The JPL Microdevices Laboratory

Dr. C. Webster, Director
Dr. S. Forouhar, Deputy Director
Mr. J. Lamb, Laboratory Manager

• MDL Facts
  – Primary goal is to develop unique micro- and nano-devices for space applications, including delivery of space-qualified components
  – Construction funded by NASA
  – Dedicated in 1988
  – 10,000 square foot cleanroom
  – Six research groups

• Key Capabilities
  – Materials growth and deposition
  – Etching (wet, dry, deep trench)
  – High-quality deep-UV photolithography
  – Electron beam lithography
  – Large-format bump-bonding
  – Material and device characterization

• Focus Areas
  – UV/visible/near-IR Si imagers
  – mid-IR III-V imagers
  – FIR/mm superconducting imagers
  – THz electronics
  – IR semiconductor lasers
  – Diffractive optics (e-beam)
  – in-situ sample characterization
  – Nanostructures (e-beam, CNT)
  – Microfluidics

• Mission/Instrument Examples
  – Mars Science Lab (TLS)
  – Herschel (HIFI and SPIRE)
  – Planck (HFI)
  – Chandrayaan-1 (MMM)
  – Mars Reconnaissance Orbiter (MCS)
  – EOS Aura (MLS)
  – Rosetta (MIRO)
Nano and Micro Systems

Goal:
Develop miniature systems utilizing nanotechnology and MEMS components to enhance the performance of existing systems, and to realize mission-enabling new system concepts.

Applications:
- In situ planetary exploration
- Sample return missions
- High-frequency imaging
- Explosives detection
- Stereo imaging
  - geological features in confined spaces
  - minimally invasive neurosurgery

Technologies:
- Carbon nanotube field emitters
- Sample verification sensors
- Microgyroscopes
- Miniature stereoendoscopes
- RF-powered sample extraction

4-mm diameter single-lens stereo camera
Carbon nanotube bundle array field emitters
High-Q Microgyroscope
Cryo-etched black Si optical absorber
RF-powered aqueous sample extractor
Sample verification sensor for sample return missions
GPS: Unique Capabilities

- JPL’s Tracking Systems Section: end-to-end GPS capability; ≈ 70 technologists, scientists, engineers with software, hardware, systems engineering expertise

- Maintain and operate a real-time global network of precision GPS receivers top panel

- Produce real-time estimates of GPS satellite orbits and clocks for NASA, commercial, and DoD customers; < 10-cm real-time positioning capability top panel shows links between ground network and GPS satellites

- Science applications middle panel: transmission to low-Earth orbiter w/ GPS receiver reveals vertical profile of temperature/humidity (left); COSMIC constellation (right)

- Mission support examples: < 1-cm precision orbit determination for Ocean Surface Topography Mission (left), GRACE (right); also Earth orientation and atmosphere/ionosphere calibrations for Deep Space Tracking support

J Zumberge, February 1, 2012
TriG GNSS - Key Features

- Scalable 3U Architecture
- Receives GNSS signals (GPS, Galileo, GLONASS, Compass,…) + DORIS
- Multiple digitally steered high-gain beams.
- Linux based Science processor allow easy modification of onboard processing by non-receiver experts
- Large reconfigurable signal processing resources
- Advanced signal processing including open-loop tracking, Blue Shift processing, etc.
- Allow either internal or external frequency reference.
- Highly reliable design with TID > 40krad
- Autonomous Operations
Science-Driven Radar Technology Development at JPL

Alina Moussessian
Radar Science and Engineering Section
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109 USA

UCLA Engineering Collaboration Open House
April 2, 2012
### Radar Technology Needs for Earth and Planetary Science and Exploration

**RF Technologies**
- mm-wave ICs
- mm-wave MIMIC TRMs
- Single-chip TRMs
- L-band TRM w/digital cal
- High-efficiency PAs
- Ultra-high stability Receivers

**Large Aperture Technologies**
- Flexible membranes
- Shaped memory materials

**Digital Technologies**
- Beamforming arrays
- On-board processing
- ASIC applications
- High-radiation tolerant electronics

**Mod./Sim./Proc., Techniques**
- Interferometry/Tomography
- Data Assimilation
- Time-series analysis

**Millimeter Wave Radar**
- Landing Radar
  - Mars, Moon hazard avoidance*
- ACE*
  - Earth clouds and precipitation
- Titan Explorer*
  - Titan clouds

