Appendix P

Validation of the Martian Thermal Environment Modelling Method using Flight Data

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Abstract

The Martian surface environment is complex to model since it is composed of multiple diurnal flux inputs and temperature sinks. The Mars environment is similar to Earth's since it undergoes seasonal changes in its weather pattern. Through the past Mars missions, the surface environment has been study extensively. New discoveries are made and scientists are having a deeper understanding of the Martian surface environment. Several engineering tools and analysis methods have been developed over the years and are used to predict and model the thermal environment for future missions. However, there are fundamental questions that are raised regarding the precision of these tools and methods. Therefore, one solution would be to perform a validation by correlating thermal model results to flight data. However, the surface environment is very dynamic in terms of wind speed and direction as well as the fluctuation in the atmospheric dust content. Therefore, it is difficult to accurately determine the exact environmental condition through one Martian day in order to perform a correlation. Nevertheless, performing such an exercise will give us a certain level of confidence on the tools and analysis methods.
The presentation will give an overview of the tools available to determine the thermal environment and will explain how such an environment can be modeled using IDEAS/TMG. Furthermore, the tools and analysis method will be validated by comparing thermal model results with flight data from the Phoenix Meteorological Instrument.

Background Information

- Several tools and analysis methods are used in the frame of the Exomars Program
  - Basic questions are asked regarding the accuracy of the tools and analysis methods to predict the Martian Environment
- Validation with flight data provides excellent feedback but it is not always possible or easy to perform
  - Few successful surface missions
  - Availability of flight data and correlated thermal models
  - Lack of Knowledge of the surrounding environment
  - In case of science instruments, science objective and science data have priority over engineering data, hence very few monitoring points
  - Time and budget allocation for thermal model correlation to flight data is not always a priority
    - No news is good news approach
- Any type of comparison with flight data provides confidence in the tools and methods, which in the end is a validation.

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Martian Environment

- Seasonal Variations that are repeatable
  - Solar Declination due to Mars axis inclination
  - Pressure variation caused by CO2 Migration
  - Atmospheric Dust increases due to storms
- Thermal designs are based on multiple Landing Sites scenarios since the landing site is selected very late in the program
  - Cope with large temperature extremes due to surface properties and seasons
  - Extremes are scattered across multiple landing site scenarios and not within one specific landing site
    - Due to different latitudes of landing sites
- In order to perform correlation, a good knowledge of landing site during operations is required
  - Atmospheric Conditions changes daily
  - Wind speed and direction
  - Surface temperature and pressure

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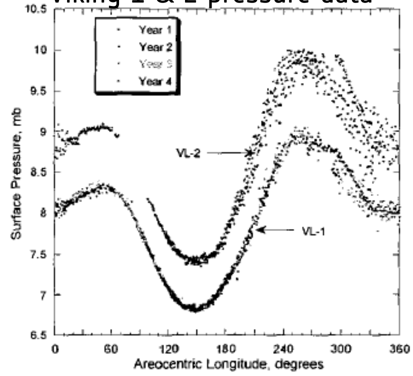
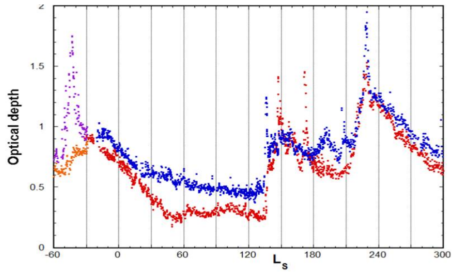
Viking 1 & 2 pressure data



MER A & B Atmospheric Data



LMD 1D Flux Engineering Tool to determine the Mars Environment

- Based on a global circulation model developed by Laboratoire de Météorologie Dynamique, through ESA Contract
  - http://www-mars.lmd.jussieu.fr/
- Produces surface temperature and solar flux profiles to be used in thermal analysis
- LMD validated 1D flux tool with Pathfinder and Viking data,
  - higher precision at Latitude -50° to 50°
- Independent comparison with JPL 1D Flux tool output was performed
- The input parameters to LMD Flux Tool are:
  - Areocentric longitude, Ls
  - Landing site latitude
  - Ground pressure
  - Atmospheric opacity
  - Local surface Albedo
  - Thermal inertia of near-surface ground layer
  - Infrared emissivity of bare ground

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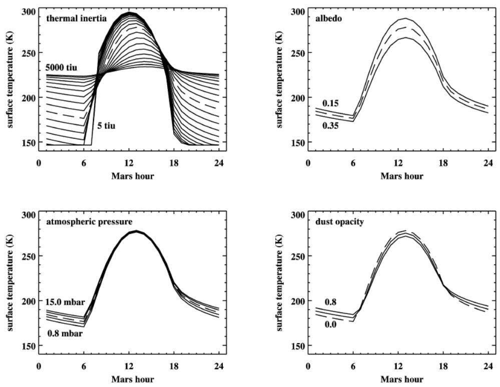
Effect of ground temperature on varying parameters



Ref: Apparent thermal inertia and the surface heterogeneity of Mars, Nathaniel E. Putzig and al. 2007

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LMD 1D Energy Balance Heat Fluxes Output

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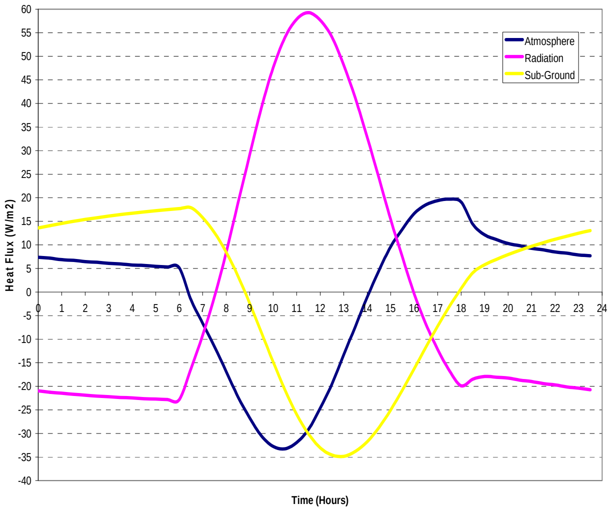
- Basic Thermal modelling software can reproduce
  - Radiative exchange
  - Ground Conductive exchange
- What is missing is the Mars atmospheric turbulent mixing model, which can be imported into the analysis from the LMD Tool
- LMD Flux tool can be used as a reference by extracting the energy balance data and compared to thermal simulation
- Always have a reference horizontal flat plate in the model in order to cross check results with Environmental inputs



