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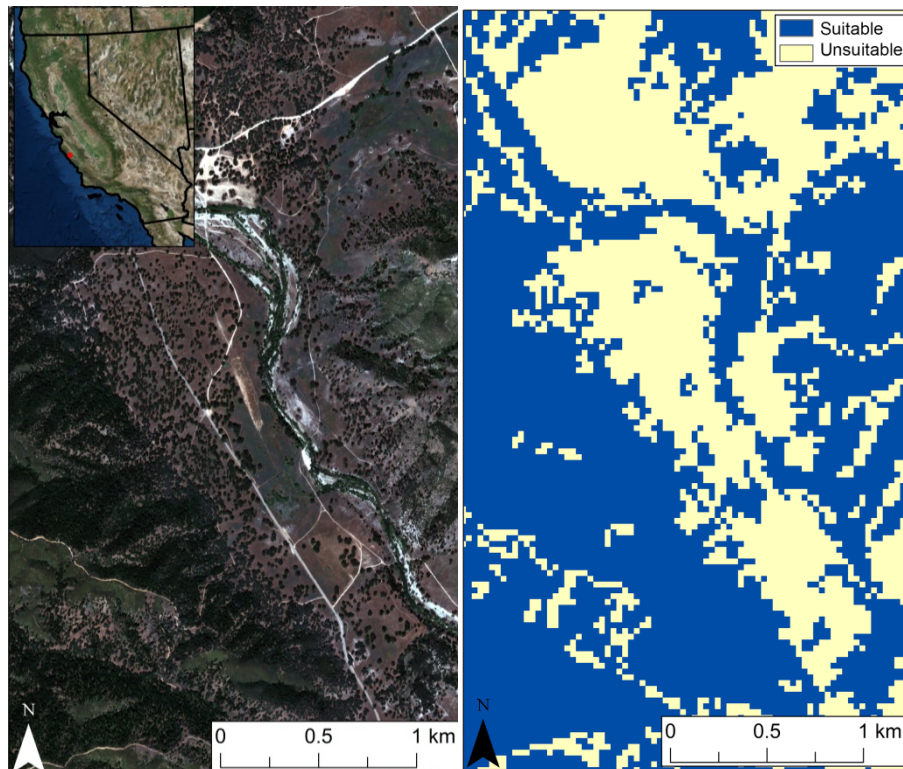


ERDC 6.2 Geospatial Research and Engineering (GRE) ARTEMIS STO-R GRAIL

Terrestrial Geospatial Remote Assessment for Ingress Locations (Terrestrial GRAIL)

Sally A. Shoop and Wendy L. Wieder

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Terrestrial Geospatial Remote Assessment for Ingress Locations (Terrestrial GRAIL)

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Abstract

The Terrestrial Geospatial Remote Assessment for Ingress Locations (GRAIL) portion of the Army Terrestrial Environmental Modeling and Intelligence System Science and Technology Objective–Research (ARTEMIS STO-R) program was developed to use remote methods of terrain analysis to search for areas suitable for vehicle or aircraft maneuverability, based on slope, roughness, vegetation, soil type, and wetness, and to also perform direct classification of imagery based on soil strength. The product of the GRAIL project was a software program entitled GRAIL Tools. Using a series of filters, GRAIL Tools first eliminates areas of unsuitable slope, land use, obstacles, and vegetation. The algorithms for these filters, using both unsupervised and supervised classification approaches, were applied and trained by a limited amount of ground truth strength measurements to improve GRAIL Tools' site selection capabilities. GRAIL Tools then searches for sites that meet geometric criteria for landing and drop zones, the final result being a map of potential landing and drop zones superimposed over satellite imagery. The first generation of GRAIL Tools has proven capable of identifying austere landing and drop zones using remote assessment techniques. GRAIL Tools has been integrated in to the U.S. Army's Situational Awareness Geospatially Enabled (SAGE) software platform.

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Preface

This study was conducted for the Assistant Secretary of the Army for Acquisition, Logistics, and Technology as part of the overarching ERDC 6.2 Geospatial Research and Engineering (GRE) Applied Research Program Army Terrestrial Environmental Modeling and Intelligence System Science Technology Objective—Research (ARTEMIS STO-R), Work Items T42 P2 448312 and 5L923J, “Geospatial Remote Assessment for Ingress Locations (GRAIL) Project.” The ARTEMIS technical program monitor was Mr. John Eylander, CEERD-RR.

The work was performed by the Force Projection and Sustainment Branch (CEERD-RRH) of the Research and Engineering Division (CEERD-RR), U.S. Army Engineer Research and Development Center, Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Dr. Harley Cudney was Acting Chief, CEERD-RRH, and Mr. J. D. Horne was Chief, CEERD-RR. The Deputy Director of ERDC-CRREL was Mr. David B. Ringelberg, and the Director was Dr. Joseph L. Corriveau.

ARTEMIS GRAIL was a four-year project, and many people contributed to the project during field collections, data analysis, and technical discussions and decisions through the years. The authors wish to acknowledge the following for their efforts: Ms. Elke Ochs, Mr. Jesse Stanley, Ms. Ariana Sopher, Mr. Randy Hill, Dr. Andmorgan Fisher, Mr. Bruce Elder, Ms. Samantha Sinclair, Mr. “Jed” Richards, Dr. Charles Ryerson, Ms. Jenny Palacio, Ms. Jaqueline Balch, and many more ERDC staff and students over the years. Dr. Sarah Kopczynski and Mr. Jason Olivier, ERDC-CRREL, reviewed the manuscript.

COL Ivan P. Beckman was Commander of ERDC, and Dr. David Pittman was the Director.

Acronyms and Abbreviations

A2/AD	Anti-Access/Area Denial
ARTEMIS	Army Terrestrial Environmental Modeling and Intelligence System
ASCE	American Society of Civil Engineers
AVT	Applied Vehicle Technology
BAEM	Boreal Aspect of Maneuver
CBR	California Bearing Ratio
COSMOS	Cosmic-Ray Soil Moisture Observing System
CRREL	Cold Regions Research and Engineering Laboratory
DCGS-A	Distributed Common Ground System–Army
DIC	Digital Image Correlation
DoD	Department of Defense
DZ	Drop Zone
ERDC	U.S. Army Engineer Research and Development Center
ET	Exploratory Team
FAO	Food and Agriculture Organization
FHL	Fort Hunter Liggett
GeoWATCH	Geospatial Weather-Affected Terrain Conditions and Hazards
GIS	Geographic Information System
GRAIL	Geospatial Remote Assessment for Ingress Locations
GRE	Geospatial Research and Engineering
ISTVS	International Society for Terrain Vehicle Systems
LEAF	Layered Elastic Analysis Formulation
LiDAR	Light Detection and Ranging

LIS	Land Information System
LWD	Light Weight Deflectometer
LZ	Landing Zone
MBPS	Map Based Planning Services
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NCSS	National Cooperative Soil Survey
NG	Next-Generation
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
NRMM	NATO Reference Mobility Model
109AW	109th Airlift Wing
RAFTER	Remote Assessment of Infrastructure for Ensured Maneuver
SAGE	Situational Awareness Geospatially Enabled
SMAP	Soil Moisture Active Passive
SSURGO	Soil Survey Geographic
STO-R	Science Technology Objective–Research
UNESCO	United Nations Educational, Scientific, and Cultural Organization
USCS	United Soil Classification System
USDA	U.S. Department of Agriculture
VWC	Volumetric Water Content
WV2	WorldView-2
WV3	WorldView-3

1 Introduction

1.1 Background

The Terrestrial Geospatial Remote Assessment for Ingress Locations project, hereafter referred to as GRAIL, of the Army Terrestrial Modeling and Intelligence System Science and Technology Objective–Research (ARTEMIS STO-R) program focuses on locating areas suitable for landing aircraft or dropping cargo and personnel in remote or austere environments. In current operations, the process for locating landing zones and drop zones (LZs and DZs) is still largely left to subject matter experts analyzing geospatial data, weather forecasts, and mission requirements with on-site observations when possible. However, on-the-ground assessment can put personnel at risk in dangerous terrain conditions and volatile or hostile environments; on-site reconnaissance can also jeopardize operation plans by making the presence of U.S. forces known in advance of entry. In the case of cold regions applications, the LZ/DZ requirements are often incomplete or based on aircraft that are no longer operational. Remote and automated assessment of potential LZs and DZs is useful both strategically and tactically to reduce or eliminate the number of sites to be visited by assessing them with stand-off capabilities and to determine the type of equipment, timing, and location based on mission and assessed or predicted terrain conditions.

1.2 Objectives

The objective of the GRAIL project was to develop and deliver an automated, evidence-based, tool-driven approach for locating areas suitable for landing aircraft or for dropping cargo and personnel in remote, austere regions.

1.3 Approach

To meet this goal, researchers from the U.S. Army Engineer Research and Development Center’s Cold Regions Research and Engineering Laboratory (ERDC-CRREL) developed methodology and algorithms that are incorporated into software called GRAIL Tools. The algorithms of GRAIL Tools are flexible with respect to the type and resolution of input geospatial data. Typically, these data layers could include digital elevation data, soil type, land cover from various forms of remotely sensed imagery, high-resolution

lidar (light detection and ranging), and other terrain datasets. The algorithms quickly identify flat, low-relief, and obstruction-free areas. Because terrain strength is a critical parameter for entry and subsequent maneuvers, terrain strength estimates using weather-based or climate-based soil moisture conditions are also included in the software.

Additionally we, the GRAIL team, supplemented GRAIL Tools' terrain search capabilities with image-processing techniques, using supervised classification analysis and machine learning, for both soil strength classification and obstacle detection (i.e., fences, telephone poles, and other linear or repeating features). These methods can be applied to other data layers or filters as required by the users. At the project start, we first documented the requirements for austere LZs and DZs and automated any well-defined criteria within a geospatial framework. The geospatial tools were designed to accommodate a variety of possible end users and available terrain data and data resolutions.

For criteria that are not easily obtained from geospatial datasets, such as terrain strength, we refined and implemented state-of-the-practice prediction models for these parameters. Because terrain strength is a key component, a major GRAIL research effort explored using remotely sensed satellite data to predict terrain strength. Weather effects on soil moisture, which influences soil strength, were incorporated using the Create LLC-generated tool called GeoWATCH. These methods are discussed more in section 5 and resulted in a major advancement in terrain assessment capability. An additional advancement looked toward extending terrain assessment capabilities to cold regions, especially areas of increased interest to the Department of Defense (DoD), such as the Arctic where sea ice, snow cover, and weather conditions present extreme challenges and terrain strength and landing zone classification schemes do not exist.

GRAIL Tools includes portable Esri-based models and python script. This will permit the software to be combined with other operational sensor applications. Using existing geospatial tools ensures user-friendly interfaces and builds on existing software-architecture capabilities. The GRAIL Tools remote assessment algorithms have been incorporated into Army geospatial software called Army Situational Awareness Geospatially Enabled (SAGE) through a format transition agreement with Distributed Common Ground System-Army (DCGS-A).

2 GRAIL Field Studies

To provide ground truth data for developing classification and predictive algorithms, we conducted GRAIL field studies. These studies collected data characterizing land type, slope, obstacles, and soil conditions, specifically soil type and moisture content, which would allow inference of strength or bearing capacity as quantified by the California Bearing Ratio (CBR).

The principal field studies took place at Fort Hunter Liggett (FHL), California. Objectives of the work at FHL were the development of remote assessment techniques for soil strength; evaluation of field testing equipment and measurement techniques suitable for characterization of austere entry points; and collection of data over several years to obtain a wide variety of seasonal conditions and to observe seasonal patterns of terrain characteristics, including strength. FHL offered a variety of terrain and landforms, including mountain passes, wide valleys, river terraces, and varied vegetation, as well as seasonally varied weather to incorporate all-season capabilities. The area also included four assault LZs and twenty DZs that were ideal for blind testing of the search algorithms. The terrain-condition data collections at FHL were concurrent with WorldView-2 and 3 (WV2 and WV3) satellite data collections, providing ground truth data for imagery-based remote-assessment algorithms. Section 6 discusses field testing from other projects, which provided additional data and expertise.

