Experiment Design Overview (EDO)

Perdigão Field Experiment

Lead Principal Investigators (U.S.):
Harindra Joseph Fernando, University of Notre Dame
Julie K. Lundquist, University of Colorado

Contributors:

Robert Banta, NOAA/ETL
Rebecca Barthelmie, Cornell University
Luciano Castillo, Texas Technical University
Tina Katopodes Chow, University of California, Berkley
Christopher Hocut, U.S. Army Research Laboratory
Petra Klein, University of Oklahoma
David Knapp, U.S. Army Research Laboratory
Laura Sandra Leo, University of Notre Dame
Jakob Mann, Danish Technical University, Denmark
Steven P. Oncley, National Center for Atmospheric Research
Jose Lahaina Palma, Porto University, Portugal
Eric Pardyjak, University of Utah
Edward Patton, National Center for Atmospheric Research
Marco Princevac, University of California, Riverside
Luis Ribeiro, Bragança Polytechnic Institute

Figure 1: A Google-Earth image of the Perdigão site with the view to the north. The locations of an existing wind turbine ('WT') and a former meteorological mast ('Met Mast') are shown, along with the two ridgelines. Airflow is almost always perpendicular to these ridgelines, either from the southwest or the northeast.
Executive Summary

Atmospheric flow in complex terrain has received increased attention in recent years because of its numerous applications, including air pollution, contaminant dispersion, aviation, Alpine warfare, and wind energy harvesting. While most relevant past research has focused on weather prediction at mesoscale (resolution on the order of km), wind energy, dispersion, and fire-fighting applications demand accuracy of predictions at microscale (tens to hundreds of meters). To this end, ERANET+, a European Union (EU) funding instrument, has granted a consortium of EU scientists a megaproject to provide the wind energy sector with more detailed resource mapping capabilities. This is to be accomplished through the creation and publication of a digital New European Wind Atlas (NEWA) based on the development of improved models and model chain for wind energy physics.

Embedded in the NEWA project is a 2017 comprehensive field campaign dubbed “Perdigão”, which will collect a reference data set at an unprecedented spatial resolution, characterizing both the mean and turbulent wind fields in a natural setting. Augmenting the basic measurement and modeling infrastructure of EU scientists with those from the US investigators will add considerable value to the NEWA project while allowing the US investigators to pursue rigorous scientific endeavors of their choosing. Significant observational resources will be deployed by the EU teams for Perdigão. NSF/LAOF systems, along with instrumentation provided by the PIs, are requested to supplement these resources to support the US research goals.

The NEWA emphasis will be to measure wind velocity. Since airflow, especially close to the Earth’s surface, depends on the thermodynamic stability of the atmosphere, a major aspect of the US participation is to measure the mean and turbulent temperature and humidity fields as well. The US investigators will use these data to understand complex terrain physical and thermodynamic processes and create new models that better represent the physics of flow over complex terrain. The requested LAOF facilities are essential to meet these objectives:

- ISFS will acquire the data from all (including an extensive set of investigator-supplied) tower-based sensors, including those to measure turbulence and thermodynamic fluxes.
- ISS will measure the in-flow and out-flow velocity and temperature profiles during the entire observation period, which is essential for setting model initial conditions.
- Water-vapor DIAL will provide humidity profiles during conditions when humidity gradients may have a large effect on boundary-layer thermodynamics.
- Radiosondes will provide the primary in situ validation for the vast array of remote sensor data in the boundary layer.

Program Rationale and Scientific Hypotheses

As described in the Scientific Program Overview (SPO), sections D.1-4, the goal of Perdigão is to improve our understanding of flow over complex terrain, including any effects of vegetation and heterogeneity at the surface, with a specific target of improving wind prediction in complex terrain at microscale. Of particular interest is the assessment of wind resources for the wind energy community, concurrent with the goals of EU investigators. During the development of the NSF project, it was pointed out the continued emphasis of microscale meteorology by other US agencies, such as the Army Research Laboratory/Office (ARL/ARO), and their possible participation with augmentation to Perdigão instrumentation. Therefore, a meeting was held at University of Notre Dame during September 25-26, 2014, with US academic and agency scientists as well as European scientists making presentations, facilitating discussions on scientific topics of urgency and developing a viable and coherent scientific plan for Perdigão. A dedicated webpage contains presentations of the meeting and other relevant information: [http://www3.nd.edu/~dynamics/perdigao/](http://www3.nd.edu/~dynamics/perdigao/). The present EDO is an outcome of the science plans originated by the team of scientists participated at the Notre Dame meeting. In addition to providing instrumentation, ARL scientists are interested in participating in this study of flow over complex terrain. NOAA scientists also have shown interest to join with in-house developed lidar technology.

The outcomes of the US participation of Perdigão campaign is expected to take the form of better numerical flow and dispersion models for complex terrain, in addition to addressing some of the scientific questions prioritized in Section D.3 of the SPO. Despite the availability of extensive literature on flow over complex terrain, the number of reference data sets by which to evaluate these models is small and some of these have been taken over sites that are quite difficult to decipher. The study of flow over a single isolated hill in Scotland (Askervein) was perhaps the most successful of these and has been used for 3 decades to develop and evaluate flow models. The key task for Perdigão
is to map out the flow field over terrain that is complex enough to provide a new challenge to existing models, but with a topography simple enough to simulate numerically. A “double hill in crossflow”, in which the wake from one ridge is expected to modify the mean and turbulent flow over the leeward ridge, was chosen specifically to address this task. The presence of moderate topographic inhomogeneities in the nominally 2D two-hill system allows investigations of 3D effects, secondary flows and flow convergence/divergence zones.

Scientific Objectives

The long-term goal of the Perdigão project is to create numerical models that better represent flow over complex terrain than those currently in common practice. In the European context, the new models are expected to contribute to a new European Wind Atlas. In the US context, the objectives are to create new scientific knowledge and develop better parameterizations for complex terrain processes, with broad impacts of future microscale model developments for wind energy prospecting, flow and dispersion in heterogeneous complex terrain as well as human resources development. To improve microscale models, better physics is needed which, in turn, requires detailed observations and analysis. We propose to observe the flow and thermodynamic fields at unprecedented spatial and temporal resolutions, including direct turbulence measurements down to dissipation scales using hot-film anemometry. To validate key inputs to these models, we also will directly measure all components of the surface energy balance (incoming and outgoing visible and infrared radiation and surface/soil heat exchange, in addition to sensible and latent heat fluxes). An extensive suite of individual and coordinated lidar scans will allow mean flow, turbulence and Reynolds stress measurements up to hundreds of meters vertically and kilometers horizontally. Science questions to be addressed are elaborated in the SPO, Section D.3.

Experimental Design and Requirements

Site Description

To enable direct comparisons with models, EU scientists have selected a site with relatively simple terrain, but is more complex than the single hill at Askervein that currently represents the benchmark data set (Fig. 1). This site in central Portugal has a pair of parallel ridges (with a valley in between) that are quasi-two dimensional. The surface is a mixture of farming areas and patches of eucalyptus for pulp and paper industry, so interactions of a vegetative canopy with the flow is observable with suitable instrumentation. The experiment is named for the local community of Perdigão (“partridge”, in Portuguese). The wind climatology of this site is ideal for fundamental studies (Fig. 2). Winds are almost always perpendicular to the ridgeline, but from both directions. Thus, instrumentation on each ridge will alternate between measuring windward and leeward conditions. Strongest winds (of greatest interest to NEWA) are in the winter (Jan—Mar), though this also is the period of highest precipitation. Summer (Jun—Aug) has the lowest winds and strongest radiative heating and thus the largest range of atmospheric stability.

A unique aspect of this site is the existence of a single wind turbine (Enercon 2MW; 82m diameter) on one of the ridges. This will allow investigation of both how the turbine power depends on the airflow at the ridge top and how the turbine wake affects local conditions. The operator of this turbine, GENERG, is willing to provide Supervisory Control and Data Acquisition (SCADA) measurements of the turbine operating parameters for this study.
**Expected Conditions**

Numerical simulations of flow at the experimental site have been carried out using the VENTOS® model developed at Porto University, Portugal. Based on these simulations, it is not possible to expect the flow to be two-dimensional (independent of the cross-wind direction) despite the nominally regular topography of this site. For winds from the SW, air appears to stall at a low-point ("gap") of the downwind ridge even though it is only about 20m lower (Fig. 3). Flow separation at the gap boundaries generates flow structures that contribute to the unsteadiness. Not surprisingly, a region of low winds, high turbulence, and potential recirculation develops in the valley between the ridges (Fig. 4). These lower winds and high levels of turbulence persist to well above the leeward ridge top, in the location where wind turbines would be installed. All of these flow features must be measured at high spatial resolution. The identification of leeward phenomena and the resulting flow distortions upstream will be greatly useful to the complex flow research community.

![Figure 3: A horizontal slice of the wind field at 40m above ground from a numerical simulation (VENTOS®) by Porto University of flow across the Perdigão site with flow from the SW. Transects (A-E) perpendicular to the hills used for model interpretation also are shown. Note that significant departures from two-dimensional flow are expected.](image1)

![Figure 4: Distance-height cross sections of the mean flow (top) and turbulence (bottom) simulated along transect E with flow from the SW. Note that flow on the downwind ridge is significantly different than that on the upwind ridge. Although flow is expected to accelerate over the lee mountain, a recirculation region exists that cause flow velocity to be unexpectedly low. If confirmed, the results will have significant practical repercussions.](image2)
Observations

Our planned field deployment would utilize state-of-the-art tower, airborne, and remote sensing instrumentation to provide an extensive, high-resolution dataset for studies of complex terrain meteorology.