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JMars Public Application

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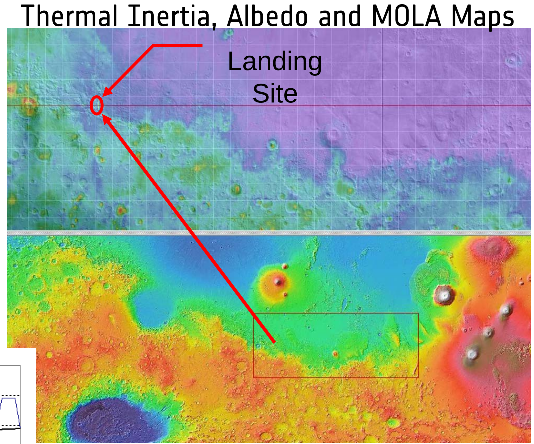
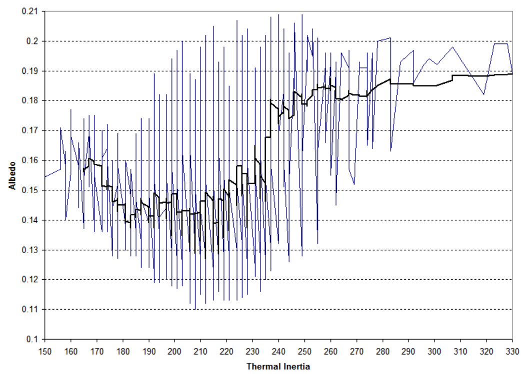
- JMars, Java application, public access to Mars remote sensing data, http://jmars.asu.edu/
- Excellent tool to extract Albedo, Thermal inertia and Altitude
  - Thermal Emission Spectrometer (TES) Albedo Maps, Mars Global Surveyor
  - TES Thermal Inertia Maps (Christensen 2001 and Putzig 2007)
  - Mars Orbiter Laser Altimeter, (MOLA) Altitude Maps, Mars Global Surveyor
- Export data to Excel for manipulation

Thermal Inertia, Albedo and MOLA Maps





Generated Albedo vs Thermal Inertia Plot for specific landing site

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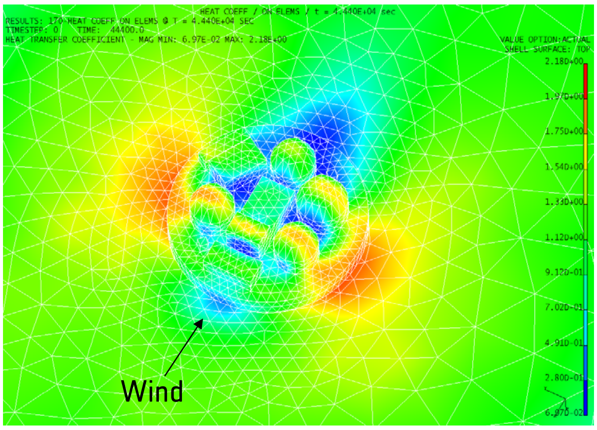
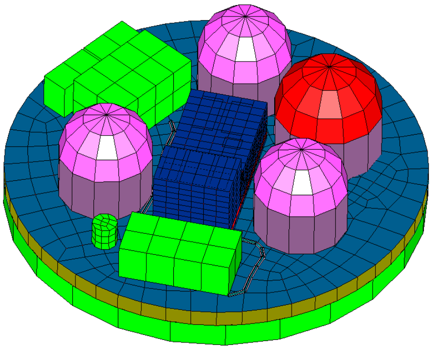
Thermal Analysis Software Tools

- Exomars Industrial team is currently using ESARAD/ESATAN for the thermal analysis of the 2016 and 2018 Exomars missions
  - Facilitates the exchange of thermal models
  - Mars Surface modeling method has been developed (Presented at previous ECLS Workshops)
- ESTEC has separate models of the EDM and Rover in I-DEAS/TMG
  - Independent cross checks with industry models
  - Allows coupling analyses between CFD and surface thermal



Heat Transfer Coefficients calculated with TMG/CFD



2016 EDM TMG Thermal Model

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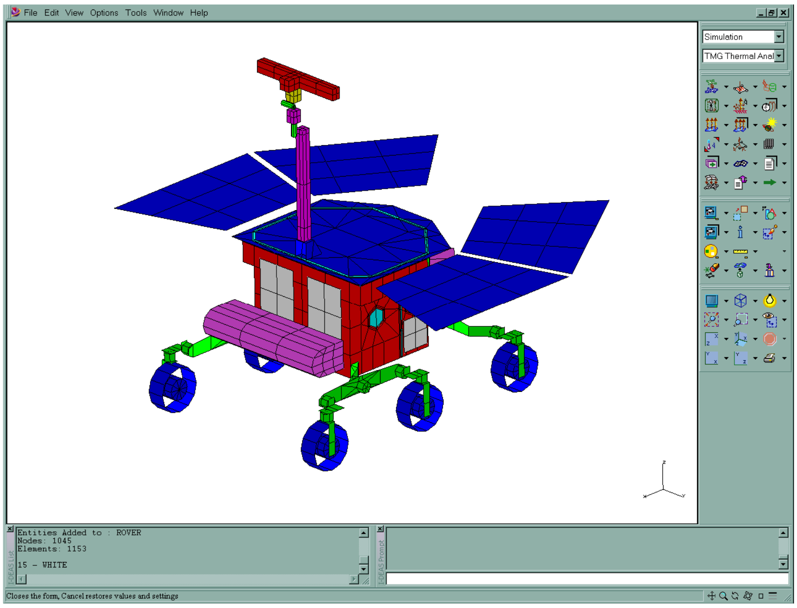
I-Deas/TMG Interface