The following field tests and data were performed or collected for GRAIL:

- Slope and roughness
- Land classification
- Unified Soil Classification System (USCS) soil classification
- Field CBR (soil strength)
- Dynamic Cone Penetrometer (soil strength)
- Clegg Impact Hammer (soil strength)
- Pilcon vane shear (soil strength)
- Cone Penetrometer (Trafficability Cone) (soil strength)
- Field Scout (volumetric water content (VWC))
- eGauge (dry and wet soil density)
- Pocket penetrometer (soil strength)
- ASD Inc. Field Spec4 High Resolution Spectroradiometer (field spectrometry)
- Soil grain size distribution

The field data collected were used in several different ways:

- To develop and refine GRAIL Tools LZ/DZ search algorithms
- To research the use of remotely sensed data to predict soil strength
- To train machine learning for obstacle detection
- To evaluate impacts of soil moisture on terrain strength
- To identify landform relationships to soil strength
- To map soil moisture to assist in remotely calculating soil strength
- To test a new mobile Cosmic-ray Soil Moisture Observing System (COSMOS) sensor
- To evaluate geospatial data for seasonal impact on strength
- To validate the Geospatial Weather-Affected Terrain Conditions and Hazards (GeoWATCH) model for downscaling soil moisture

Figures 1–3 present samples of land classification relationships to soil moisture and strength and seasonal trends in the FHL field data collections. Figure 3 shows that there was more moisture in the soil during the winter, and the CBR strength was noticeably higher during the dry summer conditions.

The GRAIL team used data gathered at FHL to develop remote methods of terrain assessment to search for areas suitable for entry and maneuver based on slope, roughness, vegetation, soil type, and wetness (Shoop et al. 2018b) and to classify imagery for soil strength (Sopher et al. 2016b, 2016c). Sopher used a maximum-likelihood supervised classification trained by a limited number of ground truth measurements or user input to apply a soil strength classification to WV2 multispectral satellite imagery, achieving encouraging results.

Because obstacles are a significant impediment to LZ/DZ assessment, West (2017) used the FHL field explorations and imagery to develop pre-processing techniques to detect linear and repetitive features contained in remotely sensed images; these features could then be used as an obstacle layer in GRAIL Tools suitability filters. Image-processing techniques, including Hough transforms, machine learning, and template matching, are capable of detecting different kinds of obstacle features within either panchromatic or true-color formats. These methods provide useful tools to help analysts automatically detect features but do not replace their expertise.

Figure 1. Average CBR and VWC based on land classification at FHL.

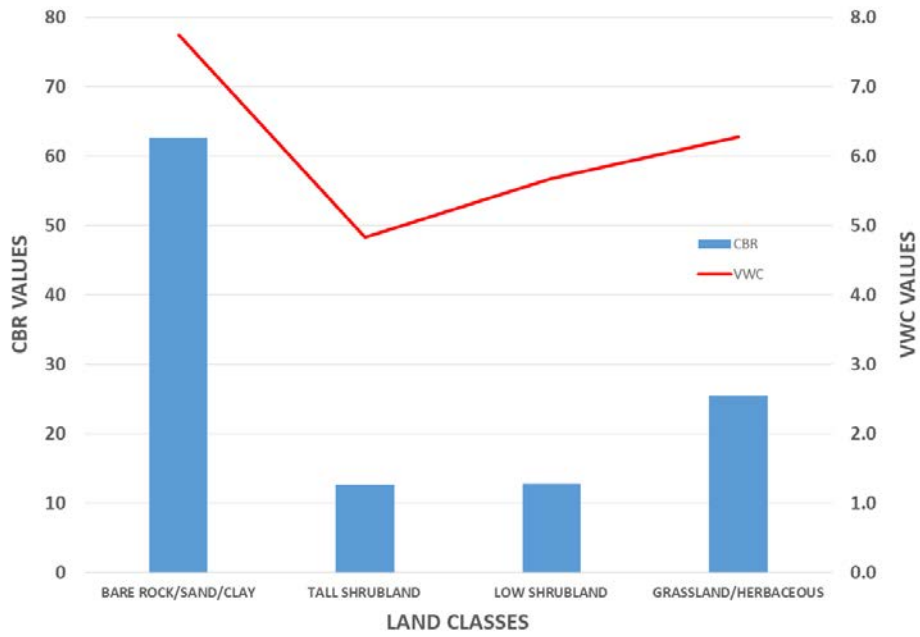


Figure 2. Seasonal change in CBR and VWC at FHL.

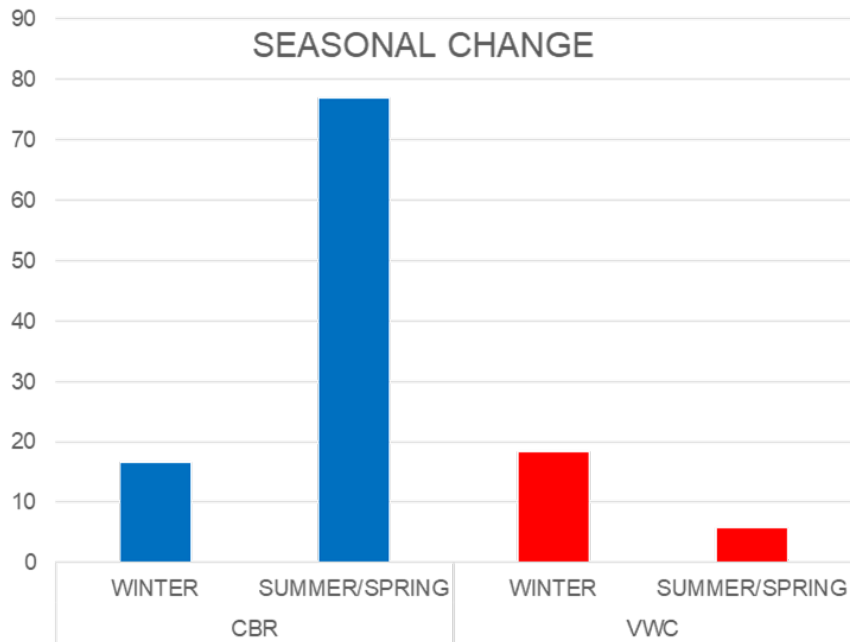
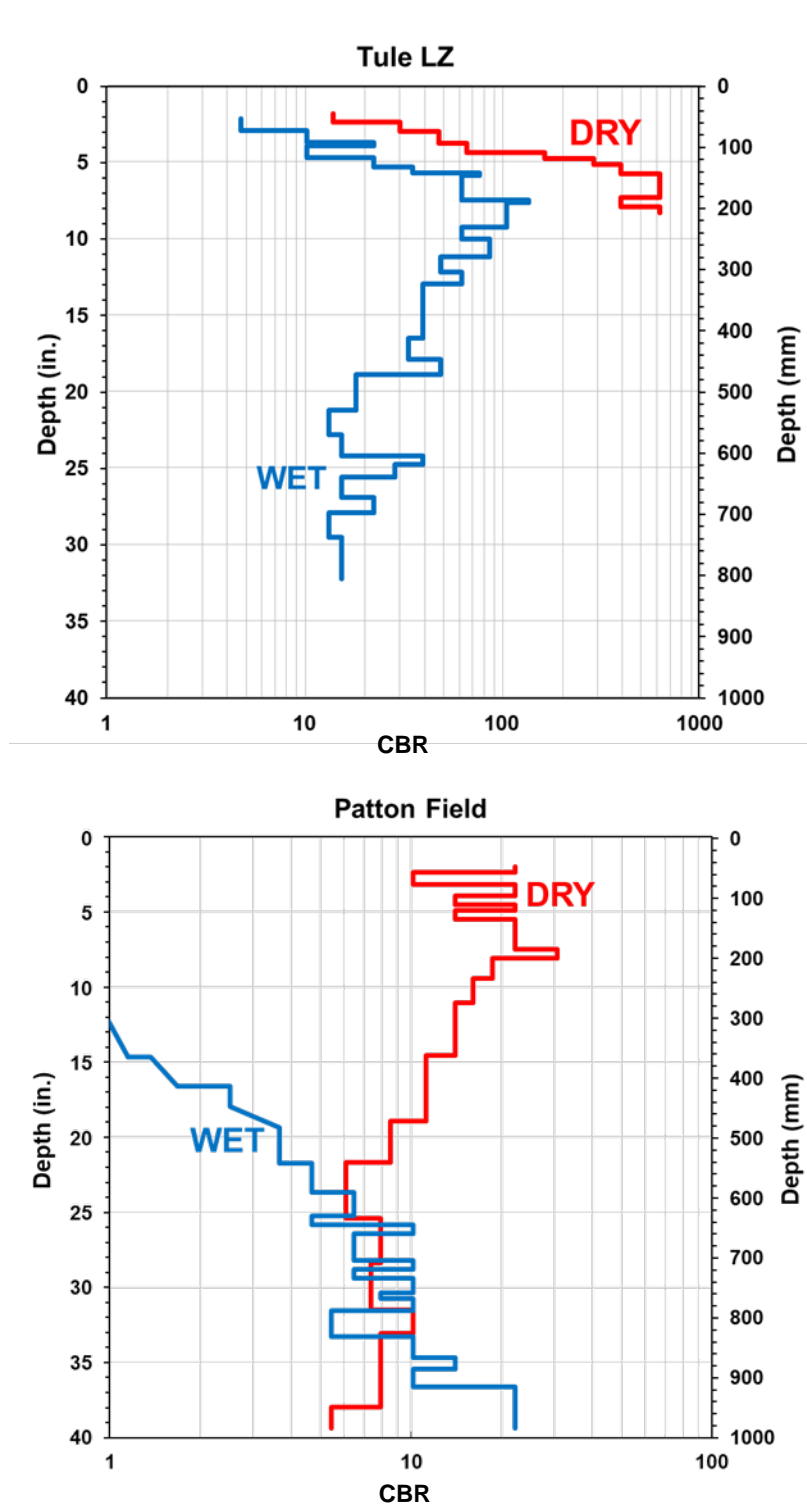


Figure 3. Changes in the CBR strength profile during wet and dry seasons at Tule (*top*) and Patton Field (*bottom*) sites.



