MOUNT**A**IN **TER**RAIN ATMOSP**H**ERIC M**O**DELING AND OBSE**R**VATIO**N**S PROGRAM

The MATERHORN:

Toward Improving the Prediction of Mountain Weather

by

H.J.S. Fernando

Environmental Fluid Dynamics Laboratories
Department of Civil Engineering & Geological Sciences
and
Aerospace & Mechanical Engineering
University of Notre Dame

Multi University Research Initiative (MURI)

June 2011 – Topic # 7 – improving mountain terrain weather

Principal Investigators:

H.J.S. Fernando
(ND) -- MATERHORN-T&P

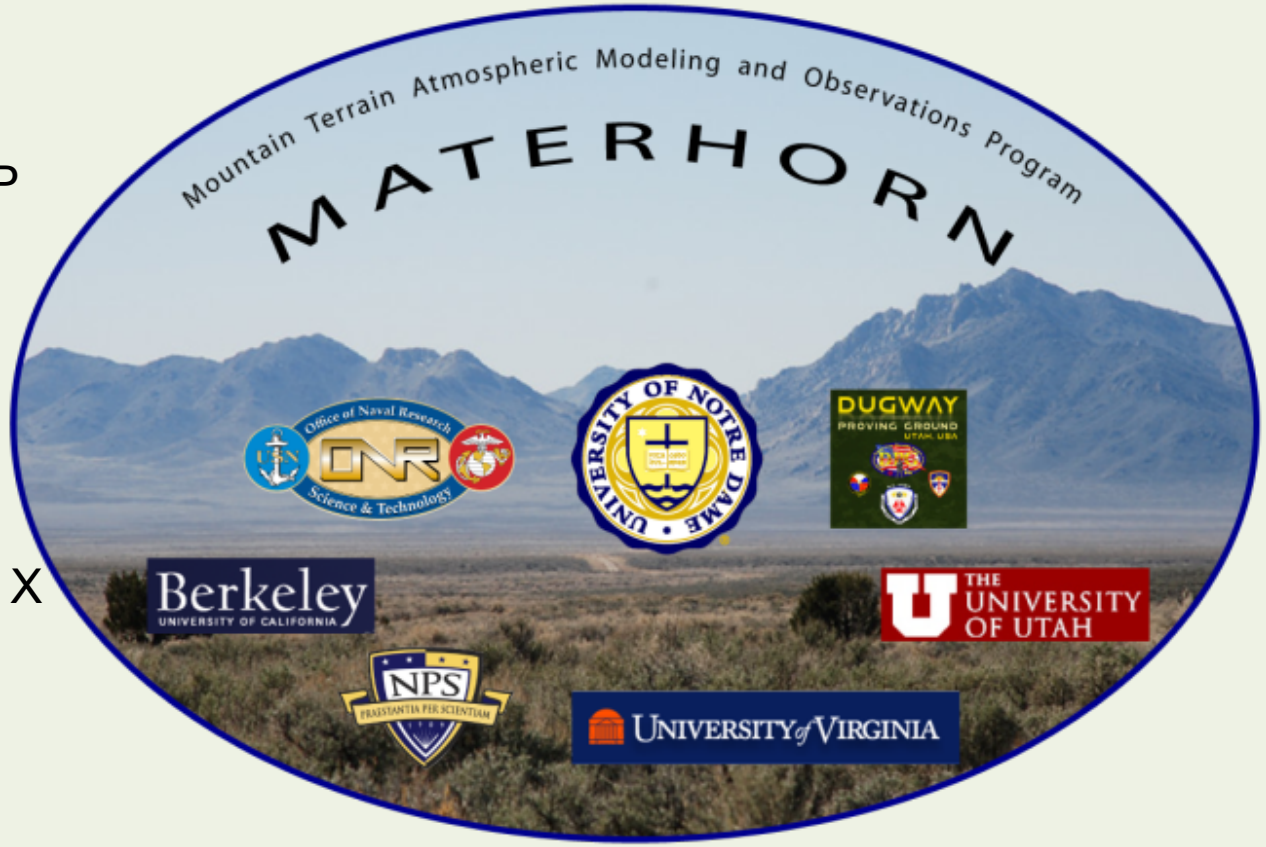
Eric Pardyjak
(UU) -- MATERHORN- X
Stephan

Stephan De Wekker
(UVA) -- -- MATERHORN- X

Josh Hacker
(NPS) -- MATERHORN-M

Tina Chow
(Berkeley)

John Pace, Dragan Zajic
(Dugway)
Jim Doyle (NRL)



Collaborators

NCAR
Princeton University
Oregon State University
University of Colorado, Boulder

IIBR, Israel
University of Bergen, Norway
University of Vienna, Austria

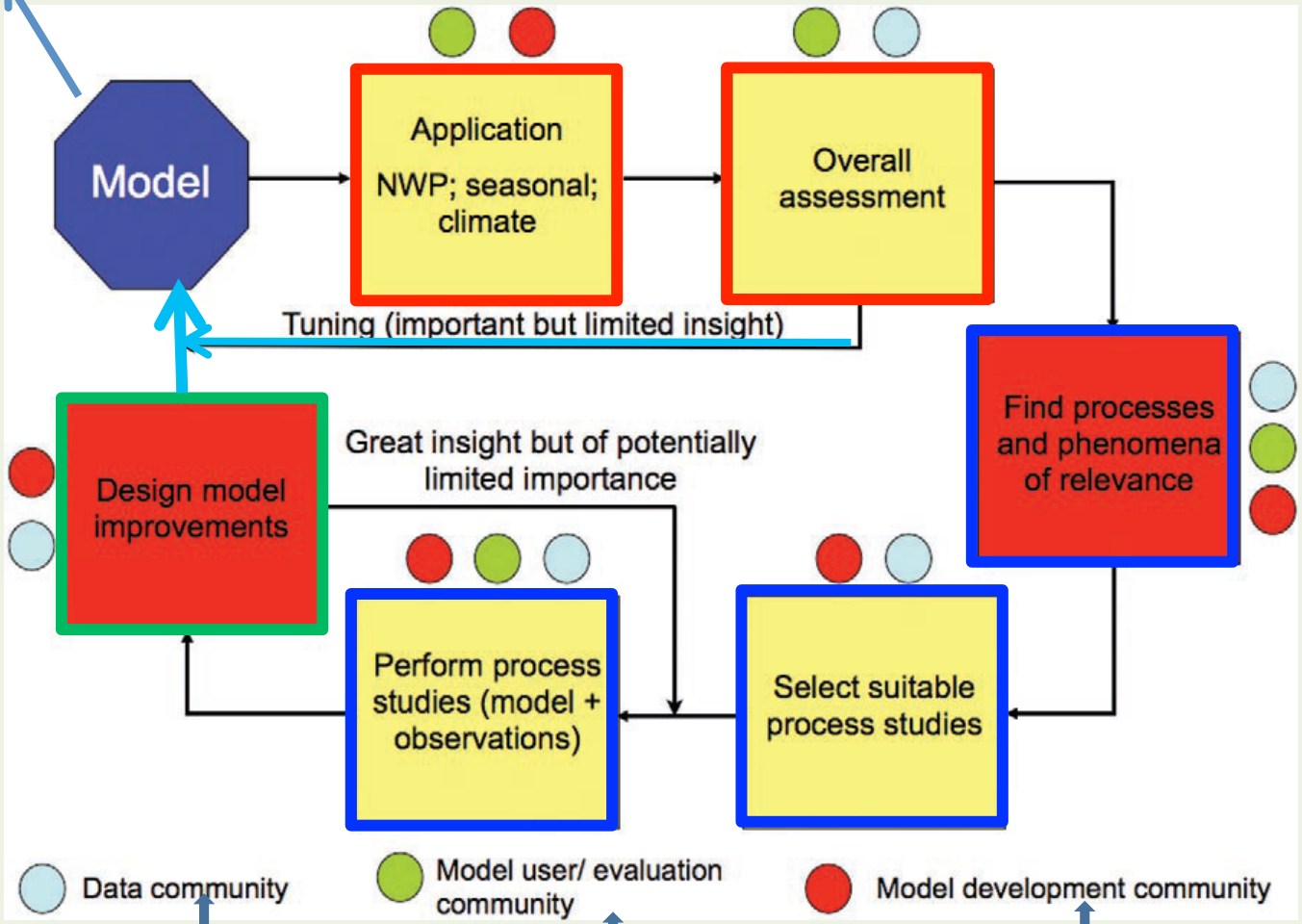
MATERHORN Goals

- identify and study the limitations of current state-of-the-science mesoscale models for mountain-terrain weather prediction
- develop scientific knowledge, technologies and tools to help realize leaps in predictability
- Assemble a group of skilled researchers with synergy - atmospheric scientists, fluid dynamicists, numerical and theoretical analysts, engineers and applied mathematicians
- Embrace all methodologies - integrate systematically
- Pursue new paradigms of modeling?