- I-Deas/TMG has a built-in capability for planet body surface analysis
- Direct and diffuse solar fluxes can be modeled
- “Space” Nodes are used to model the Sky temperature
- Ground is modeled through dedicated elements
- Wind modeled with fixed or variable heat transfer coefficients or coupled through CFD



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Diurnal Solar Heating Interface

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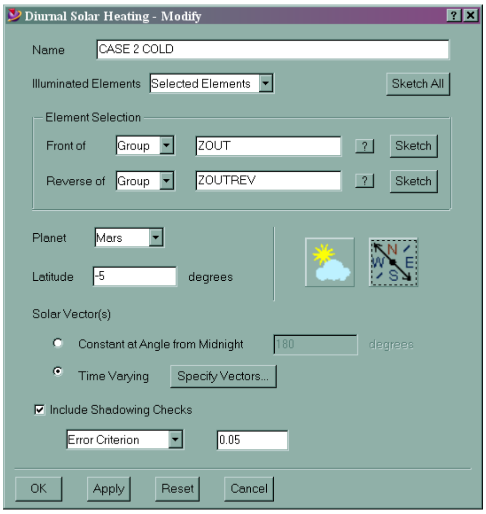

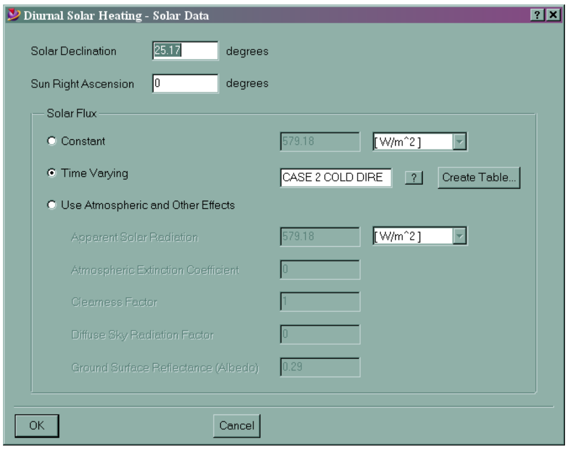

- TMG can model Atmospheric effects
  - Models are currently based on Earth Environment and not relevant to Mars
- Input time dependant Solar Flux values obtained from LMD Flux tools
  - Need to correct direct solar flux since LMD 1D calculates for a horizontal Plate
  - Sun Elevation and Azimuth data is generated by LMD Flux Tool

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Diffuse Solar Flux

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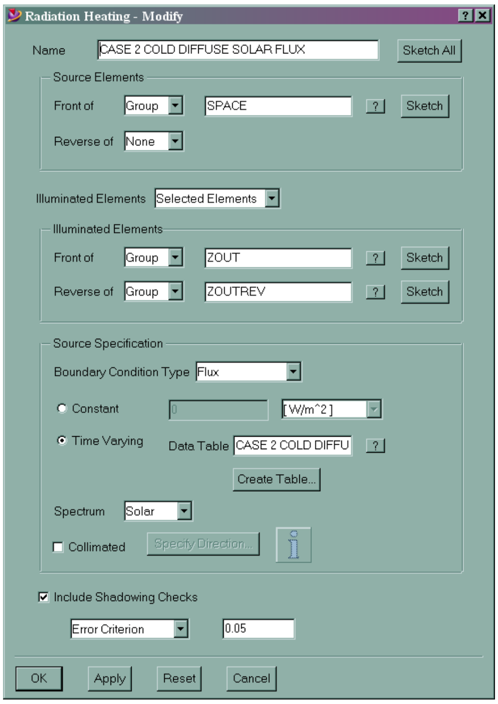
- Radiation Heating Option is used to model the Diffuse Solar Flux
- Radiation heating has the ability to emit in IR or Solar spectrum
- Source elements can be either the "Space" Node or a transparent Dome can be erected around the model to emit the Diffuse Solar flux



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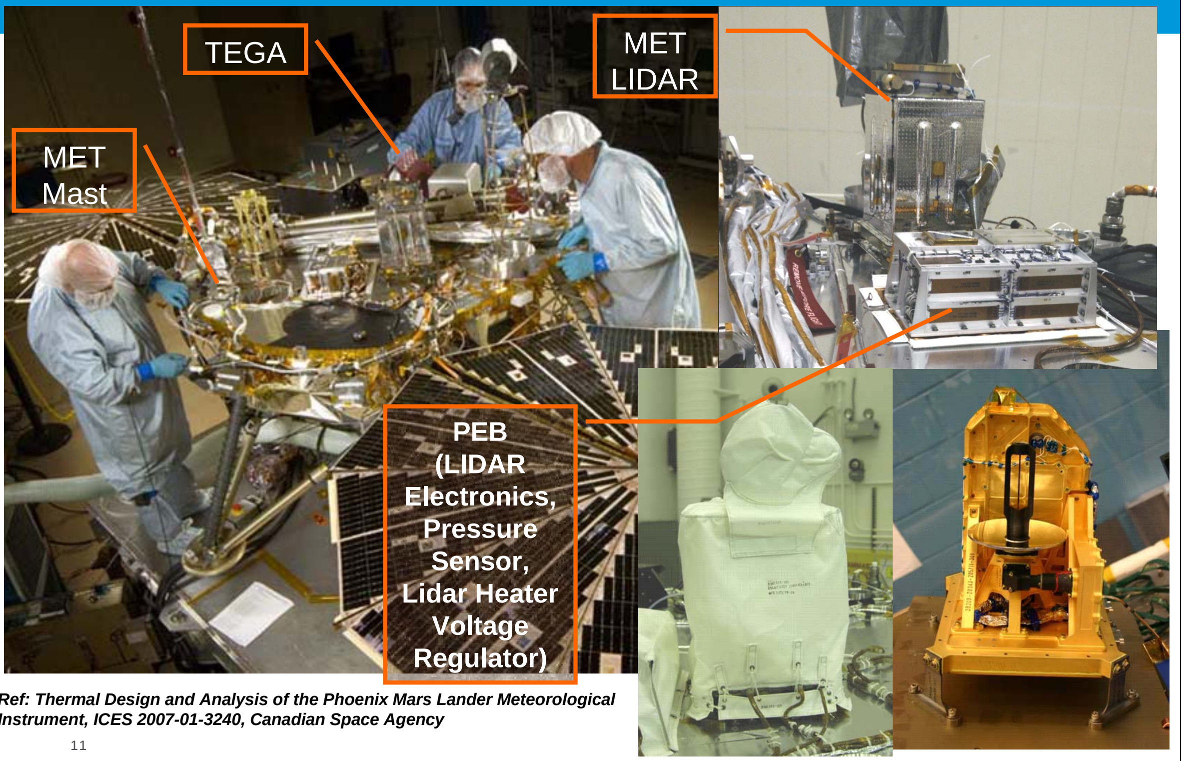
Validation using Phoenix MET Instrument Flight Data



