dependent on accurate and complete geospatial characterization of the battlespace, with relevant data and information presented in an understandable manner to enable risk-based decision-making across a broad range of operations, from small unit decisions to phase-zero preparations and humanitarian missions. Weather effects on the battlespace are poorly accounted for within the Army Geospatial Enterprise systems used to gain understanding of the situational environment, support intelligence planning of the future battlefield, and conduct short-range mission plans. This forms the basis for this research project. Our goal was to investigate and develop new methods to fuse weather products from authoritative data providers with Army decision-support methods and applications that can be integrated into Army Geospatial Enterprise–compliant geographical information systems.

This project, the Army Terrestrial Environmental Modeling and Intelligence System (ARTEMIS), overcame a number of challenges to bridge gaps between weather and impact, linking weather with Army tactical decision algorithms and models and enabling product delivery through Army Geospatial Enterprise–compliant geospatial systems. We developed teams of interdisciplinary scientists and engineers collaborating to deliver new technologies to bridge the gaps. There were also scale-dependent challenges for us to bridge. “Weather-scale” data is time dependent and available either on a “point” basis or available in gridded (raster) form that is relevant on the order of tens of kilometers horizontally. The data require large-capacity, not-easily-portable data storage devices due to the hundreds of gigabytes of data generated multiple times daily for gridded weather analysis and forecasts. At “Army scale,” sometimes referred to as “field-scale” or “microscale,” data is relevant at resolutions on the order of meters to a few kilometers. Application of weather data is challenging, especially regarding weather’s impacts on land surface water and energy balance fields, like soil moisture and soil temperature, for mobility/maneuver operations due to the highly varying characteristics of the terrain and the amount of physical computations and data required to generate those physical calculations. However, newer web-based, rapid physical models together with higher-resolution terrain characteristic provided the opportunity to bridge the scale gaps and demonstrate weather-impacts down to Army scale.

Weather and terrain impact Army operations in many ways, including but not limited to maneuver, fires, austere entry, water security, concealment and confinement, flight operations, intelligence, surveillance, and reconnaissance. The impacts could be immediate, requiring knowledge about current and future weather conditions over the next 2–3 days for a small domain, or be more broadscale, requiring conditional assessments that rely on an understanding of typical range of weather conditions in an operating area many months in advance. Regardless of the operation, blending integrated, physics-based land-atmosphere models and algorithms to apply weather-scale data to Army-scale problems provides an opportunity to deliver advanced situational awareness, to improve the speed at which Army commanders are able to understand the environment and make decisions, for the Army to understand how capable its tools are in a number of environments.

We referenced a number of approved requirements documents to support the prioritization of goals on this project, including the Meteorological and Oceanographic and Net-Enabled Mission Command Initial Capability Documents and the Distributed Common Ground System–Army Capability Development Document. Many of the unfulfilled requirements include weather-impacted mobility, line-of-sight prediction, austere entry, precision air drop and opportune airfield, and weather/climate products supporting advance planning of potential engagement zones for humanitarian assistance. We also referenced a requirements memorandum signed by Army G3/5/7 in 2011 and sent to the U.S. Air Force (USAF) A3W (Weather) components outlining important Army weather parameters along with accuracy metrics.

1.2 Objective

The ARTEMIS program was organized around a single goal of fusing weather and terrain data with military decision systems and integrating those decision models and applications into the Army Geospatial Enterprise to demonstrate machine-to-machine functionality. At the commencement of this project, we analyzed U.S. Army Training and Doctrine Command–documented capability gaps and Joint Capabilities Integration and Development System documents from the Army centers of excellence that referenced weather and climate impacts on the operational environment. From this, we developed a prioritized list of products and services that we would develop on the project. The focus for the first couple of years was oriented toward those we believed had the highest probability of successful development given the resources and technological advancements and those that would have the largest impact on improving operational support.

1.3 Approach

This report provides a synopsis of the work accomplished on the ARTEMIS project by the many smaller teams that participated in the research program, documenting work accomplished by those subteams as well as referencing their published technical reports, journal publications, and conference proceedings that provide the reader of this report with a more detailed set of documents to refer to. This overview document describes many of the major accomplishments of the project. Additional technologies investigated or developed by the many teams working on this project may appear in scientific and engineering literature but may not be described as part of this effort, especially if those tools or methods developed either did not transition or were an accomplishment primarily by only one team and resulted in a publication. This overview focused primarily on work accomplished by more than one team collaboratively, especially work that resulted in a technical transition to either an Army program of record, Department of Defense (DoD) agency, or peer-reviewed publication.

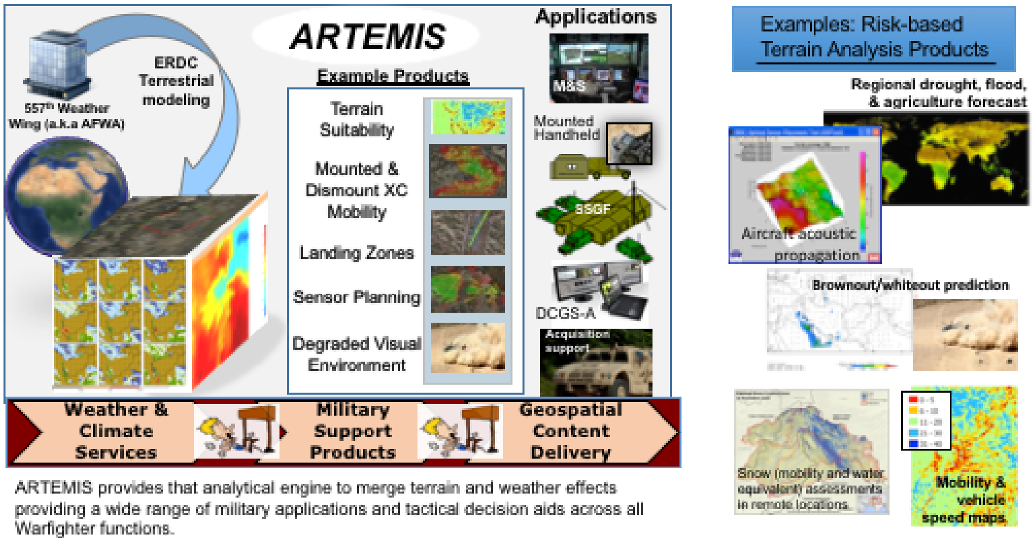
TO solve problems linking weather and terrain data with military decision applications that have the capability to support operations anywhere in the world, we had to solve the challenge of finding high resolution-terrain data and using coarse-resolution, gridded weather data to deliver products relevant at ten of meters versus tens of kilometers. Our approach to solving these problems included building partnerships with a number of DoD organizations, non-DoD government agencies, and commercial sector businesses with specific expertise or data sources that could support the goals of this project. Additionally, we built a strong internal team of experts to apply these datasets toward military-specific needs. A specific benefit was our discovery of global terrain datasets (soil texture, digital elevation models, and land use/land cover) at horizontal resolutions of at least 30 m (higher in many instances) available from the National Geospatial-Intelligence Agency. We also developed new physical mechanisms to bridge the resolution gaps between weather and Army scales.

The ARTEMIS research team used a cross-discipline, integrated plan aimed at performing research and conducting experiments collaboratively, educating each other on the challenges unique to the many disciplines supported on the project, to explore multidisciplinary solutions. This enabled rapid technical achievement rather than focusing on stovepiped, single-discipline solutions. We focused both on reutilizing existing single-discipline solutions that were well suited for further advancement to accomplish our goals and developing new methods and applications where none existed that met the technical requirements for use in the project. We included the Situational-Awareness Geospatially Enabled (SAGE) toolkit developed by the Geospatial Research Laboratory and available as a download into the Army Geospatial Enterprise version of Esri ArcMap, the NATO (North Atlantic Treaty Organization) Reference Mobility Model (NRMM) (Ahlvin et al 1992) and Standard Mobility (STNDMOB) (Baylot et al. 2005) applications, and the Weather Research and Forecasting (WRF) (Skamarock et al. 2008) and Land Information System (LIS) (Kumar et al. 2006) weather and terrain modeling software systems.

Utilizing each system, some of which were more mature from a systems-development perspective, enabled us to focus on the interdisciplinary challenges of linking the products rather than focusing on developing new capabilities from the ground up. This also supports a more rapid technology prototype demonstration and technology transition since many of the independent software systems were already accredited DoD applications but were never used to support the capabilities developed within this project. The capabilities developed using this approach greatly advance situational awareness opportunities, increase military functionality around adverse conditions, and provide new predictive geospatial content that supports gains in technical overmatch while reducing documented capability gaps. Figure 1 visually illustrates the flow of data and the types of products and systems we focused on in this project.

We focused our new technical development in areas where suitable applications were either not available or not mature enough to support our development goals. Digital output from the LIS and WRF modeling systems was used as input to soil moisture to soil strength algorithms (Garcia-Gaines and Frankenstein 2015) developed at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) and to a new soil-moisture downscaling algorithm, Geospatial Weather Affected Terrain Conditions and Hazards (GeoWATCH) (Ueckermann 2018), that was developed under a Small Business Innovative Research Award to Creare LLC, delivered to CRREL, and further linked to a new Python version of STNDMOB we developed to better integrate with geographical information systems (GIS). The downscaled soil-moisture, strength, and mobility products also supported new ingress and egress technologies developed by the ARTEMIS subproject Terrestrial Geospatial Remote Assessments of Ingress Locations (GRAIL). Output from both efforts were linked with and demonstrated within the SAGE application. The SAGE software development was accomplished by the Urban Terrain Awareness (UTA) team, also a subproject under the ARTEMIS project.

Figure 1. High-level operational concept graphic of the ARTEMIS project. The project was designed to pull weather data in from the U.S. Air Force 557th Weather Wing and then to compute higher-resolution weather and terrain products that would be used in military decision aids (*middle column of box*). The military decision-aid products would then be integrated into geographical information systems (*right column of box*). Example products are listed on the *far right side*.



ARTEMIS provides that analytical engine to merge terrain and weather effects providing a wide range of military applications and tactical decision aids across all Warfighter functions.

There were barriers to making the products we developed applicable to the Army intelligence community. To address these, we had to first better understand those needs by interacting with the Army Intelligence Center of Excellence and then develop new technical approaches to solve those problems. The Army intelligence community is focused on longer time ranges, generally months to years ahead of operations, and requires long-range advance planning tools to support their decision-making. To support this longer-range planning cycle, we linked our mobility and sensor-performance tools with an archive of gridded weather forecasts created by NOAA (National Oceanic and Atmospheric Administration) in what is informally termed a “Weather Data Cube.” The USAF hosts a similar system as a weather program of record titled “the Environmental Data Cube Support System” that uses both archived, gridded historical weather and 30-year global climate reanalyses from the NOAA Climate Forecast System. This essentially enables the use of digital climate information or historical weather-event scenarios as a way of understanding weather risk on various military planning processes. We demonstrated a sensor-performance and acoustic-planning capability within the Environmental Awareness for Sensor and Emitter Employment (EASEE) tool, which combines historical weather-scenario capabilities with acoustic and infrared predictions for the intelligence community. A user now has the ability to better understand the range of impacts that the “typical weather of the day” for any day of the year, and any location on earth, has on sensor or platform signatures through the EASEE tool. We also developed an ability to use archived gridded weather products to support mobility decision support. This capability supports longer-range, uncertainty-based estimates for a number of processes by using the range of weather conditions experienced on a day, or span of days, to assess impacts on military planning for sensor placement, ingress/egress, maneuver, and other decision-support scenarios.

2 Technical Description

Prior to ARTEMIS, the challenges caused by coarse-resolution weather data combined with the lack of availability of high-resolution, global terrain analysis products (e.g., soil texture, vegetation, digital elevation maps, etc.) limited the fusing of weather and terrain data in a geospatial information system in an automated method that would support Army military decision-making at any location globally. Several prior research efforts (e.g., Battlefield Terrain, Reasoning and Awareness, discussed further by Visone 2005) demonstrated success for limited functionality for specific geographical domains, but enabling the technology to work in support of Army global land operations was challenging due to the previously mentioned constraints. Linking weather products with military decision aids was particularly challenging because of the coarse spatial resolution, size of the data arrays, and time components of gridded forecast weather products in decision systems. The ARTEMIS program was developed to investigate solutions to those issues and more. The ARTEMIS team was built around those specific weather and terrain challenges, forming teams of experts with specific weather and terrain knowledge and experience to overcome the challenges of fusing gridded weather with terrain data and integrating products or applications into specific DoD applications and Army Geospatial Enterprise systems. This project succeeded by making the integration of weather and terrain into applications the focus, rather than a subtask, of the overall effort.

The ARTEMIS team developed a number of globally capable Army geospatial decision tools that include weather-effects and high-resolution terrain information. The prototypes developed include a cross-country mobility tool, ingress/egress analysis capability, improved the sensor-performance capability, and a geospatial weather services tools. The soil moisture and strength capability includes weather effects from precipitation, temperature influences on soil strength, and an ingress/egress analysis capability that uses terrain characterization (terrain height, slope, vegetation, soil strength, etc.) to determine site suitability for landing fixed and rotor wing vehicles and for drop zones. We also developed a sensor-performance toolkit that supports Army intelligence applications by linking the EASEE toolkit to a four-dimensional “data cube” consisting of 30 years of gridded weather and climate data and a suite of subscription services or web-service software, enabling Army tools to interact and retrieve specific parameters out of the data cube. We linked many of the capabilities developed within this project to two geospatial applications, an Esri ArcMap-based SAGE toolkit and an Open Geospatial Consortium–compliant web-browser-based mapping system called the Geocentric Environment for Analysis and Reasoning (GEAR).