Approach

(Jakob; BAMS, 2010)

Improved Modeling of Complex Terrain Weather

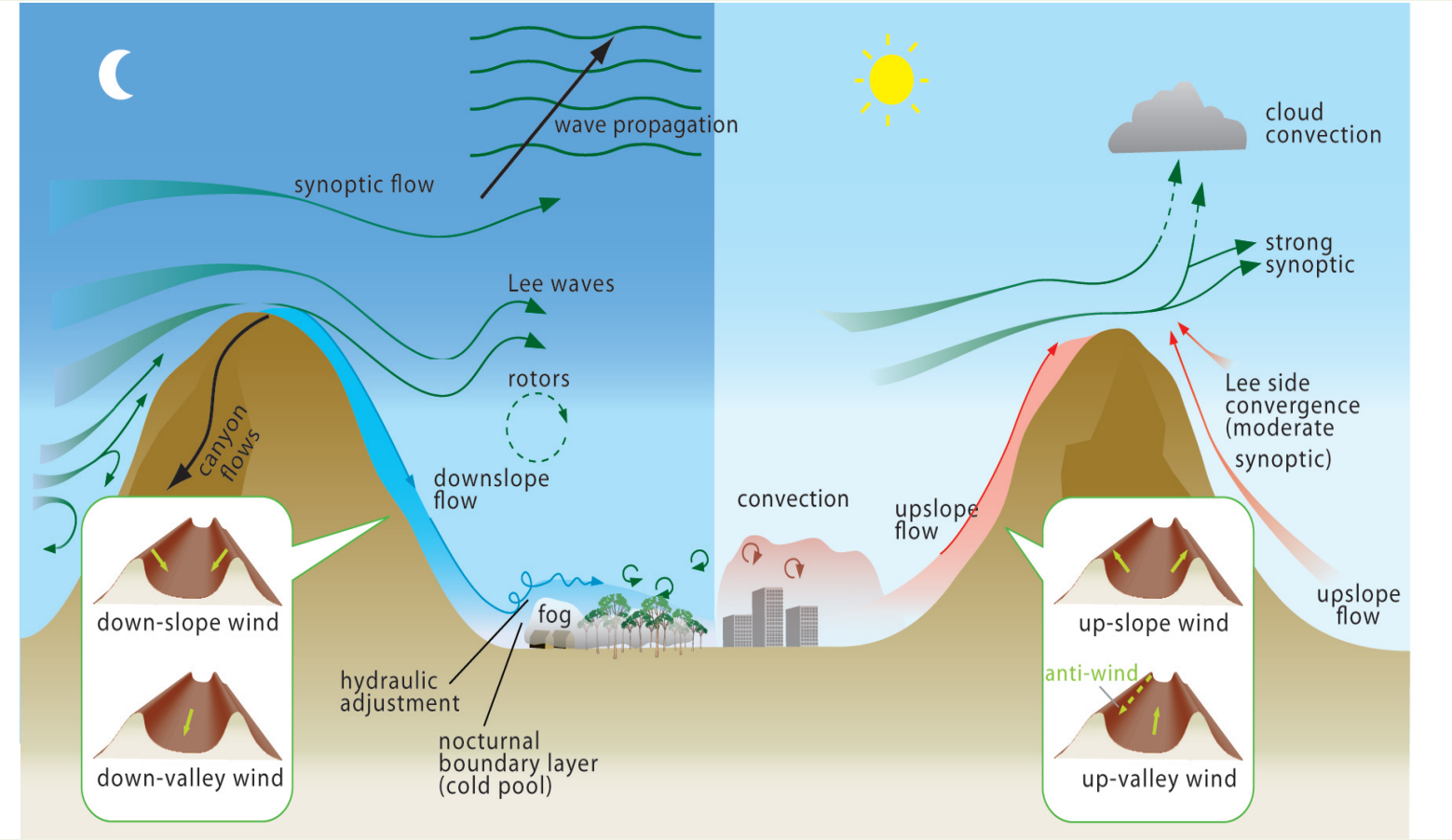


Materhorn - X
Materhorn - T

Materhorn - P (M)

Materhorn - M

Mountain terrain processes



Fernando, Ann Rev Fluid Mech. 2010

Applications

Phoenix Brown Cloud

From the *Arizona Republic*

Fog in Pooled areas

Air Quality Applications

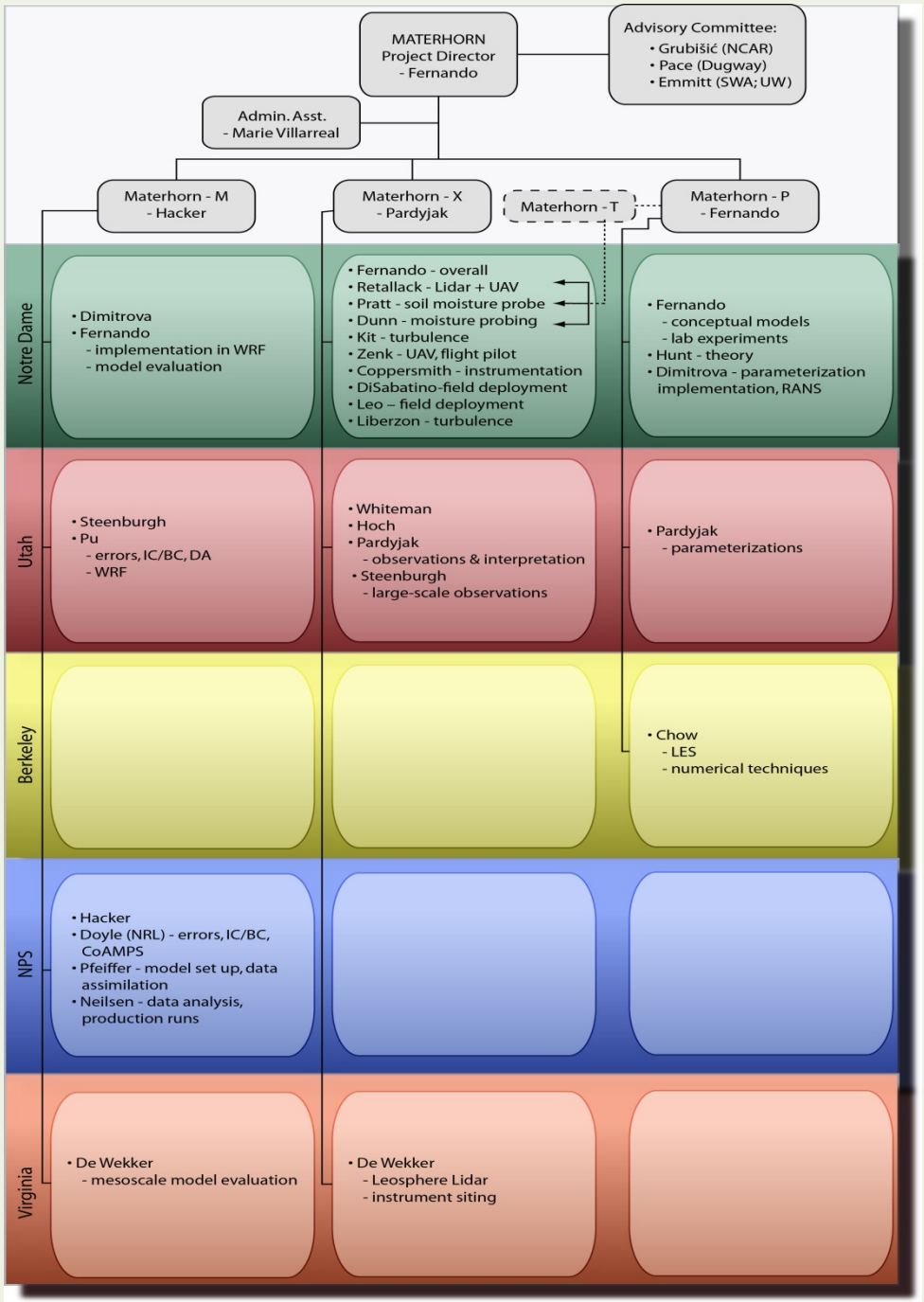
Hazardous cloud

Crews contain acid leak in Laveen; 200 residents evacuated

Mike Rynearson/The Arizona Republic

From the *Arizona Republic*

Chemical Spills in Mountainous Terrain



Participants and Administrative Structure

www.nd.edu/~dynamics/materhorn
(Scott Coppersmith)