**Microwave Radar**
- DESDynI*
  - Deformation Biomass
- SMAP*/SCLP
  - Cold Land Processes
    - Global Soil Moisture
  - Disaster management and forecasting

**Low-frequency Radar Sounders**
- Asteroids
- Earth
  - Ice thickness and aquifer depth
- Europa
  - Europa Oceans*

**Radar Interferometers**
- Tandem-L*
  - Dynamics and Ecosystems
- SWOT*
  - Ocean Structures & Circulation

*Proposed Missions Pre-decisional – for Planning and Discussion Purposes Only
JPL Radar and Science Engineering, Areas of Interest

JPL’s science-driven program focuses on exploiting commercially available components to build new technologies to meet NASA’s science goals.

Areas of interest Include:
- Science and Radar Phenomenology
- Radar System Engineering
- Hardware and Technology Development
- Radar algorithm development and data processing

Collaborations with universities, industry, other agencies, or international partners are often key to implementation.
Proposed Missions & Technologies

- >100 W, >70% PAE Solid State Amplifiers
- On-board Digital Beamforming & Calibration
- SweepSAR gap mitigation techniques
- Closed-loop (Mech-EM-DBF) antenna design
  - Ka-band reflect-arrays
  - On-board interferometry
  - >100W Solid State PA (35-36 GHz)
  - SEU Tolerant processing
  - Compact, thermally efficient electronics
  - Extreme-radiation tolerant amplifiers
    - SEU Tolerant processing
    - Compact, thermally efficient electronics
    - Extreme-radiation tolerant amplifiers
- Deployable Membrane Active Apertures
- Roll-able electronics
- Mechanical and thermal management of membrane antennas

DESDynI*  
(Deformation, Ecosystems Structure and Dynamics of Ice)  
Repeat pass, L-band Interferometric SAR

Titan Explorer/Imaging Radar  
Jupiter Europa Orbiter/Sounding Radar

GESS  
(Global Earthquake Satellite System)  
Geosynchronous SAR

SWOT*  
(Surface Water Ocean Topography)  
Single pass, Ka-band Interferometric SAR

ACE*  
(Advanced Composition Explorer)  
W-band & Ka-band atmospheric profiling radars

*Proposed Missions
Key Low-TRL Technologies

- RFIC/ASIC
  - Decrease size & power consumption
  - Increase integration and output power

- W-band arrays
  - 100’s to 1000’s
  - 1 W per channel or TR
  - Integrated backend control and processing electronics
  - Space efficient 3D integration

- On-board processing
  - Currently in Xilinx V5 class FPGAs
  - Move towards custom ASIC
    - FFTs, Presumming, DBF…

- Array-fed reflector, Digital Beamforming antenna modeling
  - Currently employ HFSS, GRASP to perform EM modeling, custom DBF algorithms to estimate SweepSAR performance
  - Move towards integrated model—eventually to a closed-loop optimization

- Large Aperture, Deployable Membrane Antennas
Radar Science

- Radar science at JPL tries to answer key questions in various science disciplines by relating geophysical parameters of interest to radar observables.
  - Radar observables take advantage of every key electromagnetic parameter that can be varied including wavelength, polarization, amplitude, phase, range, Doppler and angle.
  - Synergistic combination with other data sets (data fusion) and time series analysis are often central to extracting geophysical parameters of interest.
  - Modeling of electromagnetic interaction with various types of scatters either for geophysical inversion or to understand basic sensitivities are integral to both data exploitation and development of new measurement concepts and techniques.
  - Data analysis activities often involve sophisticated statistical or signal processing techniques in order to reliably extract subtle or potentially ambiguous signal from radar data.
  - Work varies from theoretical analysis to hands on work with radar data collected from spaceborne, airborne and ground based radar assets.