2.1 Models

2.1.1 Description of approach

The approach to the project was threefold. First, we evaluated existing weather and terrain applications (including numerical weather prediction models and land surface and terrain analysis models) available to support the research in this project. We then conducted research on new algorithms and methods to improve those models and applications that fell short of supporting Army requirements. Finally, we developed methods to integrate the weather and terrain products with existing or new Army applications and demonstrated success by integrating that output with Army Geospatial Enterprise–compliant applications. Our primary focus was not to create new weather and terrain models since there are a number of U.S. government agencies and research centers that already focus on developing new weather models and land surface models; rather, we chose to adopt community models (e.g., open-source or government-sponsored models available free for download) from the weather and land surface modeling communities, to develop applications to downscale the output from those models to better support Army needs, and to fuse the weather with Army terrain products. The next sections describes the weather and terrain numerical applications we chose to use and research we accomplished to improve those applications.

2.1.2 Terrain analysis numerical modeling testbed

The terrain analysis team first established a testbed on the DoD High Performance Computing (HPC) Navy and Engineer Research and Development Center (ERDC) Distributed Supercomputing Resource Center (DSRC) systems to house the global and regional numerical weather modeling software systems, which were used to generate gridded (raster) weather and land surface datasets, using two computing allocations for computing hours granted to the project by the USAF and ERDC computing resource allocation managers. The USAF computing allocation involved a collaboration with USAF’s 16th Weather Squadron under a subproject called the Land Information System test. The second was a new subproject created under an ERDC allocation titled ARTEMIS. The project initially used computing hours on IBM HPC systems *Haise* and *Kilrain* but migrated to Cray HPC Systems *Conrad* and *Onyx* after the IBM systems were retired. *Conrad* is a Cray XC40 system located at the Navy DSRC and consists of 1523 standard compute nodes, 8 large-memory compute nodes, and 168 Xeon Phi compute nodes. It has 208 terabytes of memory and is rated at 2 peak petaflops (DoD HPC 2013a). *Onyx* is a Cray XC40/50 system located at the ERDC DSRC and consists of 2858 standard compute nodes, 4 large-memory compute nodes, 544 KNL (Intel Xeon Phi “Knights Landing”) compute nodes, and 32 GPU (graphics processing unit) compute nodes. It has 437 terabytes of memory and is rated at 6.06 petaflops (DoD HPC 2013b). Over the course of the project, the ARTEMIS modeling team used several million compute hours, which were provided free to the project by the service allocation officers. A majority of the numerical terrain and weather modeling activities were performed by the ARTEMIS Terrestrial-Environment Rapidly Relocatable Simulation (TERRASIM) team at CRREL with support from the USAF 16th Weather Squadron and the National Aeronautics and Space Administration’s (NASA) Goddard Space Flight Center Hydrological Sciences Laboratory.

The ARTEMIS testbed consisted of two numerical terrain and weather modeling systems, the NASA LIS and the National Center for Atmospheric Research (NCAR) WRF, including a version of WRF with an atmospheric chemistry and dispersion package (WRF-Chem). The TERRASIM team used the NASA LIS (Kumar et al. 2006) global land data assimilation system for computing global and regional gridded soil-moisture and soil-temperature analyses (Figure 2).

The development of the LIS system by NASA was comanaged and financially supported by ERDC principal investigator Eylander during his tenure working for the USAF Weather Agency with the goal of improving the terrain analysis-product capabilities needed to support, among other things, Army and Intelligence Community terrain analysis needs. The ARTEMIS team used more-advanced LIS configuration options than those executed operationally by the 557th Weather Wing, including higher-resolution (down to 1 km raster grid resolution) regional configuration options, and improved some portions of the LIS model physics. The ARTEMIS team executed LIS to generate soil temperature and moisture products for several studies within the ARTEMIS project and wrote software to retrieve real-time LIS output analysis products generated by the 557th Weather Wing (Figure 3).

Figure 2. Diagram of the LIS software framework, provided by Sujay Kumar at NASA (pers. comm.). The software is organized with a core set of software management modules and drivers (LIS Core) and abstractions that include the various land surface models, data assimilation methods, meteorological input options, etc. The abstractions are controlled through the LIS configuration file a user modifies prior to executing the model.

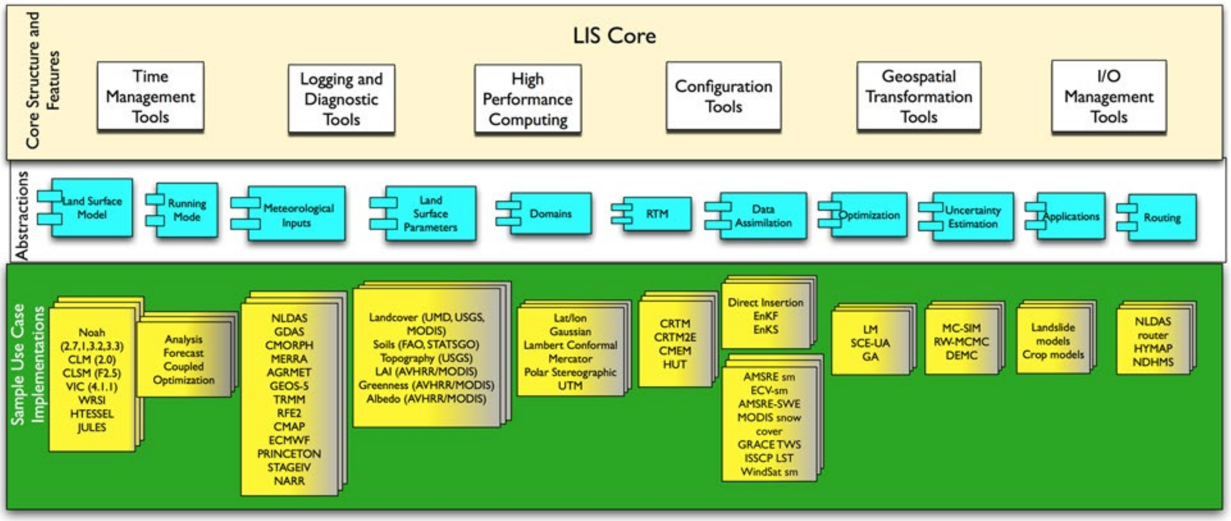
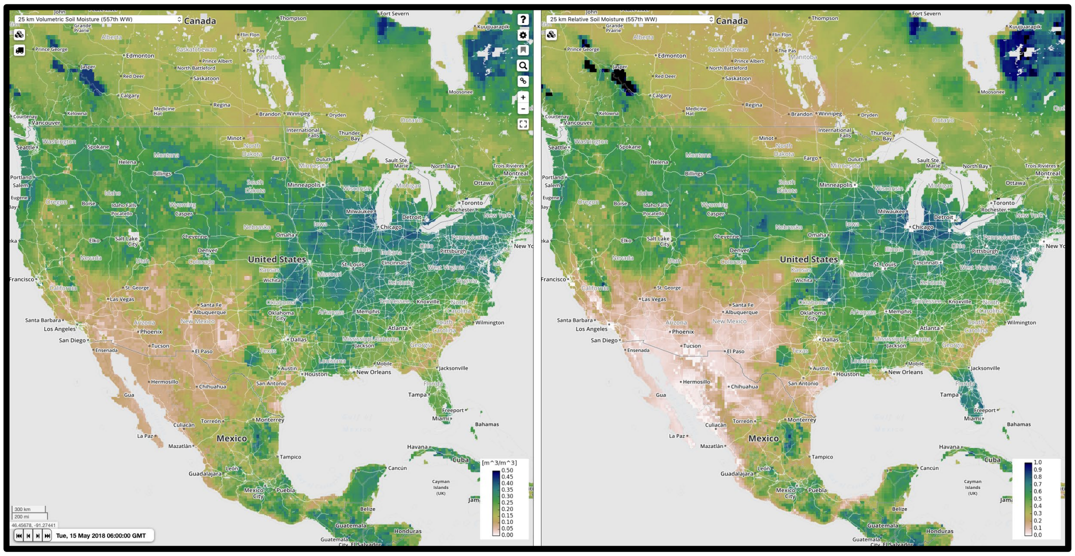


Figure 3. Volumetric soil moisture (*left image*) and relative soil moisture (*right image*) from USAF's 557th Weather Wing, produced by the Land Information System model. Volumetric soil moisture is the measure of water quantity per unit volume of soil and contains the units of m³/m³. Relative soil moisture is a unitless measure of the relative wetness of the soil related to the soil's water-holding capacity.



For ERDC LIS simulations, the data needed to initialize and supply weather information to the model came from two sources, USAF's 557th Weather

Wing and the National Centers for Environmental Prediction. The ARTEMIS testbed is housed on the same HPC architecture as the 557th Weather Wing and 16th Weather Squadron LIS testbed (*Conrad*), which is supported by the 16th Weather Squadron. The testbed has a daily feed of all the weather input data needed to execute the LIS software to generate daily soil-moisture analyses, including temperature, humidity, wind, precipitation, and snow and depth. The testbed houses surface observations and satellite data from a variety of global observing systems, including the global weather surface observation network coordinated by the World Meteorological Organization; satellite observations of precipitation from multiple U.S., European, and Japanese sources (infrared sensor data from geostationary satellites and both microwave and infrared sensor data from polar orbiting satellites); remotely sensed snow information from microwave and electro-optical/infrared sources; soil-moisture observations from satellite sources (e.g., European Advanced Scatterometer sensor); and gridded weather products provided by the NCEP Global Forecast System. The data from the 557th Weather Wing and 16th Weather Squadron is necessary to run LIS in the "AFWA" (Air Force Weather Agency) configuration, a configuration specific to the 557th Weather Wing based on the types of satellite and surface observations and gridded model data available at the 557th Weather Wing. The AFWA version was engineered to support global and regional numerical weather prediction model surface initialization and can generate products at resolutions up to 1 km horizontal resolution.

Additionally, the weather team downloaded WRF version 3.8 (Skamarock et al. 2008) from the NCAR website along with the aerosol transport modules (WRF-Chem) (Grell et al. 2005), compiled the software, and developed scripts needed to execute the software for atmospheric forecasting products generation. The WRF model was developed by a consortium of institutions and lead by NCAR and was considered a "community" model, releasing the source code to any developer interested in participating in the development of the model (WRF 2018). This enabled universities, government, and nongovernment research and operations organizations to use the model or participate in the improvement of the model. CRREL obtained the source code from the NCAR WRF developer website, installed the source code on the ARTEMIS testbed, and used the model to generate forecast products for use in the project. The specific forecast products we were interested in were the surface fields related to dust forecasting (near-surface winds, temperature, humidity, precipitation, and soil moisture);

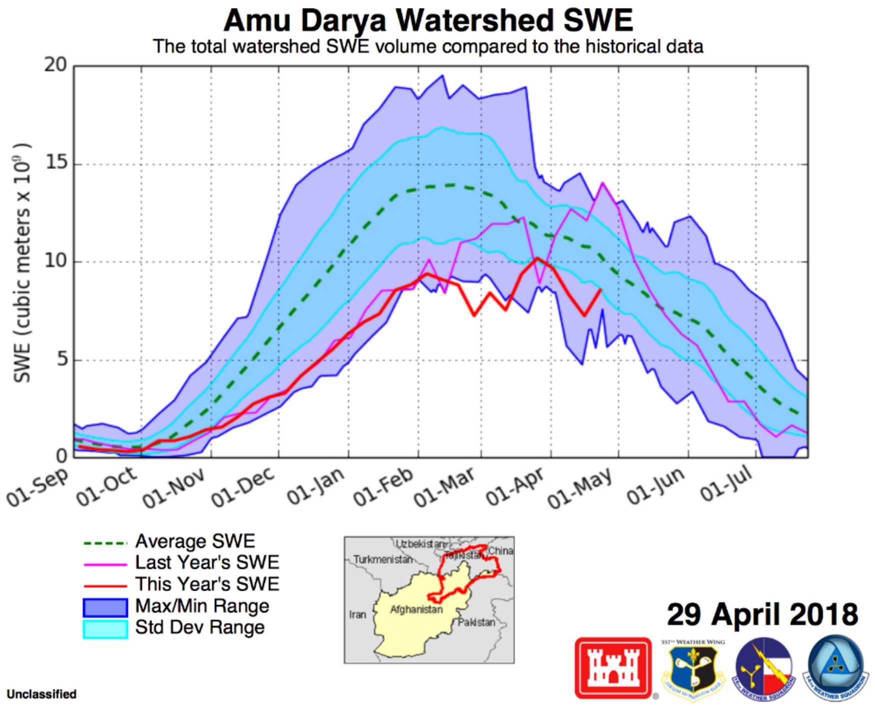
atmospheric profiles for temperature, humidity, wind, and aerosol parameters used in creating profiles for visibility applications; and forecasts of surface fields for mobility applications.

2.1.3 Snow remote-sensing and numerical-modeling research

The ARTEMIS snow science team established a testbed to evaluate remotely sensed snow-cover measurements from NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) satellite sensor and the Joint Polar Satellite System Visible and Infrared Imaging Radiometer Suite (VIIRS) satellite with the goal of improving DoD's ability to remotely measure snow cover, depth, and snowpack properties. Current DoD snow-remote-sensing technology produced operationally by the 557th Weather Wing for the U.S. Army and for other DoD organizations and services does not meet the accuracy or spatial resolution requirements specified by Army. The science for measuring snowpack (snow depth and snow water equivalent) characteristics operationally uses legacy remote-sensing techniques that rely heavily on coarse-resolution (>20 km × 20 km raster-resolution pixels) passive microwave satellite imagery from DoD and NASA satellite sensors and suffers from very high error. The snow-cover area assessments are produced from higher-resolution electro-optical and infrared (raster resolution on the order of 1 km) satellite imagery but do not provide the corresponding snow depth at the same resolution. This remote-sensing technology is based on research conducted by the USAF, NASA, and NOAA in the 1970s through the 1990s (Chang et al. 1976, 1982; Hall et al. 2002; Ramsay 1998). The ARTEMIS snow team improved upon those remote-sensing techniques and began developing new technology to improve the snow-characterization capabilities to improve our ability to support mobility, ingress and egress planning, logistical planning, and other military operations in cold and snow-covered areas.