List serve – Dan Liberzon

MATERHORN-M

- Quantifying spatial and temporal scales of error growth internal to a mesoscale model, and relating them to Initial Condition (IC) uncertainty

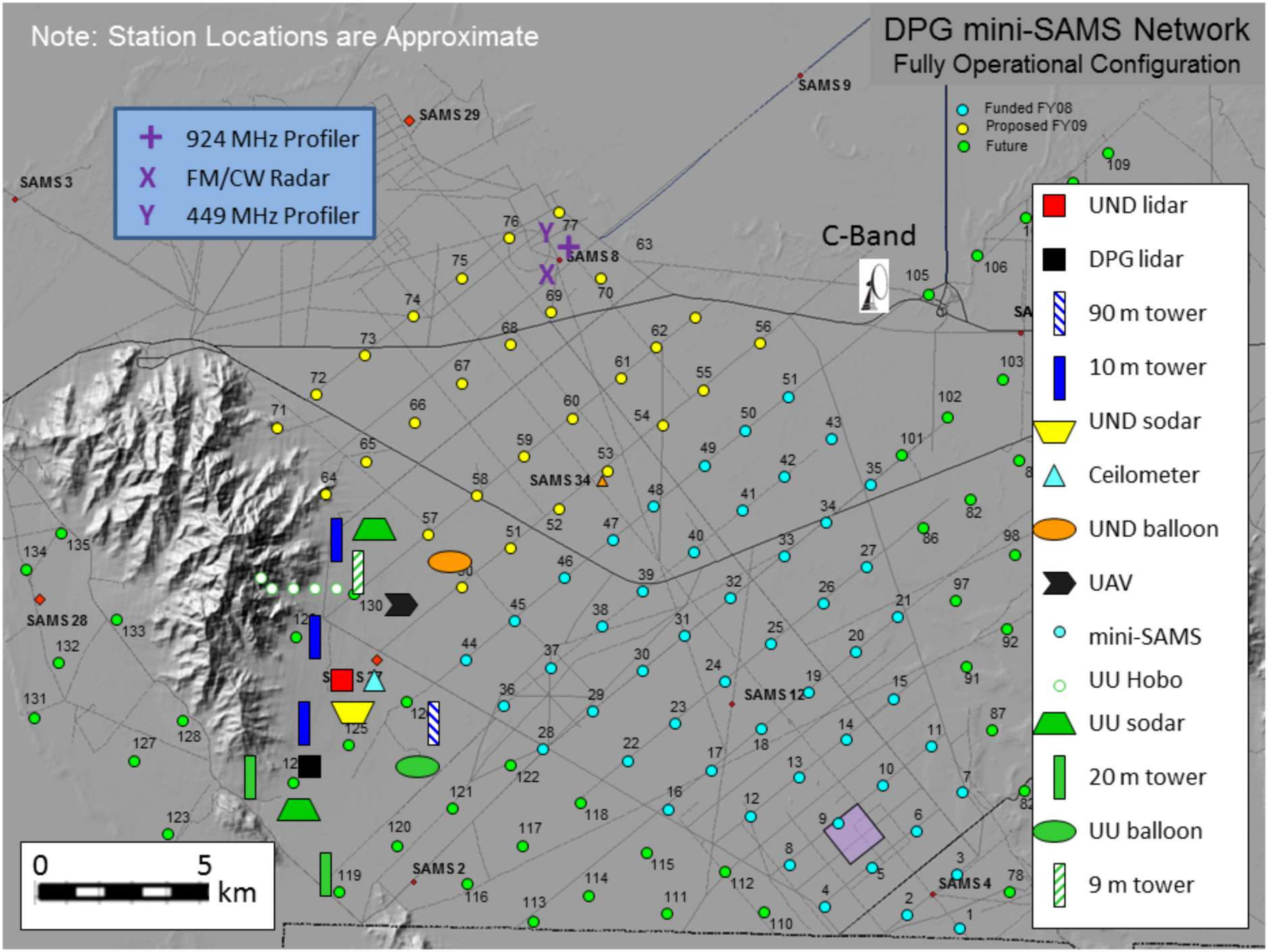
- Determining whether the errors can be reduced by improving ICs or whether we are already near the limits of predictability imposed by chaos

- Proposing and testing strategies that will help reduce the important IC errors while brining us closer to predictability limits

- Quantifying and characterizing the importance of model inadequacies in maintaining prediction errors that are not reduced as much as expected

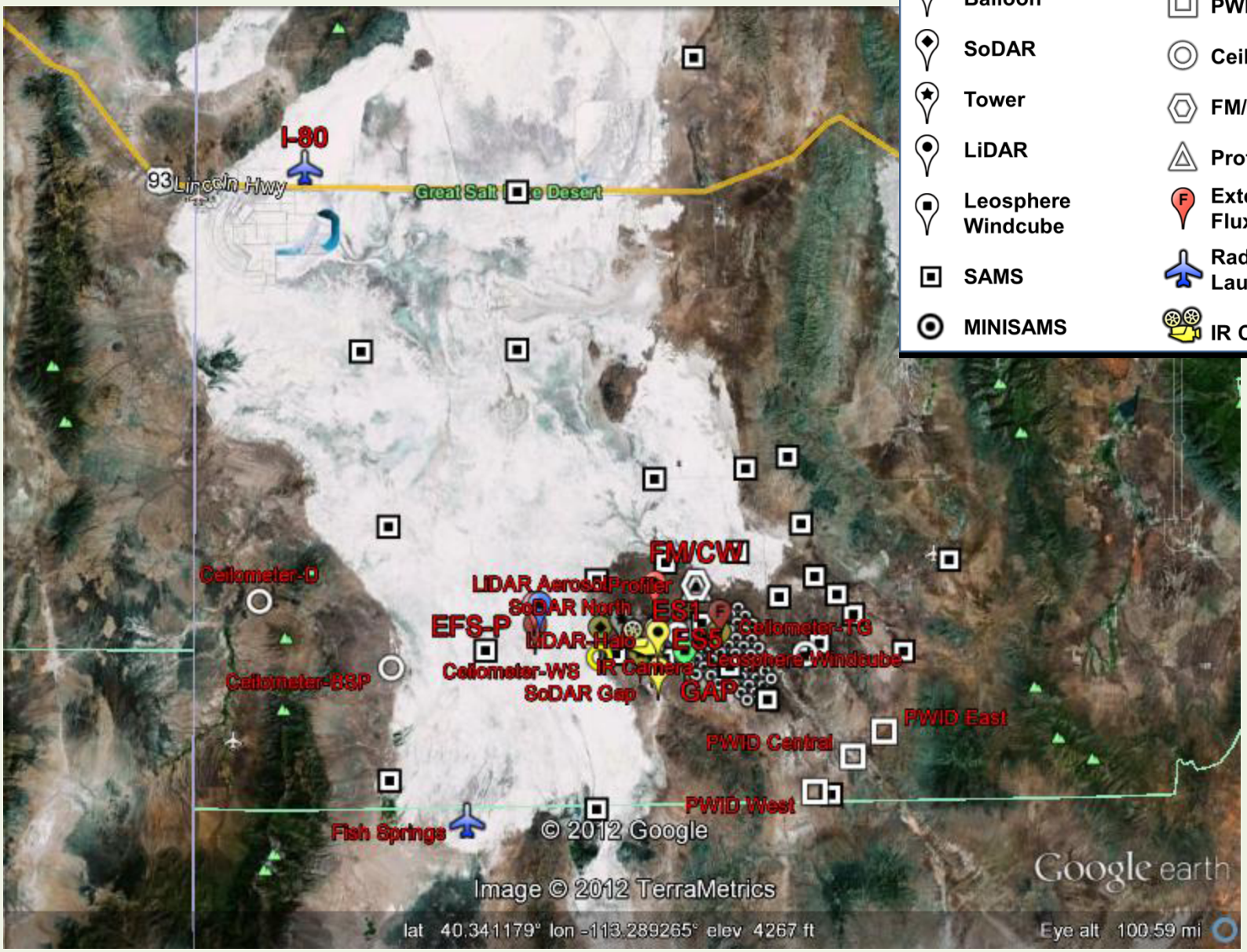
MATERHORN-X

- Surface Energy Budget and Flux
- Fine-scale Turbulence and Transport
- Stable Boundary Layer Evolution
- Unstable Boundary Layer Evolution
- Slope Flow Evolution and Interaction
- Synoptic-Thermal Flow Interaction
- Fog Formation