Ref: Thermal Design and Analysis of the Phoenix Mars Lander Meteorological Instrument, ICES 2007-01-3240, Canadian Space Agency

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Thermal Characteristics of the MET Instrument

- Thermal Characteristics of the LIDAR
  - Fiberglas thermal blanket with Betacloth as an exterior layer
  - Thermally isolated from the Spacecraft Deck
  - Main heat loss contributor is the Sky
  - Temperature sensor located on the LIDAR Chassis
- Thermal Characteristics of the Mast Base
  - Thermally coupled to the spacecraft deck
  - Low emissivity finish
  - Sensitive to Solar fluxes
  - Main heat loss contributors are natural and forced convection
  - Temperature sensor located on the Mast Base

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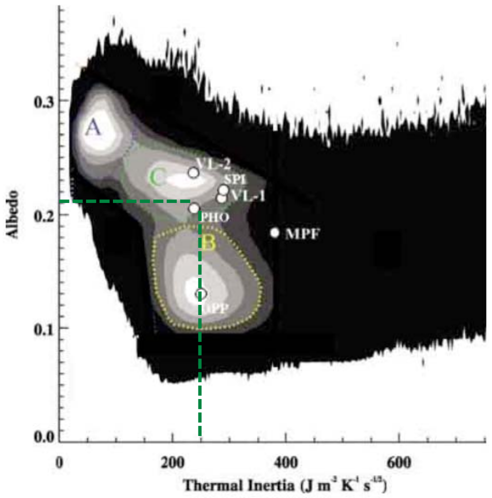
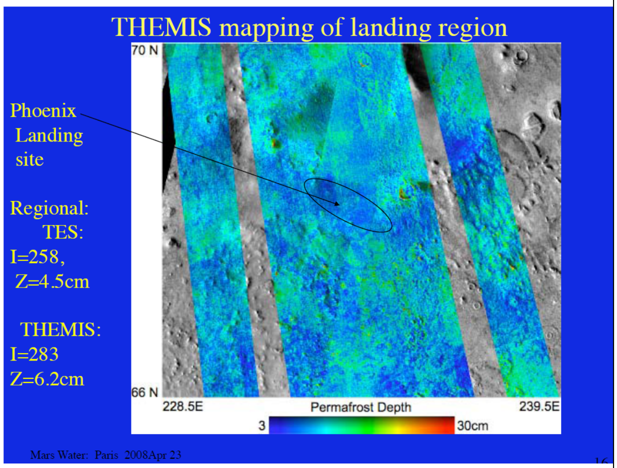
Albedo and Thermal Inertia Mapping of Landing Site

Phoenix Landing Coordinates: 68.218830N 234.250778E,
Landing Mars Solar Longitude (Ls)= 76.6. Mars Spring, May 25th 2008
Albedo = 0.21, Thermal Inertia 250



Ref: RELATIONSHIPS BETWEEN REMOTE SENSING DATA AND SURFACE PROPERTIES OF MARS LANDING SITES. M. P. Golombek and al, 2009



Ref: Martian High latitude permafrost depth and surface-cover thermal inertia distribution: Josh Bandfield and al., 2008

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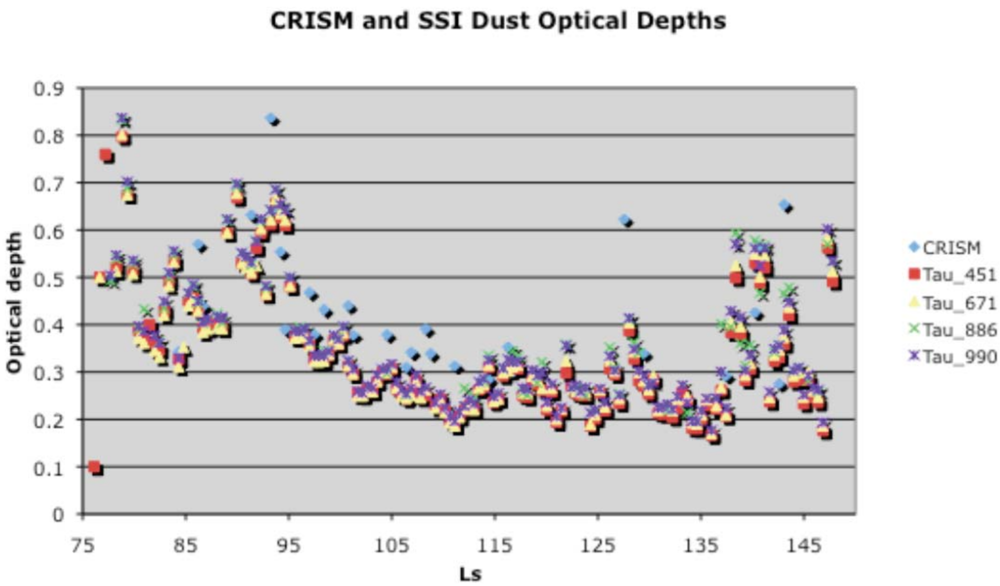
Phoenix Landing Site Optical Depth Measurements