The ARTEMIS snow team concentrated on four goals: (1) improving the relevance of snow products and the way those products are presented to users; (2) transitioning CRREL semioperational snow products developed prior to ARTEMIS over to operational agencies; (3) improving remote-sensing methods for characterizing snow-cover extent and snow depth; and (4) exploring new data-assimilation-based options for combining physics-based snow models, radiative-transfer algorithms, and satellite data together to better diagnose snow cover and snow properties. The ARTEMIS team partnered with USAF's 557th Weather Wing to transition the existing snow products, one of which was a new method of displaying snow water equivalent graphs that were more meaningful to analysts (Figure 4), delivering the software to the 14th Weather Squadron along with documentation describing the data requirements and the existing customer base that received those products from CRREL email distributions.

Figure 4. CRREL snow water equivalent charting technology as generated by the USAF's 14th Weather Squadron. The *red line* is the current year's snow water equivalent (SWE), the *purple line* is the prior year's SWE, and the *green dashed line* represents the average SWE for the domain. The *light blue region* on the graph represents the standard deviation range of the climatological period, and the *dark blue lines* represent the maximum and minimum values observed for the watershed.



In 2015, the USAF 14th and 16th Weather Squadrons implemented the technology used to generate CRREL's snow products, including automating the production of the biweekly graphs of snow water equivalent compared to climatology (Figure 4) and the maps of snow extent on various watersheds (Figure 5), as a replacement for their existing legacy snow products and took over the biweekly distribution of those products. The snow water equivalent (SWE) graphs include a comparison to the prior year's SWE, average SWE, maximum and minimum SWE, and the standard deviations based on a 30-year history of SWE as measured by defense weather satellites. The observed snow water equivalent and the historical statistics are all based on analysis of passive-microwave-imagery-based methods; the statistical average values are computed for each watershed based on historical defense satellite program passive microwave data, including the standard deviations, maximum and minimum snow water equivalent values, and data from the past two years. None of the data used to compute the products contain in situ observations.

Figure 5. Snow-covered (*blue shading*) area map produced from VIIRS satellite data using snow detection algorithms developed by CRREL and run operationally by the U.S. Air Force 557th Weather Wing. The *red lines* are watershed boundaries for Afghanistan. CRREL improved the snow cover mapping algorithms and transitioned the technology to the USAF within the ARTEMIS project.

The snow area coverage was also mapped and presented as a KML (Keyhole Markup Language) image for use in display tools, including Google Earth or other web mapping display software. These capabilities, along with the software used to generate the products, were transferred to the USAF 14th Weather Squadron in Asheville, North Carolina, for implementation in 2016. The USAF 14th Weather Squadron now produces and distributes those products operationally with U.S. Army Corp of Engineers and USAF logos.

The snow team also focused on improving the algorithms used in snow remote sensing and numerical modeling. Investigators Deeb and Vuyovich evaluated published requirements documentation produced by the U.S.

Army, Intelligence Community, and other DoD services to develop a long-term (10-year) strategic plan aimed at improving the science behind snow remote sensing and snow properties assessments. The strategic plan uses a combination of observations, remote sensing, and numerical modeling. A broad set of snow science collaborators at other national agencies, including NASA, a number of universities, and the USAF 16th Weather Squadron, evaluated the draft science plan (Vuyovich et al. 2018).

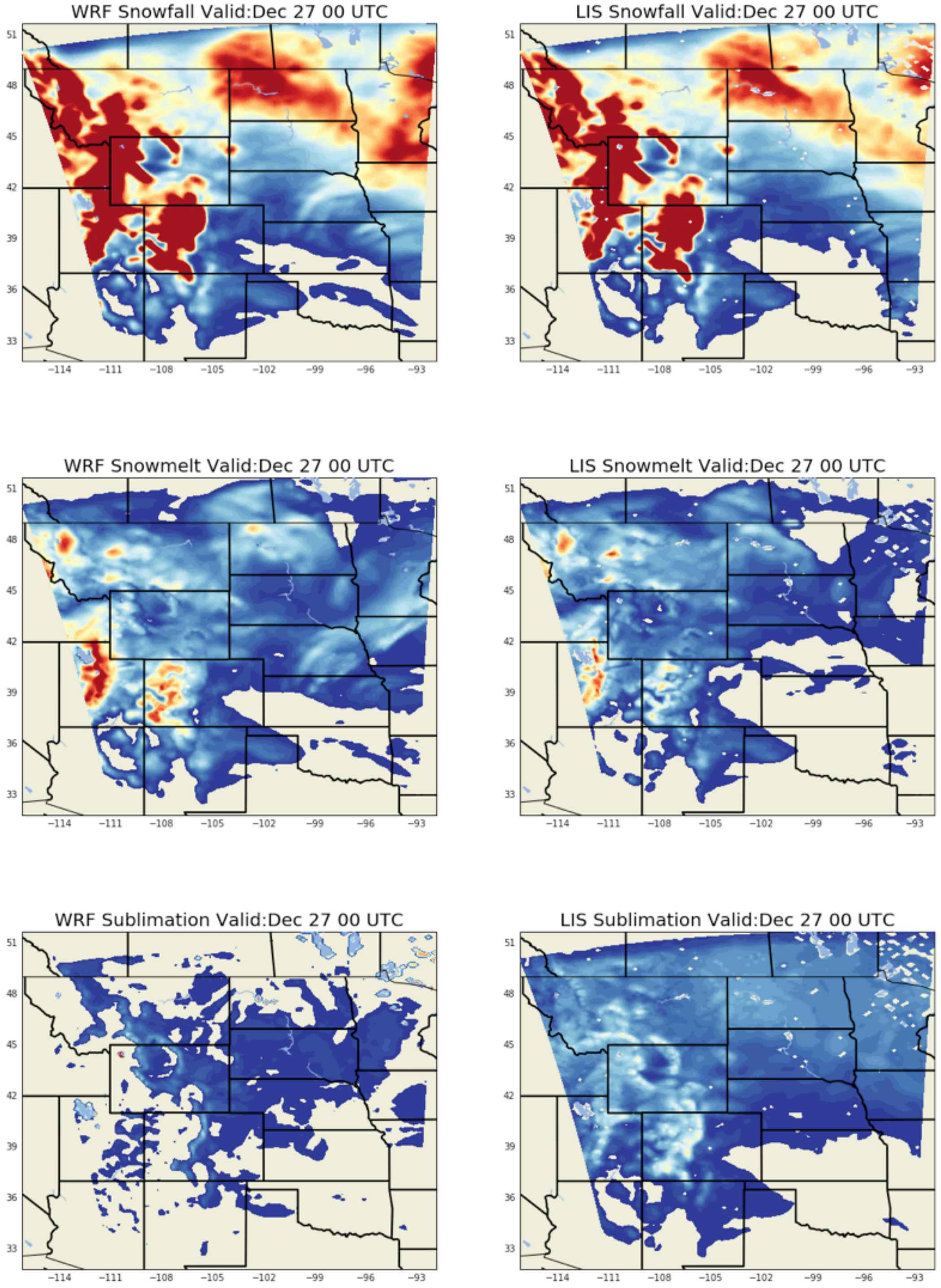
A significant portion of the last two years of ARTEMIS snow research included efforts to develop, refine, and validate coupling strategies between a land surface model and a radiative transfer model to quantify and reduce sources of uncertainty associated with the coupling process. This work was performed as part of a broader effort to increase the value of satellite remote-sensing observations in terrain models and weather prediction and to improve the snow products used to support maneuver and hydrology.

Co-investigator Letcher used the LIS and the WRF model on the ARTEMIS testbed to generate simulated snow packs over the Rocky Mountains in Colorado and the Red River basin in North Dakota and Minnesota (Figure 6). The modeled snow packs were generated with Noah version 3.6 (Chen et al. 1996) and the Noah-MP land surface models (Niu et al. 2011) and coupled to the Community Radiative Transfer Model (Chen et al. 2008; Ding et al. 2011) and the Dense Media Radiative Transfer for Multi Layers (DMRT-ML) (Picard et al. 2013) model to generate synthetic brightness temperatures. These synthetic brightness temperatures are directly comparable to satellite observation systems and can be used to assimilate satellite remote-sensing observations into numerical weather models. As a validation of the coupled land surface and radiative transfer models, Letcher compared output snow variables (e.g., depth and snow water equivalent) against available snow observations in these regions, including in situ Snow Telemetry (SNOTEL) and Soil Climate Analysis Network (SCAN) observations via the National Water and Climate Center web site (Natural Resources Conservation Service, n.d.) and the gridded observation and model Snow Data Assimilation System (SNODAS) (National Operational Hydrologic Remote Sensing Center 2004) dataset. Synthetic brightness temperatures generated though the radiative transfer model coupling were compared to the NASA Advanced Microwave Scanning Radiometer for the Earth Observing System satellite sensor gridded brightness temperature dataset.

Existing radiative transfer models (e.g., Community Radiative Transfer Model) used in weather forecasting models cannot alone simulate the seasonal evolution of observed brightness temperature over snow-covered regions due to the model's very simple treatment of surface emissivity in the microwave bands: a fixed surface emissivity for each satellite channel determined by a simple snow class (e.g., deep/dry snow vs. shallow/wet snow). The DMRT-ML can reproduce the seasonal evolution of the observed brightness temperature with some fidelity, even under more complicated snowpack conditions (e.g., liquid water in the snowpack). However, the DMRT-ML is more computationally expensive to run (up to four times the compute time) and its performance is highly dependent on how snow microstructure is parameterized in the snow model. This parameterization is subject to high amounts of uncertainty and represents a significant challenge for a globally applicable satellite data assimilation framework. In numerical models, microstructure (i.e., particle grainsize) is typically parameterized as a function of the snowpack temperature gradient. This adds an additional layer of complexity to the coupling between the radiative transfer model and the snow model. Essentially, because the effective microwave emissivity of snow is equally as sensitive to the snow grainsize as it is to snow depth, synthetic brightness temperatures are strongly impacted by the modeled internal snowpack dynamics that determine the thermal gradient of the snowpack (e.g., thermal conductivity and compaction). The key conclusion of this finding is that while improving the internal model, snowpack dynamics may have only a secondary impact on the modeled snow depth and snow water equivalent in an open loop configuration, they will likely reduce the uncertainty of synthetic brightness temperatures, increasing the value of assimilated satellite observations. By representing the modeled snowpack as a multilayer stratified snowpack, there was some modest improvement in the seasonal evolution of the brightness temperatures; however, these improvements did not appear to outweigh the increased computational expense required to use a multilayer configuration.

The LIS version of the Noah (version 3.6) land surface model contains either an error or an over simplification in how it calculates the surface exchange coefficients used in the bulk formula to compute sensible and latent heat fluxes at the surface.

Figure 6. Snowfall, snowmelt, and snow sublimation simulations from the WRF (*left column*) and LIS (*right column*) models. The sublimation results from LIS are higher than from WRF.



WRF Snowfall Valid:Dec 27 00 UTC

LIS Snowfall Valid:Dec 27 00 UTC

WRF Snowmelt Valid:Dec 27 00 UTC

LIS Snowmelt Valid:Dec 27 00 UTC

WRF Sublimation Valid:Dec 27 00 UTC

LIS Sublimation Valid:Dec 27 00 UTC

This error causes the model to over sublimate snow in the accumulation season, leading to peak snow water equivalent values up to 50% lower than without the error. This finding arose when comparing the modeled snowpack from a LIS Noah simulation forced with output from the WRF model to the snow output from the WRF simulation and finding they were substantially different. A comparison between the WRF and LIS surface coupling subroutines in conjunction with additional test simulations with modified forcing data heights and surface exchange coefficient stability corrections did not identify a single, or even primary, source of the model discrepancy. We suspect that the vertically varying structure of the WRF forcing data versus the single-level LIS forcing may play a dominant role, which makes this difference challenging to isolate and correct. Rather than attempting to correct the discrepancy, we document it for the greater scientific modeling community since the error is sufficiently large such that it has the potential to impact the interpretation of simulated snow from LIS in future studies. We are continuing to study the models under other applied research efforts to better understand the source of this difference.

2.2 Terrain phenomenology research

2.2.1 Dust research

Airborne mineral dust influences global climate and biogeochemical processes (e.g., Mahowald et al. 2005, 2010, 2014; Ravi et al. 2011; Webb et al. 2012; Boucher et al. 2013; Wang et al. 2017). Furthermore, hazardous air quality conditions created by dust can adversely affect human health, agriculture, visibility, equipment performance, and communication on regional and local scales (e.g., Rushing et al. 2005; De Longueville et al. 2010; Okin et al. 2011; Sprigg et al. 2014; Al-Hemoud et al. 2017; Middleton 2017). While considerable advancements have been made in dust event simulation, forecasting, monitoring, and hazard mitigation (e.g., Rushing and Tingle 2006; Edwards et al. 2010; Knippertz and Stuut 2014; Sheppard et al. 2016), improved dust-emission modeling approaches are needed for accurate forecasting and risk assessment (Richter and Gill 2018).

Existing soil-mobilization and dust-emission models currently have a strong dependency on land surface attribute datasets (e.g., soil texture and composition, initial “looseness” or erodibility of the soil bed, vegetation coverage, etc.) that are difficult to acquire over large spatial footprints. Convention has been to approximate these land surface features using interpolated coarse-scale approximations or lookup tables based on limited field data. These surface-trait dependencies, however, can result in up to an order of magnitude of uncertainty in simulated dust concentrations (e.g., Uno et al. 2006), which compounds downstream errors in air quality and visibility characterization models used for mission planning and intelligence applications.