Note: Station Locations are Approximate
DPG mini-SAMS Network
Fully Operational Configuration
924 MHz Profiler
FM/CW Radar
449 MHz Profiler
Funded FY08
Proposed FY09
Future
C-Band
SAMS 3
SAMS 29
SAMS 9
SAMS 8
SAMS 34
SAMS 28
SAMS 12
SAMS 2
SAMS 4
UND lidar
DPG lidar
90 m tower
10 m tower
UND sodar
Ceilometer
UND balloon
UAV
mini-SAMS
UU Hobo
UU sodar
20 m tower
UU balloon
9 m tower
0
5
km

ND UAV
Twin Otter
Datahawk - small UAVs

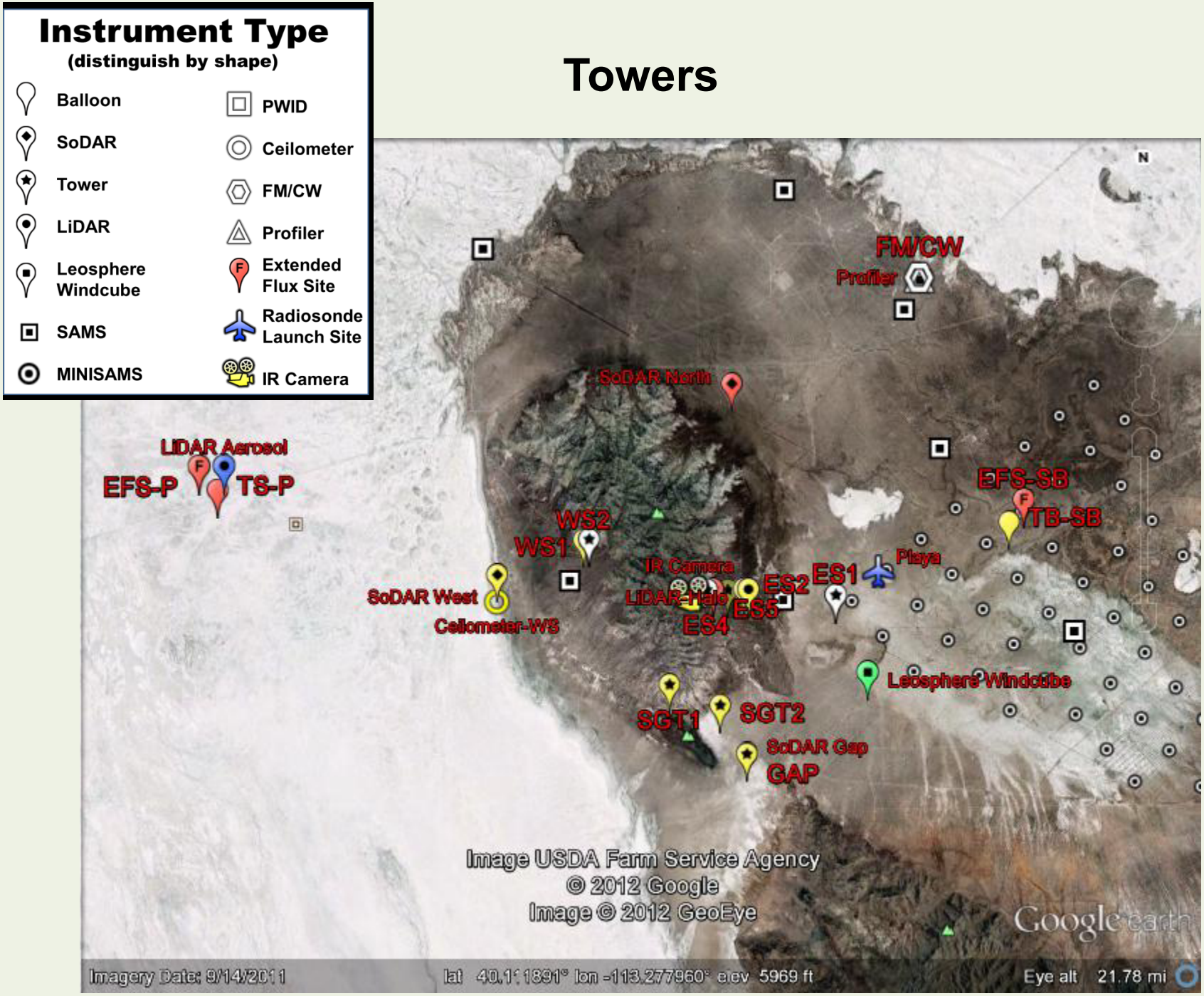
Full Site Overview



Instrument Type
(distinguish by shape)

- Balloon
- SoDAR
- Tower
- LiDAR
- Leosphere Windcube
- SAMS
- MINISAMS
- PWID
- Ceilometer
- FM/CW
- Profiler
- Extended Flux Site
- Radiosonde Launch Site
- IR Camera