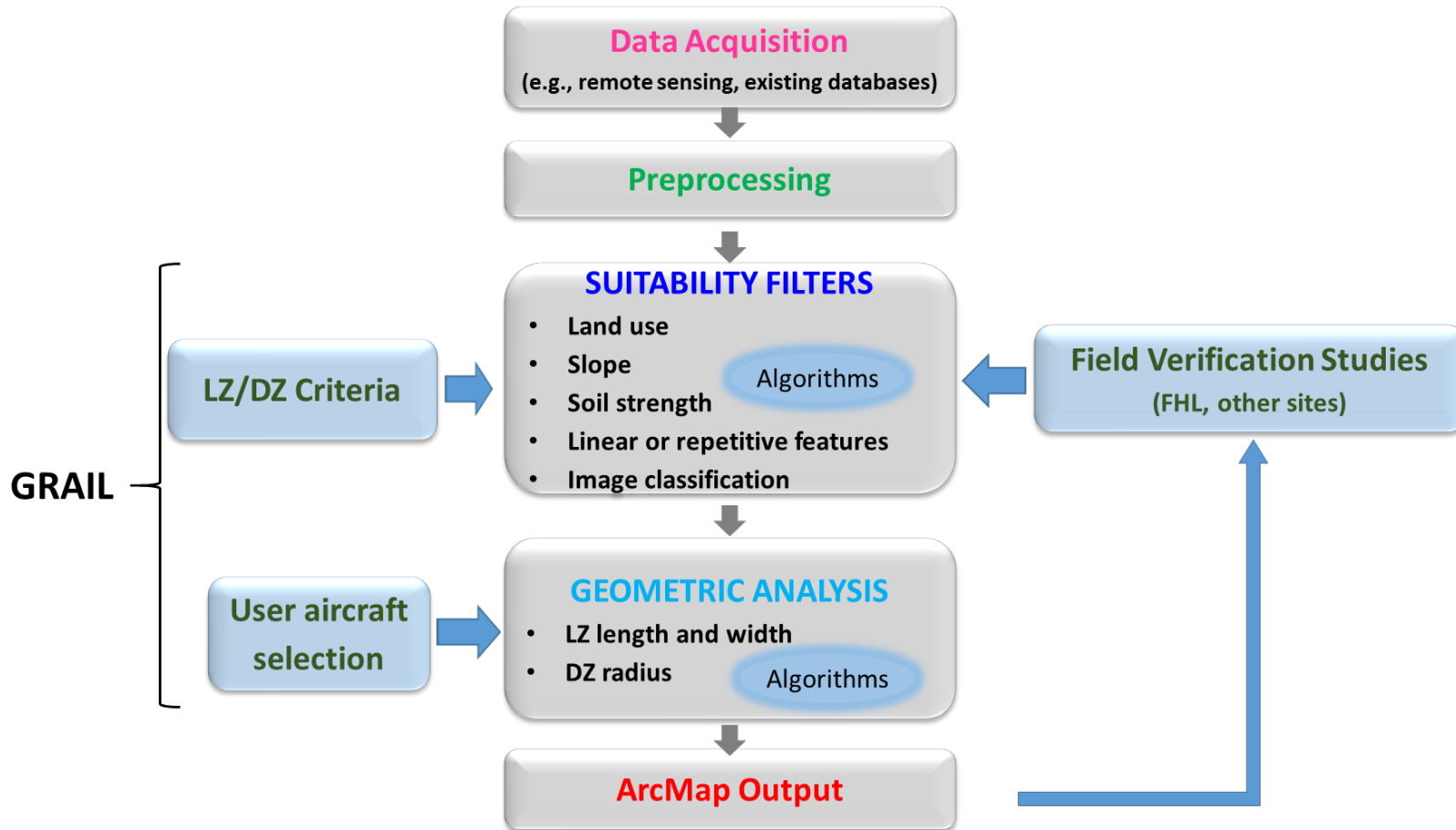
3 GRAIL Tools

The GRAIL project objectives were to deliver software tools, GRAIL Tools, and knowledge products to assist in rapidly identifying suitable LZs and DZs. Associated products are new algorithms, datasets, or methodologies to assist in the search for suitable LZs/DZs. The GRAIL products are designed to be incorporated into geospatial software functions or to generate input data layers for use within GRAIL Tools. The geospatial data layers used as input are flexible as to type and spatial resolution. GRAIL Tools aids in locating austere entry LZs and DZs by using user-specified spatial datasets, converting these to suitability layers, and then combining suitability layers in a geometric analysis based on the required LZ/DZ dimensions. The GRAIL Tools programming works within the ArcMap platform to analyze the geospatial data to determine areas of suitable land cover, ground slope, soil properties, and other data (i.e., obstacles) that would either facilitate or preclude landing or dropping cargo or personnel by filtering areas that are suitable or unsuitable for these activities. The full methodology of GRAIL Tools is detailed in Shoop et al. (2018b).

3.1 Software development methodology

The interplay between LZ/DZ criteria, algorithm development, data input, and field validation involves five steps as illustrated in Figure 4. The first two steps, which generally occur within the larger ARTEMIS program, are (1) geospatial data acquisition and (2) data preprocessing. These two steps consolidate data and prepare them for analysis with the GRAIL Tools algorithms. Data types include soil type, land classification, weather predictions, soil moisture, or any other geospatial datasets useful for LZ/DZ suitability determination. With these inputs, GRAIL Tools then (3) uses suitability filters to determine if an area is a potential LZ/DZ, (4) applies geometry analysis to determine if the required LZ/DZ will fit within the suitable land identified, and finally (5) produces outputs to present the potential LZ and DZ areas. These steps are fully compatible with existing Army SAGE/DCGS-A or other ArcGIS software, ArcGIS being the commercial GIS (geographical information system) platform for SAGE/DCGS-A.

Figure 4. GRAIL components with user input, criteria, and field verification study interactions indicated.



Applicable LZ/DZ geometric criteria from DoD, Federal, and other agencies (Wieder and Shoop 2017a) are applied in GRAIL Tools based on user-specific mission aircraft requirements. Field studies supplied ground truth data with regard to land use, soil strength, and linear and repetitive obstacle to train algorithms and to better refine these prediction capabilities.

The work performed directly under GRAIL and projects that informed or leveraged GRAIL resulted in more than 20 reports, journal articles, and conference presentations to date, in addition to the GRAIL insertion into SAGE. Section 7 provides a list of the GRAIL products and publications. This summary report will synopsise the information documented in detail by those publications.

3.2 Suitability filters

3.2.1 General filters

The GRAIL Tools software was designed with the understanding that the availability, quality, and resolution of terrain and weather datasets will vary. To handle the unknowns of data availability, we designed tools for the type of data values rather than specific datasets. One tool was created for continuous-value datasets, such as slope and wind speed. This type of data can be used to determine whether values are suitable or unsuitable based on a threshold value by using the *GRAIL Threshold Filter Tool*. A separate tool, called the *Unique Value Filter Tool*, was created for categorical data, such as land cover. These two tools allow conversion from ground-condition datasets to binary suitability criteria where zeros represent unsuitable conditions and ones represent suitable conditions. These tools can generate as many binary filter datasets as there are input datasets available for performing an LZ/DZ analysis. These layers are then combined for the final LZ/DZ search.

3.2.2 Soil Properties toolkit

The *Soil Properties* toolkit is a specific tool designed to facilitate the use of soil strength as a criteria in identifying suitable LZ/DZ locations. It uses two spatial layers as inputs: USCS soil classification and soil moisture content. These are the layers used to predict soil strength expressed as CBR by using an exponential regression equation developed and described in Shoop et al. (2008).

3.3 Geometric analysis

The user defines the geometry of the required LZ/DZ or chooses from an aircraft-specific pick list included in GRAIL Tools. GRAIL Tools currently includes criteria for the C-17 and C-130, the two fixed-wing aircraft currently used on unpaved landing strips. The LZ geometric criteria for these aircraft were taken from applicable military and civilian guidance (Wieder and Shoop 2017a).

A basic LZ analysis requires the length and width of the rectangular zone and the orientation with respect to true north on the ground. Alternatively, a sweep of a full range of LZ orientations is also possible. DZs require the zone radius only.

4 GRAIL Tools Verification and Refinement

ERDC-CRREL conducted a series of field experiments, as introduced in section 2, with corresponding analysis of geospatial datasets and site imagery to test the ability of the GRAIL Tools algorithms to correctly predict LZs and DZs. This work included ground truth surveys for vegetation and land use and identification of other features or obstacles used by the GRAIL team to evaluate whether the suitability filters were working correctly and to determine specific aspects of the algorithms requiring refinement. The team also used soil moisture and strength measurements to validate and refine the CBR soil strength model. Sopher et al. (2016b, 2016c) and West (2017) discuss in greater detail the concept of field verification and image feature detection work, respectively. Shoop et al. (2018b) and Sinclair et al. (2017, 2018*) present verification, refinement, and further validation.

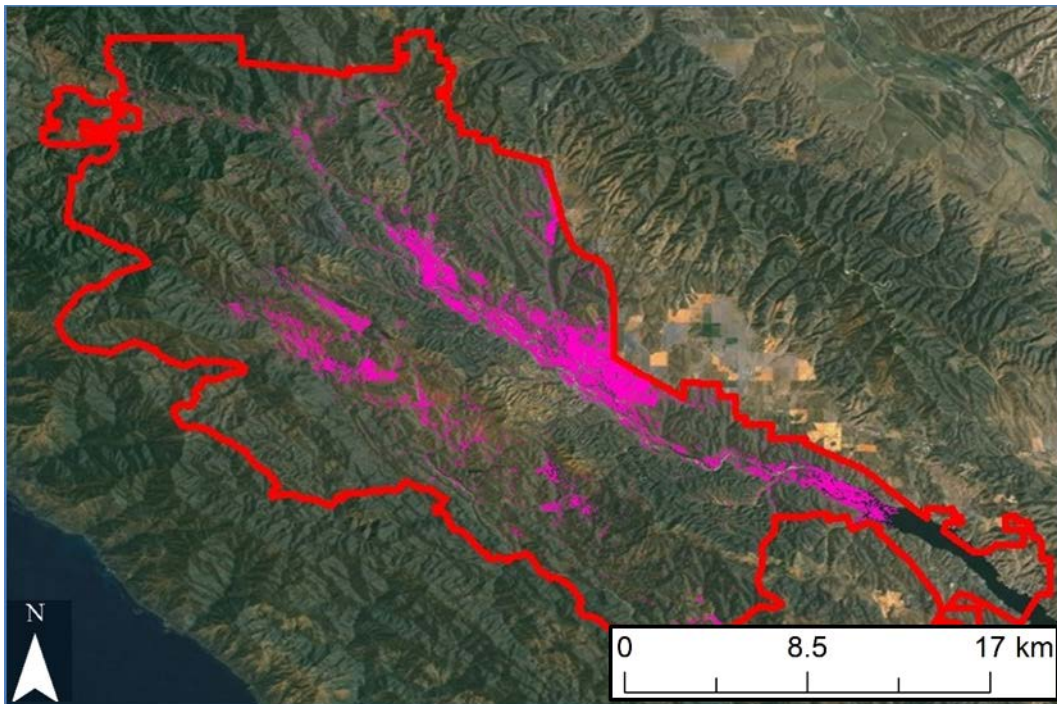
4.1 Initial assessment at FHL

In 2013 and 2014, the GRAIL team tested the initial GRAIL concept at FHL, located near the central coast of California, to assess GRAIL's feasibility and accuracy in selecting suitable ground surface areas for LZs and DZs. As discussed in section 2, field surveys conducted concurrent with the WV2 and WV3 data collection provided both ground truth data and imagery for analysis.

Figure 5 shows imagery from FHL that has been analyzed using slope and land cover criteria. Digital elevation models were used to determine areas of favorable slope, generally less than 3% or 5%, shown in pink. The land use classifications were used to select vegetation types that would eliminate areas of dense vegetation unsuitable for landing purposes.

* S.N. Sinclair and S. A. Shoop, "Detection of Austere Entry Landing Zones: A 'GRAIL Tools' Validation Assessment" (unpublished ERDC/CRREL manuscript, last modified 2018), U.S. Army Engineer Research and Development Center, Hanover, NH.

Figure 5. Potential LZ areas based on favorable cover and slope criteria. The FHL installation boundary is shown in *red* (Shoop et al. 2018b).



4.2 Field verification of search algorithms

Initial field measurements were designed to verify which algorithms worked and which failed. The GRAIL team used the outcomes to identify the science and engineering gaps requiring work to further refine the algorithms. Field sites were then chosen based on the algorithm search recommendations and known LZ locations to explore the results and to ground truth GRAIL site predictions. Initial assessments considered slope, roughness, land cover/classification, obstacles, soil moisture, soil strength, and geometrics. The information gained from identification of obstacles, soil moisture, and soil strength was used to inform research needed to develop the additional data and imagery techniques (Sopher et al. 2016b, 2016c; West 2017).

5 GRAIL Research Enhancements

5.1 Soil strength calculations from soil moisture

In addition to land classification and slope, one of the most critical filter layers is suitable soil strength. This can be calculated using the *Soil Properties* tool within the GRAIL Tools software. The *Soil Properties* tool uses the equations in Shoop et al. (2008) to predict CBR soil strength based on soil moisture content. The CBR equation varies depending on the USCS soil type; therefore, both soil type and moisture content are necessary inputs. For FHL, we used the NRCS soil classification GIS layer to get the USCS soil type (Figure 6, middle image) and soil moisture predictions from the SMAP (Soil Moisture Active Passive) satellite or the 30 m downscaled soil moisture prediction from GeoWATCH (Bieszczad et al. 2016) (Figure 6, bottom image). The final outcome of this analysis merges the soil moisture mapping and known relationships between CBR and moisture content to generate a map of soil strength as shown in Figure 6 (top image). The GeoWATCH products proved to be ideal for this purpose and are discussed in more detail in section 5.2.