The 1983 Askervein Hill study, the current benchmark, employed 45 10-m towers each with one measurement height and 4 16--50-m towers with as many as 4 levels, supporting a total of 28 3D (sonic and propeller) anemometers and about twice as many mean wind sensors. Radiosondes and a tethersonde were used at a few locations to measure conditions further aloft. Although this was an impressive array of instrumentation at that time, some flow features – specifically recirculation zones near the crest -- were not adequately sampled.

Tables I. 2-4 of SPO list the instrumentation that potential Perdigão participants could contribute to this field campaign. These tables are organized by the type of measurement: tower-based instrumentation (Table I.2), remote-sensing and related systems (Table I.3), and airborne systems (Table I.4). A landmark of this experiment is the use of at least 21 synchronized scanning lidars (seven triple lidar sets) to map out the wind field, an unprecedented feat. This use of lidars frees some 150+ sonic anemometers to concentrate on the task of mapping the turbulence field at a higher resolution and estimating the surface fluxes. Thus, we expect the Perdigão dataset to vastly improve on describing the flow field despite having about the same number of towers (50) and considerably more complex flow than at Askervein. With more than 30 wind lidars potentially available, the airflow above these towers will be well-characterized with data that are continuous in time. Clearly, the Perdigão design assures the ability to probe the planetary boundary layer with unprecedented resolution even if not all participants are funded.

Scanning lidar sampling

Given that the triple lidar is a groundbreaking addition to the ABL remote sensing equipment arsenal, and that it is a new method to generate virtual towers over large areas, a brief description of the method is in order. The method involves coordinated deployment of three scanning lidars to intersect at preselected locations, with each beam measuring the radial wind velocity, thus allowing measurement of all three components of velocity at each point without making any assumptions on the flow field. The rapid laser scanning allows obtaining profiles at different locations before the mean winds change substantially. The efficacy of the ‘triple lidar’ technique has been demonstrated by a US group at the MATERHORN Fall 2013 field experiments (Wang et al. 2015; Fig. 5a), where mean and turbulence velocities were measured and compared with sonic-anemometer measurements made from a tall tower. The European group has now automated the system, and is ready to deploy under the name ‘Windscanner’ (Fig. 5b). Their technology has been tested at an ERANET+-funded experiment at Rödeserberg in the vicinity of Kassel, Germany during end of June and mid-August 2014. The experiment consisted of six long-range WindScanners coordinated by the master computer, and was a part of the WindScanner.EU project, a collaborative effort between DTU Wind Energy, Fraunhofer-IWES and ForWind; for results, see Vasiljevic (2014).

The triple lidar methodology has been quickly adopted by lidar manufacturers to produce as an off-the-shelf system for customized production. The lidar manufacturer, Leosphere, has produced a number of Windscanners for the Denmark Technical University as a precursor to NEWA, and a total of seven sets are expected to be available for Perdigão. (The US group is working with another manufacturer, Halo Photonics, to implement a similar system).

A multi-position sampling strategy will be used for scanning lidars during Perdigão (Fig. 6).

- Long-range (up to 6.5km) Windscanner systems consisting of several coordinated scanning Doppler lidars will be deployed throughout the ridge/valley system to measure the 3-D wind field. Commercial versions are being modified to allow downward pointing, so that ridge-top scanners can view into the valley. With 18 such scanners, we expect to be able to scan much of the slopes and the boundary-layer flow as well as inflow and outflow into the region.
- At least one short-range Windscanner system will be deployed initially in a triangle centered on the wind turbine to investigate its wake and subsequently around a canopy edge, which is believed to affect the flow significantly, or other regions of interest.

Beyond the triple-lidar systems, a number of in situ (tower-based), profiling lidar, and airborne measurements will sample the flow in Perdigão.
Figure 5a: The ‘triple lidar’ deployment by the US Group (ARL, Notre Dame and University of Utah) at the MATERHORN experiment. Note the velocities along the virtual tower (Wang et al. 2015).

Figure 5b: Windscanner deployment in the Kassel experiment in the summer of 2014 (Courtney et al. 2014; Courtesy – Dr. Nikola Vasiljevic, DTU)

Tower measurements

The tower measurements with three-dimensional sonic anemometer/thermometers have three main tasks:

1. Measurement of turbulence levels and spectra to constrain model calculations, to map turbulence in the study area and validate Windscanner measurements, to determine stresses on the wind turbine, and to detect the presence of the turbine’s wake.

2. Measurement of local heat flux to determine how the thermal stability of the flow changes with position and time of day.

3. Measurement of sensible and latent heat fluxes (in combination with fast-response hygrometers), two of the major terms in the total surface energy balance (required for modeling). Each of these sites also would measure net radiation, temperature profile, and soil heat flux to complete the measurement of the surface energy balance terms. Some of these systems also will be deployed in the surrounding area to evaluate model treatment of the land surface.

The layout of these sensors (tower positions and heights of instruments on the towers, Fig. 7) has been chosen to characterize major features of the flow, along with the effects of the existing wind turbine. Of particular interest is the three-dimensional structure of flow through a low point (gap) in the NE ridge, which requires a large grid of towers. Also of interest is the velocity along the various slopes that are expected to have stagnation points due to opposing drainage and recirculation flows as well as capturing the changes thereof during the change of flow direction. Thus, our plan includes multiple cross-slope transects with multiple vertical levels, including within the vegetative canopy and outside patchy areas to investigate drainage flows under various surface conditions.

To achieve the network shown in Fig. 7, the sensors used on these towers would be pooled from several research groups (Section I, Tables I.2-4). For example 141 sonic anemometers are needed to instrument the multi-level 20, 60, and 100m towers in Fig. 7 and Table I.2 shows that 142 are available. (The need for spare instruments to address any sensor failures likely will require that these numbers change slightly.) ISFS is being asked to deploy and to acquire data from all of these sensors. In other words, ISFS would form the core for all Perdigão tower observations.

Microbarograph network

Another unique observational capability of this experiment will be the use of a nanobarometer/microbarograph network to investigate the propagation of the wind turbine wake across the valley and through the vegetation canopy. A test of this capability was done by Iowa State University in their nearby Story County wind farm, though the presence of intersecting wakes from adjacent turbines made the interpretation of data difficult (Rajewski et al.,
We expect a clearer signal since there is only one turbine. The nanobarometer network will also be able to provide information of coherent structures emanating from the turbine wakes, gap shear layers as well as internal-wave propagation under stable conditions.

**Remote sensing of wind and thermodynamic profiles**

Standard remote sensing platforms will quantify vertical profiles within and outside of the Perdigão valley, as shown in Fig. 8:

- Relatively coarse (90m) vertical resolution radar wind profilers will be used outside the valley to measure inflow and outflow conditions, critical for modeling studies.
- Profiling microwave radiometers (Friedrich et al., 2012) will determine the boundary layer temperature structure at several locations for model comparison, including inflow and outflow locations, during the intensive operations period.
- A central location in the valley will measure boundary layer profiles of wind and temperature (using NCAR’s SODAR/RASS) and water vapor using NCAR’s water-vapor DIAL. The RASS system will provide the only continuous record of temperature profiles during the unattended operations phase. The DIAL will provide unique continuous upper-air water vapor observations with high vertical resolution.
- To provide complementary wind and scalar profiles, the NSSL/University of Oklahoma Collaborative Lower Atmospheric Mobile Profiling System (CLAMPS), including a microwave radiometer, Atmospheric Emitted Radiance Interferometer (AERI), and scanning lidar also would be deployed at the central location (http://www.nssl.noaa.gov/users/dturner/public_html/CLAMPS/slide01.html). Recent data (Fig. 9) show that the AERI in particular can measure temperature profiles in the boundary layer (Klein et al., 2015).
- Six profiling lidars will be deployed at ridge locations and upwind sites, where recirculation and significant flow inhomogeneities are not expected. These systems all have a range of 200 m and rely on Doppler beam steering. Thus, their use assumes (somewhat) homogeneous flow (Lundquist et al. 2014).

**Airborne measurements**

Scanning lidars are incapable of measuring fine-scale turbulence or thermodynamic properties. For this, we will utilize both tethered lifting systems (TLS, Lundquist and Bariteau, 2014) and UAV systems that are available from several groups. In Portugal, the local hosts for this experiment at the University of Porto and the Polytechnic Institute of Bragança are collaborating with the Portuguese Air Force on a UAV research program, and they are able to allocate Portuguese airspace for UAV operations. Clearly, these arrangements still will involve some effort, especially to include non-Portuguese UAVs, however we expect this process to have a much greater chance of success of permitting these operations than in many other countries. The platform currently used by Porto Univ. is a Skywalker X8 with a 2.12m wingspan, 1kg payload, 45min. endurance, and 50km range. Typical UAV payloads include instruments for mean winds, temperature, and relative humidity, while the TLS systems can accommodate turbulence dissipation rate measurements. Flight patterns would include boxes with both along-wind and cross-wind straight-and-level flight legs at multiple altitudes (Fig. 10). If airspace management permits, vertical “saw-tooth” patterns across the top of the boundary layer may be executed to estimate entrainment, a result that can be validated by the lidar observations. TLS and UAVs would be deployed in locations where finer vertical resolution is determined to be needed, requiring near real-time display of all field data in order to identify these regions of interest. Additional TLS is likely to be available from ARL (Section I.4).

Radiosondes would be launched 3 times a day (morning transition, evening transition, and nighttime) from a location inside the valley for the 42 days of the intensive deployment in May-June. The resulting profiles will help interpret data from the remote sensors, such as identifying which areas of large backscatter gradients represent the top of the boundary layer; these data will also initialize synoptic-scale models in the “model chain” and provide estimates of large-scale synoptic forcing. These soundings will be augmented by data from a ceilometer for detecting density-stratified layers. They also will be used for supplementing existing operational upper-air measurements on the Iberian Peninsula.