<table>
<thead>
<tr>
<th>Science</th>
<th>Altimeter</th>
<th>Sounder</th>
<th>Precipitation</th>
<th>SAR</th>
<th>Scatterometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Archeology</td>
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<td></td>
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<td>√</td>
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<tr>
<td>Atmospheric Science</td>
<td>√</td>
<td>√</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Ecology</td>
<td></td>
<td></td>
<td></td>
<td>√</td>
<td></td>
</tr>
<tr>
<td>Geodesy Solid Earth</td>
<td></td>
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<td></td>
<td></td>
<td>√</td>
</tr>
<tr>
<td>Geology</td>
<td>√</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geomorphology</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Climatology</td>
<td>√</td>
<td></td>
<td></td>
<td>√</td>
<td>√</td>
</tr>
<tr>
<td>Planetary Science</td>
<td>√</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oceanography</td>
<td>√</td>
<td></td>
<td></td>
<td></td>
<td>√</td>
</tr>
</tbody>
</table>

Science activities span a broad range of disciplines using a variety of radars that are matched to the geophysical parameters of interest.
• Long history of building lidars to measure:
  - Range, distance, quantitative 3D images/movies
  - Atmospheric backscatter
  - Atmospheric polarization

• Current projects:
  - CO2LAS, remote column CO₂ measurement from an aircraft as part of the ASCENDS Decadal Survey Mission
  - Polarization lidar for atmospheric studies
  - Compact 3D imaging lidar for terrain and hazard mapping during spacecraft entry, descent and landing
CO2LAS flies on the NASA DC-8 aircraft and measures the column integrated CO$_2$ beneath the aircraft.

It uses highly stabilized lasers at different wavelengths to measure the absorption due to CO$_2$ at different points on the absorption line.

The technique can be applied to measure other atmospheric species by suitable wavelength selection.
JPLs GaAs Technology

MMIC W-band amplifiers

Multipliers/Mixers

RF → THz

2.3 x 1.6 mm

Developed as LOs for Missions

Herschel

HIFI

Useful for Laboratory and Field Spectroscopy of Gas-Phase Molecules

JPL-UCLA Engineering Collaboration Initiative Meeting - Brian Drouin
Future Directions

Improvements in Spectrometer will lead to:

• Field Missions
  – Point sensor
  – Airborne sampling

• Improved Research
  – Higher sensitivity

• Commercial Applications?
  – Pollution monitoring
  – Threat detection
  – Medical screening

➤ Compressed devices
  + “Radiometer on a Chip”
  + Improve efficiency of THz generation
  + Reduce Mass & Power
  - End-to-end tests only

➤ Cavity Enhanced Absorption
  + “THz cavity ringdown”
  + Nonlinear improvement in sensitivity
  + Improves mass & volume
  - Coupling issues
  - May require radical design

➤ FPGAs / ASICs
  + Reduces electronics to single board
  + Reduces mass & power
  - Potentially limits trade-space
**Atmospheric sounding**

- **JPL High Altitude MMIC Sounding Radiometer (HAMSR) IIP-98**
  - Microwave radiometer for 3-D all-weather temperature and water vapor sounding, similar to AMSU on NOAA platform
  - 25 sounding channels in three bands:
    50-60 GHz, 118 GHz, 183 GHz
Interferometric Radiometer Arrays

Full size GeoSTAR

183 GHz array

55 GHz array

2m
Microwave Remote Sensing Instruments

Paul Stek - Group Supervisor

Formerly led by Dr. Joe Waters
We develop microwave remote sensing instruments from concept through processed data.

Comprised of technologists, instrument scientists, high rel manufacturing engineers, and instrument operations, calibration, and data processing specialists

Emphasis is generally on the measurement system and flight implementation not on the receiver front end technology

Engineering side of the Microwave Limb Sounder team and most of the group is collocated with the MLS science team.

Developed 2 large earth observing missions - MLS on UARS and Aura

Built flight receivers for the Microwave Radiometer (MWR) on Juno and currently building flight receivers for the Advanced Microwave Radiometer (AMR) on Jason 3

Leading Scanning Microwave Limb Sounder technology development. SMLS is one of the instruments on GACM in NASA’s Earth Science Decadal survey.