Ref: PHOENIX AND MRO COORDINATED ATMOSPHERIC SCIENCE. L. K. Tamppari et al., 2009

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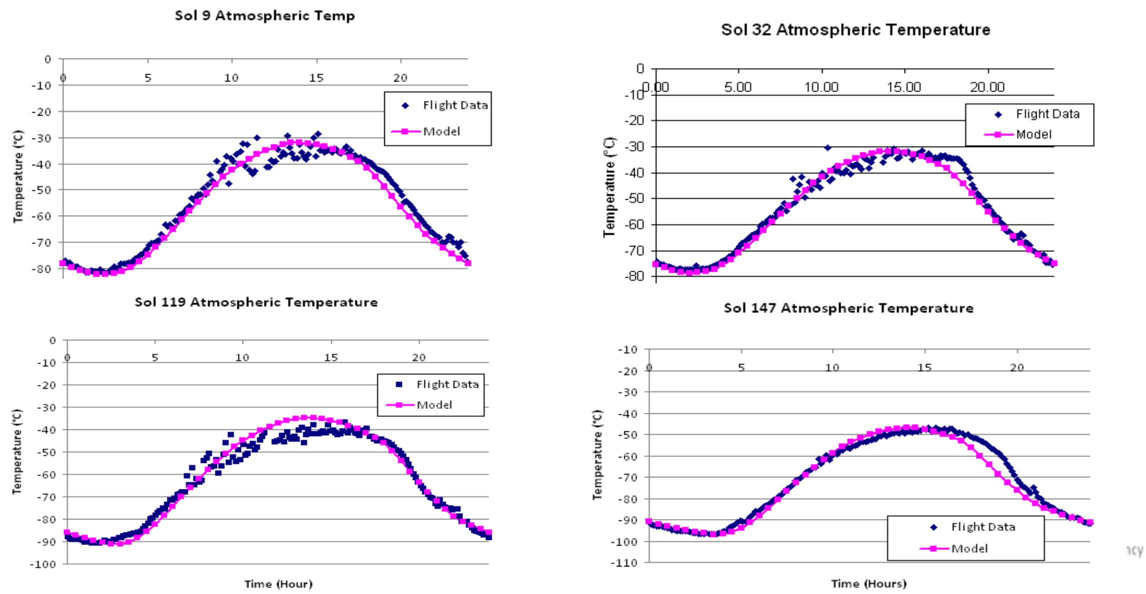
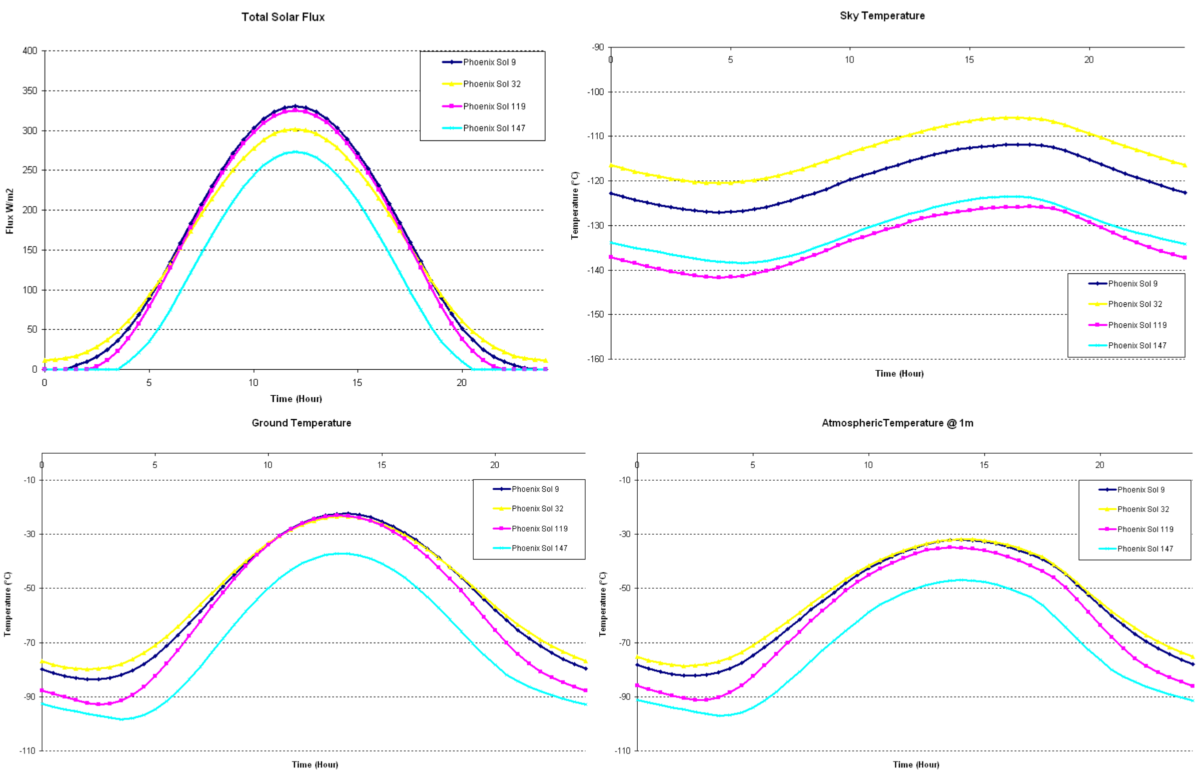
Estimates of the Phoenix Landing Site Environment Parameters

Description	Optical Depth T	Surface Albedo	Ls	Pressure Pa	Thermal Inertia (J m-2 K-1 s-1/2)	Solar Declination	Ground Emissivity	Latitude (oN)
Phoenix Sol 9	0.5	0.24	80.48	835	250	24.8	0.98	68.2
Phoenix Sol 32	0.65	0.24	90.79	801	220	25.2	0.98	68.2
Phoenix Sol 119	0.24	0.24	131.88	733	200	18.6	0.98	68.2
Phoenix Sol 147	0.5	0.26	145.82	733	210	14.0	0.98	68.2