**Surface characterization**

Laser surface mapping also will be done by the European colleagues as part of the NEWA project just before the experiment. This mapping is required to provide accurate terrain and vegetative canopy structure for modeling, to assist in data interpretation, and to extrapolate point surface energy balance measurements to the entire region.
Figure 6: One potential Windscanner deployment strategy. Note that the scan regions are larger than just the area within the triangle defined by the lidar positions. Lidars are placed mostly in the valleys to enable scanning up to the ridge crest. If commercial version of stare-down lidars are available, the siting strategy can be changed as appropriate. The locations of the wind turbine (WT), Gap in the NE ridge, and town of Foz do Cobrão are shown.
Figure 7: Layout of towers for Perdigão, coded by the tower height. The 17 towers with surface energy balance instrumentation are indicated in red. All 20m towers would have turbulence sensors at 2, 10, and 20m. The 60m towers would be instrumented at 2, 10, 20, 40, 60m, and the 100m towers also at 80 and 100m.
Figure 8: Potential layout of profiling remote instruments (except radar wind profilers, which will likely be located outside of this diagram). The central valley location will have the SODAR/RASS, DIAL, and CLAMPS (see text). Profiling lidars (WC, Z, S) should be located in regions with relatively homogeneous flow, such as the upwind locations or on ridge tops. Soundings will be located close to Foz for convenience and to avoid sondes approaching the wind turbine. Radiometers require a view of the horizon and thus will be located out of the valley.
Figure 9: (a) Mean bias (rawinsonde minus AERI) and root mean square error (RMSE), and (b) comparison of the temperature gradients between 10 m and 100 m AGL, determined from 120/106 AERI retrievals and rawinsonde observations during LABLE I and II (Klein et al., 2015).

Figure 10: Typical UAV along-valley (black) and cross-ridge (purple) flight patterns used to measure humidity and turbulence levels above the height of the towers. Only the along-valley flight legs would descend below the ridge line.
**Time Period**

The NEWA Perdigão field campaign is scheduled to be 6 months, with operations beginning December 15, 2016 (Table 1). This period was selected to sample the largest range in wind speeds, including high wind speed cases that generally occur in the winter. The tall towers are scheduled to be erected by the Portuguese team in summer 2015 to prepare for extended operations. Installation of NCAR instrumentation (in November/December 2016) likely will take longer than normal to minimize tall tower operations in cold and wet conditions that also occur in the winter.

For the first 4 months (Jan—Apr), all of the tower-based sensors and the Windscanners would be in operation, to develop a climatology of the air flow and turbulence statistics. During this time, it would be acceptable to have some data outages. Portuguese technical staff would be available for routine maintenance, so it is not expected that NCAR staff would need to be on site.

The intensive operational period to support model development would be May 1 – June 15, 2017. This period has been chosen to maximize the range of stability conditions and thus includes hot and calm summertime cases. Since this period would occur at the end of the 6-month NEWA Perdigão campaign, the general flow pattern will be known, allowing labor-intensive resources (airborne platforms and scanners) to be concentrated in regions of interest and allow for adjustment to new insights regarding the flow in the valley discovered during the previous four months. During this intensive period, all profiler and airborne instruments would be deployed. We anticipate a brief instrument intercomparison period, with colocation of similar instruments for the first few days (as in Fig. 11).

![Figure 11: Example instrument co-location for preliminary intercomparison period (image courtesy Lundquist, from the CWEX-13 experiment).](image)

**Table 1: Significant activity timeline for Perdigão.**

<table>
<thead>
<tr>
<th>Start Date</th>
<th>Activity</th>
<th>Responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Summer 2015</td>
<td>Tall tower erection</td>
<td>Portuguese Consortium</td>
</tr>
<tr>
<td>Summer 2016</td>
<td>Tower sensor/Windscanner preparation</td>
<td>PIs, NCAR, DTU</td>
</tr>
<tr>
<td>15 Oct 2016</td>
<td>Tower equipment shipping</td>
<td>NCAR</td>
</tr>
<tr>
<td>15 Nov 2016</td>
<td>Tower/Windscanner equipment set-up</td>
<td>PIs, NCAR, DTU, Portuguese</td>
</tr>
<tr>
<td>15 Dec 2016</td>
<td>Unattended operations period</td>
<td>Portuguese (others remote monitoring)</td>
</tr>
<tr>
<td>15 Mar 2017</td>
<td>Profiler equipment shipping</td>
<td>PIs</td>
</tr>
<tr>
<td>15 Apr 2017</td>
<td>Profiler equipment set-up</td>
<td>PIs</td>
</tr>
<tr>
<td>25 Apr 2017</td>
<td>Instrument intercomparison period</td>
<td>PIs</td>
</tr>
<tr>
<td>1 May 2017</td>
<td>Attended intensive operations period</td>
<td>All participants</td>
</tr>
<tr>
<td>15 Jun 2017</td>
<td>All equipment tear-down</td>
<td>All participants</td>
</tr>
<tr>
<td>15 Jul 2017</td>
<td>Return shipping</td>
<td>NCAR, DTU</td>
</tr>
</tbody>
</table>
Project Management

The Perdigão study has two major and mostly complementary goals. The Wind Resources assessment project is the focus of the European participants and is being led by the Danish Energy Authority. The European group and NCAR will collect tower, scanning lidar, and radar and sodar profiler data over the entire 6 months. This EDO is to support the scientific inquiries and complex-terrain flow modeling endeavors of the U.S. participants led by Joseph Fernando, University of Notre Dame. As just mentioned, the U.S. participants will require a higher density of observations, but for a shorter (6 week) period of time. The project leads have been in constant communication since the onset of planning for this experiment in early 2013. There also is the possibility of smaller (separately-funded) “piggy-back” studies, such as a water budget study in the valley, which would use mostly the same instrumentation. The US Army Research Laboratory is also planning to join the experiment with their own resources because of their interest in microscale modeling of limited areas as well as developing model chains (see letter in Section J and their instrumentation contributions in Section I).

All of these major goals will need to be coordinated. Strong collaborative relationships have been established through regular visits of European participants to NCAR and Notre Dame, visits of US participants to Perdigão (the first visit took place September 4-6, 2014) as well as via the intense two day workshop held during September 25-26, 2014 with significant Army Research Laboratory involvement. Because of the synergism and cordiality established, we expect the coordination to be straightforward. Following the determination of which US investigators are funded by NSF and the plans of ARL, we plan the following in-person meetings, supplemented by more frequent teleconferences:

- March 2016: Two-day investigator meeting (all NSF-funded investigators as well as European collaborators) in the town of Vila Velha de Ródão, a city in the proximity of the field site, which includes a site visit to Perdigão and further discussions on Perdigão science issues as well as fine-tuning of instrumentation sites and logistics.
- May-August 2016: Several visits of the PI to Colorado are expected, to meet with co-PI, LAOF personnel and visiting EU investigators to NCAR.
- September 2016: Visit of PIs to Porto and field site for finalizing instrument siting.

In-the-field coordination will be minimal. The deployment strategy for the vast majority of instrumentation will not need to be changed during the entire program. In-field coordination will be required only for the labor-intensive UAV and tethered lifting system measurements. Daily or every-other-day coordination and weather discussion meetings will be held during the 42-day intensive observing period to identify optimal times for tethered lifting system and UAV flights to ensure adequate sampling of gap flow events (flow from the northeast) and wind turbine wake events (flow from the southwest at wind speeds between 8 and 12 m s\(^{-1}\) at turbine hub height).

Field Operations

Since the airborne systems and some of the lidar scanning strategies will require operational decisions by field staff, a local operations center will be established by the Portuguese colleagues, and it likely will be near the town of Perdigão, in the municipality of Vila Velha de Ródão, whose government is eager to host this program. Since the technical resources available in Perdigão are limited, a data center with more internet connectivity and support for larger group meetings will be available at Porto University, about 2.5 hours away (Fig. 12). Operations meetings will require the use of WWW-based tools to involve participants at these two locations and at their home institutions.

UAV operations will be coordinated by the Portuguese Army/Air Force through their Projeto de Investigação e Tecnologia em Veículos Aéreos Não-Tripulados (PITVANT) program. This project has developed UAV and RPV technologies for both military and civilian applications in Portugal, and has partnered with the Porto University to develop applications. PITVANT plans to supply multiple UAVs with trained UAV pilots for Perdigão and is able to allocate airspace within Portugal for UAV operations. PITVANT also has an airbase in Portugal for UAV operations, including UAS training and certification.

(http://www.afceaportugal.pt/2013/eventos/Apresenta%C3%A7%C3%A3o_AFA_PITVANT.pdf)

The Cost Estimate Request for the NSF LAOF facilities includes a request for NCAR/EOL operations support. This project would greatly benefit from EOL’s experience with the planning and implementation of international programs, including project planning in advance of the deployment, creation a Perdigão International Operations
Plan that describe all deployment aspects of the project, along with the collaboration with European colleagues on the configuration and implementation of a suite of web-based tools to display real/near-real time observations from the Perdigão network.

Logistics

Our Portuguese hosts have already been in contact with power and telecommunications utilities to determine how to implement this experiment plan. The local power utility industry in particular sees the opportunity to support wind energy research as a direct benefit to them and has been very cooperative.

NCAR/EOL usually creates a wireless local-area network (LAN, often using long-range WiFi) to bring data back to their operations base, which we expect will be at or near the local operations center. The PI team would like to use this, or a parallel, LAN to monitor other instrument systems. From there, data would be distributed over the wired internet to Porto University, where they would be further disseminated via windscanner.eu (see Data Handling, below). Local telecommunications companies are in talks to become full members of the Portuguese Windscanner Consortium to support windscanner.eu. Thus, adequate networking bandwidth is expected to be available.