Research Staff:
Richard Cofield (MLS optics design)
Dr. Robert Jarnot (MLS Instrument Scientist, spectrometer lead)
Ryan Monroe (digital signal processing)
Dr. Frank Maiwald (Microwave to THz receivers and sources)
Dr. Sharmila Padmanabhan (Microwave radiometer systems)
Dr. Paul Stek (cryogenic instruments, plasma fusion diagnostics)
Jordan Tanabe (Microwave Engineer, UCLA graduate student)
Research Interests

- **Instrument calibration and operation**
  - For limb sounding spectroscopy (MLS) and nadir viewing water vapor (AMR on Jason)

- **Microwave Optics**
  - Large (4-meter 200-600 GHz) antennas
  - Quasi-optical systems
  - Antenna characterization
    - 8x8 foot near field antenna range good to 660 GHz

- **Signal processing for microwave radiometry**
  - Digital polyphase spectrometers
  - FPGA based 3 GHz bandwidth 8K channels
  - Custom ASIC 750 MHz 8K channels developed with UCB & BWRC (Dan Wertheimer, Prof. Bora Nikolic)

- **Suborbital technology demonstration**
  - Airborne and balloon cryogenic microwave limb sounders
Imaging Spectrometer Development at JPL

Imaging spectroscopy concept
Surface material identification
Hazards/episodic events
Vegetation health/productivity

AVIRIS (1987)
MaRS (2006)
M3 (2008)
NGIS (2011)
PRISM (2012)
UCIS (2012)
HyTES (2012)
Imaging Spectrometer Development at JPL

- **High SNR**
- **Calibration accuracy**
- **Uniformity**
- **Subtle spectral features**

- Innovative optical and mechanical design to minimize optical elements and combine high throughput and wide field.
- Diffraction grating development for spectral efficiency and polarization control.
- Alignment and measurement techniques for achieving ~1% pixel level accuracy.

- Required Uniformity
- Failure by "frown"
- Failure by twist
- Failure by Spectral-IFOV-shift 4-1

- Hyperion is ~1992 equivalent

- M³ Spectra Plagioclase (anorthosite)
- Reflectance
- Pyroxene Features in 2 & 4

- Radiance (mW/cm²/nm/mr)
- Wavelength (nm)
NASA Aircraft Resources

William H. Mateer II
Jet Propulsion Laboratory

william.h.mateer@jpl.nasa.gov
NASA Airborne Science Platform Overview

• NASA Airborne Science Program (ASP) operated out of HQ, but with a wide variety of airborne platforms located at DFRC, ARC, DAO, JSC, WFF, and commercial locations
  – See following for examples of payload accommodation and flight regimes
• Aircraft (piloted and UAS) are available for a variety of missions, including instrument development (pathway to space), scientific research, and disaster response
• Airborne missions include large, multi-year, multi-discipline, multi-platform to small, single instrument missions
• Research calls include SARP and NSPIRES (e.g., IIP, AITT, ROSES)
• JPL can collaborate with UCLA on proposals for NASA aircraft usage
• JPL has the capabilities to develop flight qualified hardware
### NASA Airborne Platforms (Examples)