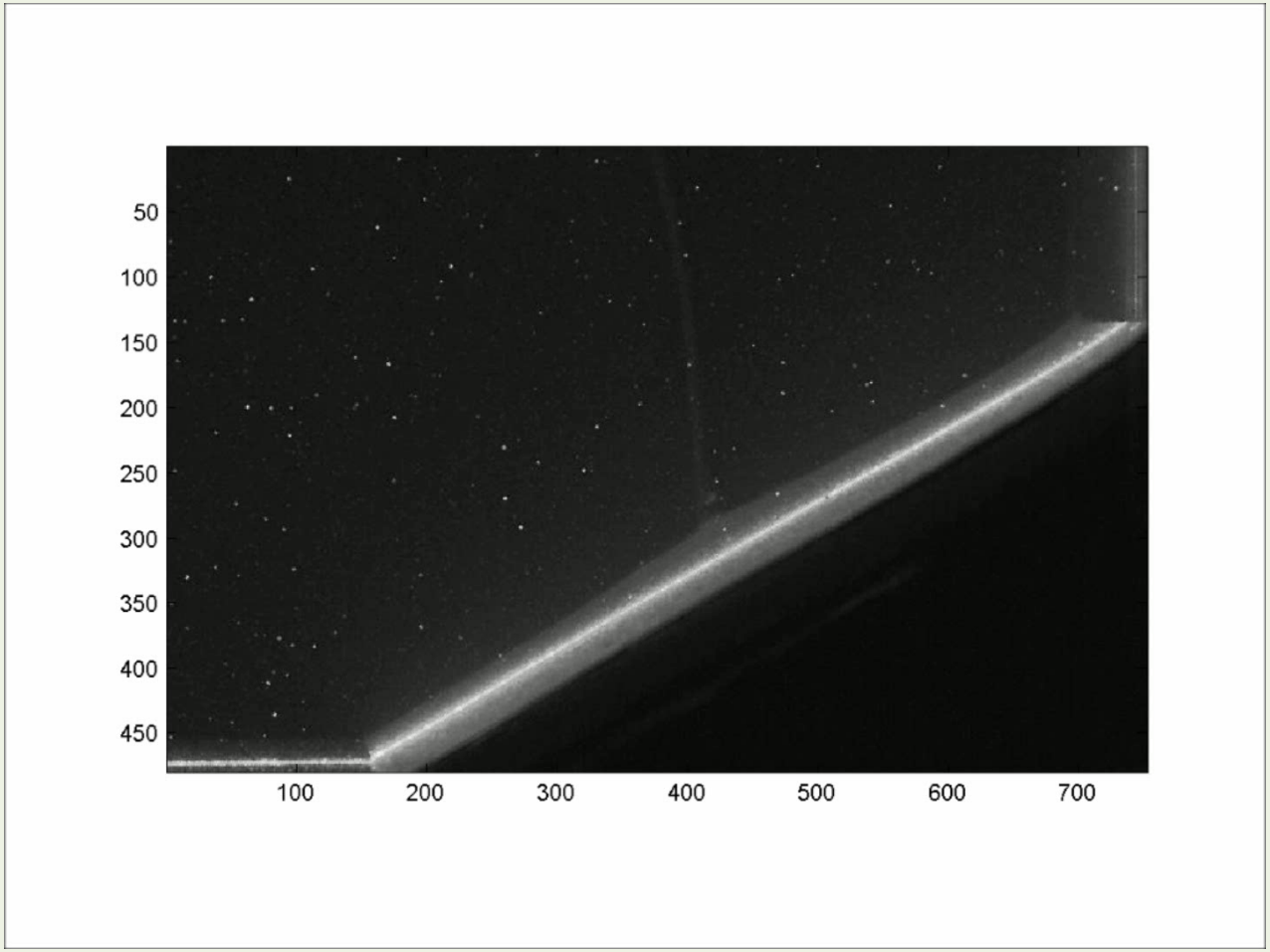
Towers


Instrument Type
(distinguish by shape)
Balloon
SoDAR
Tower
LiDAR
Leosphere Windcube
SAMS
MINISAMS
PWID
Ceilometer
FM/CW
Profiler
Extended Flux Site
Radiosonde Launch Site
IR Camera
FM/CW
Profiler
SoDAR North
LiDAR Aerosol
EFS-P
TS-P
EFS-SB
TB-SB
WS2
WS1
IR Camera
Playa
ES1
ES2
ES5
ES4
SoDAR West
Ceilometer-WS
LiDAR-Halo
Leosphere Windcube
SGT1
SGT2
SoDAR Gap
GAP
Image USDA Farm Service Agency
© 2012 Google
Image © 2012 GeoEye
Google earth
Imagery Date: 9/14/2011
lat 40.111891° lon -113.277960° elev 5969 ft
Eye alt 21.78 mi

MATERHORN-P

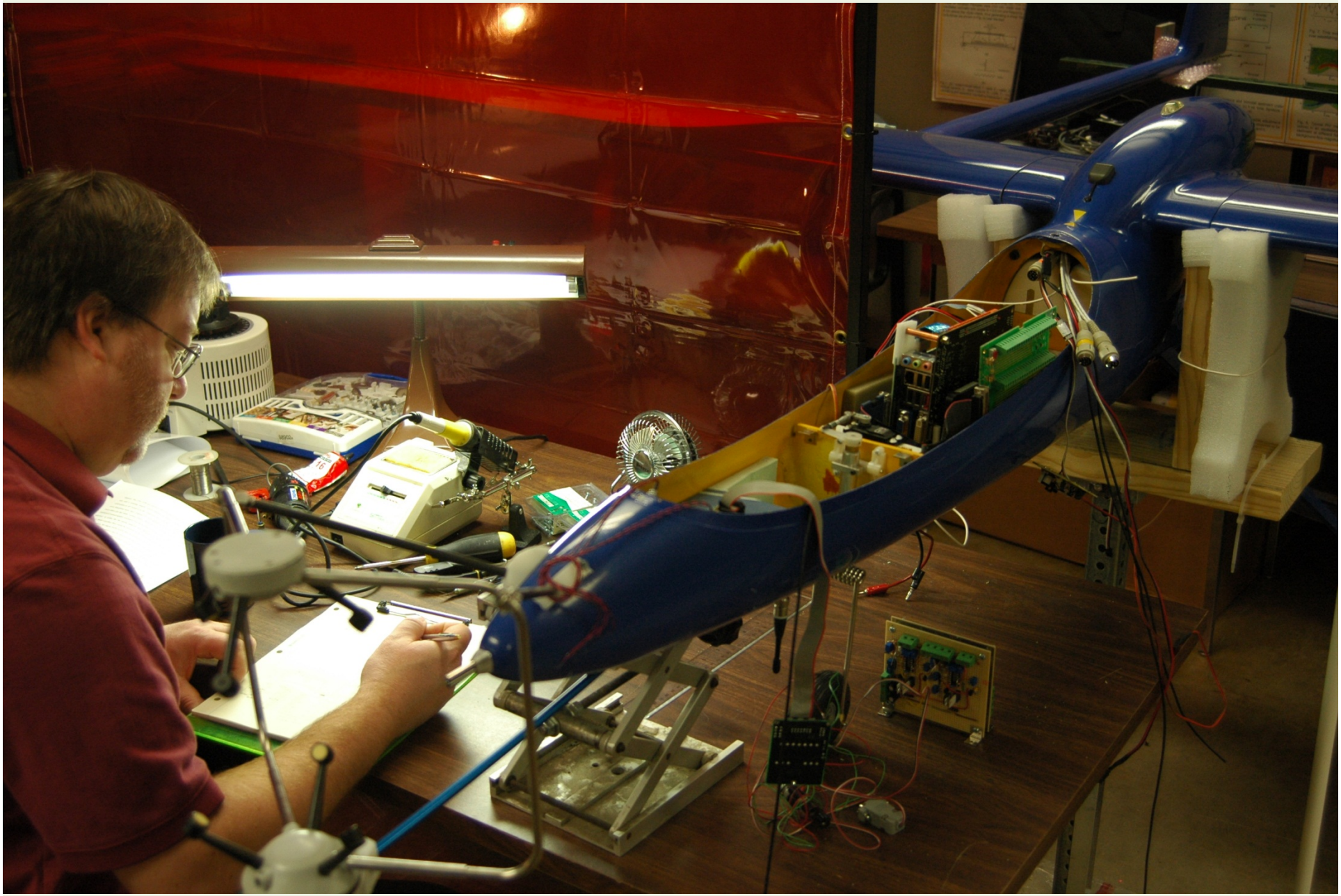
- Parameterizations based on process studies)
  - LES, Laboratory, field data, theory
- Inclusion in the models, verification

Laboratory Experiments



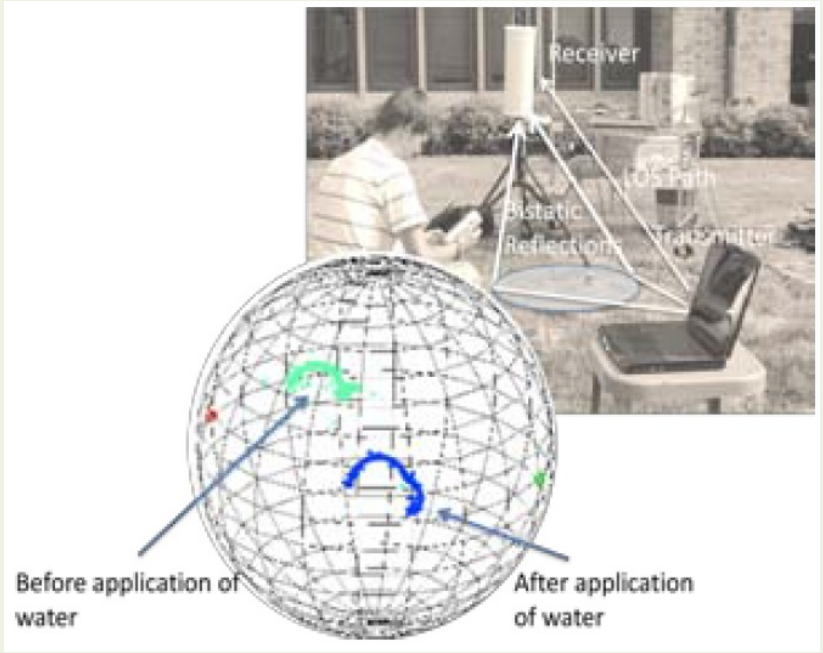
MATERHORN-T

- Instrumented UAV
- Combo system – hot-film/Sonic combination
- Fog Aerosol Sampling System (FASS)
  - Fog droplet size distribution (5 ranges)
  - 880 nm light attenuation
- Soil moisture sensing using Radio frequency (RF) polarimetry