National and International transportation of equipment to and from the field site will follow standard procedures. European participants likely will use standard air or ground couriers and/or transport equipment themselves. NCAR/EOL would pack the bulk of their equipment into several 20’ seacontainers for ocean shipping to the site. The investigators of this EDO would like NCAR/EOL to supply 2 additional seacontainers for coordinated shipping from/to Boulder of their instrumentation. These containers would serve as bulk storage facilities at or near the Operations Center for the duration of the project as well as return shipping. No special customs requirements should be necessary for import/export to/from Portugal. Owing to carnet restrictions, all equipment must return to the U.S. in less than a year, which should be possible even including set-up and tear-down for the 6-month deployment.

Within a 25 min. drive from the site are several small communities with guesthouses as well as the city of Castelo Branco, with access to most services. Passenger train service is available from Lisbon to the town of Vila Velha de Ródão, located about 10 min. drive from the site. This is the city where the funded investigators and EU participants plan to have a planning meeting in March, 2016.

Data Handling

To avoid duplication of effort, we are requesting that NCAR/EOL acquire data from all tower-based sensors. EOL has experience with most, if not all, of the sensors that the other groups would provide. Low-cost wireless connections, such as Bluetooth, could be used to send data from the 49 towers shown in Fig. 7 to the 20 ISFS data systems currently available (since the distances are small). All of these data would be archived in the standard NIDAS format and distributed to the PI team in NetCDF.

The European Windscanner Consortium (WindScanner.eu) will provide data archiving and real-time display for all of the Perdigão data. The architecture of a new database for lidar and tower mounted instrumentation has been recently completed by this Consortium, which incorporates the latest standards in e-science and data-object-based identification, including cloud computing (Gomes, et al. 2014). This database has been developed to host the Windscanner and other lidar data, and can accommodate data from the other (e.g. in-situ) measurement systems that would be deployed for Perdigão. Being a European national infrastructure project, Windscanner offers training and collaborative opportunities to both EU and international participants.

As mentioned above, sharing of at least a subset of data in real-time will be crucial to operations planning. Since these products will utilize data from different groups, by using instruments from different manufacturers, this data exchange (also required for post-processing) will be greatly facilitated by use of a common data format. Real time sharing will also allow quick intercomparisons between certain instruments, as the domain is densely instrumented. The Perdigão investigators will use NetCDF for this format to enable producing data products from a variety of sources, such as distance-height presentations of all of the profiling lidars on a given transect.
ERANET+ projects such as Perdigão require open access to facilitate use of these data by the international community. All the US participants in principle have agreed to open access, but the final decision on a data use policy awaits the participant meeting in March 2016.

Figure 12: Data flow from sensor systems to users worldwide for Perdigão. Note that primary data hosting will be by the windscanner.eu, located in Porto.
References


Section I: Facilities, Equipment, and Other Resources

A confirmed list of equipment to be available for Perdigão is given below, including the cost estimate provided by the facility manager at EOL/NCAR for LAOF participation. Note that additional instrumentation may be available through EU and US participants through new acquisitions.

Table I.1: Perdigão Preliminary Cost Estimates

<table>
<thead>
<tr>
<th>Facility or Service (EOL/NCAR)</th>
<th>Estimated Cost</th>
<th>Funding Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISFS (Integrated Surface Flux System)</td>
<td>477K</td>
<td>NSF Deployment Pool</td>
</tr>
<tr>
<td>ISS (Integrated Sounding System; 915 or 449 MHz wind profilers with RASS and radiosonde launching capability)</td>
<td>414K</td>
<td>NSF Deployment Pool</td>
</tr>
<tr>
<td>Subtotal</td>
<td>891K</td>
<td></td>
</tr>
<tr>
<td>Water Vapor Lidar</td>
<td>71K</td>
<td>NSF Special</td>
</tr>
<tr>
<td>Special funds (Project Management, SA support etc.)</td>
<td>170K</td>
<td>NSF Special</td>
</tr>
<tr>
<td>Subtotal</td>
<td>241K</td>
<td></td>
</tr>
<tr>
<td>TOTAL (Deployment Pool &amp; Special)</td>
<td>1,132,000</td>
<td></td>
</tr>
</tbody>
</table>

Table I.2: Tower-based instrumentation potentially available from Perdigão participants; NCAR requires NSF approval

<table>
<thead>
<tr>
<th>Measurements</th>
<th>Quantity</th>
<th>Institution</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface Energy Balance</td>
<td>10</td>
<td>NCAR/EOL (ISFS)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Univ. Utah</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Univ. Notre Dame</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Univ. Calif., Riverside</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meteorology (including towers)</td>
<td>8</td>
<td>DTU Climatological packages (T, RH, radiation P)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15 (LEMS)</td>
<td>Univ. Utah (mean wind speed, wind direction, air temp, surface temp, solar radiation, soil moisture/temp)</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other Equipment</td>
<td>2</td>
<td>Univ. Notre Dame</td>
<td></td>
</tr>
<tr>
<td>LiCORS (H2O/CO2)</td>
<td>1</td>
<td>Univ. Oklahoma</td>
<td></td>
</tr>
<tr>
<td>LiCOR</td>
<td>1</td>
<td>Univ. Notre Dame</td>
<td></td>
</tr>
<tr>
<td>Krypton Hygrometer</td>
<td>1</td>
<td>Univ. Calif., Riverside</td>
<td></td>
</tr>
<tr>
<td>Combo hot-film/sonic system (dissipation)</td>
<td>2</td>
<td>Univ. Notre Dame</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Additional 3D Anemometers</td>
<td>14</td>
<td>NCAR/EOL (ISFS)</td>
<td>NCAR requires NSF approval</td>
</tr>
<tr>
<td></td>
<td>70</td>
<td>Danish Tech. Univ., DK</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>INEGI, PT</td>
<td></td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>Univ. Porto, PT</td>
<td></td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>Univ. Notre Dame</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>Univ. Utah</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Univ. Calif., Riverside</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Univ. Oklahoma</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Cornell Univ.</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Quantity</td>
<td>Institution</td>
<td>Comments</td>
</tr>
<tr>
<td>----------------------</td>
<td>----------</td>
<td>----------------------------------</td>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>Wind profiler</td>
<td>2, 915 or 449 MHz</td>
<td>NCAR/EOL (ISS)</td>
<td>NCAR Requires NSF approval</td>
</tr>
<tr>
<td>SODAR</td>
<td>1 Metek w/RASS</td>
<td>NCAR/EOL (ISS)</td>
<td>NCAR Requires NSF approval</td>
</tr>
<tr>
<td>Water-vapor DIAL</td>
<td>1</td>
<td>NCAR/EOL (RSF)</td>
<td>NCAR requires NSF approval + special funds.</td>
</tr>
<tr>
<td>Profiling LIDAR</td>
<td>3 WindCube V1, 2 Zephir VP, 1+ SpiDAR</td>
<td>Univ. Colorado, Cornell Univ.</td>
<td></td>
</tr>
<tr>
<td>Scanning LIDAR</td>
<td>2 HRDL/Halo, 1 Galion, 3 Windscanner, 15 Windscanner, 3 Windscanner, 1 Halo, 1 Halo, 2 Halo</td>
<td>NOAA/ETL, Cornell Univ., Fraunhofer IWES, DE, Danish Tech. Univ, DK, Danish Tech. Univ, DK, Univ. Oklahoma, Univ. Notre Dame, U.S. Army Research Lab.</td>
<td>Range: 6km, Range: 6km, Range: 1500m (total of 7 triple lidars from EU with a total of 21 lidars), Possible triple with Notre Dame</td>
</tr>
<tr>
<td>SODAR</td>
<td>1 SODAR/RASS, 2 SODAR, 1 SODAR/RASS</td>
<td>NCAR/EOL, Univ. Oklahoma, Univ. Notre Dame</td>
<td></td>
</tr>
<tr>
<td>Profiling Radiometer</td>
<td>2 AERI/Microwave, 1 Radiometrics, 1 Radiometrics</td>
<td>Univ. Oklahoma, Univ. Notre Dame, Univ. Colorado</td>
<td></td>
</tr>
<tr>
<td>Ceilometer</td>
<td>1 Vaisala</td>
<td>Univ. Notre Dame</td>
<td></td>
</tr>
<tr>
<td>DTS</td>
<td>1</td>
<td>U.S. Army Research Lab.</td>
<td>(Distributed temperature measurement system)</td>
</tr>
</tbody>
</table>

Table I.3: Remote-sensing and related systems potentially available from Perdigão participants. **Confirmed unless shaded; NCAR requires NSF approval**

<table>
<thead>
<tr>
<th>Type</th>
<th>Quantity</th>
<th>Institution</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1m wingspan UAV</td>
<td>1</td>
<td>Univ. Colorado</td>
<td>Fine-scale turbulence</td>
</tr>
<tr>
<td>4m wingspan UAV UAS fleet</td>
<td>1</td>
<td>Univ. Notre Dame</td>
<td>Turbulence, including fine-scale</td>
</tr>
<tr>
<td></td>
<td>3+</td>
<td>Univ. Porto, Portugal</td>
<td>PTU, possibly wind</td>
</tr>
<tr>
<td>Tethersonde</td>
<td>1 TLS</td>
<td>Univ. Colorado</td>
<td>Fine-scale turbulence</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Cornell Univ.</td>
<td>Meteorology</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Univ. Notre Dame</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 TLS</td>
<td>U.S. Army Research</td>
<td></td>
</tr>
</tbody>
</table>

Table I.4: Airborne systems potentially available from Perdigão participants.
<table>
<thead>
<tr>
<th>Lab</th>
<th>1</th>
<th>NCAR/EOL (ISS)</th>
<th>Part of wind profiling system, Vaisala system. 126 sondes requested. (NCAR requires NSF approval) InterMet system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiosondes</td>
<td>Univ. Notre Dame</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Digital Surface Mapping</td>
<td>1</td>
<td>Joanneum Research, Austria</td>
<td>Using lidar, Photogrammetry, Radargrammetry and Interferometry</td>
</tr>
</tbody>
</table>
J. Special Information and Documentation

This section contains information on European participation (Tables J1 and J2), the data management plan, information on prospective projects of the US participants (pages j-3 to j-10), a letter of collaboration from the co-PI Professor Julie Lundquist (page j-11) and support letters (pages j-12 and j-13). The participants section contains summary of projects to be proposed by University of Notre Dame, University of Colorado (Boulder), Cornell University, University of California (Berkeley), University of Oklahoma, University of Utah, University of California (Riverside) and Boise State University.