To better investigate processes related to dust lofting, the ARTEMIS dust team developed a new testbed, termed the Dynamic Undisturbed Soils Testbed to Characterize Local Origins and Uncertainties of Dust (DUST-CLOUD) initiative, to provide the U.S. Army with novel methodologies for analyzing and predicting terrain surface conditions known to affect dust emission and soil strength. This multidisciplinary effort leveraged expertise from numerical modelers, engineers, physical scientists, lab specialists, desert rangeland managers, and operational weather centers to explore techniques for relating dust processes to geomorphic landform traits and readily available parameters detected via satellite. The DUST-CLOUD team included participants from several ERDC laboratories (CRREL, Geospatial Research Laboratory, Environmental Laboratory, and Geotechnical and Structures Laboratory), the U.S. Department of Agriculture Agricultural Research Service, the U.S. Geological Survey, the Center for Snow and Avalanche Studies' Colorado Dust-on-Snow Program, the Desert Research Institute, Cardiff University, and the University of South Dakota.

DUST-CLOUD included a series of numerical modeling, remote sensing, GIS, field, and laboratory research efforts designed to (1) establish reliable, first-order approaches for characterizing arid region soil erodibility; (2) assemble and assess regional archives of satellite-based observations to evaluate the error and uncertainty of the new terrain characterization approaches; and (3) better understand physical processes controlling dust emissions in areas not well represented by the new characterization techniques. These efforts laid the foundation necessary for ERDC to continue advancement of dust-source representation in decision aids used by the Army for degraded visual environment, air quality, mobility, and equipment performance applications.

We evaluated the performance of three commonly used dust-emission schemes, including the AFWA scheme, which is a physical component of the WRF model used by USAF to simulate dust emissions in the authoritative DoD air quality, visibility, and radiative transfer models (e.g., LeGrand et al. 2019; Letcher and LeGrand 2018). Our findings suggest that although the AFWA scheme is less physically sophisticated than other available options, it may outperform more advanced models in the U.S.

Central Command area of operations due to the more advanced models' stronger dependency on poorly represented terrain attributes.

A popular approach for solving the surface characteristics dilemma is to use spatially (and in some cases, temporally) varying erodibility indices to capture soil-binding processes not explicitly resolved by models. These indices are usually incorporated into dust schemes as an emission flux multiplier. Several proxy- and remote-sensing-based parameterization options are available for use that do not require intensive in situ campaigns to produce (e.g., Zender et al. 2003; Walker et al. 2009; Ginoux et al. 2001, 2010; Bullard et al. 2011). Many of these options, however, were only intended for global modeling applications and include assumptions that break down at grid spacings finer than 10 km, or erroneously augment or reduce simulated dust emission in instances where dust-emission process-based algorithms could have accurately simulated conditions on their own.

The DUST-CLOUD effort included several studies aimed at developing and evaluating a novel scale-aware, geomorphic erodibility parameterization designed to avoid the errors and double counting issues inherent to existing dust-source characterization techniques (e.g., Jones 2016). This new approach uses geomorphic landform designations (e.g., playas, alluvial features, etc.) as a proxy for dust-emission potential and combines physically based theory with a geomorphic-based optimization algorithm to better enable representation of dust-emission flux patterns over vast spatial footprints. Due to the success of these efforts, our dust-emission parameterization approach is currently being tested for use in the operational dust model used by USAF for Army weather support.

In addition, we conducted several field and laboratory-based studies to further investigate soil attributes associated with various arid-region landforms to better understand potential sources of uncertainty in our new dust-source characterization approach. Studies by Doherty et al. (2018) and Bigl et al. (2019) suggest that variations in soil surface crusting may be a notable source of uncertainty and warrant further basic research investment to establish suitable algorithms for representing crusting processes in dust-emission models. Our microscale investigations also revealed that soil microbial community patterns were characteristic of landform type (Barbato et al 2018), which suggests that microbial composition assessment may be a promising technique for corroborating airborne or deposited dust particles with a particular group of dust sources. These findings along with our research exploring the evolution of dust particles deposited in snowpack suggest microbial dust “hitch-hiker” provenance may be a good approach for verifying landform classification maps and simulated dust concentrations.

We also investigated the role of analyst subjectivity on the reproducibility of regional-scale active dust-source datasets assembled using the Walker et al. (2009) technique, which is often used to assess dust-emission scheme accuracy in remote locations (e.g., Sinclair and Jones 2017). With this technique, a number of analysts with geoscience backgrounds were trained by an expert over a nondedicated two week time period to independently identify an unobscured plume head in dust-enhanced satellite imagery and digitize the locations in geospatial maps. Our results suggest that up to 17 km of locational error should be considered when using these datasets to account for analyst subjectivity and potential downwind advection of dust prior to satellite detection (Sinclair and LeGrand 2019). Additionally, most of the plume heads identified during this study (>90%) were not marked by all participating analysts, which indicates that dust-source maps generated using this technique may differ substantially between users. We concluded this approach was not suitable for quantitative model validation; however, the active dust-source-density datasets produced for this effort were provided to the 557 Weather Wing and 16th Weather Squadron as an additional means for configuring dust sources in their regional ensemble.

The overall findings from the ARTEMIS DUST-CLOUD initiative suggest that geomorphic dust-emission analogs may notably improve air quality and soil erosion models used for a variety of Army applications. Furthermore, we suggest that the Army explores use of dust-emission analogs for other terrain applications affected by soil mechanics (e.g., soil strength and land surface hydrology).

2.2.2 Biosentinels research

Biosentinel refers to organisms that respond to changing environmental conditions and can serve as environmental sensors. Effective situational awareness heavily relies on understanding soil processes contributing to the activity and stability of soils. Soil serves as a rich source of biodiversity because it is teeming with living organisms, including beneficial and harmful ones. Soil is constantly changing in time and space, impacting the soil ecosystem on diurnal, seasonal, climatological, substrate, vegetation, and moisture cycles. Specifically, soil biological activity contributes to the following DoD issues: the breakdown of toxic industrial chemicals and toxic industrial materials; interference with fielded sensors; improvements in soil stability; and the capability, with sufficient activity in the soil, to serve as an energy source. Current geospatial models are limited because they do not incorporate biological processes that affect the behavior of soils (i.e., their stability). Organisms play a significant role in these soil behaviors and in turn can affect the attenuation of materials on surface soils, the recalcitrance of asymmetric agents, and the mechanical properties and stability of the soils. Therefore, their incorporation in modeling is paramount to more effectively predict processes at the air-soil interface. By coupling a soil biochemical layer to terrain characterization, the models will be more robust and will better predict events occurring on the soil surface for enhanced capabilities for the Army and the Nation. In the Dynamic Representation of Terrestrial Soil Predictions of Organisms' Response to the Environment (DRTSPORE) component of ARTEMIS, we provided a tactical decision aid that forecasts biological activity as a geospatial layer on a terrain map that includes information of soil texture classifications aligning with the U.S. Department of Agriculture classifications. With this intelligence, analysts will be able to refine maneuver support and sensor placement in theater.

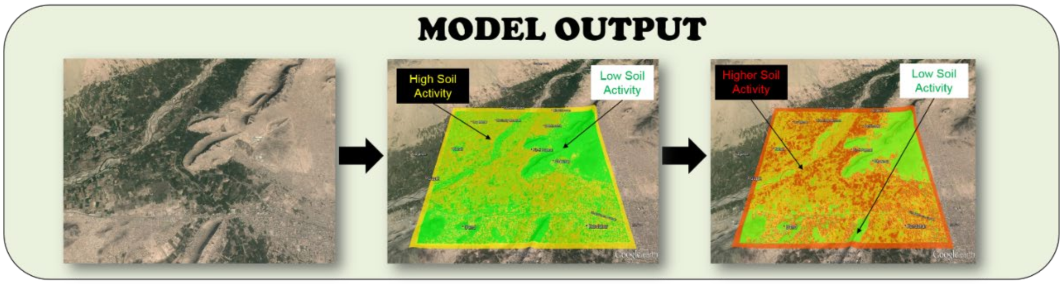
The primary objective of DRTSPORE was to develop an intelligence tool that adds a biochemical layer to current high-resolution, remotely sensed terrain and sophisticated land surface models and weather products from TERRASIM. DRTSPORE is the first of its kind, mainly because of the technical challenges associated with modeling complex and dynamic biological processes occurring at the soil surface. The purpose of DRTSPORE was to understand biochemical features in the environment and to address the following:

- Provide predicted rates of soil activity for biosensor placement
- Understand baseline biochemistry for sensor placement
- Understand soil microbiome composition for degradation of sensitive materials and deposited signatures
- Provide predicted rates of soil activity for degradation of biological and chemical threats

The DRTSPORE research effort resulted in the following outcomes:

- We were able to generate an assessment of the attenuation of signatures on surface soils, described in Barbato et al. (2016).
- We conducted an extensive laboratory study to develop an empirical dataset for the soil model by subjecting four soils to a range of environmentally relevant conditions (Barbato et al. 2015).
- We formulated a model of soil activity based on remotely sensed and predicted parameters (Figure 7), developed a calculation engine to create the geospatial layer, improved the DRTSPORE model to incorporate specific biochemical activities, and conducted a laboratory study developed to exhibit how biologic material within soils can be harvested as an energy source (Barbato et al. 2017) and demonstrated that for a small light-emitting diode.

Figure 7. DRTSPORE model output showing predictions of soil microbial activity from high-resolution digital elevation models and weather forecasts over a 10-day period over Kandahar.

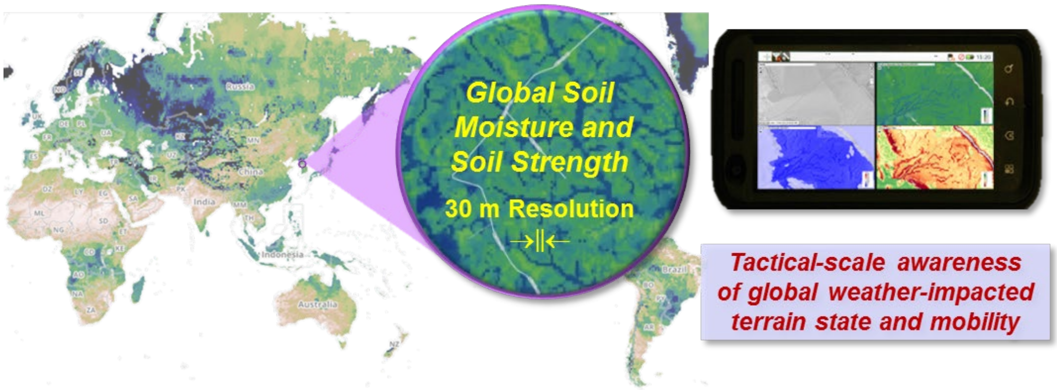


2.3 Weather-informed mobility

The Army has developed a number of mobility applications to support cross-country mobility estimation based on soil type and strength; however, a key consideration in the computation of soil strength is the soil moisture. Until recently, the only way to account for soil moisture in the computation of vehicle mobility in Army applications was to either use coarse-resolution climatological datasets or require the user to directly supply an informed value (based on recent precipitation) as input to the decision aid. The lack of high-resolution (e.g., 1 km raster resolution or finer), physics-based analyses and predictions of soil moisture combined with challenges linking time-sensitive weather data with Army mobility applications in geospatial systems was difficult to overcome. The ARTEMIS program successfully developed and prototyped a tool that combines weather and terrain data, computes 30 m resolution soil moisture and soil strength globally, and uses those products to initialize the STNMOB application. All the products computed or used as part of the tools were integrated into a web-based open GIS system for demonstration and potential use by engineers, analysts, and commanders at all echelons. The capability was developed and fielded with considerable contribution by Creare LLC scientists and engineers using Army Small Business Innovative Research and Army Rapid Innovation Fund support as a component of the ARTEMIS effort, with the capability named the Geospatial Weather Affected Terrain Conditions and Hazards (GeoWATCH). This capability will enhance situational awareness and intelligence preparation for the battlefield and will support dismounted and mounted cross-country mobility analyses, opportune airfield placement, basing considerations, and flood mapping.

A key component in the GeoWATCH tool is a Creare-developed soil-moisture downscaling algorithm, which filled a critical gap in our ability to apply weather data from existing USAF weather and terrain predictions to Army simulation systems. As illustrated in Figure 8, GeoWATCH provides prediction of 30 m resolution global soil moisture, soil strength, and vehicle speed through physics-based downscaling of authoritative operational weather products supplied by the 557th Weather Wing and disseminates these data products using open-standards protocols and data formats adopted by the Army Geospatial Enterprise. Downscaling in this case is defined as a method to increase the resolution of coarse raster data to very fine resolutions, in this case soil-moisture products. The Creare downscaling algorithm ingests coarse-resolution dynamic soils content (moisture, temperature, snow, etc.) from USAF's 557th Weather Wing and produces a product at a 30 m to 90 m resolution globally.

Figure 8. GeoWATCH overview. GeoWATCH predicts global weather-impacted terrain conditions, including soil moisture, soil strength, and vehicle speed, at tactical-scale resolution. It features open-standard data formats and transmission protocols, enabling access from any networked device.