MATERHORN-T

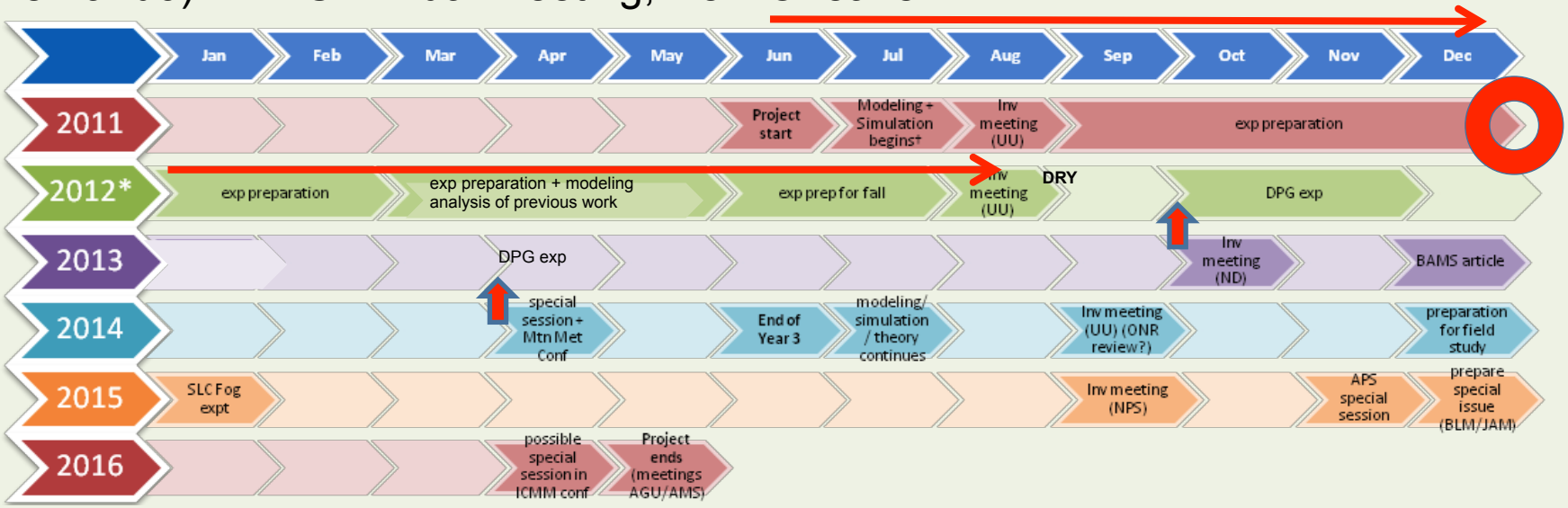
- Soil moisture sensing
- Radio frequency (RF) polarimetry (exploits time dispersion between the polarization modes)
- Measurement footprint O(1000m^2)



Timeline

Special Session on Complex Terrain (DeWekker & Chow) – AGU Fall SF

Special session on Atmospheric Observations and Modeling in Complex Terrain (Fernando) – AMS Annual Meeting, New Orleans



25 Aug. - 28 Aug. 2012: MATERHORN-X-DRY
25 Sept. – 25 Oct. 2012: MATERHORN-X-FALL
22 April – 19 May 2013: MATERHORN-X-SPRING

Senior Personnel (13)

- Harindra Joseph Fernando (University of Notre Dame)
- Thomas Pratt (University of Notre Dame)
- Patrick Dunn (University of Notre Dame)
- Mike Zenk (University of Notre Dame)
- Reneta Dimitrova (University of Notre Dame - 5)
- Eric Pardyjak (University of Utah)
- Sebastian Hoch (University of Utah)
- Z. Pu (University of Utah)
- J. Steenburgh (University of Utah)
- D. Whiteman (University of Utah -5)
- Fotina Katopodes Chow (University of California, Berkeley -1)
- Stephan J.F. De Wekker (University of Virginia - 1)
- Joshua Hacker (Naval Postgraduate School -1)

Collaborators (7)

(listed in the Proposal)

- James Doyle (Naval Research Laboratory)
- John Pace (US Army Dugway Proving Grounds)
  Dragan Zajic (US Army Dugway Proving Grounds)
- Dennis Garvey (Army Research Laboratory)
- Yansen Wang (Army Research Laboratory)
- Julian Hunt (University of Cambridge, University of Notre Dame)
- Eliezer Kit (Tel Aviv University, University of Notre Dame)
- David Emmitt, Simpson Weather Associates

Post-Doctoral Fellows (6)

- Charles Retallack (University of Notre Dame)
- Dan Liberzon (University of Notre Dame)
- Laura Leo (University of Notre Dame)
- Vigneshwaran Kulandaivelu (University of Utah)
- Zeljko Vecenaj (University of Virginia)
- Jared Lee (Naval Postgraduate School)

Graduate Students (16)

Yingjie Sun (M.S., University of Notre Dame)
Jordan Bryant (M.S., University of Notre Dame, ESTEEM Fellow)
Chris Hocut (Ph.D., University of Notre Dame)
Zachariah Silver (Ph.D., University of Notre Dame)
Kelly McEnerney (Ph.D., University of Notre Dame)
Michael Thomson (Ph.D., University of Notre Dame, 6)
Jason Simon (Ph.D., University of California, Berkeley)
Matthew Jeglum (Ph.D., University of Utah)
Derek Jensen (M.S., University of Utah)
Jeff Massey (Ph.D., University of Utah)
Hailing Zhang (Ph.D., University of Utah)
Xuebo Zhang (M.S. University of Utah, 5)
Ehsan Erfani (Ph.D., University of Virigina)
Maj. Paul Homan (Ph.D., Naval Postgraduate School)
Capt. Sean Wile (M.S., Naval Postgraduate School)
Capt. Hank Chilcoat (M.S., Naval Postgraduate School, 3)

Undergraduates (9)

Patrick Conry (University of Notre Dame)
Mike Higginson (University of Notre Dame)
Kristin Stryker (University of Notre Dame)
Rich Strebinger University of (Notre Dame)
Greg Brownell (University of Notre Dame)
Kevin Peters (University of Notre Dame)
Capt. Samuel White University of (Notre Dame)
Sahan Fernando (University of Notre Dame)
Nipun Gunawardena (University of Utah)

Technical Staff (5)

- Neil Dodson (University of Notre Dame, Research Engineer)
- Scott Coppersmith (University of Notre Dame, Research Engineer)
- Orson Hyde (University of Notre Dame, Technical Assistant)
- Mary Jordan (Naval Postgraduate School)
- Cale Fallgatter (University of Utah)

Visiting Faculty (4)

- Professor Silvana Di Sabatino, University of Selento, Italy
  - Full Time; ND lead for Materhorn-X
- Nick Ovenden (University College, London, UK)
- Peter Baines (University of Melbourne)
- Andrey Grachev (NOAA)

Official Collaborators (7)

- Professor Joachim Reuder, University of Bergen, Norway
- Dr. Stefano Serafin, University of Vienna, Austria
- Dr. Dorita Rostkier-Edelstein, Environmental Sciences Division, IIBR, Israel
- Professor Marcus Hultmark, Princeton University
- Professor Chad Higgins, Oregon State University, Corvallis, Oregon, USA
- Professors Ben Balsley, University of Colorado, Boulder, USA
- Professor Dale Lawrence, University of Colorado, Boulder, USA

Administrative Support

Marie Villarreal (University of Notre Dame)

Technical Support
Ricky Villarreal (University of Notre Dame)

Published Papers or in Press (2)

De Wekker, S.F.J., K.S. Godwin, G. D. Emmitt, and S. Greco, 2012: Airborne Doppler lidar measurements of valley flows in complex coastal terrain. *J. Appl Meteor. Climat*. doi: http://dx.doi.org/10.1175/JAMC-D-10-05034.1"/10.1175/JAMC-D-10-05034.1.

Lozovatsky, I. and Fernando, H.J.S. "Mixing Efficiency in Natural Flows," *Philosophical Transactions, Proceedings of the Royal Society (Lond)*, In Press, 2012.

Papers Submitted (7)

- Dallman, A., DiSabatino, S. and Fernando, H.J.S., Flow and Turbulence in an Industrial/Suburban Roughness Canopy, *Journal of Environmental Fluid Mechanics*, submitted, 2012.
- Fernando, H.J.S., Verhoef, B., Di Sabatino, S., Leo, L. and Park, S. The Phoenix Evening Transition Flow Experiment (TRANSFLEX), *Boundary Layer Meteorology*, Revision submitted, 2012.
- Leo, L., Fernando, H.J.S and Di Sabatino, S., Flow in Complex Terrain with Coastal and Urban Influence, *Journal of Applied Meteorology and Climatology*, Submitted for publication.
- Pu, Z. and H. Zhang, 2012: Assimilation of near surface observations over complex terrain: EnKF versus 3DVAR. *Q. J. Roy. Meteorol. Soc.* (Under Revision).
- Whiteman, C. D., R. Garibotti, and J. Whiteman, 2012: Rime mushrooms on mountains: Their causes and impacts on mountaineering. Bull. *Amer. Meteor Soc.*, submitted.
- Zhang, H., Z. Pu and X. Zhang, 2012: Examination of flow-dependent errors in near-surface temperature and wind from WRF numerical simulations over complex terrain. *Wea. Forecasting.,* submitted.
- Nadeau, D.F., Pardyjak, E.R., Higgins, C.W., and Parlange, M.B., Similarity scaling over 1 a steep alpine slope. Boundary-Layer Meteorology, submitted, July 2012.