European Participation

**Table J1: European national participants in ERANet+ Wind Resources program**

<table>
<thead>
<tr>
<th>Country</th>
<th>Participant Organization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>Danish Energy Authority (DEA; Coordinator)</td>
</tr>
<tr>
<td>Belgium—Flemish Region</td>
<td>Department of Economy, Science, and Innovation (of the Flemish Government) (EWI)</td>
</tr>
<tr>
<td>Belgium—Walloon Region</td>
<td>Service public de Wallonie (SPW)</td>
</tr>
<tr>
<td>Germany</td>
<td>Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety (BMU)</td>
</tr>
<tr>
<td>Latvia</td>
<td>Latvijas Zinatnu Akademija (LAS)</td>
</tr>
<tr>
<td>Portugal</td>
<td>Fundação para a Ciência e Tecnologia (FCT)</td>
</tr>
<tr>
<td>Spain</td>
<td>Ministry of Economy and Competitiveness (MINECO)</td>
</tr>
<tr>
<td>Sweden</td>
<td>Energimyndigheten (SWEA)</td>
</tr>
<tr>
<td>Turkey</td>
<td>Scientific and Research Council of Turkey (TUBITAK)</td>
</tr>
</tbody>
</table>

**Table J.2: NEWA funding contributions and proposed expenditures by country. (The expenditures are larger, due to the EU contribution.)**

<table>
<thead>
<tr>
<th>Country</th>
<th>National Contribution (in €)</th>
<th>Proposed Expenditure (in €)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>2,000,000</td>
<td>3,537,583</td>
</tr>
<tr>
<td>Belgium—Flemish Region</td>
<td>500,000</td>
<td>1,035,432</td>
</tr>
<tr>
<td>Belgium—Walloon Region</td>
<td>350,000</td>
<td>719,260</td>
</tr>
<tr>
<td>Germany</td>
<td>1,500,000</td>
<td>2,237,648</td>
</tr>
<tr>
<td>Latvia</td>
<td>700,000</td>
<td>1,044,728</td>
</tr>
<tr>
<td>Portugal</td>
<td>500,000</td>
<td>746,269</td>
</tr>
<tr>
<td>Spain</td>
<td>1,500,000</td>
<td>2,238,806</td>
</tr>
<tr>
<td>Sweden</td>
<td>1,000,000</td>
<td>1,549,381</td>
</tr>
<tr>
<td>Turkey</td>
<td>750,000</td>
<td>1,271,391</td>
</tr>
</tbody>
</table>

Data Management Plan:

To avoid duplication of effort, the participants have requested that NCAR/EOL acquire the data from all tower-based sensors. EOL has extensive experience with most, if not all, of the sensors that the other groups would provide. All of these data would be archived in the standard NIDAS format and distributed to the PI team in NetCDF.

The European WindScanner Consortium will also provide data archiving and real-time display for Perdigão. The architecture of a new database for LIDAR and tower mounted instrumentation has been recently finished under this Consortium, which incorporates the latest standards in e-science and data-object-based identification. This database has been developed to host the Windscanner and other LIDAR data and can accommodate data from the other (e.g. in-situ) measurement systems that would be deployed for Perdigão (see: Gomes et al. 2014). These data will be made available to EOL immediately.
Sharing of at least a subset of the data in real-time will be crucial to operations planning. Since these products will utilize data from different groups, using instruments from different manufacturers, the data exchange (also required for post-processing) will be greatly facilitated by the use of a common data format such as NetCDF. A common format also will help in producing data products from a variety of sources, such as distance-height presentations of all of the profiling LIDARs. Final decision on the data format and modus operandi of data exchange await the first meeting of the international participants, in March 2016. The European Perdigão organizers, however, strongly favor open access, to facilitate use of these data by the international community. This sentiment is shared by the US participants.

A comprehensive database would be maintained by EOL/NCAR, which has been the norm in past complex projects involving LAOF.

To test the functionality of the database, existing data and previously not publicly released data from the Bolund (flow over a small escarpment), Falster (flow over a forest edge) and other experiments will be uploaded and made available for the partners, and soon thereafter to the general public.
**Project Name** - Perdigão: Multi-Scale Flow Interactions in Complex Terrain

**PI** - Harindra Joseph Fernando (Wayne and Diana Murdy Professor of Engineering and Geosciences, Department of Civil & Environmental Engineering and Earth Sciences, University of Notre Dame).

**Research Goals** – Complex-terrain flow studies have many important application areas, including air pollution, aviation and wind energy prospecting. Such flows encompass a range of scales, from macro- to micro-, the former characterizing terrain-modified synoptic flow whilst the latter paring down to energy-dissipating (Kolmogorov) scales. In the recent (2012, 2013) MATERHORN complex-terrain field campaigns, we observed some new types of flow interactions across spatial scales (Fernando & Pardyjak, 2013, EOS, 94 (36)), which include collisions/mergers between valley and slope flows, penetration of separated flows into valley atmosphere, and distortion of stably stratified flow by the terrain. Unsteadiness, spasmodic turbulence events and energy transfer between space-time scales are characteristics of these events, which have important repercussions. The placement of localized dense instrumentation clusters in MATERHORN was intended for different purposes, and hence was barely suitable for detailed studies of the above phenomena, but high-resolution distributed array of European instrumentation at Perdigão compounded with the possibility of deploying additional US instrumentation offer opportunities for intensive studies of the above (and possibly new) phenomena. The two-dimensionality of the twin-mountains at Perdigão allows further studies on upstream influence, flow distortion, separation at the hilltop and morning transition in a natural, yet almost idealized setting. 3D variation to the topography such as gaps and varying valley width, however, can complicate the flow. We plan to deploy a suite of instrumentation discussed in Section I.2 to study flow collisions and gap studies.

The research questions to address include: (i) Does the nominally two-dimensionality of the valley create slope/valley flow collisions different from those of 3D valleys wherein the events are spatially and temporally intermittent? What are the fluxes and turbulence associated with collisions and how can they be parameterized in meso- and micro-scale models? (ii) What mechanisms determine the interaction of thermally driven flows with overlying synoptic flow? (iii) How does the separated flow at the mountaintop penetrate in to the valley (e.g. separated flow), and how does it affect the mountain located behind? (iv) Unlike in 3D cases, under strongly stable conditions, a dividing streamline is absent in 2D flows, and hence may lead to upstream blocking. How far upwind does the blocked region persist, and what determines its scale? How does the presence of gaps change such upstream influence? (v) The 2D topography allows investigations of the morning transition from down- to upslope-flow and the breakdown of cold air in the valley in an idealized setting, allowing investigations on the mechanism proposed by Whiteman (*J. Appl. Met.*, 21, 1982) and Princevac & Fernando (*J. Fluid Mech.*, 216, 2008). Are these models realistic and under what conditions do they work?

**Role in the Overall Program** – The Notre Dame Group will mainly focus on flow dynamics in the complex terrain boundary layer, in particular the interaction of flows of different scales as well as synoptic flow interactions with the two-mountain system under neutral and stratified flow conditions. This will complement individual flow, turbulence, waves, radiative and plant-canopy processes in complex-terrain as well as microscale modeling and Large Eddy Simulation (LES) studies to be conducted by other US participants. The approximate two dimensionality of the flow is expected to have marked differences with 3D natural flows, but the idealized nature of flow in Perdigão offers unique opportunities for working synergistically with numerical and laboratory modelers. Europeans will mainly focus on developing a wind Atlas, micro-scale modeling and flow in upper part of the boundary layer.

**Expected Sponsor** – NSF (Negotiations are underway with ARL on additional LiDAR deployments)

**Cost Estimate (Research and Field Support)** – Field support: Equipment shipping and handling - $20K; travel support (2 people, 7 weeks, per Diem and airfare) - $28K; Material and supplies – $15K; equipment charges (LiDAR, service) – $20K. Research Support (Years 1-3): Salaries + benefits (years 1-3, PI and Grad student) - $ 180K; Publications – 8K; Other travel – 12K. Overhead - $ 147

**Total for 3 Years - $430,000**
**Project Name** - Perdigão: Boundary-Layer Dynamics and Turbulence Dissipation in Complex Terrain

**PI** - Julie K. Lundquist (Assistant Professor, Department of Atmospheric & Oceanic Sciences, University of Colorado at Boulder (CU-Boulder); Fellow, Renewable & Sustainable Energy Institute), Katja Friedrich (Assistant Professor, Department of Atmospheric & Oceanic Sciences, CU-Boulder), Dale Lawrence (Professor, Aerospace Engineering Sciences, CU-Boulder)

**Research Goals** – This field campaign will collect detailed data critical for improving atmospheric simulation models for applications in air pollution, aviation meteorology and wind energy production. The high density of European instrumentation at Perdigão, extended by additional US instrumentation proposed here, offers opportunities for intensive studies of flow and turbulence in complex terrain.