GeoWATCH's ground-state predictions are generated via a physics-based downscaling approach that fuses weather-scale (1/4 degree spatial scale) land surface model estimates of soil moisture and land surface water and energy fluxes, with terabytes of geospatial data, including topography, land cover, soil classification, and vegetation information, at high resolution (1 to 3 arc-second spatial scale). The weather-scale, near-surface soil-moisture estimates are ingested from 557th Weather Wing operational products, including LIS data for historical and current conditions and GALWEM (Global Air-Land Weather Exploitation Model) data for short-term forecast conditions. A two-stage, physics-based hydrological model is then applied to downscale the weather-scale data to the high resolution of the available topographical data sets. The first downscaling stage computes steady-state soil-moisture redistribution due to topography and soil texture effects using a topographically based hydrological model (TOPMODEL) formulation (e.g., moisture from the water table is allocated toward regions with a high topographic wetness index) (Beven et al. 1995). The second downscaling stage accounts for dynamic weather-driven effects by computing water balances that disaggregate water fluxes from the weather-scale land surface model based on the high-resolution geospatial data (e.g., transpiration water fluxes are allocated toward regions with greater vegetative coverage). The results of these two downscaling stages are then combined, yielding global, high-resolution, near-surface (top 10 cm) soil-moisture estimates. These downscaled soil moisture values are combined with the higher resolution soil textures and deeper layer, coarser resolution soil moisture values to compute soil strength and mobility at 30-meter resolution globally for unfrozen soils.

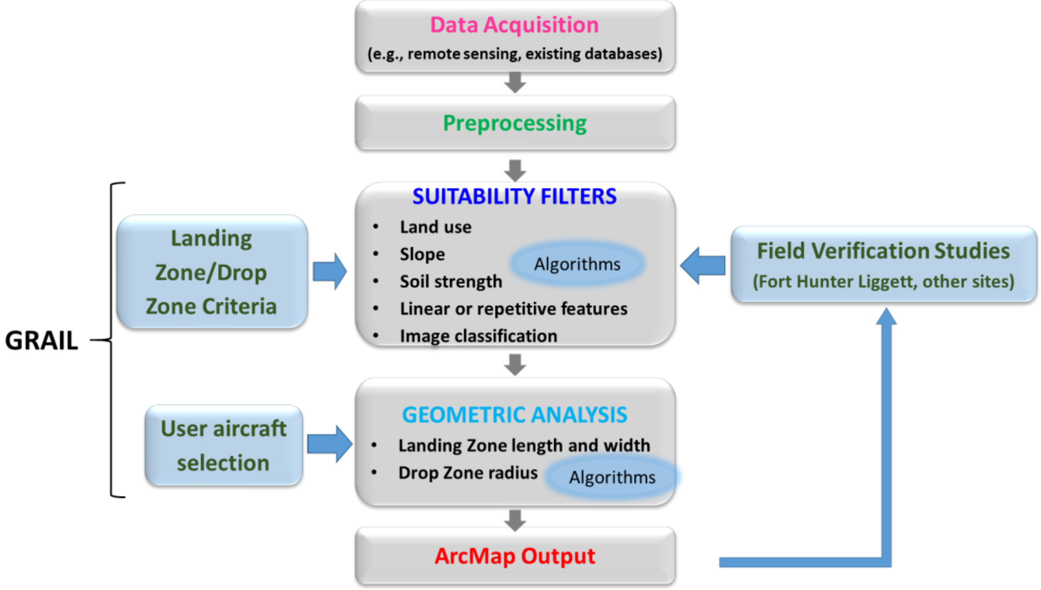
GeoWATCH's high-resolution soil-moisture estimates enable generation of near-real-time, weather-impacted, cross-country mobility products (e.g., estimated soil strength and speed maps for Army vehicles) through integration with a new Python language version of the U.S. Army STNDMOB (Baylot et al. 2005) software (which is based on the NATO Reference Mobility Model). The integrated GeoWATCH and STNDMOB algorithms have been implemented in a high-performance, cloud-based computing architecture that provides real-time, on-demand, interactive access to products by using a map user interface accessible from any modern web browser and Open Geospatial Consortium–compliant Web Mapping Service and Web Coverage Service endpoints for ingestion by GIS such as Esri ArcGIS and other geospatial client software. A user can visit the site and view analyses and forecasts of soil strength for any location globally, generating the highest-resolution products for any region in seconds. Additionally, military users can compute vehicle speed assessments for cross-country mobility (output from the STNDMOB application) for the same domain again in tens of seconds (depending on the size of the domain). A demonstration version of GeoWATCH is available at https://mobility.crearecomputing.com/.

2.4 Remote assessment for ingress/egress locations

The ARTEMIS Terrestrial Geospatial Remote Assessment for Ingress Locations (GRAIL) project focused on creating a series of geospatial tools to identify locations for the opportune landing of both rotorcraft and fixed-wing aircraft, as well as drop zones for cargo and personnel in remote austere regions to support Army operations (Figure 9). Most of the capabilities developed with GRAIL are described in (Shoop and Wieder 2018). Currently, characterizing potential landing zones requires troop deployment and portable equipment to measure soil strength. The GRAIL team's goal was to automate much of that process using a combination of remote-sensing techniques and numerical methods to characterize potential landing locations for both Army aerial vehicles and for USAF C-17 and CH130 airplanes, which are used to transport Army materiel and personnel and are the two aircraft currently used on unpaved landing strips. The GRAIL team focused on developing these tools using Esri ArcMap, aiming for final integration inside the SAGE application, working jointly with the UTA team. The team focused much of their efforts and field work on identifying landing zone and drop zone areas for Fort Hunter Liggett, California, while also exploring the Nevada National Security Site and a farm field in Nebraska.

The GRAIL team focused on developing site suitability filters to create automated methods to evaluate the properties of a potential landing location, including the vegetation characteristics (location and type), soil strength, and potential obstacles (power lines and other obstacles that would impact the landing or drop zone site). The soil strength was investigated using model-based methods and evaluating remote-sensing methods. Some datasets required to execute the algorithms are available from existing geospatial datasets, including digital elevation models, terrain slope, and soil classification datasets, and were available as raster data layers either due to other ARTEMIS research efforts or available from other agencies. Additionally, the GRAIL team evaluated using the GeoWATCH data as part of the decision-making algorithm.

Figure 9. Diagram outlining the components of the GRAIL toolbox development, including the user input and field validation studies (after Shoop and Wieder 2018).



The GRAIL team conducted a number of field studies to validate the results in seasonal conditions over several years, including obstacle detection and soil strength, at Fort Hunter Liggett. Data collected included terrain slope and roughness, land classification, soil classification, soil strength using a number of different measurement methods, field spectrometer data, and soil grain size distribution. Collecting these data enabled validation and verification of the automated methods being developed.

The results of the project include a prototype capability to remotely assess potential landing zone and drop zone locations. The automated tools successfully located a number of potential runways for fixed-wing aircraft (Figure 10), landing zones for rotorcraft, and drop zones for personnel and cargo (Figure 11) using soil slope, land use information, and soil strength, and are currently being integrated into the SAGE toolkit. The team has evaluated using both model-based and remote-sensing-based soil-moisture and soil-strength products as input into the model and provided some validation of those products (see Shoop et al. 2018).

Figure 10. Potential C-130 assault landing zone sites at Fort Hunter Liggett, California, located by the GRAIL Tools from (Shoop and Wieder 2018). The key in the *upper left* indicates the orientation (compass degrees) of the runway.

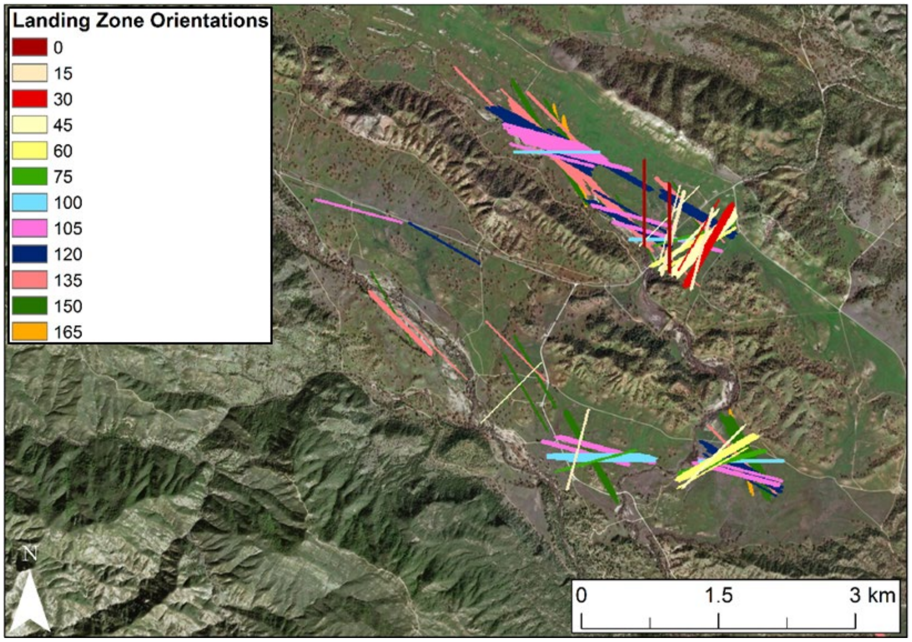
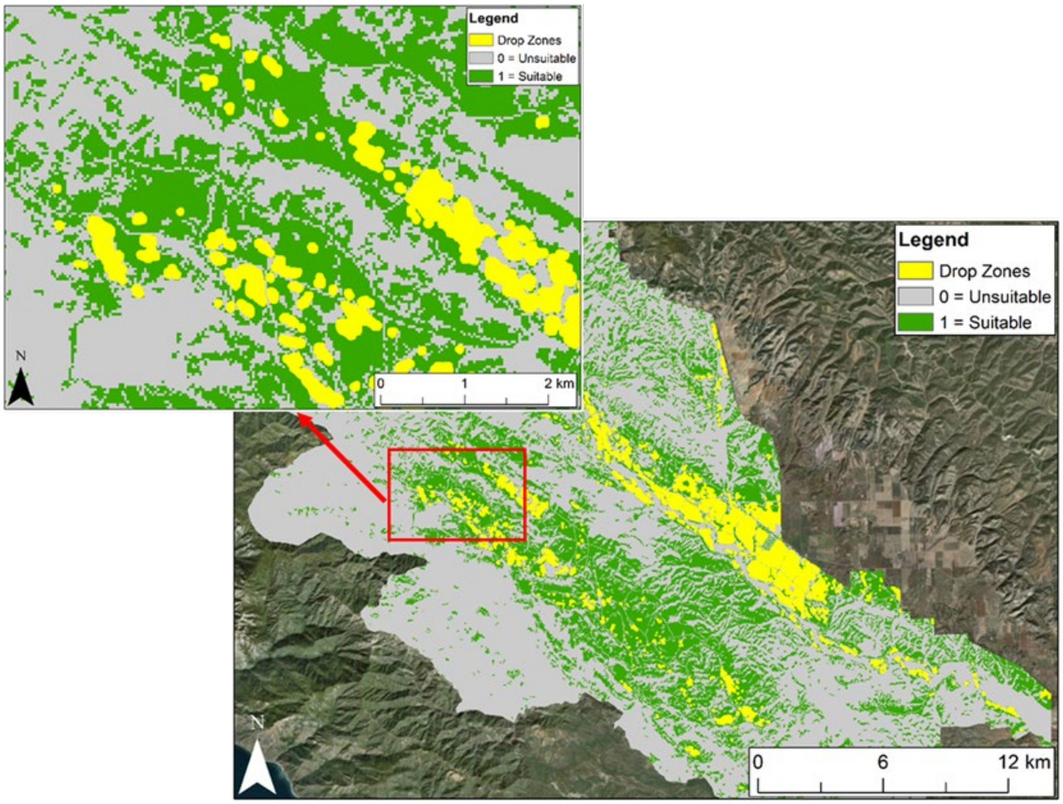


Figure 11. Drop zones for 50 and 150 foot radius locations in Fort Hunter Liggett, California (Shoop et al. 2018). The color key in the *upper right* of both images labels the locations suitable for drop zones (*yellow colors*) versus unsuitable zones (*gray*).



2.5 Sensor performance

The goals of the sensor-performance research and development within ARTEMIS by the SPRUCE team focused on how weather and terrain data were incorporated into EASEE acoustic, radio-frequency (RF), and probabilistic line-of-sight predictions and how to incorporate the capability to use the environmental data cube (EDC) to feed EASEE, to improve the environmental support for infrared-sensing/sensor-performance prediction, and to develop a new web-services capability that would support broader distribution of sensor-performance tools to multiple programs of record or to users.

2.5.1 Improved acoustics in EASEE

At the project onset, the SPRUCE team devoted time toward model validation and transition of EASEE version 2. In support of model validation goals, ARTEMIS members participated in an experiment conducted jointly with the U.S. Coast Guard involving collection of acoustic data from HC-130J and HC-144A flights off Cape Cod.[*] Aircraft recordings and audibility assessments were made from boats and were compared with predictions from EASEE. The predicted audibility distances underestimated the actual audibility distances by roughly 40%. The likely causes were the variable noise background on the boat and the human audibility model, which does not adequately capture the acuity of humans for discerning a sound in background noise when actively listening. In addition to the aircraft study, the SPRUCE team also added a new numerical method for efficient calculation of acoustic pulse propagation over ground surfaces (Vecherin and Albert 2018).

The SPRUCE team extended EASEE version 2 to enable calculations with high-resolution terrain, soil, soil moisture, snow, and land cover data. These extensions provided full support two-dimensional variations in these properties, including standard geospatial data formats for land cover and soil. An extensive scheme was developed to infer unspecified terrain properties. For example, if the user provides land cover but not soil data,

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[*] Albert, D. G., J. J. Gagnon, and G. L. Hover. 2015. "U.S. Coast Guard Aircraft Noise Study." Hanover, NH: U.S. Army Engineer Research and Development Center. (Report submitted to the U.S. Coast Guard. Available upon request.)

reasonable values will be inferred for the soil based on the land cover.[*] Although the inferences are by no means perfect, they are helpful in improving the model predictions. For example, if vegetation is present, it is generally true that the ground consists of an acoustically soft (absorbing) material such as sandy or clay/silty soil, as opposed to an acoustically hard (reflective) material such as rock or asphalt. Probabilistic line-of-sight models were also added to EASEE to support situations where land cover partially obstructs visibility.