Papers in Preparation (6)

- Sun, Y., J. Bryant, T. Pratt, and Y. Pengkun, Temperature Sensitivities of an RF Polarization-Based Soil Moisture Sensor (likely submission at the end of July to a Journal):
- Sun, Y., J. Bryant, T. Pratt, Y. Pengkun, D. Jensen, and E. Pardyjak**,** Short Term Field-ScaleTesting of an RF Polarization-Based Soil Moisture Sensor in Mountainous Terrain (likely submission at end of September):
- Pardyjak, E.R., J.R. Stoll, H.A. Holmes, and C. Higgins, The nocturnal boundary layer over the playa in Utah's West Desert, in preparation for *Boundary-Layer Meteorology*
- Pardyjak, E.R., J.R. Stoll, H.A. Holmes, and C. Higgins, The nocturnal boundary layer over the playa in Utah's West Desert, in preparation for *Boundary-Layer Meteorology*.
- Hocut, C., Liberzon, D. and Fernando, H.J.S. Separation of upslope flow on mountain slopes, to be submitted to the *Journal of Fluid Mechanics*.
- Večenaj, Ž., and S.F.J. De Wekker, 2012: (Non-)stationarity in the near-surface turbulence time series over complex terrain. Manuscript in preparation for *Boundary Layer Meteorology*.

Conference Papers (2)

- Monti, P., Fernando, H.J.S. and Princevac, M., "Waves and Turbulence Contributions to Stratified Turbulence in Katabatic flows," Proceedings, 7th International Symposium of Stratified Flows, (Ed. A. Cenedese), 22-26 August, 2011.

- Fernando, H.J.S. The Mountain Terrain Atmospheric Modeling and Observations (MATERHORN) Program: An Overview, Extended Abstract, American Meteorological Society 92nd Annual Meeting, New Orleans, Paper 11.12, 2012.

Conference Presentations (34)

- Simon, J.S., Lundquist, K.A., and F.K. Chow. 2012. Application of the immersed boundary method to simulations of flow over steep, mountainous terrain. *15th Conference on Mountain Meteorology,* Steamboat Springs, Colorado, August 20-24, 2012. [poster]
- Zajic, D., J. C. Pace, C. D. Whiteman, and S. W. Hoch, 2012: An Overview of the Granite Mountain Atmospheric Sciences Testbed (GMAST). 17th Conference on Air Pollution Meteorology with the A&WMA, January 2012, New Orleans, LA.
- Zajic, D., J. C. Pace, C. D. Whiteman, and S. Hoch, 2011: The Granite Mountain Atmospheric Sciences Testbed (GMAST): A Facility for Long Term Complex Terrain Airflow Studies. AGU Fall Meeting, 5-9 December 2011, San Francisco, CA.
- C. D. Whiteman and S. W. Hoch, M. Jeglum and L. Campbell: MATERHORN-X Field Studies. MATERHORN Kick-off Meeting, Salt Lake City, UT., 8 Sept. 2011.
- Pardyjak, E.R.: MATERHORN-X. MATERHORN Kick-off Meeting, Salt Lake City, UT., 8 Sept. 2011.
- Pardyjak, E.R., D. Nadeau, C. Higgins, H. Huwald, and M. B. Parlange, 2012. Developing an improved understanding of steep slope evening transition processes. 92nd American Meteorological Society Annual Meeting, January 22-26, 2012, New Orleans, 11.6.
- Pardyjak, E.R., D. Alexander, M. Lothon, F. Lohou, S. Derrien; J. Reuder, D. Legain, O. Traulle, H. Pietersen, O. Decoster, G. Canut, C. Darbieu, A. Garai, E. Pique, 2011: First results from the surface heterogeneity focus area of the Boundary Layer Late Afternoon and Sunset Turbulence (BLLAST) Experiment, Abstract A41A-0034, presented at 2011 Fall Meeting, AGU, San Francisco, Calif., 5-9 Dec.
- Massey, J. D., W. J. Steenburgh, J. C. Kneivel, M. E. Jeglum, and S. W. Hoch, 2012: Observations and modeling of thermally driven flows over the Great Salt Lake Desert. 15th Conference on Mountain Meteorology, American Meteorological Society, 20-24 Aug 2012.
- Pu, Z. and H. Zhang, 2012: Examination of Flow-Dependent Errors in Near-Surface Temperature and Wind from WRF Numerical Simulations over Complex Terrain. 3rd WRF Users Workshop, June 26-29. 2012.

- Pu,Z. and H. Zhang, 2012: Evaluation of the Diurnal Variation of near-Surface Temperature and Winds From WRF Numerical Simulations Over Complex Terrain and the Impact on Assimilation of Surface Observations, *17th Conference on Air Pollution Meteorology with the A&WMA,* January 22-27, 2012, New Orleans, LA
- Zhang, H., C. W. Pace and Z. Pu, 2011: Evaluation of the Diurnal Variation of near-Surface Temperature and Winds From WRF Numerical Simulations Over Complex Terrain, *AGU Fall Meeting*. December 5-9, 2011. San Francisco, CA.
- Pu, Z. and H. Zhang: On the assimilation of surface observations over complex terrain: EnKF vs. 3DVAR. *AGU Fall Meeting*. December 5-9, 2011. San Francisco, CA.
- De Wekker, S.F.J., 2012: Convective Boundary Layer Heights in Mountainous Terrain. New Insights From Observations in the Appalachian Mountains. 17th AMS Conference on Air Pollution Meteorology with the A&WMA, New Orleans, LA, 22-26 January 2012.
- Večenaj, Ž., and S.F.J. De Wekker, 2012: Averaging Time Scale for Daytime Turbulent Flux Measurements in a Wide and Steep Valley. 17th AMS Conference on Air Pollution Meteorology with the A&WMA, New Orleans, LA, 22-26 January 2012.
- De Wekker, S.F.J., J. Doyle, Q. Jiang, K. Godwin, E. Erfani, G. D. Emmitt, 2011: Investigation of multi-scale flow interaction in the Salinas Valley using a combination of airborne Doppler lidar data and a mesoscale numerical model. AGU Fall meeting, San Francisco, CA, 5–9 December 2011.
- Retallack, C., H. Fernando, E. Pardyjak, S.F.J. De Wekker, J.C Pace, 2011: The MATERHORN Experiment. AGU Fall meeting, San Francisco, 5–9 December 2011.
- Di Sabatino, S., Leo, L., Fernando, H.J.S., Cacciani, M., Caasanta, G., Martano, P., Dallman A., Mammarella, M.C. and Grandoni, G., Atmospheric Boundary Layer in a Narrow-Coastal Valley: Modelling Implications, *Geophys. Res. Abs.*, Vol. 13, EGU2011-8764, EGU General Assembly 2011.
- Monti, P. Fernando, H.J.S. and Princevac, M., On Quantifying Waves and Turbulence Contributions in Katabatic Flows, 7th International Symposium on Stratified Flows, 22nd to 26th of August 2011.
- Fernando, H.J.S., “Evening Transition in Complex Terrain of Inland and Coastal Areas, Special Symposium on Geophysical Turbulence,” AAAS Pacific Division, 92nd Annual Meeting, San Diego, CA, June 12-16, 2011.

- Liberzon, D, Hocut, C. and Fernando, H.J.S., Thermally Driven Upslope Flow in Mountainous Terrain, *Bull. Am. Phys. Soc.,* **56(18)**, 216, 2011.
- Lozovatsky, I. and Fernando, H.J.S., Mixing Efficiency in Natural Flows, 3rd International Conference 'Turbulent Mixing and Beyond', Trieste, Italy, 21 July - 28 August, 2011.
- Hocut, C., Liberzon, D. and Fernando, H.J.S., "Thermally Driven Upslope Flow in Mountain Terrain," American Meteorological Society 92nd Annual Meeting, New Orleans, Paper 11.3, 2012.
- Leo, L., DiSabatino, S, and Fernando, H.J.S., "Flow in Complex Terrain with Coastal and Urban Influence, American Meteorological Society 92nd Annual Meeting," New Orleans, Paper 11.1, 2012.
- Dallman, A., DiSabatino, S., Leo, L.S. and Fernando, H.J.S., "Flow Characteristics in an Urban Area Located in Complex Terrain," American Meteorological Society 92nd Annual Meeting, New Orleans, Paper 11.4, 2012.
- Di Sabatino, S., Leo, L., Liberzon, D., Retallack, C., Coppersmith, R.S., Sentic, S., Huq, P., Hocut, C., Fernando, S. and Fernando, H.J.S., Evening Transition of Atmospheric Boundary Layer (ABL) in Heterogeneous Flat Terrain," American Meteorological Society 92nd Annual Meeting, New Orleans, 2012.
- Fernando, H.J.S. and Lozovatsky, I., Mixing Efficiency in Natural Flows, *Ocean Sciences Meeting*, TOS/ AGU/ASLO Proc., 110, 2012.
- Retallack, C., Fernando, H.J.S and Hunt, J.C.R., "Turbulent stratified flows over orography with large scale forcing-concepts and idealised models," 15th AMS Conference on Mountain Meteorology, 20-24, August, 2012.
- Hocut, C., Liberzon, D. and Fernando, H.J.S., "Thermally Driven Upslope Flow Separation in Steep Mountainous Terrain," 15th AMS Conference on Mountain Meteorology, 20-24, August, 2012.
- Fernando, H.J.S. "Flow and Dispersion through Urban Canopies," Invited Speaker, Symposium Honoring Professor C.C. Mei, American Academy of Arts and Sciences, Boston, May 20, 2011.