Embedded in the larger context of questions on flow in complex terrain, we plan to focus on: i) documenting and understanding the diurnal cycles of wind, turbulence, turbulence dissipation rate, and atmospheric stability at the Perdigão double-hill site and ii) how this daily cycle in atmospheric stability affects the evolution of wind speed and turbulence at turbine altitudes and the resulting evolution of wind turbine loads and wind turbine wakes in complex terrain. We plan to compare these observations to simulations with mesoscale WRF, the large-eddy simulation (LES) mode of WRF (Mirocha, Lundquist, and Kosovic *Mon Weather Rev* 138 2010), and WRF-LES with an actuator disk model for representing a wind turbine and its wake (Mirocha, Lundquist, et al. *J Renew Sust Energy* 6 2014 and Aitken, Lundquist et al. *J Renew Sust Energy* in review, 2014).

**Role in the Overall Program** – The CU-Boulder team plans to deploy instruments to collect both routine and intensive sets of observations. On a routine basis, 2 Doppler wind LiDARs would quantify winds and turbulence between 40m and 220m above the surface while a microwave radiometer would provide temperature and humidity profiles between the surface and 10 km. We propose that these routine measurements to be supplemented with intensive observations from a tethered lifting system (TLS), which observes winds, temperature, humidity, and turbulence dissipation rate between the surface and 1-2 km, and unmanned aerial systems (UASs) instrumented for mean winds, temperature, and humidity observations as well as for turbulent dissipation rate estimations. Optimal siting will be determined in coordination with other project partners, from Europe and the US. The CU-Boulder instrumentation will be operated at the Perdigão site by PI Lundquist, co-PI Lawrence, a technician and 2 graduate students.

The team has extensive experience with *in situ* and remote sensing of the atmospheric boundary layer: all the instruments proposed above have been used by PI Lundquist and Co-I’s Friedrich and Lawrence in detailed flow studies either within a 300MW wind farms in the US (LiDARs, radiometer; see Rajewski, Lundquist et al. *Bull Amer Meteor Soc* 94 2013; Rhodes and Lundquist *Bound-Layer Meteor* 149 2013) or in observational campaigns at the Dept. of Energy’s National Wind Technology Center (tethered lifting system, UASs, LiDARs, radiometer; see Friedrich et al. *Geophys Res Lett* 39 2012 ; Aitken et al., *J Atmos Ocean Tech* in press 2014; Lundquist and Bariteau, *Bound-Layer Meteor* in review 2014). All instruments, including the *in situ* instrumentation (TLS and UAS) have software developed for transmitting data in real-time during data collection to enable optimization of the observational campaigns. The LiDAR systems have collected important data quantifying inhomogeneous flow such as that in wind turbine wakes (Rhodes and Lundquist *Bound-Layer Meteor* 149 2013), and that experience will be critical in interpreting lidar measurements in the complex terrain of Perdigão.

**Expected Sponsor** – NSF

**Cost Estimate (Research and Field Support)** – Field support: $214 K (includes transportation, carnet, and operation costs for lidars, radiometer, UAS, and TLS facilities, salaries for PI (1m) and co-PI (1m), technician (3m), and 2 grad students (3m) to cover time in the field and during set-up/take-down periods, plus indirect costs). Research Support (Years 1-2): Salaries + benefits + tuition waivers (years 1-2, PI and 1 Grad student) - $ 103K; Publications – 9K; Travel – 9K. Overhead - $71 – Total 186K (2 years). Total for 3 Years - $400,000
**Project Name** - Perdigão: Wind Energy Meteorology and Turbine Wakes

**CoPIs** - Rebecca J. Barthelmie, Croll Fellow and Professor of Mechanical Engineering and Sara C. Pryor, Professor of Earth and Atmospheric Sciences, Cornell University.

**Research Goals** – Improved understanding of the mean and fluctuating components of the flow across and within wind farm arrays and across the swept area of wind turbine rotors is critical to improved wind power plant design and operation. The New European Wind Atlas project with which we will collaborate will generate high-resolution analyses of wind and flow regimes over Europe and more specifically will lead to new insights into flow and wake behavior in complex and inhomogeneous terrain that has universal application. The Cornell group anticipates deploying the instrumentation described below during their participation in the planned Perdigão field experiment and will run targeted WRF simulations to support data analysis. The contribution will be focused on and two key research questions. (i) To what degree are wind and turbulence profiles through the heights relevant to wind energy ‘non-ideal’ relative to theoretical predictions made by invoking similarity theory (or derivatives thereof)? (ii) Can the meandering component of wind-turbine wake expansion be quantified and differentiated from diffusive expansion (with a specific focus on wake behavior in complex terrain) using scanning lidar to track wake characteristics downstream? (Barthelmie and Pryor, 2013: *Appl Energ*, 104, 834-844. Barthelmie, Hansen and Pryor, 2013: *P IEEE*, 101, 1010-1019.).

| Pulse scanning lidar (Galion) | Wind speed (ws), direction (wd), turbulence intensity (TI). Details = f(operating mode). Vertical range ~1000 m horizontal range 1-4 km |
| Continuous wave vertically-pointing Doppler lidars (ZephIR 150 and 300) | 2 ws, wd, TI. Vertical range 40-200 m (5 or 10 heights) |
| Gill WindMaster Pro 3-D sonics | 3 u, v, w, T at 20 Hz |
| Anasphere tethersonde | Profiles ws, wd, T, RH to 1 km |
| Other: TSI CPC3788, 3025, FMPS3091, APS3321, Licor | Fluxes of other scalars (particles, CO2, H2O), particle size distribution (relevant to lidar retrievals) |

**Role in the Overall Program** – Measurements and modeling of fluxes, wind profiles and wakes. The team from Cornell University has many years of fieldwork experience with scalar flux measurements and remote sensing and in situ measurements observations at wind farms (in the context of resource and wake studies; e.g. Barthelmie et al., 2014: doi: 10.1175/BAMS-D-12-00111.1). Rebecca Barthelmie previously held positions at DTU-Risø in Denmark, where she ran the offshore wind measurement network. She is author of ~110 journal papers and is co-chief editor of the journal *Wind Energy*. She led the wind turbine wake workpackage of the EU UPWind project, and currently leads the ‘3D Wind’ project funded by the Department of Energy which is focused on use of remote sensing technology to describe flow in complex environments and a NSF project that is focused on measurement strategies to quantify wind characteristics and wakes for large wind farms. Sara Pryor has published ~120 journal articles, and is editor of the *Journal of Geophysical Research: Atmospheres*. She has extensive experience with scalar flux measurements in inhomogeneous environments (Pryor et al., 2011: *Atmos Chem Phys*, 11 1641-1657) and is currently lead on an NSF project focused on wind resource and extreme wind characterization (Pryor and Barthelmie, 2013: In *Climate Vulnerability: Understanding and Addressing Threats to Essential Resources*, Academic Press; Pryor et al., 2011: *Atmos Chem Phys*, 11 1641-1657). Both Barthelmie and Pryor have long-standing collaborations with a number of the European groups involved in the European Wind Atlas initiative and the planned Perdigão experiment.

**Expected Sponsor** - NSF

**Anticipated cost of participation in a 4 weeks field experiment in Portugal and related modeling & data analysis** Costs for experiment: Shipping equipment + carnet: $22,000. Salaries+fringe: $125,000. Travel for PI’s +graduate students: $16,000. IDC: $118,000. Graduate student support (salary, tuition, health) = $98,000.

**Total for two years - $347,000**
**Project name** - Perdigão: Improved turbulence closure models and the immersed boundary method for LES of flow over complex terrain

**PI** - Fotini Katopodes Chow (Associate Professor, Civil and Environmental Engineering, University of California, Berkeley)

**Research Goals** - Improved turbulence closure models and representation of terrain are crucial areas of need for large-eddy simulations over complex terrain, with profound impacts for wind energy applications. Previous work by the PI on Askervein Hill indicated that the choice of turbulence model was critical for accurately predicting wind speedup, turbulence intensity, and separation over the hill (Chow & Street, *JAM*, 48, 2009). Previous work also showed that numerical errors due to terrain-following coordinate systems are non-negligible for moderate or steep slopes. The immersed boundary method (IBM) was implemented into WRF to mitigate such errors, which enabled enable simulation over very steep slopes (Lundquist et al., *MWR*, 140, 2012). In this approach, the model topography is “immersed” within a Cartesian grid, and interpolation techniques are used to enforce boundary conditions on the immersed surface. The IBM approach has the ability to represent complex mountainous terrain (e.g. Granite Mountain, Utah) with ~10 m resolution even when terrain slopes approach 90 degrees (which cannot be handled using traditional WRF coordinates). Current work with the MATERHORN project is extending WRF-IBM to handle Monin-Obukhov theory for the surface momentum fluxes.

The Perdigão field site includes steeper, more complex terrain than Askervein, and with dense instrumentation it will provide an excellent test bed for developing turbulence closure models and gridding techniques. The proposed work will focus on further development and testing of the immersed boundary method, incorporating real lateral boundary forcing, improved turbulence models and surface roughness effects, including tall vegetation. We propose to:

1. Incorporate real lateral boundary conditions and improved surface roughness with WRF-IBM by leveraging ongoing work, also in collaboration with LLNL. We will include vegetation effects and study the role of surface roughness on flow separation and turbulent structures. We will develop a nesting procedure that will allow WRF-IBM simulations to be nested within WRF simulations, to enable mesoscale to microscale nesting. This requires development of new coupling strategies to address grid discontinuities when transitioning from terrain-following to IBM coordinates.

2. To couple WRF-IBM with the dynamic reconstruction turbulence closure models previous found to perform well in the Askervein Hill study (and numerous other studies). We will simulate as fine as 10 m resolution for short time periods, to investigate turbulent structures that can affect wind turbine performance. We will investigate stably-stratified turbulence, extending previous work over rolling hills in the CASES-99 field campaign, which found evidence of gravity waves, intermittently stable flow, and demonstrated the critical role of topography, even in mildly complex terrain (Zhou & Chow, *JAS*, 70, 2014).