<table>
<thead>
<tr>
<th>Platform Name</th>
<th>Center/Operator</th>
<th>Duration (hours)</th>
<th>Useful Payload (lbs)</th>
<th>GTOW (lbs)</th>
<th>Max Altitude (ft)</th>
<th>Air Speed (knots)</th>
<th>Range (Nmi)</th>
<th>Operators</th>
<th>Cost ($/flt-hr)</th>
<th>Available Power (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC-8</td>
<td>DFRC, UND</td>
<td>12</td>
<td>30,000</td>
<td>340,000</td>
<td>41,000</td>
<td>450</td>
<td>5,400</td>
<td>42 + 8</td>
<td>6,500</td>
<td></td>
</tr>
<tr>
<td>ER-2</td>
<td>DFRC</td>
<td>12</td>
<td>2,900</td>
<td>40,000</td>
<td>70,000</td>
<td>410</td>
<td>5,000</td>
<td>1</td>
<td>3,500</td>
<td>30 kVA, (115 VAC at 400 Hz) 10KVA (28 VDC)</td>
</tr>
<tr>
<td>G-III - DFRC</td>
<td>DFRC</td>
<td>7</td>
<td>2,610</td>
<td>69,700</td>
<td>45,000</td>
<td>459</td>
<td>3,400</td>
<td>8 + 2</td>
<td>2,500</td>
<td></td>
</tr>
<tr>
<td>G-III - JSC</td>
<td>JSC</td>
<td>7</td>
<td>2,610</td>
<td>69,700</td>
<td>45,000</td>
<td>459</td>
<td>4 + 2</td>
<td>2,500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Global Hawk</td>
<td>DFRC</td>
<td>31</td>
<td>1,500</td>
<td>25,600</td>
<td>65,000</td>
<td>335</td>
<td>11,000</td>
<td>0 (UAS)</td>
<td>6,500</td>
<td></td>
</tr>
<tr>
<td>P-3 Orion</td>
<td>GSFC (WFF)</td>
<td>14</td>
<td>14,700</td>
<td>135,000</td>
<td>32,000</td>
<td>400</td>
<td>3,800</td>
<td>3,500</td>
<td>115V 60Hz single phase; 115V 400Hz 3 phase; 28V DC</td>
<td></td>
</tr>
<tr>
<td>WB-57</td>
<td>JSC</td>
<td>6</td>
<td>6,000</td>
<td>63,000</td>
<td>&gt; 60,000</td>
<td>410</td>
<td>2,500</td>
<td>3,500</td>
<td>110V/60Hz AC, 110V/400Hz AC, and 28 VDC</td>
<td></td>
</tr>
<tr>
<td>B-200 - DFRC</td>
<td>DFRC</td>
<td>6</td>
<td>1,850</td>
<td>12,500</td>
<td>30,000</td>
<td>272</td>
<td>1,490</td>
<td>2</td>
<td>168.5 A at 28 VDC</td>
<td></td>
</tr>
<tr>
<td>B-200 - DOE</td>
<td>ARC / DOE</td>
<td>6.75</td>
<td>2,000</td>
<td>14,000</td>
<td>32,000</td>
<td>250</td>
<td>1,883</td>
<td>5</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>B-200 - LARC</td>
<td>LARC</td>
<td>6.2</td>
<td>4,100</td>
<td>13,500</td>
<td>35,000</td>
<td>260</td>
<td>1,250</td>
<td>4</td>
<td>168.5 A at 28 VDC</td>
<td></td>
</tr>
<tr>
<td>B-200 - WFF</td>
<td>WFF</td>
<td>5.5</td>
<td>2,000</td>
<td>12,500</td>
<td>35,000</td>
<td>260</td>
<td>2,075</td>
<td>1 - 9</td>
<td>28VDC</td>
<td></td>
</tr>
<tr>
<td>C-23 Sherpa</td>
<td>WFF</td>
<td>7</td>
<td>7,000</td>
<td>27,100</td>
<td>20,000</td>
<td>190</td>
<td>1,800</td>
<td>10</td>
<td>28VDC</td>
<td></td>
</tr>
<tr>
<td>Cessna 206H</td>
<td>LARC</td>
<td>5.7</td>
<td>1,175</td>
<td>3,600</td>
<td>15,700</td>
<td>150</td>
<td>700</td>
<td>2</td>
<td>180A at 28Vdc</td>
<td></td>
</tr>
<tr>
<td>HU-25C Falcon</td>
<td>LARC</td>
<td>3</td>
<td>3,000</td>
<td>32,000</td>
<td>42,000</td>
<td>430</td>
<td>1,900</td>
<td>350 amps DC, 47 amps AC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ikhana</td>
<td>DFRC</td>
<td>24</td>
<td>2,000</td>
<td>10,000</td>
<td>&gt; 40,000</td>
<td>171</td>
<td>3,500</td>
<td>0 (UAS)</td>
<td>~6 KW at 28 VDC</td>
<td></td>
</tr>
<tr>
<td>Learjet 25</td>
<td>GRC</td>
<td>3</td>
<td>3,200</td>
<td>15,000</td>
<td>45,000</td>
<td>350</td>
<td>1,200</td>
<td>3 + 2</td>
<td>250A at 28Vdc</td>
<td></td>
</tr>
<tr>
<td>S-3B</td>
<td>GRC</td>
<td>6</td>
<td>12,000</td>
<td>52,500</td>
<td>40,000</td>
<td>450</td>
<td>2,300</td>
<td>4</td>
<td>150KW at 110/400Hz</td>
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</tr>
<tr>
<td>SiERRA</td>
<td>ARC</td>
<td>10</td>
<td>100</td>
<td>400</td>
<td>12,000</td>
<td>60</td>
<td>600</td>
<td>0 (UAS)</td>
<td>1,500</td>
<td>19Amps @ 28 V DC</td>
</tr>
<tr>
<td>T-34C</td>
<td>GRC</td>
<td>3</td>
<td>500</td>
<td>4,400</td>
<td>25,000</td>
<td>75</td>
<td>700</td>
<td>2</td>
<td>60A at 28Vdc</td>
<td></td>
</tr>
<tr>
<td>Twin Otter - GRC</td>
<td>GRC</td>
<td>3</td>
<td>3,600</td>
<td>11,000</td>
<td>25,000</td>
<td>140</td>
<td>450</td>
<td>2 + 2</td>
<td>200A at 28Vdc</td>
<td></td>
</tr>
<tr>
<td>UC-12B - LARC</td>
<td>LARC</td>
<td>6.2</td>
<td>4,100</td>
<td>13,500</td>
<td>31,000</td>
<td>260</td>
<td>1,250</td>
<td>4</td>
<td>200A at 28Vdc</td>
<td></td>
</tr>
</tbody>
</table>