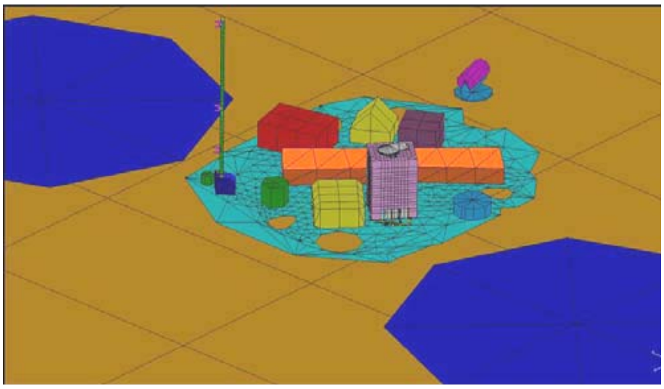


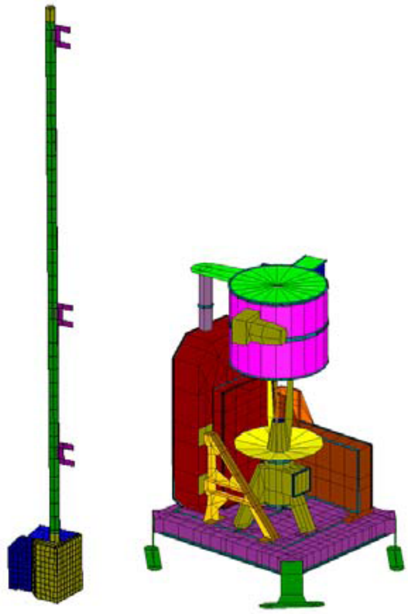
Calculated Phoenix Boundary Conditions using LMD 1D Flux Tool



Phoenix MET Thermal Model

- Thermal Model was built by the Canadian Space Agency
- Generated and analyzed using I-DEAS NX12 and TMG 12
- Model Correlated by Ground Testing in a Martian Thermal Environment





Ref: Thermal Design and Analysis of the Phoenix Mars Lander Meteorological Instrument, ICES 2007-01-3240, Canadian Space Agency

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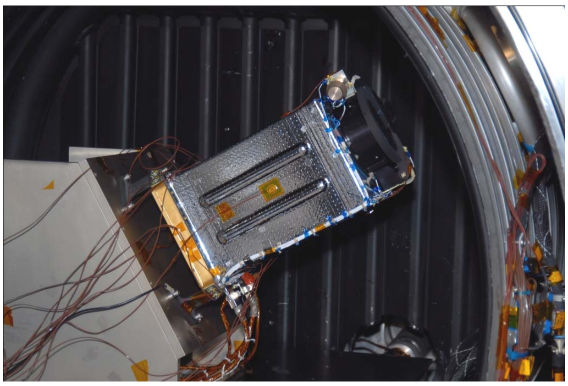
MET LIDAR Thermal Testing

- Tested in an 8 mBar CO_2 environment in order to verify
  - Thermal design
  - Thermal distortion effect on alignment
  - Performance over temperature
- Thermal chamber temperature varied from 30°C to –100°C
  - CO_2 will condense below –100°C
- Natural Convection inside the LIDAR during testing was significant
  - Heat transfer coefficient correlated to test data and adjusted for Mars gravity



Ref: Thermal Design and Analysis of the Phoenix Mars Lander Meteorological Instrument, ICES 2007-01-3240, Canadian Space Agency

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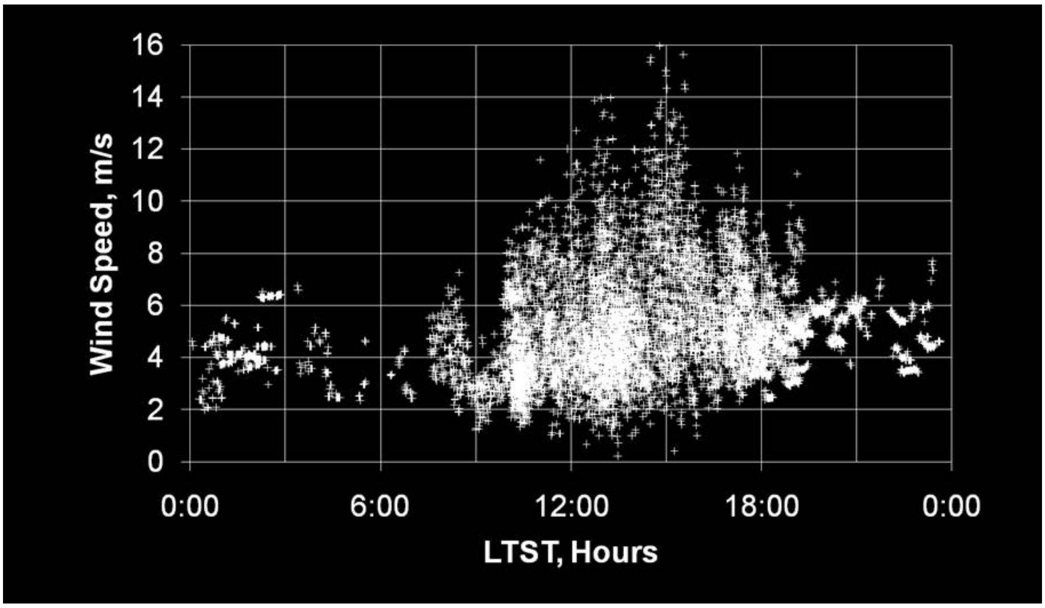
Phoenix Measured Wind Speed over the mission



Ref: Phoenix Mars Lander Mission: Thermal and CFD Modeling of the Meteorological Instrument based on Flight Data, ICES 2010 AIAA 2010-6195, Stéphane Gendron and al., Canadian Space Agency

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Calculated Forced Convection Coefficients