Many features were also added to EASEE to support arbitrary directivity for source emissions and sensor responses (e.g., RF antennas and acoustic microphone arrays). The directivity functions use the fields of view, explicit azimuth/elevation rasters, or spherical harmonics (Vecherin et al. 2011). Fully three-dimensional (3-D) rotations of the directivity functions, as specified with Tait-Bryan angles, were also added. These extensions greatly facilitate realistic calculations with aircraft and other platforms that can rotate arbitrarily.

As part of a joint project with NASA, the Nord2000 sound propagation model (a widely used heuristic model that incorporates detailed terrain modeling) and the Glasberg-Moore human auditory critical band model were also integrated into EASEE (Wilson et al. 2016b). The upgrade of the human auditory model addressed issues identified during the U.S. Coast Guard aircraft audibility study as described previously. Initial support was added for calculations involving 3-D weather data and statistical analysis from ensemble weather forecasts. Wilson et al. also developed new approaches to performing uncertainty sampling and variance reduction in acoustic calculations, published in an invited paper at InterNoise 2016 (Wilson et al. 2016a).

Another innovation was the addition of a capability for dynamic "discovery" and loading of new target signatures via XML (eXtensible Markup Language) files. This enables ingestion of new signatures into EASEE

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[*] Wilson, D. K., D. J. Breton, L. E. Waldrop, D. R. Glaser, R. E. Alter, C. R. Hart, W. M. Barnes, M. T. Ekegren, M. B. Muhlestein, M. Mishra, M. A. Niccolai, M. J. White, C. Borden, and E. Fahy. Forthcoming. "Signal Propagation Modeling in Complex, Three-Dimensional Environments." ERDC/CRREL Technical Report. Hanover, NH: U.S. Army Engineer Research and Development Center.

without recompilation of the code, which is a particularly valuable capability when running EASEE on systems that do not have the necessary software compilers installed to recompile the code.

The SPRUCE team refactored the EASEE software into two separate Java projects. The first project, called EASEELib, contains the militarily sensitive, proprietary, and export-controlled components along with advanced propagation models and other capabilities used to perform high-fidelity calculations of sensor performance. EASEELib is marked with Distribution Statement D, meaning that distribution is limited to the DoD and U.S. DoD contractors. The second project, called KNEE (which stands for “KNEE is not EASEE in its Entirety”) is a stripped-down, light-weight version of EASEE, composed almost entirely of Java code with very few external dependencies. It is marked with Distribution Statement C, meaning that distribution of KNEE is authorized to U.S. Government Agencies and their contractors. Also, the SPRUCE team developed a toolbar to run EASEE from ArcGIS, which is the software most commonly used by terrain analysts in the Army and intelligence community. Python scripts and graphical user interface elements were developed for this purpose. An International Society for Optics and Photonics conference paper (Waldrop et al. 2017) details the use of EASEE in open-architecture software environments and described the XML communications protocol and EASEE Web Service that was originally developed by Atmospheric and Environmental Research Inc. as part of the previously mentioned Rapid Innovation Fund contract.

Finally, the SPRUCE team collected acoustic signatures for a Cessna 172N Skyhawk at the end of fiscal year (FY) 16 at the Claremont Municipal Airport in Claremont, New Hampshire. The signatures were obtained on land in a stationary configuration approximately 50 m from the starboard side of the craft. Signatures were also obtained from the ground while the aircraft traveled at elevations of 305 and 610 m. The flight included paths that were with the wind, into the wind, and perpendicular to the wind direction.

The SPRUCE team was able to acquire acoustic signatures of U.S. Army helicopter platforms in conjunction with the U.S. Army’s 1st Cavalry Division out of Fort Hood, Texas. Acoustic signatures were measured for the Apache AH-64 and the Blackhawk UH-60 helicopters that were hovering, rotating, and traveling at various rates of speed and at multiple elevations. An article appearing in the Unites States Army Aviation Digest July 2017 issue (Hughes 2017) highlighted the use of EASEE by the Army's 1st Cavalry Division, lauding the capability by stating, "This application greatly enhances mission analysis as pilots, planners, and analysts can determine optimal locations and routes to reduce audibility of friendly assets and employ sensors monitoring enemy activity."

Additionally, in FY17, the EASEE code was moved from a subversion repository hosted at the Defense Information Systems Agency ProjectForge website to a GitLab site hosted at the ERDC Information Technologies Laboratory (ITL). The primary reason for the transition was cost savings since Defense Information Systems Agency was to begin charging fees for ProjectForge, whereas the ITL site was free to the project. But, the conversion from Apache Subversion to GitLab was also desirable from the standpoint of leveraging the many advanced features of Git for code management. The transition, which involved many upgrades to EASEE in terms of its organization and implementation of a Maven build script, went smoothly. EASEELib is maintained in the ITL GitLab site hosted behind the Defense Research and Engineering Network firewall, whereas KNEE is maintained on the "public-facing" website, which can be accessed by approved users outside of ERDC with CAC cards. In related FY18 activities, the code repository was further restructured to separate proprietary RF and infrared modeling capabilities so as to facilitate distribution of EASEE without these components.

Also in FY17, a substantial expansion of weather assimilation capabilities in EASEE was undertaken to support ingestion of data from the 3-D WRF and GALWEM model forecasts and the loading and performing calculations on weather forecast ensembles. Infrasound calculations were also incorporated into EASEE (Glaser et al. 2017) as were the automated backpropagation (compensation for the source-receiver geometry) and denoising of signature data, thus enabling nonexpert users to incorporate their signature data collections. This new capability was applied to a data collection at Marine Base Quantico on two small unattended aerial vehicles, namely the Phantom quadcopter and the Parrott Discovery, thus enabling the application of EASEE to the growing practical threat of these small unmanned aircraft systems.

The primary activity in FY18 was the creation of EASEE Version 3, which is the first version of EASEE to provide full support for signal propagation calculations with 3-D weather and complex terrain characteristics. To lay the groundwork for the ingestion of high-resolution atmospheric and terrain data into EASEE from a variety of data sources, components of the code handling geographic coordinate transformations were entirely revamped. A fully functional abstraction layer, capable of converting data grids between any geographic coordinate systems, was written so that EASEE can independently ingest terrain elevation, soil, land cover, and atmospheric data on any geographic projection, at any resolution, and with any corner coordinates. Presently, latitude and longitude, Universal Transverse Mercator, and Lambert projections are explicitly implemented. All signal propagation calculations are performed on a Universal Transverse Mercator projection with a domain that is set dynamically when the propagation algorithm runs rather than when the propagator is constructed as in previous versions of EASEE.

The next major activity in creating EASEE version 3 involved extensive upgrades to the propagation calculations and the parameter classes supporting these calculations (Wilson et al. 2018). The previous parameter classes were partitioned into separate classes for the computational parameters and for the environmental properties. These are now referred to as the “parameter” and “media” classes, respectively. The parameters object is always constructed at the same time the propagator is constructed. The media object may be specified when the propagator is constructed or later within the flow of a full EASEE calculation. The media classes play a key role in EASEE as they automatically convert the user-specified environmental data to the information needed by the propagation calculation. In EASEE version 3, the media objects contain only the information that is strictly necessary for the propagation calculation to run. The conversion of the user environmental data is now invoked dynamically at runtime so that extraneous data are not unnecessarily converted and stored.

Media specifications were written to support “homogeneous,” “polar,” and “Cartesian” specifications of the environmental properties. “Homogeneous” means that the environmental properties do not vary with regard to the horizontal coordinate although they may still vary vertically. This representation is essentially the legacy EASEE version 2 approach. “Polar” means that the environmental properties vary in three dimensions and are specified on an azimuth/range grid relative to a known geographic origin. “Cartesian” also means that the environmental properties vary in three dimensions, except that they are specified on a regular rectangular grid. Propagation models, depending on how they are formulated, support one or more of these three specifications. The supported specifications are indicated using Java generics to ensure that the algorithm is applied only to the geometry of environmental data for which it is intended.

EASEE version 3 also introduced a new scheme for specifying RF features. RF calculations are complicated by the extremely broad range of wavelengths and phenomena of interest. We focused the RF implementation on the VHF (very high frequency), UHF (ultrahigh frequency), SHF (superhigh frequency), and EHF (extremely high frequency) ranges since these incorporate most of the communication and signal detection scenarios of importance for Army tactical applications. Separate modeling sequences were implemented for the VHF/UHF and the SHF/EHF ranges since the propagation physics and noise considerations are quite different for these ranges. The cutoff between the two was placed at 1 GHz since this follows the Institute of Electrical and Electronics Engineers standard, and most VHF/UHF models apply only below this frequency. Within the VHF/UHF range, the Hata RF propagation model (Hata 1980) was implemented along with appropriate noise background models based on the International Telecommunications Union 372 standard. Within the SHF/EHF range, line-of-sight propagation models are used, and the background and sensor self-noise are specified relative to the thermal background level.

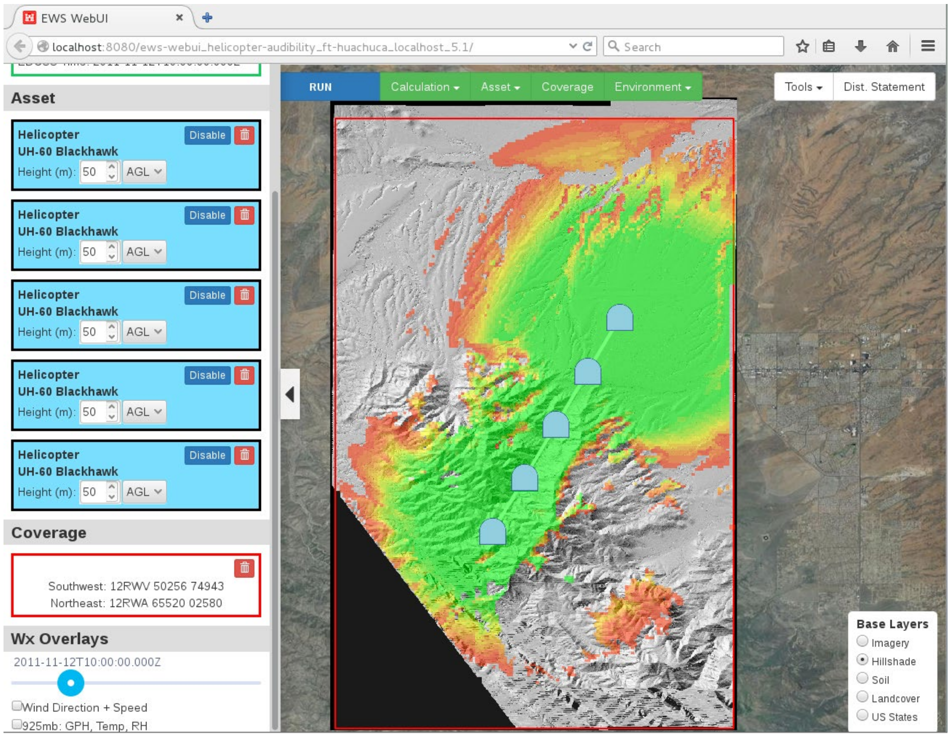
A strategic plan for the future development and transition of EASEE was also written in FY18 (Wilson et al. 2019).

2.5.2 EASEE Web Services design

As part of the ARTEMIS project, in combination with an Army Rapid Innovation Fund task, Atmospheric and Environmental Research Inc. developed a web-based version of the EASEE software for potential integration into web-based GIS systems. This web-based version of EASEE, termed EASEE Web Services (EWS) includes the core EASEE java library developed by the CRREL EASEE team with a new web user interface (WebUI) instead of the Matlab user interface. This method of integrating EASEE into a web-based geospatial display enables a user to interact with EASEE on a remote server without needing to have the software installed directly on the device and enables any web-connected device (desktop or mobile) to interact with the software. The WebUI (Figure 12) integrates EASEE with terrain imagery from authoritative sources (e.g., Army Geospatial Center) using Web Mapping Services elevation data with Web Coverage

Services and geospatial services from any shared (Enterprise) Open Geospatial Consortium–compliant server. The EWS software has been deployed at the Army Geospatial Enterprise "node" for testing and demonstration within multiple Army Geospatial Enterprise programs of record at the Army Geospatial Center.

Figure 12. Web-based user interface for the EASEE system. The graphical illustration on the *right side* of the image is acoustic propagation of an Army helicopter flying along a path through a valley near Fort Huachuca, Arizona, that ends at the base. The user interacts with menus along the top of the display, including weather information, asset type, sensor model, and other information about the sensors and environment. The *left side* contains asset information about the height of the flight path. The user can use the slider bar in the lower left to look at the results over time as well as overlay some weather information.