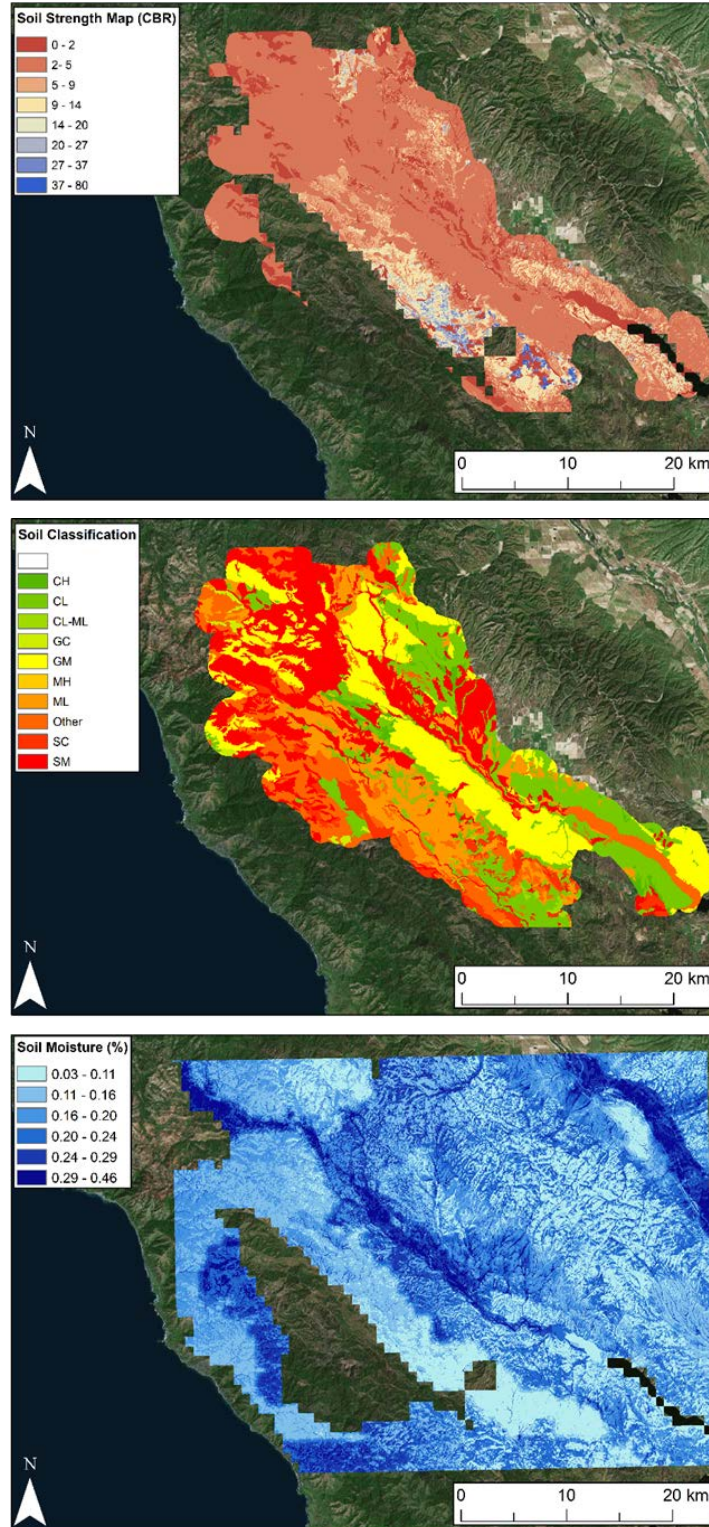
5.2 Comparison of GEOWATCH products and field measurements

GeoWATCH is a hydrometeorological modeling approach and cloud-based computing architecture for generating high-resolution estimates of soil moisture content and soil strength (Bieszczad et al. 2016). These ground-state conditions are produced with global coverage at spatial scales of tens of meters; and the hydrometeorological modeling approach is applicable to climatological, current, or forecast weather conditions.

GeoWATCH's ground-state predictions are generated using a physics-based downscaling approach that fuses weather-scale ($1/4^\circ$ spatial scale) land-surface-model estimates of soil moisture and land surface water and energy fluxes with geospatial data, including high-resolution topography, land cover, soil classification, and vegetation information (1 to 3 arc second spatial scale). A two-stage physics-based hydrological model is then applied to downscale the weather-based soil moisture predictions. The first downscaling stage computes steady-state soil moisture redistribution due to topography and soil texture effects. 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 (Bieszczad et al. 2016).

Figure 6. Soil strength in terms of CBR (*top image*) calculated using USCS soil class (*middle*) and the soil moisture data from GeoWATCH (*bottom*).



The results of these two downscaling stages are then combined, yielding high-resolution soil moisture estimates on a 30-m raster grid. These estimates are then used with soil texture classification data as inputs to soil strength prediction algorithms (e.g., estimation of the rating cone index in the case of GeoWATCH or CBR in the case of GRAIL Tools). GeoWATCH provides either historical or near-real-time global soil moisture predictions (Bieszczad et al. 2016).

The GRAIL team compared field-measured volumetric content and soil strength with GeoWATCH-predicted data from three locations: FHL; the Baltic region of Europe; and Mooers, New York. The New York sites investigated were drained with drain tiles (tiled) and undrained (untiled) agricultural fields. Statistical methods were used to execute this comparison, and this work is ongoing (S. Beal, CRREL, pers. comm., 2018).

For the Baltic region, the 30 m moisture data from GeoWATCH downscaling and the original 25 km volumetric soil moisture from the Air Force Weather Agency's Land Information System (LIS) have more than a 50% disagreement with the measured data. This low number is partially explained because 100% of the area sampled was drained with ditches, subsurface tile drains, or both. The moisture distribution process in the GeoWATCH products are based on natural landscapes without drainage improvements. Even so, the average and median GeoWATCH strength values were 70% accurate compared to the field strength measurements.

At the FHL site, the soil moisture agreements were generally 65% to 100% accurate. The Mooers, New York, measurements had a 50% to 85% agreement with the GeoWATCH 30 m volumetric moisture data. With regard to the strength data, the untiled average and median values reached about a 90% accuracy compared to the GeoWATCH data.

Preliminary statistical analysis shows an interesting mix of numerical representations and accuracy between the GeoWATCH and the field measurements. Future studies evaluating the GeoWATCH soil data layers will continue to enhance the accuracy of information.

5.3 Estimating terrain strength from imagery

The GRAIL team explored a new technique to use multispectral imagery to classify the terrain into categories related to strength or stiffness. While

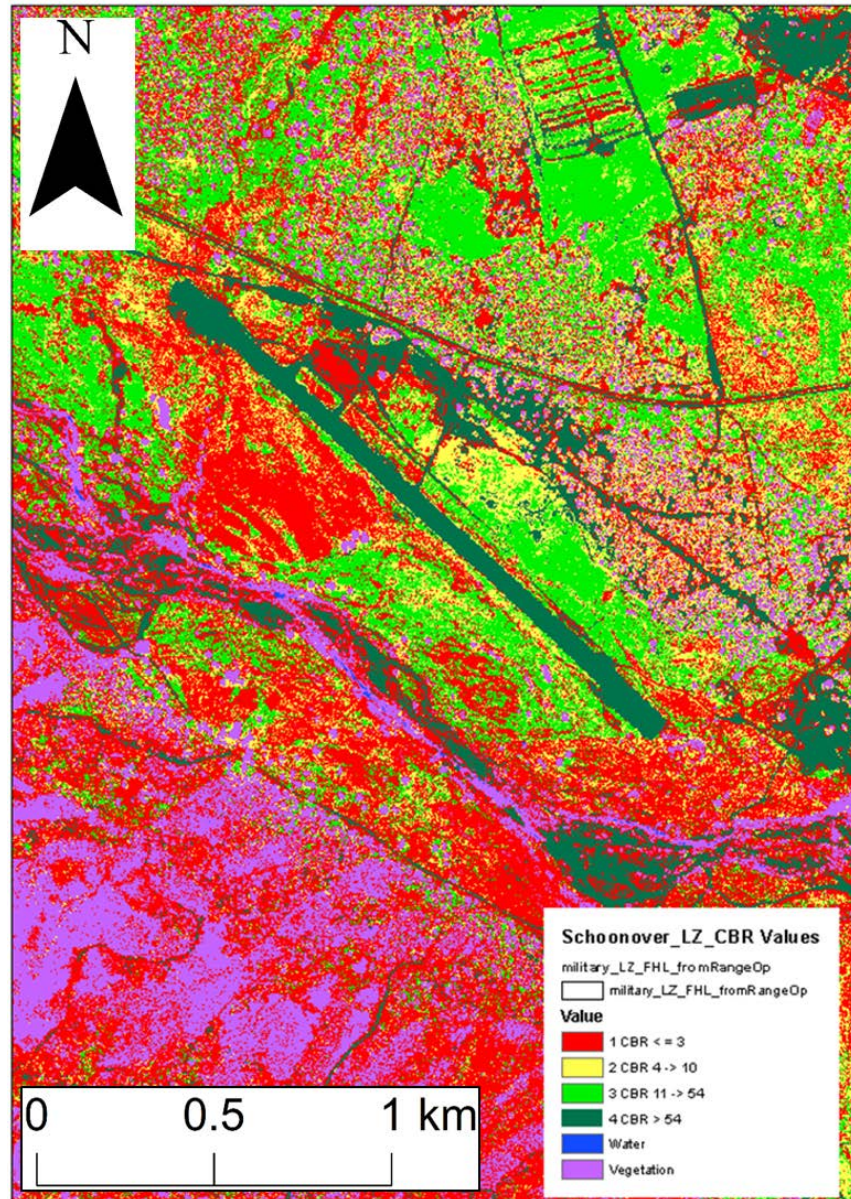
this is counterintuitive because strength or stiffness are related to a physical loading of the surface, the bearing capacity of the terrain can be related to other parameters that are expressed at the surface, such as the type, quantity, quality of the vegetation, soil texture and mineralogy, or other parameters that we still are not able to broadly classify, such as grain angularity. Sopher et al. (2016b, 2016c) explored image classification for strength. Classification is the process of categorizing each pixel of an image into a certain spectral class to describe what kind of object—or in the case of GRAIL, land cover, obstacle, or soil strength—that pixel depicts. Supervised classifications use training data, which are groups of pixels that the analyst knows to be of a certain information class, or characteristic on the ground (ground truth), to improve algorithm capabilities.

The findings of Sopher et al. (2016b, 2016c) demonstrate that initial assessments of multispectral satellite imagery classifications and ground spectra evaluation show potential for classification related to terrain strength. In Sopher's study, eight strength categories were adequate for classifying an image for terrain strength. An example of a supervised classification using CBR training data clearly shows and appropriately classifies the strength of the unpaved Schoonover Airfield (Figure 7) along with other unpaved assault landing strips. While the theoretical basis is not well understood, a rigorous statistical analysis of image classification for strength was initiated by Palacio et al.* to follow up Sopher's work.

Continued image classification work with the FHL datasets explored maximum likelihood, user's choice, random forest, linear discriminant analysis, and principal components classifications analysis technics (Palacio et al., unpublished manuscript). The predictor variables were WV3 bands; and the response variables were the levels of soil strength from 1 to 8, referred to as classes. Statistical methods and machine-learning approaches for high dimensionality reduction reduced the number of variables, and Palacio et al. evaluated different types of algorithms for unsupervised and supervised learning.