Heat Transfer Coefficients Calculated using CFD

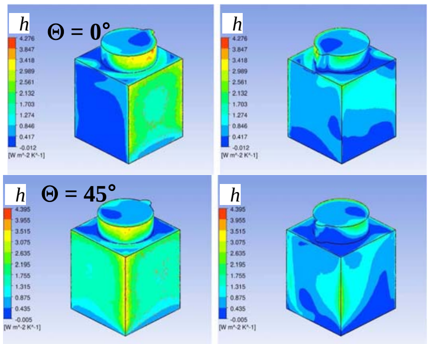
U_∞ (m/s)	Θ (degrees)	h_{avg} (W/m²/K)	h_{min} (W/m²/K)	h_{max} (W/m²/K)
4.14	0	0.94	0.00	4.30
4.14	45	1.12	0.00	4.40

$$0.94 \leq h_{avg} \leq 1.18 \text{ W/m}^2\text{/K}$$

Box Shape Empirical Equation for Heat Transfer Coefficient

$$\frac{hd}{k_f} = 0.102 \cdot \mathrm{Re}_{df}^{\,0.675} \cdot \mathrm{Pr}_f^{\frac{1}{3}}$$

h=0.91 W/m²/K for 4 m/sec Wind



Ref: Phoenix Mars Lander Mission: Thermal and CFD Modeling of the Meteorological Instrument based on Flight Data, ICES 2010 AIAA 2010-6195, Stéphane Gendron and al., Canadian Space Agency

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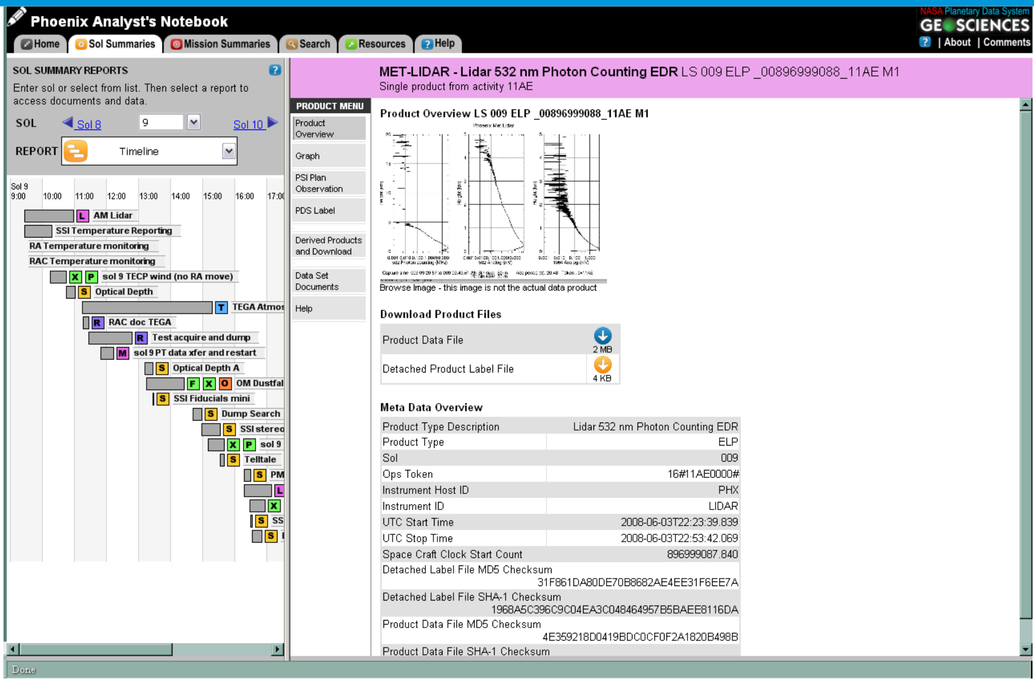
Phoenix Instrument Flight Data Available through Public Website



21 *Ref: http://an.rsl.wustl.edu/phx/solbrowser/default.aspx*

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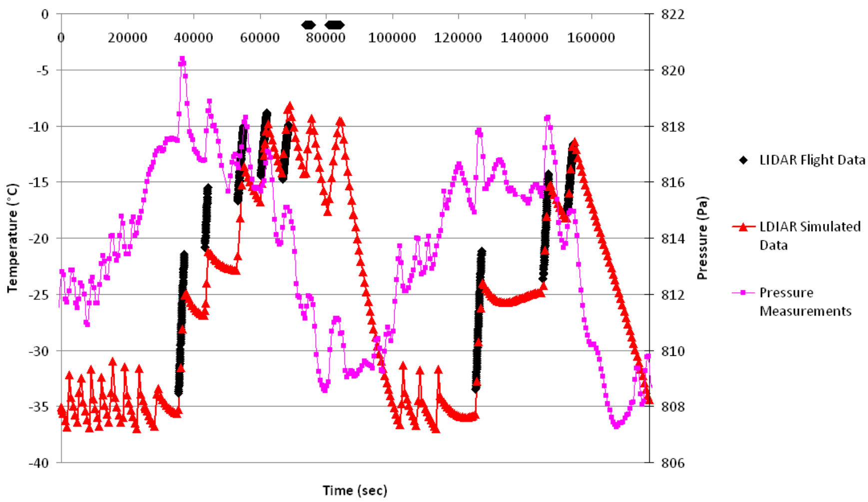
LIDAR Simulated and Flight data Comparison for SOL 32-33

- Pressure sensor located on the PEB, which housed the LIDAR electronics and LIDAR Keep Alive Heater Voltage Regulator
- Temperature variations affect the pressure measurements, which provide information on the duty cycle of the LIDAR heater



22 ***Ref: Phoenix Mars Lander Mission: Thermal and CFD Modeling of the Meteorological Instrument based on Flight Data, ICES 2010 AIAA 2010-6195, Stéphane Gendron and al., Canadian Space Agency***

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LIDAR Simulated and Flight data Comparison for SOL 9 and 119