Helicopter
UH-60 Blackhawk
Height (m): 50 AGL

Helicopter
UH-60 Blackhawk
Height (m): 50 AGL

Helicopter
UH-60 Blackhawk
Height (m): 50 AGL

Helicopter
UH-60 Blackhawk
Height (m): 50 AGL

Helicopter
UH-60 Blackhawk
Height (m): 50 AGL

Southwest: 12RWV 50256 74943
Northeast: 12RWA 65520 02580

2011-11-12T10:00:00.000Z

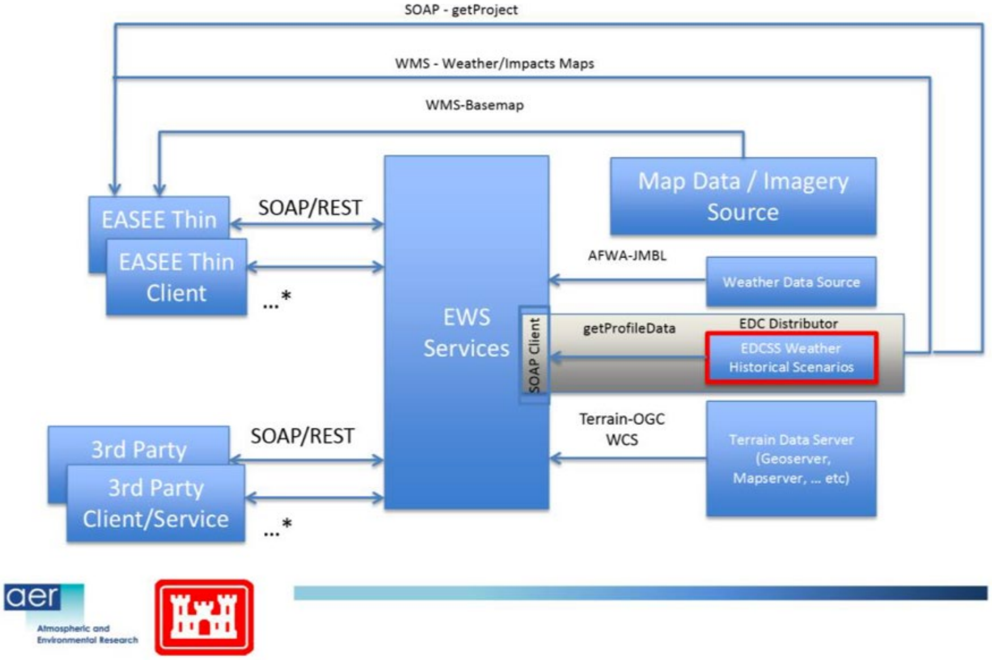
☐ Wind Direction + Speed
☐ 925mb: GPH, Temp, RH

2.5.3 Integration of a four-dimensional weather system support to EASEE

Feedback from U.S. Army Intelligence organizations (Intelligence Center of Excellence, Distributed Common Ground System–Army leadership, etc.) on the use of weather in military decision systems provided direction for the merging of the EASEE tool with another DoD-sponsored software system originally known as the Environmental Data Cube Support System, developed by Atmospheric and Environmental Research Inc. with DoD funding. Under the ARTEMIS project, the software system was further developed into a system termed the Geospatial Weather Services (GWX) and expanded into a service that can serve up digital weather products for use in Army tactical decision aids. The GWX system is a combined weather database and software services system that enables users to request specific types of weather scenarios based on stored, gridded weather products. The database houses 30 years of gridded, worldwide atmospheric analyses computed by the NOAA Climate Forecast System (CFS) model (termed reanalysis or CFSR), available online for download from the NOAA Climate Prediction Center. The GWX system also includes the WRF model as an application to support downscaling of the gridded weather data to higher resolutions up to 1 km using the CFSR data as the input. The services portion of GWX includes a WebUI that communicates with the EDC data distributor to receive weather project listings to be displayed to the user for selection. This involved implementing a JQuery, a JavaScript-based library for web processing, Simple Object Access Protocol (SOAP) request on the EDC distributor. Finally, Atmospheric and Environmental Research Inc. developed and implemented a JavaScript software routine that will submit an EASEE request for the detection of friendly assets calculation and implemented an EDC Distributor SOAP client that enables EWS to retrieve weather data from the EDC Distributor. The supporting Java code was generated automatically using Apache CXF, an open-source, web services framework, and the EDC Distributor Web Service Definition Language. The client was integrated into the JsonXMLProcessor class, and the EASEE XML Schema Definition was modified to include specification of an EDC request with the parameters project name, component name, product name, and the date and time. Figure 13 provides an overview of the software design.

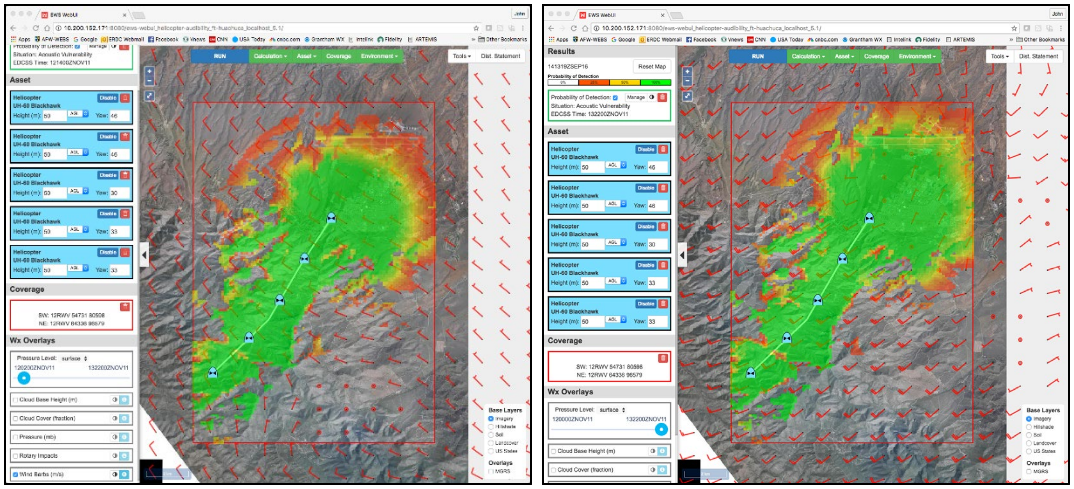
Atmospheric and Environmental Research Inc. developed a demonstration version of GWX with high-resolution, aircraft-acquired lidar terrain data and weather scenarios for the area surrounding Fort Huachuca and provided the tool to the ARTEMIS team for evaluation and demonstration. The gridded weather data were higher-resolution WRF model products generated and housed within the data cube for a prior Marine Air Command and Control Systems Training Exercise at Marine Corps Air Station Yuma. The data has a 5 km spatial resolution and was downscaled from CFSR for 10–16 November 2011 and is a mix of good and bad days as a front moves into the southwest coast (but dissipates as it moves inland). The weather package contains all of the weather parameters required by EASEE, and significant weather impacts can be observed on both infrared and acoustic sensor performances. The weather data package also contains georeferenced overlays of weather products and the Army Integrated Weather Effects Decision Aid system impact products that can be viewed in the EWS WebUI. Both the profile data and some weather product overlays were packaged into the distributor for ingestion and display by EWS. The entire system was deployed on a single CentOS version 7, Linux-based operating system within a distributable virtual machine with the new "rotorcraft audibility" WebUI, EWS with a new SOAP weather client, the EDC Distributor, and GeoServer with terrain and weather graphics.

Figure 13. Diagram of the EASEE Web Services software describing the flow of data and methods used to feed data to compute EASEE products in a web services platform.



CRREL used the EWS-GWX capability to demonstrate the use of weather scenarios supporting decision-making for Army-specific support. We executed the EWS software for two different days, the first day being 12 November 2011 at 2200 UTC (Coordinated Universal Time) and the second day being 13 November 2011 at 22 UTC, to illustrate the effect of wind on rotorcraft audibility for the Fort Huachuca region (Figure 14). The differences in weather between the two dates include differences in cloud cover and wind direction, which impacted flying conditions and acoustic signatures. In the results shown in Figure 14, the only change in the scenario is the weather. The route the helicopter is flying is identical in both scenarios, as is all the terrain information, flight path altitude, etc. The difference in the acoustic signature in both images is different once the vehicle exits the valley southwest of Fort Huachuca and enters the region of flatter terrain. The weather (winds, temperature, etc.) impacts the acoustic signature propagation on the northeast area of the domain, suppressing signatures somewhat on 12 November, probably due to a northwesterly wind, while on 13 November the winds are out of the southwest. The inclusion of Army-integrated, weather-impacts, decision-aid rules allows the user to not only understand the effects of weather on sensors and signatures but also to merge those results with weather that would impact flight routing due to other weather impacts (visibility, winds, precipitation, etc.).

Figure 14. Two illustrations of using EASEE running in a web services environment (showing over Fort Huachuca, Arizona, and the surrounding area) by using the Geospatial Weather Services capability to support weather impacts. The weather scenario is for 11–13 November 2011 and includes temperature, winds, humidity, cloud-cover information (including base height, coverage), and Army Integrated Weather Effects Decision Aid rules. During the period, a frontal passage caused a change in weather that influenced acoustic propagation. Both model runs are for a helicopter flight path. The difference in weather conditions causes a difference in acoustic propagation between the two time periods. The image on the *left* includes weather conditions from 14-November-2011 at 1400 UTC while the image on the *right* is weather conditions from 13-November-2011 at 2200 UTC.



Probability of Detection: ☑
Situation: Acoustic Vulnerability
EDCSS Time: 121400ZNOV11

Helicopter
UH-60 Blackhawk
Height (m): 50 AGL Yaw: 46

Helicopter
UH-60 Blackhawk
Height (m): 50 AGL Yaw: 46

Helicopter
UH-60 Blackhawk
Height (m): 50 AGL Yaw: 30

Helicopter
UH-60 Blackhawk
Height (m): 50 AGL Yaw: 33

Helicopter
UH-60 Blackhawk
Height (m): 50 AGL Yaw: 33

SW: 12RWV 54731 80598
NE: 12RWV 64336 96579

Pressure Level: surface
120000ZNOV11 132200ZNOV11

☐ Cloud Base Height (m)
☐ Cloud Cover (fraction)
☐ Pressure (mb)
☐ Rotary Impacts
☑ Wind Barbs (m/s)

141319ZSEP16

Probability of Detection: ☑
Situation: Acoustic Vulnerability
EDCSS Time: 132200ZNOV11

Helicopter
UH-60 Blackhawk
Height (m): 50 AGL Yaw: 46

Helicopter
UH-60 Blackhawk
Height (m): 50 AGL Yaw: 46

Helicopter
UH-60 Blackhawk
Height (m): 50 AGL Yaw: 30

Helicopter
UH-60 Blackhawk
Height (m): 50 AGL Yaw: 33

Helicopter
UH-60 Blackhawk
Height (m): 50 AGL Yaw: 33

SW: 12RWV 54731 80598
NE: 12RWV 64336 96579

Pressure Level: surface
120000ZNOV11 132200ZNOV11

☐ Cloud Base Height (m)
☐ Cloud Cover (fraction)

2.6 Validation of tools and quantitative metrics

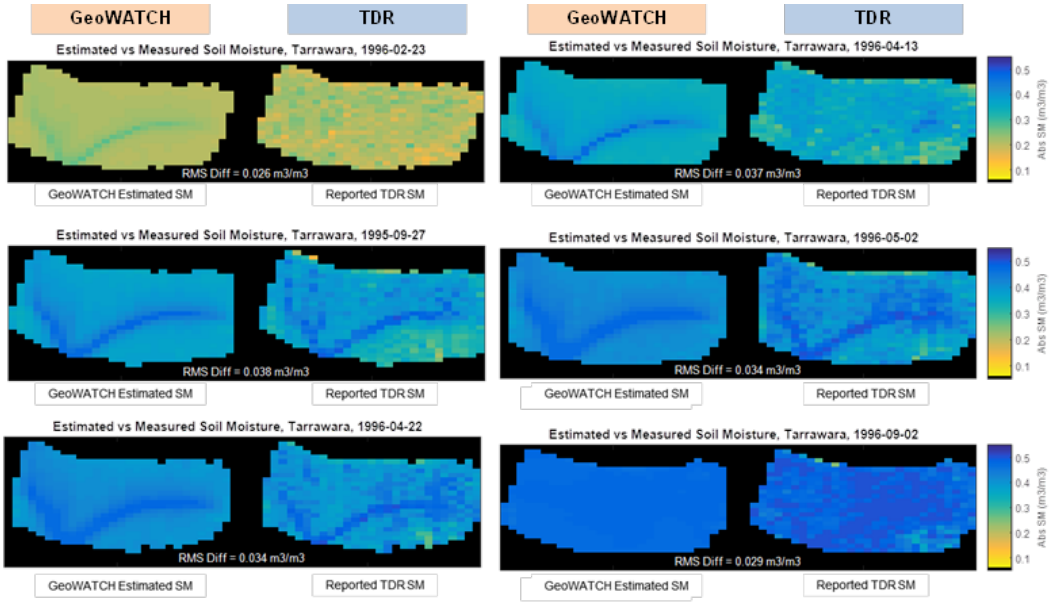
Table 1 below lists the metrics established at the beginning of the project using Army G3/5/7 approved metrics for soil moisture, soil temperature, and snow depth. The project achieved all the resolution and product development goals stated in the proposal, with real-time demonstrations delivering significant advances over current capabilities. An automated, predictive, weather-impacted maneuver capability was largely nonexistent before the project, with mobility forecasts created only by analysts that manually combined coarse-resolution weather knowledge manually into geospatial tools using documented field manual guidance as a method to predict mobility. ARTEMIS now delivers domain knowledge of future vehicle-class mobility as a guidance product for military mission planners. We developed a remote assessment of weather- and climate-impacted socio-cultural stability largely not available from an analyst-produced assessment prior to the project. We integrated higher resolution weather products with the sensor-performance tool to deliver improved acoustic predictions in variable terrain and delivered improved snow characterization algorithms supporting Army movement/maneuver. Table 1 provides the metrics from the ARTEMIS proposal updated to state the achievements of the project.

Table 1. Metrics Technical Readiness Levels (TRLs) and pre- and post-ARTEMIS metrics achieved during the 4-year span of the project.