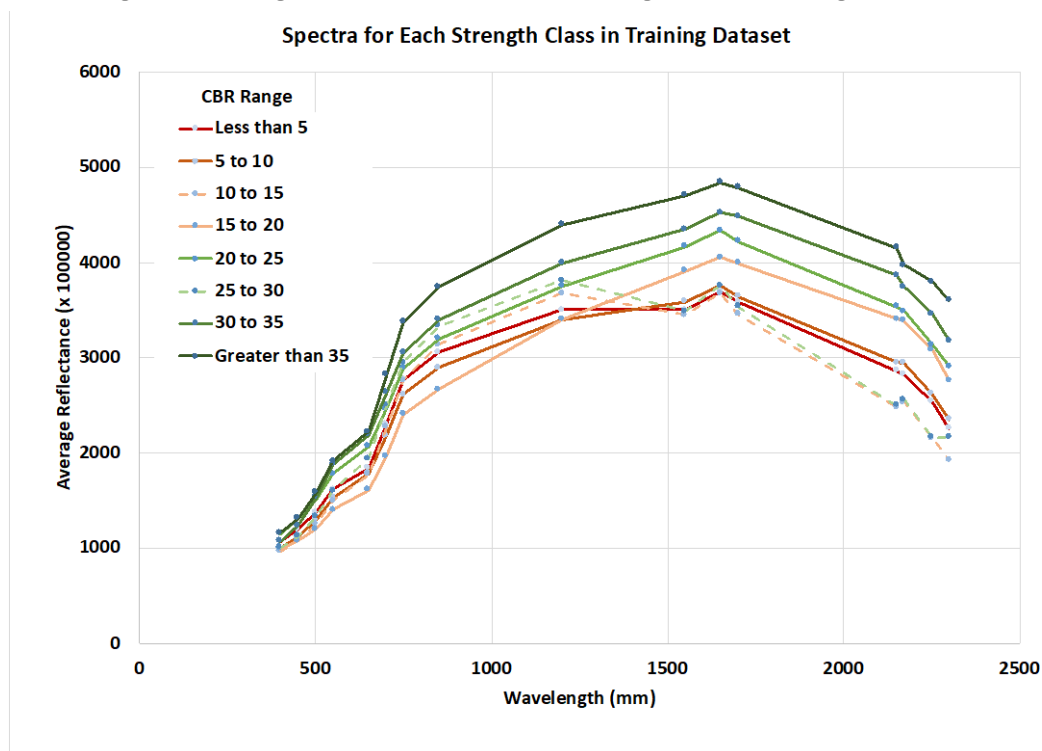
* J. Palacio, S. A. Shoop and A. Sopher, "Soil Strength Analysis Using Remote Sensing" (unpublished ERDC/CRREL manuscript, last modified 2018), U.S. Army Engineer Research and Development Center, Hanover, NH.

Figure 7. A 2013 WV2 image after a supervised classification for soil strength.



The strength measurements Palacio et al. used for classification were Clegg Impact values taken during the field measurements, which were converted CBR and grouped into strength classes. The spectral reflectance values from the bands were affected by the level of soil strength from each class. Classes 4 through 8 generally increased in radiance throughout the wavelengths (Figure 8).

Figure 8. Average reflectance profiles for training data from strength classes.



Since machine learning is meant for large datasets, the work of Palacio et al. required validation and accuracy assessment using ground truth data. The data was partitioned into training and testing data so the study would not run into bias issues and yield misleading results. The distribution of the data was assessed to make sure the classifications did not violate the main assumptions. An unsupervised method, such as principal component analysis, was compared to linear discriminant analysis as both are linear transformation methods for high dimensionality reduction to eliminate noise. Subsequently, user's choice, maximum likelihood, and random forest algorithms were used for supervised classification. The user's choice employed the same algorithm as the maximum likelihood classification and aimed to improve the maximum likelihood technique by adding user-defined classes for known suitable or non-suitable terrain categories where ground measurements were not needed. The user's choice and the maximum likelihood overall accuracy was around 65%, and the random forest achieved 86.7%. The Kappa coefficient, a measure of the level of agreement, also shows random forest is a better classifier (85%) compared to the other analysis methods (65%). These findings suggest that reasonable predictions of soil strength in less accessible areas can be aided by satellite data.

5.4 Using machine learning for obstacle detection

An additional requirement for an LZ search is to avoid obstacles such as fences, ditches, and power lines, which may not be easily detected on normal terrain datasets or imagery. West (2017) explored feature detection methods and machine-learning algorithms for automatically detecting linear and repetitive features. The approach developed could be used to identify key obstacles, which could then be included in the *Locate Landing Zones Tool* as a binary layer that indicates zero “pass” where obstacles are present.

5.5 Vegetation impacts on soil strength

The presence of vegetation can significantly affect soil strength, depending on factors pertaining to the type of vegetation and soil and conditions such as moisture content. Vegetation is used in a variety of application for soil stabilization and soil strength improvement. When selecting terrain suitable for LZs and DZs, vegetation may improve terrain strength enough to allow operations on otherwise weak soils. Conversely, other types of vegetation, such as trees and shrubs, would present obstacles to aircraft operations.

Wieder and Shoop (2017b, 2018) conducted a literature review on the state of the knowledge of vegetation impact on soil strength. They found that significant work has been done on reinforcing soils with various types of vegetation primarily for slope stabilization and erosion control. To a much lesser extent, other research has focused on the impact of vehicles on vegetated soils. Both sets of work have included laboratory testing, field observations and in situ testing, and development of various models to predict soil, root, and combined root-soil behaviors.

The review identified the need for accurate definition and characterization of the vegetative root material. Sampling and imaging techniques are beginning to be used to fully characterize root systems. Vegetation type, diameter, length, size distribution, mass, surface area, etc., are all important parameters that could be related to adhesion, shear, tensile, and compressive behavior. Additional studies are necessary to determine whether these parameters are adequate for a wide variety of soil-vegetation combinations. At a minimum, the vegetation description should include the type and size of the plants and a measure of the above and below ground biomass (organic material). Beyond this, the root length per soil volume, root

surface area, and root average diameter appear to be the more critical measurements (Wieder and Shoop 2018).

The review concluded that models of the vegetation and soil interaction need continued development. Attempts to incorporate some major factors such as the tensile strength of the roots need to be expanded to model other mechanisms, such as root adhesion. Methods to adjust the model based on the importance of the different mechanisms for different soil and vegetation combination are needed, as are the input parameters for such models. In addition, macroscale approximations will be useful for quantifying estimates of the terramechanics properties of vegetated terrain at the larger landscape scale.

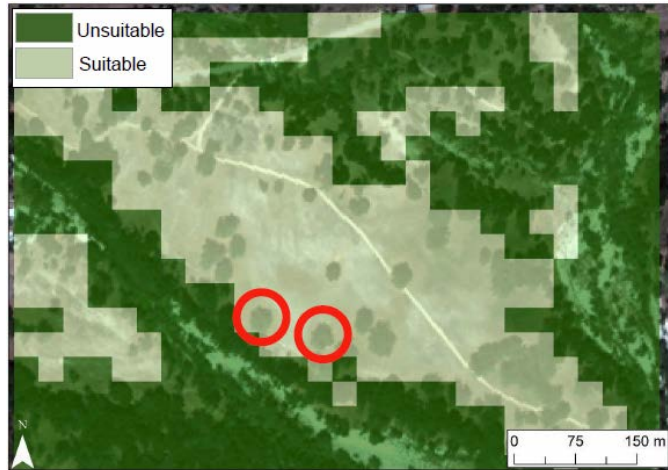
5.6 Resolution effects

Field explorations at FHL identified data resolution issues that can impact GRAIL Tools LZ/DZ search results. For example, large, widely spaced trees could pass as suitable under the 10 m land classification suitability filter where the terrain was classified as open (not forested) (Figure 9). Therefore, the GRAIL team developed a protocol to deal with input datasets of different resolutions. This can be done in one of two ways: (1) using the fishnet tool in ArcGIS to “downscale” coarser resolution data or (2) using the resample tool in ArcGIS, projecting the data to the correct coordinate system and clipping the data to a given area of interest prior to resampling. In addition, in some instances, 1 m (3 ft) data is too fine, often getting no potential LZs results, but 30 m (100 ft) data is too coarse, resulting in LZs with trees of significant size.

5.7 Landform effects on soil strength

Landscape-scale geomorphology is a visible reflection of hydrological, meteorological, and geological surface processes, which control sediment production, delivery, and soil development. Connecting geomorphology to soil strength parameters can enable the prediction of compressive and shear soil strength—important knowledge for mobility and dust emission modeling. The objective of work by Shoop et al. (2018a) was to empirically relate a wide range of soil strength metrics to geomorphic landforms. Their initial experiments focused on alluvial and aeolian landforms in the Sonoran Desert. Future plans expand this to glaciated landforms of interest in northern environments of current military threats.

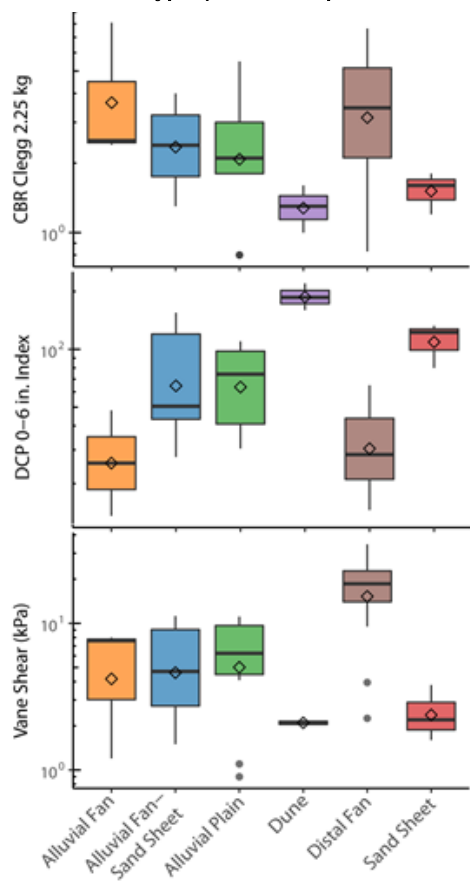
Figure 9. WV3 image of an open field with intermittent trees (*top*). The 10 m (33 ft) land classification suitability filter does not identify trees, such as the two circled in red, and therefore classifies the area as a “suitable” region (*middle*). The 1 m (3 ft) land classification suitability filter includes the trees correctly in a therefore “unsuitable” region.



Soil strength, dust emission, and soil composition measurements were made at 42 sites in California and Arizona, and these data were compared with geomorphic landform classifications (Shoop et al. 2018a). Metrics of soil bearing capacity (i.e., Clegg hammer and cone penetrometers) and of soil shear strength (i.e., vane shear) varied significantly between landform types. The aeolian landforms, dune and sand sheet, had significantly lower compressive and shear strength than the alluvial landforms (Figure 10). Silt and clay content are positively correlated, and sand content negatively correlated, with soil strength. The distal fan landform generally has greater soil strength than the other alluvial landforms and has a greater proportion of silt. Large variability in soil strength within landform groups is in part the result of sampling some end-member sites (i.e., a river channel and previously agriculturally modified land).

Most soil strength metrics are uncorrelated with dust emission flux and susceptibility, with the exception of the pocket penetrometer, Torvane, and vane shear that partially explained observed dust emission potential.

Figure 10. Comparison of select soil strength measurements with landform type (from Shoop et al. 2018a).



6 Collaborative Projects

6.1 Runways on snow and ice

6.1.1 Resolute Bay, Canada, Joint Task Force North austere landing on sea ice

Shoop et al. (2015) documented Operation NUNALIVUT 2014, conducted by Joint Task Force North during March and April of 2014, in the vicinity of Resolute Bay, Nunavut Territory, Canada. The aim of the exercise was to develop force projection capabilities and further knowledge for operating in an austere and remote environment while demonstrating capability in the Arctic. As part of this exercise, the 109th Airlift Wing of the New York Air National Guard demonstrated the capabilities of the LC-130 Hercules (Figure 11) in support of and in coordination with the Royal Canadian Air Force and ERDC-CRREL.