**Role in the Overall Program**

The UC Berkeley group will focus on LES model development (immersed boundary method and turbulence models) and simulation of specific flow events (e.g. intermittent turbulence) to complement detailed field experiments. Other modeling groups will focus on developing multi-GPU accelerated methods, a wind map and micro-scale modeling. We will leverage Dr. Katherine Lundquist’s LLNL-supported research on numerical modeling efforts.

**Expected Sponsor**: NSF

**Cost Estimate (Research and Field Support):** – Research Support (Years 1-3): Salaries + benefits (PI and grad student) - $90K; Publications/Travel – $10K. 
**Total for 3 years ~ $300,000**
Project Name - Perdigão: Stability Effects on the Boundary-layer Structure in Complex Terrain

Pls - Petra Klein (Associate Professor and Edith Kinney Gaylord Presidential Professor, School of Meteorology, University of Oklahoma), David Turner (Physical Scientist, Forecast Research and Development Division, National Severe Storms Laboratory, Norman, OK)

Research Goals – Complex-terrain flow studies have many important application areas, including air pollution, aviation and wind energy production. The high-resolution distributed array of European instrumentation at Perdigão, along with the prospect of additional US instrumentation being deployed, offers unprecedented opportunities for intensive studies of flow and turbulence structure in complex terrain. The collected data sets are expected to advance the scientific understanding and forecasting tools for application areas with broad impacts.

Within the larger scope of research questions raised in SPO/EDO, we plan to focus, in particular, on: (i) what dynamical processes determine the diurnal variation of wind, temperature, and humidity profiles at the Perdigão site? (ii) how the flow and turbulence structure within the valley is altered by atmospheric stability and synoptic scale conditions?, and (iii) how these findings influence the siting and performance of wind turbines in complex terrain. The collected data will be compared against data sets collected in previous single-mountain experiments as well as 3D terrain and model outputs of WRF and LES runs.

Role in the Overall Program – We propose to deploy the mobile ground-based remote sensing thermodynamic profiling facility CLAMPS (OU/NSSL), which consists of three advanced remote sensors: (a) a Halo Photonics Doppler lidar for measuring the horizontal winds in the boundary layer up to cloud base; (b) a multi-channel microwave radiometer (MWR) for providing thermodynamic profiles during non-precipitating weather conditions; and (c) an AERI infrared spectrometer that also provides thermodynamic profile information (at higher vertical resolution than the MWR). We will be able to provide profiles of temperature, water vapor, and winds in the atmospheric boundary layer at better than 5-minute temporal resolution. This high temporal resolution will allow us to study in-depth the transition of the flow and turbulence structure in the morning and evening. The lidar will be operated using different scanning strategies to get both mean flow and turbulence data. The optimal siting and choice of scanning strategies will be determined in coordination with other project partners from Europe and the US. The AERI and MWR will provide important information about atmospheric stability within the valley. The CLAMPS facility will be operated at the Perdigão site by PI Klein, a technician and a graduate student. The scientific analysis will additionally be supported by Co-PI Turner, who will test and apply different retrieval algorithms for the AERI and MWR data sets.

CLAMPS is currently developed as part of an NSF MRI grant. All instruments have been purchased and tested. The instruments are currently being integrated into a trailer, which can be pulled by a pick-up truck. The system can be operated using a generator or wall-outlet. In the summer of 2015, CLAMPS will be operated by the PI's during the PECAN experiment. The team has extensive experience in in-situ and remote sensing of the atmospheric boundary layer and the PI currently also collaborates on a funded research project with Lawrence Livermore, which focuses on the suitability of lidar observations for wind energy studies.

Expected Sponsor – NSF (D. Turner’s effort will be supported through NOAA)

Cost Estimate (Research and Field Support) – Field support: $235 K (includes transportation and operation costs for CLAMPS facility, salaries for PI (2 mo.), technician (3 mo.), and 2 grad students (3 mo.) to cover time in the field and during set-up/take-down periods, plus indirect costs). Research Support (Years 1-2): Salaries + benefits + tuition waivers (years 1-2, PI and 1 Grad student) - $ 87K; Publications – 6K; Travel – 9K; Network connections – 2K. Overhead - $ 50 – Total 154K (2 years).

Total for 2 years: $389,000
Project Name - Perdigão: Evening transition and turbulent flux characterization in mountainous terrain

PI - Eric R. Pardyjak, Professor, Mechanical Engineering, University of Utah

Research Goal - The primary goal of this project is to better understand turbulence processes in mountainous terrain, particularly during the evening transition when the atmospheric boundary layer is highly non-stationary. This transition period is particularly critical as it leads to the set-up of the nocturnal boundary layer and the potential decoupling of winds from the surface. The Perdigão site, while idealistic and approximately 2D nominally, it has sufficient complexity to exhibit a series of dominant events during evening transition, depending on levels of synoptic flow influence. We will quantify fluxes of momentum, heat, moisture and CO₂ with the goal of developing a baseline understanding of pre-wind farm fluxes over the undulating terrain of Perdigão. Further, we will address the challenges and uncertainty in those measurements. In particular, trace-gas flux measurements in complex terrain should be interpreted with caution given the breakdown of assumptions associated with heterogeneity and stationarity, amongst others (e.g. Feigenwinter et al., Agr. Forest Met., 148, 2008; Aubinet et al., Ecol. App., 18, 2012). We will work to utilize the best existing technologies and theories to quantify fluxes, but we will also attempt to develop improved understanding of the methodologies. Finally, we will use the datasets to investigate improved turbulence flux parameterizations for mesoscale models.

Role in the Overall Program - Pardyjak and his students will deploy equipment during the field experiments with measurements focusing on near surface turbulence processes. Our group has extensive experience in making turbulence measurements in mountainous terrain. We will use this expertise to help in the experimental planning as well as conducting the experiments. We will deploy two 20m eddy-flux towers with infrared gas analyzers for continuous measurements of momentum, heat, moisture and CO₂ fluxes at a single height, as well as sonic anemometers, thermocouples and low speed humidity sensors at four additional levels to characterize flow near the surface. These stations will be set up as full surface energy budget stations with radiation measurements. In addition, the stations will include soil property sensors to better understand the role of the ground heat/moisture fluxes and energy/moisture storage in the soil. During the intensive observational campaigns, we will deploy two scintillometry systems in the study region to capture the spatially averaged sensible heat fluxes over distances ranging from ~500m-2km. These distances are closer to typical grid resolutions for mesoscale weather predictions. Finally, we will deploy approximately ten LEMS (low-cost energy budget measurement stations) throughout the region. These solar powered stations, developed at the University of Utah EFD lab, are easily deployed in mountainous terrain. They monitor incoming solar radiation, air temperature, relative humidity, surface temperature, soil temperature and soil moisture. With relatively large numbers, they help provide an understanding of spatially varying variables. We will use the datasets to better understand the physics of surface layer fluxes during transition and develop new parameterizations.

Expected Sponsor – NSF

Cost Estimate (Research and Field Support) - Field support: Equipment maintenance + Shipping + travel + lodging: $31K. Research Support (Years 1-3): Salaries + benefits (years 1-3, PI and Grad student) - $ 122.5K; Non-field Supplies: $600; Publications – 5K; Travel – 5K. Overhead - $80.4.

Total for 3 years - $244,500
Project Name - Perdigão: Surface Energy Balance, Turbulence and Internal Waves in Complex Terrain

PI: - Marko Princevac (Associate Professor, Department of Mechanical Engineering, University of California, Riverside)

Research Goals – Slope flows in complex terrain are receiving increased attention due to their relatively recently acknowledged importance in air pollution transport and potential for wind energy production. Models have been developed to describe their intensity (mean wind speed), vertical structure (depth and layered structure governed by different physics), and turbulence and mixing. These models include: Princevac et al. (JFM, 533, 2005; JAS, 65, 2008) for downslope flows, Princevac and Fernando (JFM, 616, 2008) for morning break up of nocturnal stable cold pools, Princevac and Fernando (Phys. Fluids, 19(10), 2007) for initiation of upslope flows and Hunt at al. (JAS, 60, 2003) for fully developed upslope flows and evening transition. Although these models describe the complete diurnal cycle of slope flows, the needed inputs are not commonly available from readily available field observations or from common meteorological stations. For example, to calculate the upslope mean velocity as per Hunt et al. (2003) one needs the convective velocity scale which follows from the sensible heat flux. Further, although the models for flow intermittency on simple slopes are developed, it is not clear how this intermittency is affected by realistic interactions of multiple slope flows, valley and synoptic flows and irregular terrain features, slope discontinuities, and heating non-uniformities due to the terrain shading and land use effects.

We will address the following research questions: (i) How does the complex topography affect the slope flow intermittency? (ii) What are the effects of slope discontinuities and non-uniformities in heating/cooling on the slope flow structure (mean velocity, turbulence and flow depth)? (iii) Under which conditions the up/downslope flows are detrained from the surface? (iv) Can the ratios of four radiation components (incoming and outgoing long and short radiation) be a good representation of the land use? If so, can the sensible and latent heat fluxes be modeled using only a few components of radiation data at a specific site?

We plan to deploy towers instrumented with sonic anemometers for detailed turbulence measurements and radiometers, hygrometers and soil heat-flux plates for detailed energy balance measurements.

Role in the Overall Program – The UCR group will focus on the intermittence of and wave-like features embedded in slope flows (e.g., Princevac et al., JAS, 65, 2008), which can have adverse effects on wind turbine efficiency. If the slope flow period/frequency for a specific site is known in advance, one may be able to optimize the turbine and take advantage of wind pulsations. With this in mind, a special attention will be given to the internal wave phenomena in complex terrain under the framework outlined in Monti et al., Env. Fluid Mech., 14, 2014). Data from sonic anemometers will be filtered and FFT is performed to delineate dominant frequencies at each measurement site. These frequencies will be analyzed with respect to local slope, local stability parameters (Richardson number/Obukhov length) and turbulence parameters such as friction velocity, turbulent kinetic energy (TKE) and non-dimensional rms velocities. Next we will focus on the near surface energy balance. We will build models for sensible and latent fluxes based on measured radiation components. Out work will complement those of the other investigators, in that the focus will be on waves and surface energy balance.