Measure	Pre-ARTEMIS	Project Objective	Army Objective	Results	TRL
Soil moisture for mobility, landing zone, sensing	Daily values; 4 incremental values of climatological soil wetness (wet, average-dry) based on user input of surface condition	Volumetric soil moisture in 5% increments, 10% error; at 1-hour intervals; 30 m resolution	5% error at 1-hour increments; resolutions less than 1 km	Relative and Volumetric soil moisture at 1% increments for 2 m soil profile at 3-hour increments, soil-strength products, and vehicle speed analysis products all available hourly at 30 m resolutions for any location worldwide, also producing forecasts for each parameter out to 144 hours	5
Snow depth for mobility, landing zone, sensing, etc.	Daily values, >30% error	<1 in. error at 6-hour increments; 1 km resolution products	1 in. error at 6-hour increments; resolutions less than 1 km	Daily snow depth and snow-cover products at 1 km resolution, with some decrease in error over pre-ARTEMIS products	5
Soil temperature	User input	1°C accuracy; hourly products; 1 km resolution	1°C accuracy; hourly products; <1 km resolution	Hourly products at 1 km resolution; relative error is approximately 10%	5

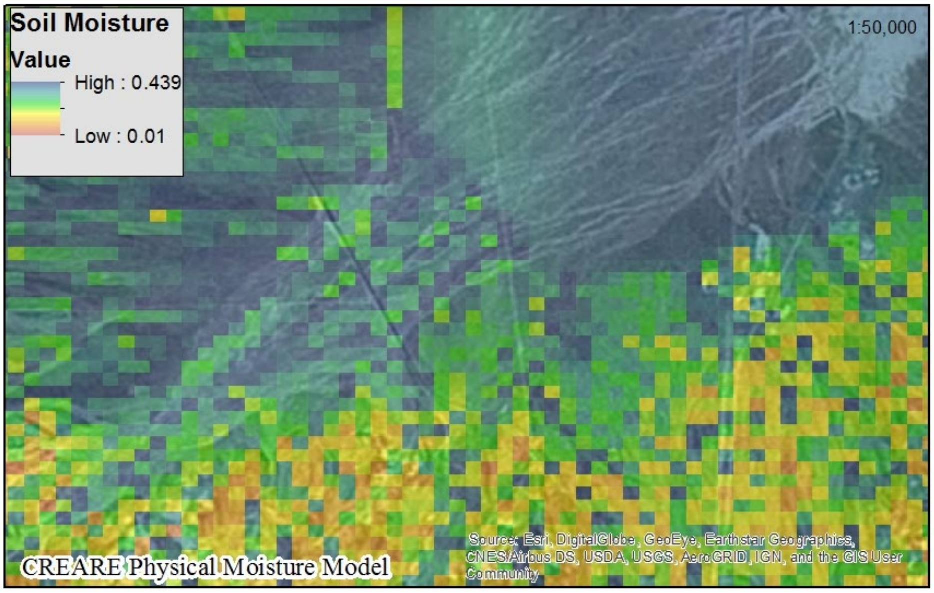
Each team was responsible for providing validation metrics for each of the tools they were developing. Several of the teams working on ARTEMIS gathered a significant amount of validation from field studies and are still in the process of evaluating much of that data; however, we have completed some validation for the GeoWATCH, GRAIL, and EASEE tools. Audette et al. (2017) performed validation on the GeoWATCH tools using in situ soil-moisture measurements compared against individual catchment basins. One example of a catchment-based validation is illustrated in Figure 15. Audette et al. (2017) evaluated soil-moisture results from both the USAF LIS output and the GeoWATCH results against time domain reflectometry (TDR) measurement data for the Tarrawarra, Australia, watershed (Western and Grayson 1998). The GeoWATCH tool captures the overall spatial structure of the soil moisture for the domain, but it misses the noisy scatter while improving upon the coarse resolution data provided by the USAF. The resolution of the USAF data limits validation at these scales (tens of meters). Overall the GeoWATCH tool was better than the coarser resolution data, reducing the error by almost 10% and producing a root mean square error value between three and four percent. Similar results were available for the Shale Hill, Pennsylvania, watershed.

Figure 15. Comparison of GeoWATCH soil moisture products with TDR data from the Tarrawarra watershed in Australia. For each of the six dates shown, ranging from dry to saturated soil conditions, the image on the *left* is the initial USAF 25 km LIS product. The *middle* image is the downscaled soil moisture from GeoWATCH, and the image on the *right* is the TDR measured soil moisture. (Audette et al. 2017).



The Terrain Phenomenology and Data Collection (TerraPAC) team conducted a number of soil-moisture measurements using a cosmic-ray neutron method in the Nevada National Security Site and other locations, exploiting the inverse relationship between the content of hydrogen in the soil and the intensity of neutrons released from pools of hydrogen in soils due to interaction with cosmic rays (Zreda et al. 2008). They performed a number of studies comparing the COSMOS data gathered in the study with different numerical models and soil moisture estimate techniques, also comparing the measurements to TDR data collected. GeoWATCH results from the Nevada National Security Site (Figure 16) are uncorrelated with TDR probe measurements, likely due to higher soil-moisture measurements in the wash channel where the GeoWATCH product increases available soil moisture instead of reducing it. While this may be a reasonable assumption to make in more highly eroded regions, Nevada's extreme aridity has not broken the soil down in the wash into finer grained soils. The coarse soil is quick to dry out as opposed to soils at higher elevation in which dust and finer-grained soil is more abundant due to biological action and aeolian deposition.

Figure 16. GeoWATCH output for the Nevada National Security Site. The region of *darker blue* colors extending from the *upper right* towards the *middle* of the image exists in a coarse-grained wash. Soil-moisture measurements for this region were much lower than the model-estimated values.



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

3 Summary of ARTEMIS Major Accomplishments

The ARTEMIS team successfully developed a number of prototype- and demonstration-quality applications, published a large number of technical reports, journal articles, and military conference proceedings that improve DoD's knowledge base or future operational capabilities. We entered into a technical transition agreement with Project Manager Terrestrial Sensors to transition the EASEE technology into an Army program of record and have a Knowledge Transition Agreement being negotiated with another Army program of record at the end of the 4-year project period of performance. We developed a soil moisture downscaling tool that enables direct use of digital weather information by Army mobility and maneuver applications. We improved the EASEE application with higher-resolution, 3-D weather products and developed a web-based version of EASEE and linked EASEE with the GWX capability to improve the application's ability to support Army military intelligence-type decision making. Finally, we developed a suite of ingress/egress methods that were integrated into the SAGE application. Each of those tools achieved a technical readiness level of 5 by the end of the project, with the GeoWATCH and EASEE applications achieving a TRL of 6 through the Rapid Innovation Fund program.

As part of the research process, the ARTEMIS team conducted a number of field studies in the U.S. desert southwest and on military installations in the west to better understand the relationships between weather and weather impacts on military operations and documented those findings in science and engineering publications. We evaluated the relationships between soils, soil moisture, soil crusting, and soil biological activity to improve our ability to predict degraded visual environments. We studied seasonal changes in soil moisture and soil strength on two military installations, the Nevada National Security Site and Fort Hunter Liggett, to be able to better predict mobility, site suitability for aircraft landing, and ingress/egress planning and documented those studies in technical reports and peer-reviewed publications. We significantly increased our understanding of the soils and terrain and how biological material in the terrain affects soil strength and dust lofting prediction. We conducted a number of studies to better understand signal propagation in varying weather and terrain environments and documented this knowledge in peer-reviewed journal articles and military conference and symposia proceedings.

3.1 Technical Transitions

The ARTEMIS team has completed or is on track to complete a number of technical transitions, including to Army programs of record and USAF programs of record and to a number of defense-related customers. For Army programs of record, the ARTEMIS team has delivered the EASEE tool to the Army Integrated Ground Security Surveillance Response–Capability program of record and obtained a signed Technology Transition Agreement through the Program Executive Officer for Intelligence, Electronic Warfare, and Sensors.

Early in FY19, the ARTEMIS team worked with Distributed Common Ground System–Army to develop a Knowledge Transition Agreement for future technical transition of GeoWATCH, EASEE, and updated SAGE capabilities. The Knowledge Transition Agreement did not obtain complete success as GeoWATCH was a commercial product and not fully under ERDC control. In addition, the EASEE and SAGE software was already transitioned to Program Executive Officer for Intelligence, Electronic Warfare, and Sensors. Therefore, the knowledge being provided by ERDC was already obtained and an additional agreement was not necessary. Finally, the Distributed Common Ground System–Army management emphasized that transitioning of knowledge or capabilities needed to occur prior to or during FY18 given that the ARTEMIS program ended at the beginning of FY19. Despite the issues with establishing a new Knowledge Transition Agreement, the SAGE capabilities improved under the ARTEMIS program have transitioned to Distributed Common Ground System–Army. Further, the SAGE utilization of GeoWATCH products for mounted mobility route planning will be used within Distributed Common Ground System–Army once GeoWATCH becomes an operational capability at the USAF 557th Weather Wing.

Additionally, the ARTEMIS team transitioned snow remote-sensing-algorithm improvements and snow analysis-product capabilities to USAF's 557th Weather Wing using the Army Regulation 115-10 (joint publication with the USAF Air Force Instruction 15-157) as the basis for a transition support agreement. The improved algorithms have been fully transitioned to the USAF and are now running operationally within the USAF 16th and 14th Weather Squadrons. Whereas Army weather support is a function of the USAF under Army Regulation 115-10, transitions of any capability to the 557th Weather Wing will support both USAF and Army operations.

Early in FY19, after a slight delay arranging for resources at the 557th, the GeoWATCH system has successfully transitioned onto a development server within the USAF 2nd Weather Group, with USAF Life Cycle Management Center acquisition program manager approval and oversight. This transition enables future support of U.S. Army Intelligence and Security Command's National Ground Intelligence Center and National Geospatial-Intelligence Agency operational requirements.

3.2 Using ARTEMIS tools for direct Army support

Over the course of this research project, the ARTEMIS team had the opportunity to provide a number of Army organizations data from tools developed in the project during acquisition studies and intelligence applications. The U.S. Army Tank-Automotive and Armaments Command and Tank Automotive Research and Development and Engineering Command were conducting an Analysis of Alternatives acquisition study in 2016 for a new Army vehicle and received several designs for a new ground combat vehicle and asked us to provide some data to test the combat vehicle simulations. CRREL staff completed a number of NRMM simulations supporting the Analysis of Alternatives study. Those runs included NRMM runs based on three wetness scenarios for four vehicles, with vehicle files provided by the U.S. Army Tank Automotive Research, Development, and Engineering Center. The wetness scenarios represent dry, wet, and saturated conditions. The dry and wet scenarios for the four vehicles were mapped for the two study domains. Both areas of interest are essentially no-go for all vehicles for the saturated case. Vegetation effects were ignored for this portion of the study. Additionally, CRREL provided geospatial cross-country vehicle speeds, soil moisture, and soil strength using the STNDMOB application and GeoWATCH tool. The ARTEMIS weather and terrain modeling testbed provided the source of the archived weather information used to initialize the GeoWATCH tool.

During the last two years of the ARTEMIS project, the GRAIL team was asked to support a number of studies for U.S. Army Korea, using GeoWATCH and GRAIL projects to compute simulations for maneuver and ingress options for military planning in the region. The results of these simulations are contained in a classified report available on the Secret Internet Protocol Router Network (SIPRNet).

4 Conclusion

Weather and terrain impact Army operations in many ways, including but not limited to maneuver, fires, austere entry, water security, concealment and confinement, flight operations, intelligence, surveillance, and reconnaissance. The ARTEMIS project goals were to overcome the challenges of integrating weather with military decision aids and inserting the output as data layers in Army Geospatial Enterprise–compliant geographic information systems. Our interdisciplinary approach enabled us to build solutions to both improve the weather modeling software in the ARTEMIS weather and terrain testbed, to use that data to support downstream applications, and to use real-time weather feeds from the USAF to compute real-time military products like mobility and sensor-performance products. This highly successfully project resulted in a number of new and improved applications and methods that will improve decision-making through better situational understanding of the environment and improved capabilities directly supporting intelligence preparation of the battlefield.

The ARTEMIS project outcomes included a number of capabilities, including the GeoWATCH application, ingress/egress planning tools, improved sensor-performance software using higher-resolution weather data and more supportive of the Army intelligence community through the linking of EASEE with GWX. We conducted a significant amount of research and development on improving soil-strength prediction, dust lofting prediction, and understanding the role of biologic activity the soil on soil strength and soil crusting. We were able to demonstrate that the new mobility tools achieve Army requirements for soil moisture and temperature resolution while making improvements in snow detection technology closer to Army goals and developing a long-term plan outlining the research needed to meet Army requirements.

We successfully transitioned capabilities developed in the project to other organizations, including the USAF's 557th Weather Wing, 513th MI Brigade, National Geospatial-Intelligence Agency, National Ground Intelligence Center, and U.S. Army Project Manager for Terrestrial Sensors, and are developing a Knowledge Transition Agreement with the Distributed Common Ground System–Army program of record.

If all of the applications and methods are able to be successfully inserted into or used by Army operations, these tools should improve decision-making at all echelons and improve the Army's ability to anticipate, prepare, and operate in environments where weather impacts the fight and will provide a better understanding of how weather influences enemy operations.

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14. ABSTRACT

The Army Terrestrial Modeling and Intelligence System (ARTEMIS) research program focused on developing innovative methods of fusing weather data from authoritative sources with geospatial content and services to fill a number of identified Army capability gaps. The tools developed within the ARTEMIS research program can support operations anywhere in the world, supporting Army Global Land Operation's needs. We overcame technology challenges that limited the use of gridded weather products and digital terrain products with Army tactical decision aids, providing relevancy to the impacts of weather and terrain on military operations beyond the current methods of delivering weather impacts on the battlefield via PowerPoint briefings. The project benefited from the recent availability of higher-resolution global soil texture, digital elevation models, and land use and land cover datasets provided by the National Geospatial-Intelligence Agency. Teams working on the AR-TEMIS research program developed tools and capabilities that integrated weather digital products into the Army Geospatial Enterprise–compliant systems to deliver fused all-weather and all-season military decision aids (e.g., maneuver, austere entry, sensor performance, and other typical terrain analysis tasks) in a method that supports risk-based assessments.

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