Figure 11. LC-130 skiway operations (Shoop et al. 2015).



The 109th Airlift Wing is the DoD's only ski-capable tactical airlift unit. The goals of the skiway exercise were to test skiway reconnaissance and construction techniques for austere polar environments and to provide LC-130 ski landing and snowfield combat offload resupply to Canadian

Arctic ground forces. The reconnaissance portion of the mission was conducted by personnel from the 109th Airlift Wing and engineers from ERDC-CRREL between 18 and 22 March 2014 and was supported by the 440 Squadron of the Royal Canadian Air Force (CC-138 Twin Otters). Camp setup and runway construction began 12 April 2014 followed by LC-130 landing and combat offload operations shortly after. This project demonstrated joint operational capabilities for Arctic search and rescue and science support. It also supports ERDC-CRREL research efforts to generate geospatial and weather-focused search algorithms for suitable landing and drop zones in austere environments.

The Operation NUNALIVUT 2014 skiway exercise offered insight into criteria, data, and tools that would facilitate future aircraft missions to austere Arctic areas. Future needs include (1) LC-130 ski landing requirements, as applying criteria for wheeled aircraft is too conservative; (2) addressing temperature and loading conditions, which were out of range of historic information; (3) more time for on-site camp setup and runway preparation; (4) extending and possibly automating imagery and geospatial analysis; (5) addressing missing datasets for Arctic operations (e.g., bathymetry); and (6) combining high-resolution satellite imagery and on-site data to explore extending the ERDC-CRREL GRAIL Tools for austere entry landing zones in Arctic locations.

6.1.2 Strength analysis of Phoenix runway, Antarctica

Sopher and Shoop (2017) documented modeling used to evaluate design and construction of the new Phoenix compacted-snow runway in Antarctica for the first wheeled C-17 aircraft landing (Figure 12). Snow density from the target design and snow density of the as-built Phoenix runway structure were used to determine basic elastic parameters for use in Layered Elastic Analysis Formulation (LEAF). LEAF is part of a software package developed by the Federal Aviation Administration that allows for forward calculation of runway stress, strain, displacement, and associated principal stress and strain based on design aircraft loading. This is the first time the model was used for a snow runway; and it provided valuable insight for design, construction, and runway performance for the first landing of the C-17 on compacted snow. The model is flexible enough for simulating additional aircraft that might use the runway in the future and may prove to be a future avenue for increasing the capabilities of GRAIL Tools for site assessment in Arctic regions.

Figure 12. First landing on the newly constructed Phoenix runway.



6.2 COSMOS

COSMOS is a soil moisture sensing system developed for use in the agricultural industry. In cooperation with the University of Nebraska–Lincoln, Wieder et al. (2016, 2018) documented fieldwork in Nebraska with the COSMOS remote soil moisture sensing system coupled with soil strength measurements to explore the usefulness of the sensor in the context of strength assessment on agricultural lands. The study investigated using the Light Weight Deflectometer (LWD) as a soil surface strength tool for the purposes of assessing bearing capacity of soft soils. The LWD measurements were performed with those from more “standard” soils tests (i.e., the Dynamic Cone Penetrometer, Cone Penetrometer, and Clegg Impact Hammer) to determine if the LWD produced results that compared with these methods. The strength test data were also used to calculate CBR to see if the different test methods produced similar CBR values that could in turn be used to predict the bearing capacity of the sites and augment the GRAIL Tools soils strength prediction capabilities. The study also compared the strength data with the corresponding soil water content data taken by the University of Nebraska–Lincoln to determine if soil moisture was an indicator of soil strength.

The LWD testing performed gave promising results that correlated with the standard Dynamic Cone Penetrometer, Cone Penetrometer, and Clegg testing to determine soil strength in the lean clays tested. Strength values from the three agricultural sites were generally less than 5 CBR, indicating very soft soil surface conditions. With regard to soil strength and the soil water content measured during the project, although the best correlations follow the same parabolic trends for soil strength versus water content

used by engineers, this dataset showed no strong correlations. The factors that influence soil strength, such as water content, soil density, grain size, and grain size distribution, are complex and often site or soil specific. In addition, the presence of plant roots in the soil, both of harvested corn and growing soybeans at these agricultural field test sites, may influence both the soil moisture distribution and the basic soil strength.

However, COSMOS offers both a roving and stationary soil moisture measurement that may in turn provide data for seasonally adjusting soil strength in terms of changing moisture content. Outcomes of this field work and data analysis demonstrate the utility of COSMOS for providing another potential data source for GRAIL Tools.

6.3 NATO efforts on the Next-Generation NATO Reference Mobility Model

In 2014, the North Atlantic Treaty Organization (NATO) Applied Vehicle Technology (AVT) Exploratory Team 148 (ET-148) was formed to explore the development of an improved Next-Generation NATO Reference Mobility Model (NG-NRMM) (McCullough et al. 2017). A development path forward was identified and initiated in a subsequent NATO research task group (AVT-248) to implement ET-148 recommendations. One key area for improvement was the vehicle-terrain interaction (terramechanics) models defining important performance metrics for off-road performance in differing soils and environmental conditions. The initial implementation focused on existing “simple” terramechanics models as a practical improvement to the incumbent NRMM Cone Index empirically based method without requiring the computational power of the large-scale complex discrete element model methods that are the targeted long-term solution. Practical approaches and limitations to the implementation of these existing simple terramechanics models with three-dimensional vehicle models are described along with parameter identification approaches and their limitations (McCullough et al. 2017).

The NATO AVT-248 subcommittee on simple terramechanics plans to conclude its work in 2018 by establishing the NATO Standards Recommendation documentation and by supplying prototypical demonstrations of GIS-based end-to-end mobility modeling that incorporate existing simple terramechanics models. A follow-on NATO Cooperative Demonstration of Technology meeting was subsequently planned to demonstrate the state-of-the-practice in September 2018.

Combined with the promise of onboard parameter estimation, simple terramechanics methods have become the de facto standard for multibody vehicle dynamic models of off-road mobility. When coupled with specific vehicle test benchmarks, this will establish a vehicle-terrain interaction modeling method for NG-NRMM that is verified and validated to be capable for predictive analysis of vehicle mobility for operational analysis, acquisition, and vehicle design.

6.4 Digital image correlation (DIC) for mobility studies

A joint team from the University of Pretoria in South Africa and ERDC-CRREL assessed digital image correlation (DIC) technology, developed at the University of Pretoria, for off-road vehicle dynamics for all-season and all-terrain viability through a Foreign Technology Assessment Support program at ERDC-CRREL in Hanover, New Hampshire (Botha et al. 2016; Sopher et al. 2016a; Shoop et al. 2016a, 2016b).

Advancements in camera technology and computational power has allowed algorithms to determine feature and depth tracking of surfaces in sequential images at near real time. These advancements have enabled the application of DIC to measure surface and velocity profiles and deformation from a reference state for terrain or for tires. In large off-road vehicle dynamics, DIC can be used to assess and validate terramechanics models by monitoring the road or terrain surface before and after the tire passes and the motion of the vehicle or tire. And, when used as real-time feedback with driver assists or control software, DIC can improve maneuverability of vehicles. From these measurements, the terrain roughness and deformation can provide terrain trafficability and the relative terrain and tire motion used for vehicle safety systems.

The objectives of the University of Pretoria and ERDC-CRREL project were to evaluate the application of DIC on military vehicles to measure deformation and vehicle motion on variable terrain surfaces with the ultimate goal of providing additional information to the driver, vehicle control system, or real-time data assimilation for mobility and maneuver optimization.

Experiments took place during February and March of 2016 and included using the DIC technology on three vehicles: the CRREL Instrumented Vehicle, which is a fully instrumented research vehicle; a newly acquired and instrumented military High Mobility Multipurpose Wheeled Vehicle; and a large off-road military vehicle called a Heavy Expanded Mobility Tracked

Vehicle, which was not otherwise instrumented. In all, over 92 specific tests were conducted; and surfaces included snow, ice, ice-covered water, asphalt, grass, frozen ground, thawing ground, and various soils. The DIC technology performed successfully on all three of the vehicles and in every combination of terrain surface and vehicle maneuver tested (Shoop et al. 2016a, 2016b).

6.5 Frost Action in Soils: Fundamentals and Mitigation in a Changing Climate

American Society of Civil Engineers (ASCE) is currently publishing an updated monograph on frost action in soils.* This document contains case studies on climate impacts to soil properties that will greatly assist in adapting GRAIL Tools for Arctic and Subarctic locations. Significant technological advancements addressing frost action in soils have occurred in the years since the 1984 ASCE Frost Action Monograph. In addition, climate change poses questions regarding associated effects on freeze–thaw action. This publication serves to update the current state of the knowledge on frost action for cold regions engineering practitioners. The first section presents the fundamentals of frost heave and thaw weakening, effects on roads and other structures, and the projected effects of climate change on frost action. The second section presents mitigation of frost heave and thaw weakening within pavement structures. The manuscript concludes with case studies: frost mitigation under building perimeter slabs; evaluating frost contributions to pavement performance for optimizing repairs; and investigation, mitigation, and rehabilitation techniques for frost effects on roadways. The intent of this publication is to describe the challenges of cold regions engineering in a changing climate and to provide state-of-the-art tools for addressing these.

6.6 Baltic Maneuver Study

The Baltic Maneuver Study evaluated seasonal conditions in the Baltic states (Estonia, Latvia, and Lithuania) that influence the state of the terrain, such as frost, thaw, snow and ice cover, and therefore vehicle maneuverability. The summer conditions in the Baltic region are overall very wet. Much of the terrain is saturated at certain times of the year; and therefore

* S. A. Shoop, ed., “Frost Action in Soils: Fundamentals and Mitigation in a Changing Climate” (unpublished ASCE manuscript, last modified August 2018), American Society of Civil Engineers, Reston, VA.

nearly all of the terrain, both fields and forest, are artificially drained with ditches or tiles. The formerly glaciated terrain includes many moraines and other landforms composed of till, which included highly organic soils (i.e., peat, bogs, and muskeg). The flat, wet terrain could be difficult to traverse in summer but under winter conditions offers significant bearing capacity improvement. ERDC-CRREL conducted field work in these areas to further tune GRAIL Tools to these terrain and climate conditions. Further study in this complex area is under consideration.

6.7 Seasonal maneuver requests from theater

Cooperative efforts between ERDC-CRREL and others are ongoing in Arctic and Subarctic regions of the globe in areas where the effects of snow, ice, freeze, and thaw have significant impacts on terrain strength properties and subsequently maneuverability, particularly austere entry and vehicle mobility. Terrain analysis supporting these studies includes an emphasis on snow characterization (i.e., strength, density, and water content); frost and thaw depth and timing; and ice cover extent, thickness, and quality. Each of these offers a significant new source of data to refine GRAIL Tools for these environments. These efforts also include vehicle testing, which will provide data to validate and update models for predicting mobility for the current vehicle fleet for seasonal terrain conditions.

7 Major Products

7.1 GRAIL Tools

GRAIL Tools uses remote methods of terrain analysis to search for areas suitable for vehicle or aircraft maneuverability based on slope, roughness, vegetation, and soil strength. Using a series of filters, GRAIL Tools algorithms first eliminate areas of unsuitable slope, land cover, and obstacles. The ERDC-CRREL team applied both unsupervised and supervised image classification approaches and used a limited amount of ground truth strength measurements to verify that GRAIL Tools would select sites that meet criteria for LZs and DZs and to further refine the algorithms. These algorithms were applied to WV2 multispectral satellite imagery with reasonable results when tested across an operationally active site.

GRAIL Tools LZ and DZ analysis results are loaded in ArcMap and grouped by suitability acceptance levels (i.e., 100% and 95%). LZs are further subdivided into LZ ground orientation angles. This allows users to toggle result layers in support of more nuanced flight planning efforts. Figure 13 shows an example output from an LZ analysis. Results are plotted at orientations of 15° increments or other user-defined intervals.