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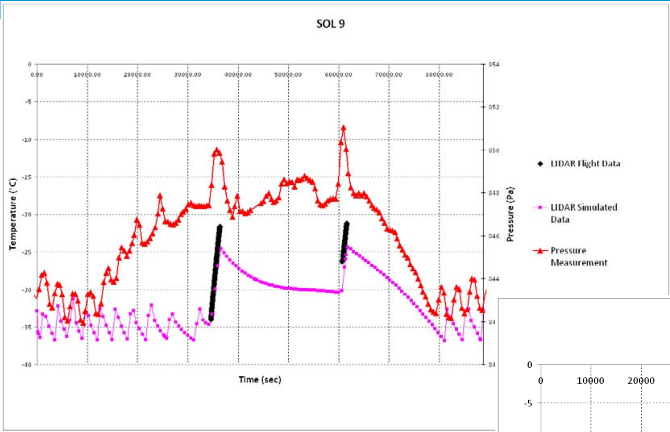

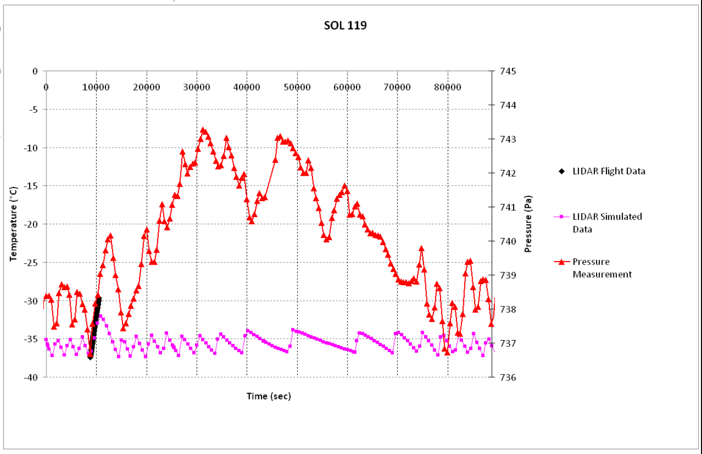

Ref: Phoenix Mars Lander Mission: Thermal and CFD Modeling of the Meteorological Instrument based on Flight Data

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MAST Base and TEGA Simulated and Flight data Comparison

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- Larger temperature differences when compared to the LIDAR data
- Uncertainty in the optical finish, as well as the level of accumulated Dust
- Forced Convection uncertainty, wind gust/speed and direction, blockage effects
- Large Temperature difference for the TEGA instrument could be related to the power dissipation during operations since TEGA model used is based on assumptions

Sol #	LTST (hrs:min)	MAST ITB Flight T (°C)	MAST ITB Model T (°C)	MAST ITB ΔT (°C)	TEGA Flight T (°C)	TEGA Model T (°C)	TEGA ΔT (°C)
9	2:36	-68,1	-82,2	-14,2	-69,9	-72,4	-2,5
	15:07	-12,9	-26,0	-13,2	-15,1	-23,8	-8,7
32	2:48	-69,4	-78,2	-8,9	-67,8	-69,8	-2,0
	14:29	-13,6	-22,7	-9,2	-14,9	-23,1	-8,2
119	2:45	-77,8	-89,9	-12,2	-81,5	-80,1	1,4
	14:18	-16,5	-27,4	-11,0	-7,3	-32,1	-24,8
147	3:26	-85,9	-98,2	-12,4	-90,6	-92,1	-1,5
	14:24	-24,8	-40,8	-16,1	11,0	-43,2	-54,2

Ref: Phoenix Mars Lander Mission: Thermal and CFD Modeling of the Meteorological Instrument based on Flight Data

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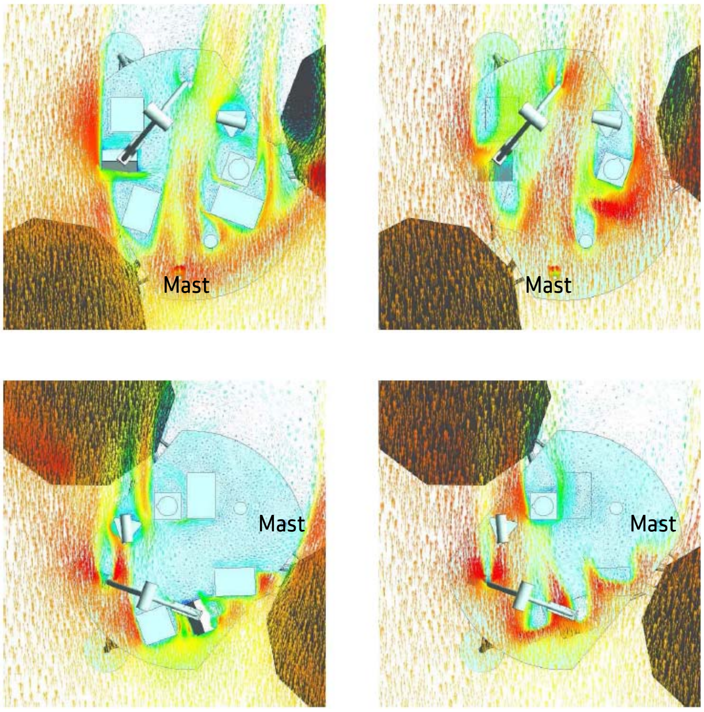
Phoenix Lander Wind Profile Predictions

- Depending on the wind direction, the MET Mast Base may experience significant wind blockage



Ref: Phoenix Mars Lander Mission: Thermal and CFD Modeling of the Meteorological Instrument based on Flight Data, ICES 2010 AIAA 2010-6195, Stéphane Gendron and al., Canadian Space Agency

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Conclusion

- Analysis methods is in agreement with flight data even though the process to determine the environment relies on remote sensing data and atmospheric models, which have a certain uncertainties
- Model of the LIDAR correlates very well since it is less sensitive to wind effects
- MET Mast predicted temperatures have a 9°C to 16°C difference with the flight data.
  - Mainly due to the optical finish uncertainty and wind blockage effects
- This aspect will be critical for the Exomars 2016 Lander mission
  - Further investigation could be performed on the Phoenix Flight data in order to further explain the temperature differences, e.g. including variable heat transfer coefficient

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Acknowledgement
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Canadian Space Agency
Stéphane Gendron, Guanghan Wang, Xin Xiang Jiang,
Darius Nikanpour
University of Alberta
Jeffrey A. Davis, Carlos F. Lange
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