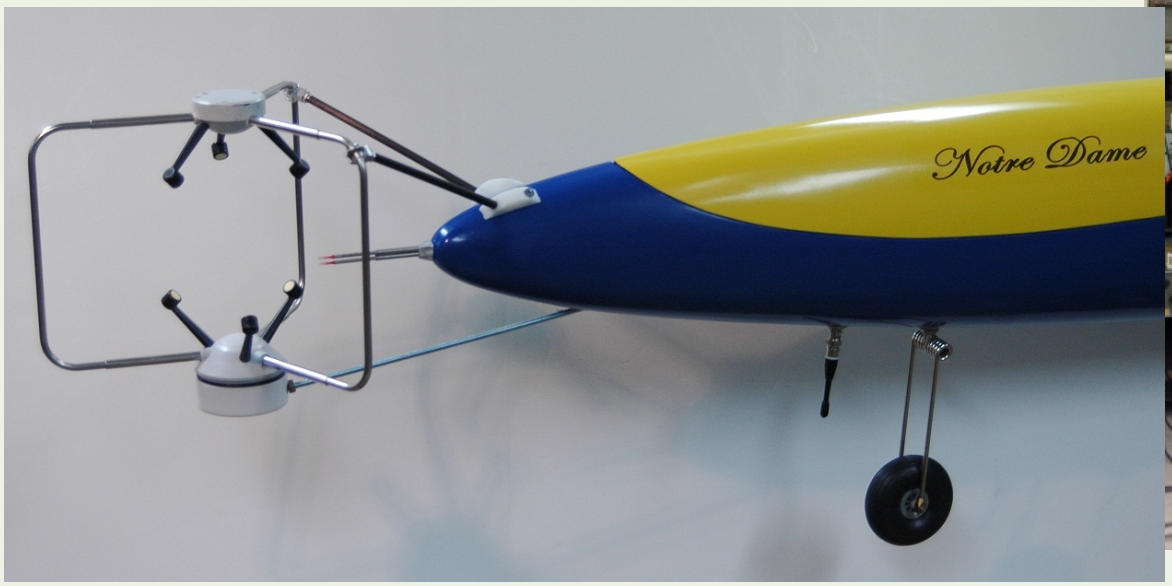
- Fernando, H.J.S. “Air Quality at Different Spatial Scales: Panel Discussion,” Invited Speaker, 5th Annual CENSAM (Center for Environmental Sensing and Modeling) Workshop, MIT-Singapore Alliance, Jan 12-13, 2012.
- Fernando, H.J.S., “Mixing in Stratified Shear Layers, including the Effects of Topography, Invited Speaker, Workshop on Physical Processes in the Bay of Bengal and Monsoon ISO. 5-7 March, Indian Institute of Sciences, Bangalore, 2012.
- Fernando, H.J.S., Pardyjak, E., Zajic, D., De Wekker, S.J.F., and Pace, J., The Mountain Terrain Atmospheric Modeling and Observations (MATERHORN) Program: The First Field Experiment (MATERHORN-X1), Invited Paper, *American Geophysical Union*, Fall Meeting, 2012.
- Večenaj, Ž., and S.F.J. De Wekker,2012: Nonstationarity in the surface layer over complex terrain during T-REX. 15th AMS Conference on Mountain Meteorology, Steamboat Springs, CO, 20-24 August 2012.
- Večenaj, Ž., and S.F.J. De Wekker,2012: Exploring Monin-Obukhov similarity in the surface layer over complex terrain during T-REX. 15th AMS Conference on Mountain Meteorology, Steamboat Springs, CO, 20-24 August 2012.

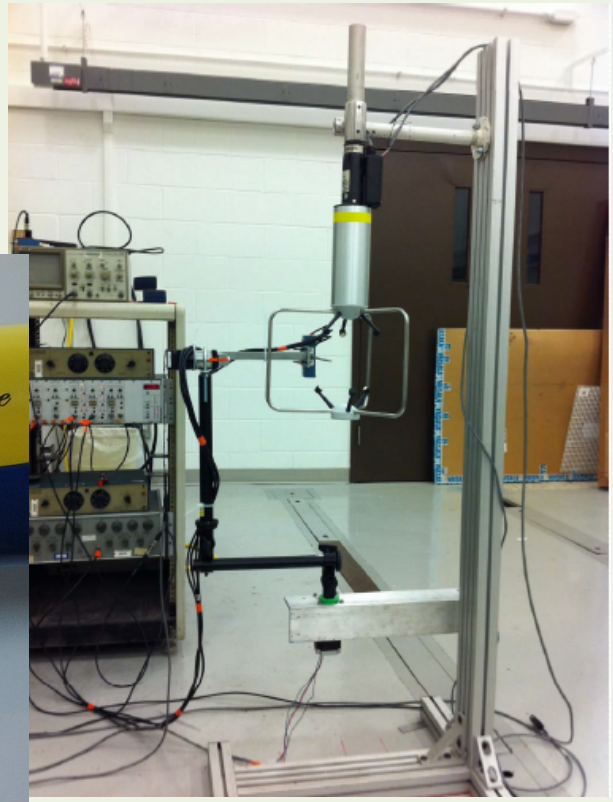

KEEP
CALM
AND
CARRY
ON

Thank you

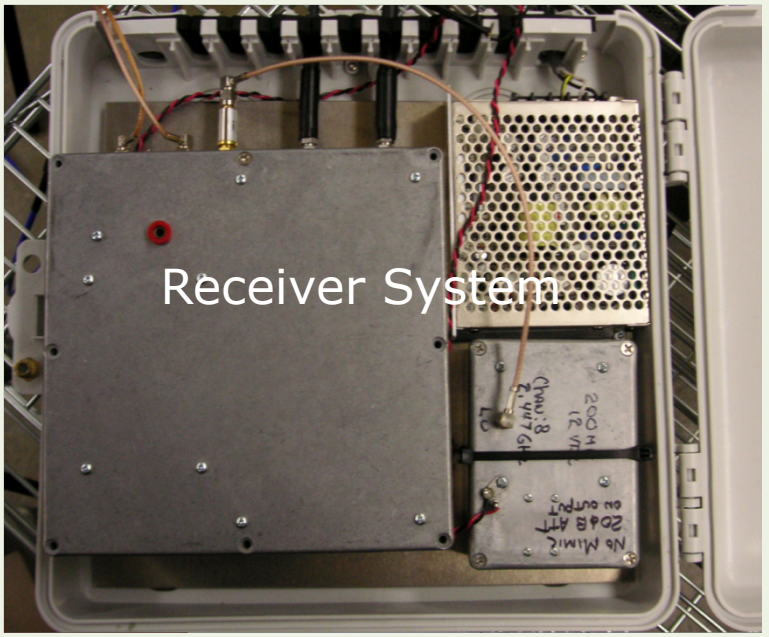
MATERHORN-T

- Unmanned Aerial Vehicle
  - Temperature, humidity, wind velocity
  - Turbulent components (combo probe)
  - Onboard data acquisition
  - Automated flight tracks
  - Fog droplet size distribution (FASS)





Soil Moisture Sensing



- Built-up 2.4 GHz system; Ready for preliminary testing on campus at end of January (White Field)
- Preliminary 915 MHz and 450 MHz systems will be built-up by the end of February
- Methods to compensate for temperature sensitivities are being considered.
- Requesting testing time at Dugway in April, May, or June (e.g., 1 week) to vet system