For DZs, a circular area is used, making the search much simpler. Figure 14 shows suitable DZs based on the size requirement of 15.2 m and 45.4 m (50 ft and 150 ft) radius zones (Wieder and Shoop 2017a). The raster cell size for this image is 2 m (6.5 ft). The potential DZs, depicted as yellow circles, were generated using land classification and slope suitability filters and the two size requirements. The land classification suitability filter results are also displayed, with green regions depicting all suitable areas, including those that are not contiguous and therefore do not meet the geometry requirement. The region in the red box is enlarged in the top left for a better view of DZ output.

Figure 13. Potential C-130 assault LZ sites located by GRAIL Tools at various orientations (Shoop et al. 2018b).

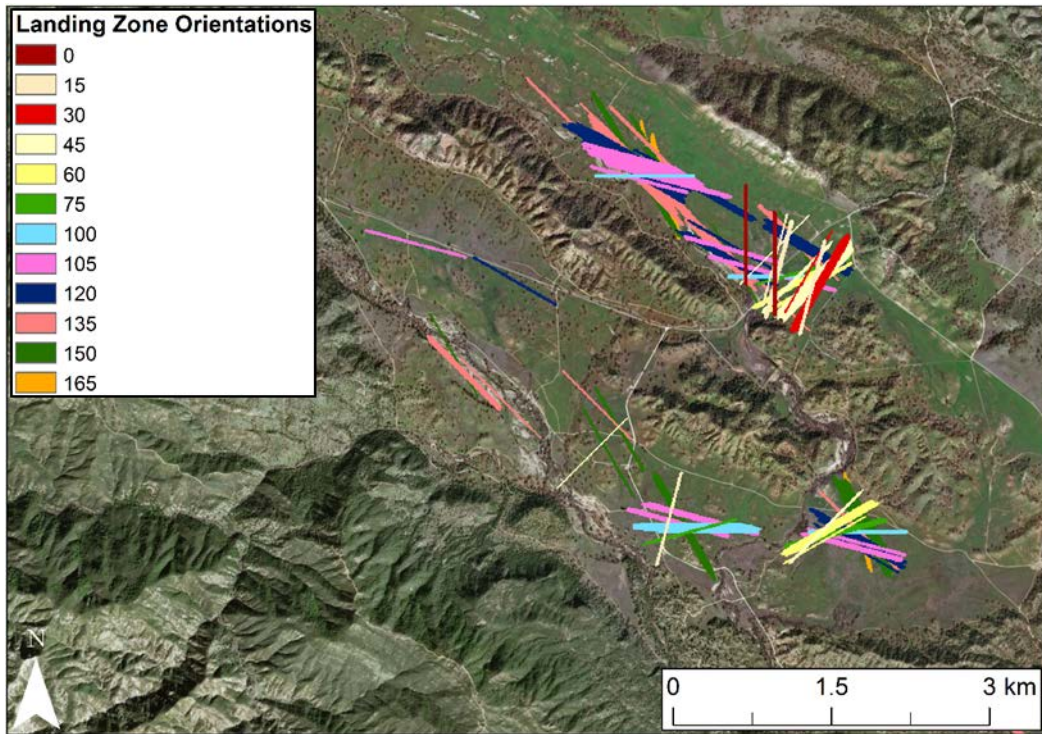
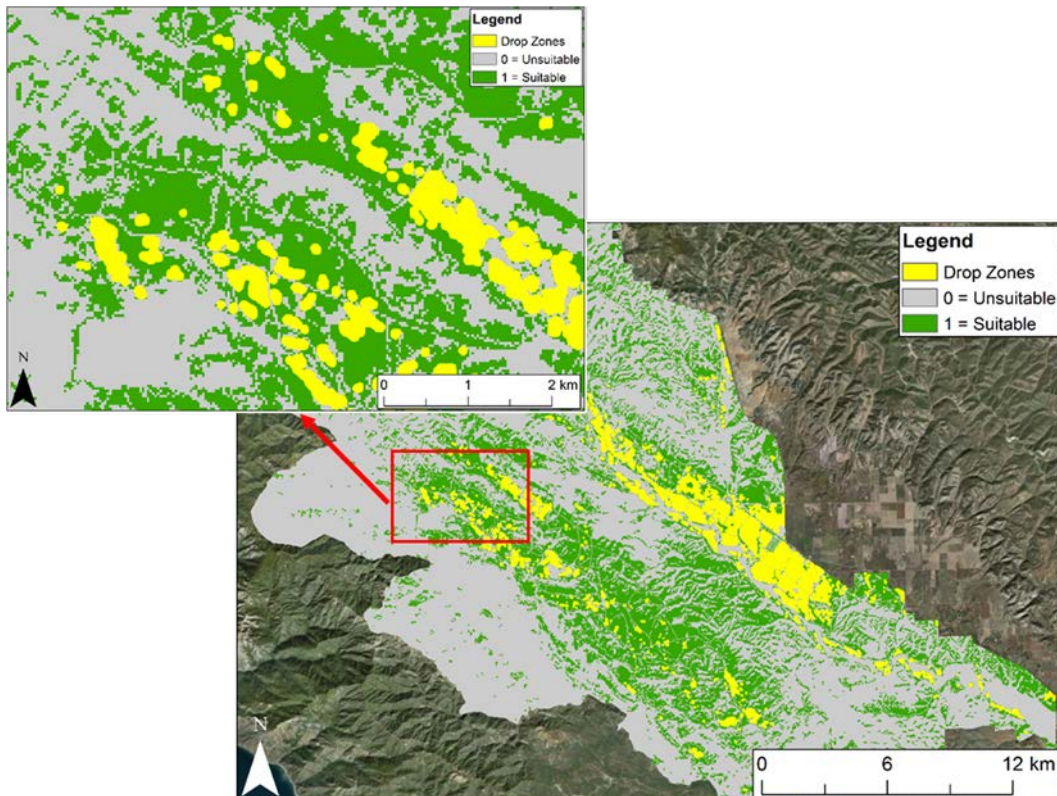


Figure 14. *Locate Drop Zones Tool* result for 15.2 m and 45.4 m (50 ft and 150 ft) radii.



7.2 GRAIL Tools integration into SAGE

The GRAIL Tools output is compatible with existing SAGE software through ArcToolbox and is being integrated with SAGE to support operational planning. ArcToolbox is standard within Esri's ArcMap and allows users to easily develop, automate, and deploy custom geoprocessing applications. Both SAGE and GRAIL Tools have been built using this same underlying technology. SAGE primarily uses Esri's Model Builder functionality; and GRAIL Tools uses ArcPy, Esri's Python geoprocessing programming toolset. Migrating GRAIL Tools into SAGE can include minor modifications to scripts to create Model Builder models where GRAIL will facilitate customizations by Soldiers. Portions of GRAIL Tools can be incorporated directly through the use of Model Builder calls to Python scripts.

GRAIL Tools will be divided into the broad product categories of foundation products used in SAGE, which typically are run at the beginning of a mission and used as input to other tools, and mission-specific products. SAGE experts involved in transitioning the ARTEMIS project will determine the most appropriate mapping between the two toolsets. Tools for creating filters will likely be identified as foundation products. The generalized *Unique Value Filter Tool* and *Threshold Filter Tool* currently in GRAIL Tools can be further specialized for specific standardized datasets (e.g., Digital Globe GeoCover land use / land cover data) as desired to simplify the analysis (Digital Globe 2018). The original tools can be maintained to allow advanced users the ability to fine-tune an analysis and incorporate specialized or future datasets.

As new datasets become available, such as new obstacle-detection products and meteorological information, we recommend new filter processes be created to facilitate incorporation.

The GRAIL team recommends one or more new LZ geodatabases be established as foundation products within SAGE to store suitability filter results. This creates a self-contained, easily transferrable dataset that can be shared across SAGE implementations and workstations.

7.3 Papers and reports

At present, the ARTEMIS GRAIL project has contributed to ten conference papers or presentations, six reports, and four journal articles. Several more reports are currently in publication. Additional journal articles are

expected due to the lag time between completion of research, submissions, and full acceptance. Table 1 provides a simplified list of titles, authors, type of publication, and status.

Table 1. GRAIL publications list.

Status/Date	Author	Title	Publishing Information
In prep.	Sinclair, S.N., and S. A. Shoop	Detection of Austere Entry Landing Zones: A "GRAIL Tools" Validation Assessment	Unpublished ERDC/CRREL manuscript, last modified 2018. Hanover, NH: U.S. Army Engineer Research and Development Center
In prep.	Haehnel, R. B., G. L. Blaisdell, T. Melendy, S. Shoop, and Z. Courville	A Snow Runway for Supporting Wheeled Aircraft: Phoenix Runway, McMurdo, Antarctica	ERDC/CRREL TR-XX-XX. Hanover, NH: U.S. Army Engineer Research and Development Center.
In prep.	Shoop, S. A., A. Sopher, J. Palacio	Soil Strength Analysis Using Remote Sensing	ERDC/CRREL TR-XX-XX. Hanover, NH: U.S. Army Engineer Research and Development Center.
In final revision	Shoop, S., A. Sopher, and W. Wieder	Estimating California Bearing Ratio for Low Strength Soils by Using the 2.25 kg Clegg Impact Hammer and Soil Moisture Content	ERDC/CRREL TR-XX-XX. Hanover, NH: U.S. Army Engineer Research and Development Center.
In final revision	Shoop, S. A., Editor	Frost Action in Soils: Fundamentals and Mitigation in a Changing Climate	ASCE Technical Publication Series
2018	Shoop, S. A., S. A. Beal, W. L. Wieder and E.V. McDonald	Soil Strength Analysis of Sonoran Desert Landforms	ERDC/CRREL TR-18-14. Hanover, NH: U.S. Army Engineer Research and Development Center.
2018	Shoop S. A., W. L. Wieder, E.S. Ochs, and S. N. Sinclair	Using GRAIL Tools to Remotely Assess Terrain conditions for Austere Entry	ERDC/CRREL TR-18-5. Hanover, NH: U.S. Army Engineer Research and Development Center.
2018	Wieder, W. L., and S. A. Shoop	State of the Knowledge of Vegetation Impacts on Soil Strength and Trafficability	<i>Journal of Terramechanics</i> 78:1-14.
2018	Wieder, W., S. Shoop, L. Barna, T. Franz, and C. Finkenbiner	Comparison of Soil Strength Measurements of Agricultural Soils in Nebraska	<i>Journal of Terramechanics</i> 77:31-48.
2017	Sopher, A., and S. Shoop	Stress Analysis of the Phoenix Compacted Snow Runway to Support Wheeled Aircraft	In <i>Proceedings, ASCE Congress on Technical Advancement 2017</i> , 161-172.

Table 1 (cont.). GRAIL publications list.