Expected Sponsor – NSF

Cost Estimate (Research and Field Support) – Field support: $10K per year. Research Support: Salaries + benefits for Graduate student - $40K and PI – $12K per year. Overhead - $33K per year

Total for 3 years - $285,000
**Project Name** - Perdigão: Multi-scale High Resolution Study of Thermally-Driven Winds over Arbitrarily Complex Terrain

**PI:** - Inanc Senocak, Associate Professor, Boise State University

**Research Goal** – Complex terrain flows are characterized by very high Reynolds numbers with a rough boundary layer and different stratification regimes. The linear theory of Jackson and Hunt helps explain flows over low hills. A fundamental understanding of complex terrain flows is missing, which forces numerical modelers to apply theory from flat terrain flows to complex terrain, and mostly under neutral stratification, which can be inadequate. Because high Reynolds number computations are under resolved in the vicinity of a rough surface, numerical treatment of the surface and turbulence parameterizations benefits directly from the availability of a theory of winds over complex terrain. Therefore the goal is to better understand the influence of thermal stability and vegetation cover turbulence over complex terrain using very fine resolutions. Numerical simulations will be used to seek answers to the following science questions: i) What are the mechanisms by which near-wall turbulence is created anisotropically over complex terrain? Do these mechanisms persist in the slope-roughness space? ii) How do turbulent length scales vary in the leeward and windward side of the terrain as a function of stratification levels? iii) What are the effective terms (in the leeward and windward side of the terrain) and the role of higher order moments in the turbulent kinetic energy budget?

**Role in the Overall Program** – Senocak will deploy a micro-scale model (GIN3D in-house model) and a mesoscale model (WRF) in a multi-scale fashion to provide a very-high resolution test-bed model that will help achieve one of the chief scientific goals of the Perdigão project, which is to improve the numerical models and parameterizations used in complex terrain wind applications. GIN3D is a multi-GPU parallel large-eddy simulation wind solver for complex terrain. It is based on a buoyancy-driven incompressible formulation and an immersed boundary method for arbitrarily complex terrain. Each code will be executed at resolutions that are best fit for the underlying parameterizations. Lateral boundary conditions over complex terrain will be formulated to admit mesoscale wind and turbulence information such that the energy cascade can be sustained within the micro-scale model without resorting to expensive recycling approaches. Senocak will also simulate (within GIN3D) the single wind turbine in the Perdigão area using an actuator line wake model to investigate the performance of a wind turbine in complex terrain environment, and its potential impact on the surface fluxes of heat and moisture in the wake.

Senocak’s research on complex terrain flows has been funded by an NSF CAREER grant from the Energy for Sustainability Program, a collaborative grant from the Algorithms for Threat Detection Program, and most recently through the Sustainable Software Infrastructure Program at NSF. Although the immersed boundary method (IBM) is highly flexible for complex geometry at moderate Reynolds numbers, it fails to predict the correct turbulent stresses when used in conjunction with a turbulence model for high Reynolds number flows. In a turbulent channel flow simulation, the issue manifests itself as a severe log-layer velocity mismatch. Therefore a particular research focus of Senocak has been to improve the calculation of turbulent stresses at an arbitrarily complex terrain by coupling the IBM to the subgrid-scale model. The Perdigão Project will provide Senocak with the high-resolution information to further refine the calculation turbulent stresses within an immersed boundary formulation under different stability regimes. This work will complement and cross-fertilize with Tina Chow’s work to include an IBM within the WRF model.

**Expected Sponsor** – National Science Foundation

**Cost Estimate (Research and Field Support)** - Budget will support a graduate student and one-month of Senocak’s time for each year. Budget includes travel for one conference presentation per year for the PI and the graduate student. **Total for 3 years - $232,000**
December 29, 2014
University of Colorado at Boulder
Boulder, CO 80309-0311

Prof. Harindra Joseph Fernando
Civil and Environmental Engineering and Earth Sciences
University of Notre Dame, Notre Dame, IN 46556

Dear Prof. Fernando,

I am writing to confirm my enthusiastic participation and collaboration in the “Scientific Program Overview (SPO) for ERANET+: Perdigão Field Experiment” proposal that you are submitting to the National Science Foundation as PI with myself as co-PI. Our European colleagues, under the auspices of the New European Wind Atlas (NEWA) project, are making considerable investments in the Perdigão field experiment. Our proposal seeks funding to support the activities of US investigators to extend those measurements to explore fundamental questions in atmospheric flow in complex terrain. By leveraging substantial European investment in the Perdigão experiment for wind energy applications, our efforts and those of other US investigators will result in unprecedented insights. Building on two planning meetings in the US (2013 and 2014) as well as a site visit to Perdigão in September of 2014, we are requesting funding to carry out field measurements and modeling studies based on a spring/summer 2017 Perdigão deployment.

As co-I for the American component of Perdigao, I bring experience in organizing, designing, and executing boundary layer field experiments (CASES-97, CASES-99, JU2003), including wind energy experiments (TWICS-2011, CWEX-11, TODS, and CWEX-13). My research group and I utilize Doppler lidars for wind and turbulence profiling, a tethered lifting system for detailed airborne turbulence measurements, a microwave radiometer for temperature/moisture profiling, and unmanned aerial systems. We collaborate extensively with national laboratories and other universities, as well as wind energy industry partners and instrument developers. Beyond our experimental toolkit, we use mesoscale and large-eddy simulations to explore boundary-layer dynamics and to assess the effects of wind energy development on local environments.

I fully intend to submit a full proposal to NSF in the near future for my graduate students and I to participate in the important 2016-2017 Perdigão field experiment.

Kind Regards,

Prof. Julie K. Lundquist
Dept. of Atmospheric and Oceanic Sciences
Fellow, Renewable and Sustainable Energy Institute
University of Colorado at Boulder
jlundquist@colorado.edu
http://atoc.colorado.edu/~jlundqui
voice: 303/492-8932
Physical and Dynamic Meteorology Program
Division of Atmospheric and Geospace Sciences
National Science Foundation

Ladies/Gentlemen,

This is to express our fullest support for the proposal entitled "The Perdigão Field Experiment" submitted to NSF by Harinda Joseph Fernando and Julie Lundquist. It seeks support for field and numerical studies of flow over two parallel mountains located surrounding the Vale Cobrão, near the town of Perdigão in Portugal. The measurements assets of the US investigators will complement those that will be deployed by a European research team directed by me. We are funded by the European Union (EU) and nine national funding agencies at a level of slightly more than 13 M Euros to develop a new European Wind Atlas in support of wind energy harvesting, including the development of fundamental understanding of complex terrain flows at microscale. The funding instrument involved is the ERANET+ Program of the EU. There are eight participating countries for the project, and the overall program includes five field and a myriad of numerical studies. Currently, 96% of the budget has been secured with one last country expected to sign soon. The Perdigão experiment is one of the largest and principally process-oriented studies of the wind atlas project. The five-year EU project start date is May 1.

One of the remarkable and unprecedented aspects of the experiment is the deployment of seven windtracer triple-lidar systems that include twenty one lidars, both long and short range. These systems will allow scanning of large flow volumes in the slope-valley system as well as the approach and wake flows of the mountains. Lidars together with other remote sensors and high resolution point probes to be deployed by the US group and others will provide a unique benchmark data set for process studies and microscale model validations. The experimental studies are to be augmented by novel numerical modeling at microscale, thus expanding research horizons for numerous research groups all over the world.

We will provide some necessary logistical support for the US participants, and look forward to meld the technical expertise and instrumentation of the European and US groups at the Perdigão field study. We think the time is ripe for more cross-Atlantic research collaboration.

Sincerely,

[Signature]

Professor Jakob Mann, Ph.D.
President of European Academy of Wind Energy (EAWE)
DTU Wind Energy
Technical University of Denmark
tel: +45 4677 5019
e-mail: jmeq@dtu.dk
Program Officer  
Physical and Dynamic Meteorology Program  
Division of Atmospheric and Geospace Sciences  
National Science Foundation  

Dear Sir/Madam:  

The U.S. Army Research Laboratory (ARL) is interested in obtaining high quality measurements in complex terrain at a decameter scale resolution for dispersion model validations with battlefield applications. We understand that the proposal, "The Penedo Field Experiment," submitted to the National Science Foundation by Joseph Fernando and Julie Lundquist directly addresses our research interests in studying small-scale atmospheric flows. We would like to express our interest in joining the project by deploying several atmospheric sensing instruments, specifically, two LiDARs (Light Detection and Ranging) and a Distributed Measurement System (DTS). Our involvement would provide an additional application area for the proposed work, beyond wind energy.  

Because of ARL’s keen interest in the proposed topic, the Army Research Office recently funded a workshop at Notre Dame on microscale modeling and observations in complex and heterogeneous terrain. Four of our scientists participated in the workshop, and provided science input to the projects' science goals. We are also developing a new ARL Meteorological Sensor Array at White Sands Missile Range in New Mexico for microscale and mesoscale measurements that could yield further insights to the Penedo measurements. We are aware that ARL is not eligible for NSF funding, but we will seek alternate sources of funding to participate in this very important field study.  

In the last few years, we have had a positive experience in working with the Notre Dame scientists. We look forward to working with Notre Dame in the future, and are anxious to see the proposed project come to fruition.  

Sincerely,  

Pamela A. Clark  
Chief, Battlefield Environment Division