Status/Date	Author	Title	Publishing Information
2017	McCullough, B., P. Jayakumar, J. Preston-Thomas, H. Hodges, and S. Shoop	Simple Terramechanics Models and their Demonstration in the Next Generation NATO Reference Mobility Model	In <i>Proceedings, 2017 NDIA Ground Vehicle Systems Engineering and Technology Symposium</i> , 8–10 August, Novi, MI.
2017	Wieder, W. L., and S. A. Shoop	Vegetation Impact on Soil Strength: A State of the Knowledge Review	ERDC/CRREL SR-17-2. Hanover, NH: U.S. Army Engineer Research and Development Center.
2017	Wieder, W. L., and S. A. Shoop	Landing Zone and Drop Zone Criteria	ERDC/CRREL SR-17-1. Hanover, NH: U.S. Army Engineer Research and Development Center.
2017	West, B.	Linear and Repetitive-Feature Detection within Remotely Sensed Imagery	ERDC/CRREL TR-17-6. Hanover, NH: U.S. Army Engineer Research and Development Center.
2017	Sinclair, S., S. Shoop, and E. Ochs	A Remote Assessment Technique to Locate Austere Landing Zones for Military Aircraft	Poster Abstract. Geological Society of America Annual Meeting, Seattle WA, 22–25 Oct. 2017.
2016	Botha, T., S. Els, S. Shoop, C. Becker, and A. Sopher	Three-Dimensional Rut Profile Measurement in Snow and Mud	In <i>Proceedings, 8th Americas Conference of the International Society for Terrain Vehicle Systems (ISTVS)</i> , 12–14 September, Detroit, MI, Paper number 41.
2016	Shoop, S., S. Els, C. Becker, T. Botha, and A. Sopher	Evaluation of Digital Image Correlation Technique for Off-Road Mobility in All-Season Conditions	In <i>Proceedings, 8th Americas Conference of the International Society for Terrain Vehicle Systems (ISTVS)</i> , 12–14 September, Detroit, MI, Paper number 83.
2016	Sopher, A., S. Shoop, J. Stanley, S. Els, C. Becker, and T. Botha	Instrumentation and Testing of a High Mobility Multipurpose Wheeled Vehicle	In <i>Proceedings, 8th Americas Regional Conference of the International Society for Terrain Vehicle Systems (ISTVS)</i> , 12–14 September, Detroit, MI, Paper number 97.
2016	Sopher, A. M., S. A. Shoop, J. M. Stanley, and B. T. Tracy	Image Analysis and Classification Based on Soil Strength	In <i>Proceedings, 8th Americas Conference of the International Society for Terrain Vehicle Systems (ISTVS)</i> , 12–14 September, Detroit, MI, Paper number 98.
2016	Wieder, W., S. Shoop, and L. Barna	Comparison of Soil Strength Measurements of Agricultural Soils in Nebraska	In <i>Proceedings, 8th Americas Conference of the International Society for Terrain Vehicle Systems (ISTVS)</i> , 12–14 September, Detroit, MI, Paper number 85.

Table 1 (cont.). GRAIL publications list.

Status/Date	Author	Title	Publishing Information
2016	Shoop, S., A. Sopher, J. Stanley, T. Botha, C. Becker, and S. Els	Digital Image Correlation for Off-Road Mobility	In <i>Proceedings, 2016 NDIA Ground Vehicle Systems Engineering and Technology Symposium</i> , 2–4 August, Novi, MI.
2016	Sopher, A. M., S. A. Shoop, J. M. Stanley, and B. T. Tracy	Image Analysis and Classification Based on Soil Strength	ERDC/CRREL TR-16-13. Hanover, NH: U.S. Army Engineer Research and Development Center.
2015	Shoop, S. A, T. Melendy, B. Tracy, J. Stanley, C. Souza, M. Sala, and R. Thivierge.	Expedient Skiway Reconnaissance and Operations near Resolute Bay, Canada	<i>Cold Regions Engineering 2015</i> , 476–487. New York, NY: American Society of Civil Engineers.
2015	Frankenstein, S., and S. Shoop	Characterization of the Physical Properties of Frozen Soil under Varying Ice Content	In <i>Proceedings, ASCE Conference on Cold Regions Engineering</i> , 19– 22 July, Salt Lake City, 13–24.
2015	Shoop, S, B. Coutermarsh, T. Cary, and H. Howard	Quantifying Vegetation Biomass Impacts on Vehicle Mobility	<i>Journal of Terramechanics</i> 61:63– 76.

8 GRAIL Follow-On Recommendations

User input continues to inform future advancements to GRAIL Tools. The GRAIL team has identified analysis of approach and take-off angles, and availability of a buffer zone around LZ/DZ locations to perform specific mission tasks for the next software version. Data for these additional capabilities are readily available. Future code development followed by algorithm verification and validation will enable new tools to perform these secondary analyses. Additionally, more aircraft can be added to the pick list with further input from the operations community.

GRAIL currently focuses on soil systems, but parameters and datasets for cold regions, such as snow-covered, ice-covered, or frozen ground, are being developed concurrently with other research programs in this area. Other work under ARTEMIS GRAIL has included several initial field collection campaigns at austere regions such as Antarctica, Alaska, Canada, and northern Scandinavia, which are setting conditions necessary for the development and testing of a “Cold GRAIL” toolkit. This will become especially relevant for the DoD as operational requirements in regions with cold-impacted terrain become increasingly relevant to national security. Additionally, to improve application of GRAIL across a wide variety of users, we recommend an expanded user-weighted, risk-based approach.

8.1 Transition through MBPS

Transitioning GRAIL Tools to Map Based Planning Services (MBPS) would deliver a rapid, automated, expeditionary site planning capability for remotely locating large, smooth, flat, and obstruction-free LZs and DZs globally in all seasons. We recommend this transition include user interface menus to exploit a variety of currently available imagery sources, sensing capabilities, and weather information to assess LZ and DZ suitability with respect to user-provided criteria within hours of data acquisition to expedite mission planning and to minimize the need for pre-mission boots on the ground.

The project will also provide enhanced, timely moisture and soil strength estimates by using multiple physical principles to increase accuracy and reduce uncertainty. These include using geophysical algorithms that couple soil properties with current and near-term advances in satellite-initi-

ated soil moisture data and using multispectral/hyperspectral soil signatures to directly estimate soil strength. Techniques will be field validated. These advanced algorithms will increase accuracy, fidelity, and confidence in estimating the strength and operational capability of located natural terrain LZs, DZs, and deployment routes for logistics and distribution.

8.2 Future research and development plans

GRAIL Tools should be expanded to address austere entry in Northern regions of interest to the DoD. The Boreal Aspect of Maneuver (BAEM) one-year effort (Fiscal Year 2018) under the Remote Assessment of Infrastructure for Ensured Maneuver (RAFTER) program addresses the unique issues related to austere entry and maneuver in northern environments. A new program proposal to characterize and predict cold region terrain conditions for entry and maneuver is included in the ERDC Fiscal Year 2019 research program proposal called Entry and Sustainment in Complex, Contested Environments. Resulting technologies will be integrated within software and demonstrated by physical exercises, with the goal of enabling entry and maneuver dominance in northern environments.

The purpose of the BAEM program is to develop a clear understanding of the strengths and limitations presented by the terrain in northern environments on austere entry and maneuver capabilities, capitalize on those conditions, and enable that knowledge for strategic planning and tactical advantage through geospatial decision aids and physical demonstrations.

BAEM will address unique issues and critical characteristics of northern regions. Snow and ice top the list as do predictions of freeze and thaw. Other unique conditions not represented well in current DoD capabilities are operations in areas of heavy peat and muskeg organic terrain, with extreme bearing capacity variations with seasons, and forested terrain important for concealed and autonomous vehicle operations.

BAEM's products include the following:

1. Methodology for global analog assessment of cold regions terrains
2. Analysis of methods for producing global frost depth datasets
3. Experiments to evaluate terrain characterization methods for snow, ice, and peat/muskeg

These are being documented in the following topic areas:

1. Snow characterization for mobility assessments
2. LWD use on compacted snow and ice surfaces
3. Development of a nondestructive remote assessment of snow strength: snow micro-penetrometer, ground-based radar, and satellite-based radar observations
4. Global characterization of freezing and thawing ground
5. Estimating forest parameters using airborne and ground-based techniques
6. Physical properties of highly organic soils and their importance to mobility considerations

9 Conclusions

The GRAIL efforts under the ARTEMIS STO-R program have made significant advances in the remote assessment of terrain and soils for locating potential LZ and DZ sites for military operations. Sources of high-quality geospatial data have been identified and preprocessing procedures defined to produce global imagery tailored to this analysis. With these datasets as input, GRAIL Tools uses suitability filters to determine if an area is a potential LZ/DZ with regard to slope, land use, and soil strength. GRAIL Tools then applies geometric analysis to determine if the required LZ/DZ will fit within the suitable land identified and finally outputs the potential LZ and DZ areas superimposed over the geospatial imagery. The GRAIL Tools output is compatible with existing Army SAGE software within DCGS-A.

Verification and refinement work took place at FHL, California, and was used to help develop and train the suitability filter algorithms with regard to vegetation, obstructions, and soil strength. Future work at a variety of sites, with the addition of work in Arctic and Subarctic regions with snow, ice, and freezing and thawing soils, will evolve GRAIL Tools further to handle the full spectrum of global terrain where military operation may be required.

The GRAIL research has contributed to the scientific and engineering state of knowledge through 26 reports, journal articles, and conference presentations. Furthermore, DoD interest in the GRAIL project has led to GRAIL Tools software and its capabilities being demonstrated to numerous DoD organizations. As a result, formal 6.3 transition and implementation through the ERDC program on Power Projection in Anti-Access/Area Denial (A2/AD) Environments, with proponents in Army Aviation, is scheduled to start in Fiscal Year 2019.

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Appendix A: GRAIL Data Sources

Table A-1. Data sources for GRAIL Tools input.

Dataset	Provider	Data of Interest	Resolution or scale
Soil Survey Geographic (SSURGO) ¹	U.S. Department of Agriculture, Natural Resources Conservation Service, National Cooperative Soil Survey (USDA-NRCS NCSS)	United Soil Classification System (USCS) soil type, water table depth, wetness or drainage, cone index, and texture	Scale varies: 1:12,000 to 1:63,360
Food and Agriculture Organization (FAO) Soils Portal ²	United Nations	International soils data and maps	1:50,000 scale
European Soils Database ³	European Soil Data Centre	Soils and soil hydraulic data	Resolution varies: 250 m to 10,000 m (820 ft to 6 miles)
National Land Cover Database (NLCD) ⁴	U.S. Geological Survey	Natural and manmade land cover	30 m (98 ft) resolution
WorldView-2 and 3 (WV2 and WV3) ⁵	Digital Globe	Imagery	WV2: panchromatic 0.46 m (1.5 ft), multispectral 1.84 m (6 ft) WV3: Panchromatic 31 cm (1 ft), multispectral 1.24 m (4 ft)
LiDAR ⁶	National Oceanic Atmospheric Administration (NOAA)	Topography	
Soil Moisture Active Passive (SMAP) ⁷	National Aeronautics and Space Administration (NASA)	Soil moisture	40 km (25 mile) resolution
Modern-Era Retrospective analysis for Research and Applications (MERRA) ⁸	NASA Global Modeling and Assimilation Office	Climatology, gridded temperatures, and snow parameters	
GeoWATCH ⁹	Creare LLC	Soil moisture and strength	30 m (100 ft) or less
Cosmic-Ray Soil Moisture Observing System (COSMOS) ¹⁰	National Science Foundation, University of Arizona, University of Nebraska-Lincoln, and Hydroinnova LLC	Soil moisture	

1 USDA-NRCS (n.d.)

2 FAO (2017a, 2017b)

3 European Soils Data Centre (2018)

4 Multi-Resolution Land Characteristics Consortium (2011)

5 Digital Globe (2018)

6 NOAA (2015)

7 NASA (2015); Jet Propulsion Laboratory (2015)

8 NASA (2017)

9 Bieszczad et al. (2016)

10 Wieder et al. (2016, 2018)

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14. ABSTRACT
The Terrestrial Geospatial Remote Assessment for Ingress Locations (GRAIL) portion of the Army Terrestrial Environmental Modeling and Intelligence System Science and Technology Objective–Research (ARTEMIS STO-R) program was developed to use remote methods of terrain analysis to search for areas suitable for vehicle or aircraft maneuverability, based on slope, roughness, vegetation, soil type, and wetness, and to also perform direct classification of imagery based on soil strength. The product of the GRAIL project was a software program entitled GRAIL Tools. Using a series of filters, GRAIL Tools first eliminates areas of unsuitable slope, land use, obstacles, and vegetation. The algorithms for these filters, using both unsupervised and supervised classification approaches, were applied and trained by a limited amount of ground truth strength measurements to improve GRAIL Tools' site selection capabilities. GRAIL Tools then searches for sites that meet geometric criteria for landing and drop zones, the final result being a map of potential landing and drop zones superimposed over satellite imagery. The first generation of GRAIL Tools has proven capable of identifying austere landing and drop zones using remote assessment techniques. GRAIL Tools has been integrated in to the U.S. Army's Situational Awareness Geospatially Enabled (SAGE) software platform.

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