### Notes

- Partial Listing of Aircraft available to NASA investigations
- Points of Contact and additional information at [http://airbornescience.nasa.gov/](http://airbornescience.nasa.gov/)

### Acronyms

- **ASP** - Airborne Science Program (NASA HQ, Washington, DC)
- **DFRC** - Dryden Flight Research Center (Edwards Air Force Base and Palmdale, CA)
- **DOE** - Department of Energy
- **GRC** - Glenn Research Center (Cleveland, OH)
- **GSFC** - Goddard Space Flight Center (Greenbelt, MD)
- **JSC** - Johnson Space Center (Houston, TX)
- **LaRC** - Langley Research Center (Hampton, VA)
- **MT** - Mohawk Technologies (Lantana, FL)
- **NASA** - National Aeronautics and Space Administration
- **OPTEC** - OPTEC Solutions (Yuba City, CA)
- **SI** - Starfighters Inc. (JFK Space Center, FL)
- **TOI** - Twin Otter, International (Grand Junction, CO)
- **UND** - University of North Dakota
- **WFF** - Wallops Flight Facility (Wallops Island, MD)
Data management and analysis

Paul von Allmen

- Climate data analysis (POC: Seungwon Lee)
  - Build information system to co-locate and merge climate data to understand climate and weather processes
- Climate model evaluation using A-train satellite observations (POC: Chengxing Zhai)
  - Use NASA A-train satellite data to evaluate the performance of climate models for IPCC/AR5
- Provenance services for multi-sensor merged climate data records (POC: Hook Hua)
  - Automated capture of provenance for multi-sensor climate data production and “exploratory computing”
- OSCAR: Online system for correcting atmosphere in radar (POC: Paul von Allmen)
  - Develop online facility to compute the water vapor corrections to InSAR imaging
- ISO geographic metadata for Earth science data products (POC: Hook Hua)
  - Ease implementation and utilization of the ISO 19115 metadata standard into Earth science data products
Modeling activities

- Thermo-physical properties of asteroids and comets (POC: Paul von Allmen)
  - Model temperature profiles at surface and inside of small bodies in solar system
- Rarefied gas dynamics (POC: Paul von Allmen)
  - Compute non-equilibrium flow and expansion of low-density fluids
- Non-LTE radiative transfer (POC: Seungwon Lee)
  - Model radiative transfer with non-local thermal equilibrium molecular population
- First principles simulations of thermoelectric materials (POC: Paul von Allmen)
  - Use modeling to discover new materials with improved thermoelectric figure of merit
- Multi-scale modeling of nanostructures and devices (POC: Paul von Allmen)
  - Atomic level large scale modeling to support design of nano-scale devices
- CIELO: Multidisciplinary analysis of precision deployable systems (POC: Greg Moore)
  - Research, develop, and infuse software infrastructure tools for analysis-driven design of precision, integrated systems
Exploit spatial, temporal, and between-variable correlations to optimally estimate a bivariate field. Optimal = minimum uncertainty.

Instruments provide data at different resolutions, times and with different statistical characteristics. Rigorously quantify and propagate uncertainties of the estimates.

Massive Data Set Analysis

How do we understand data structure, within and between scales, in massive data sets?

- Stratify the data into meaningful subsets (e.g., lat/lon/time).
- Summarize the subsets using multivariate distribution estimates. Be sure these are constructed in a way that makes them comparable.
- Use a distance metric between distributions to quantify relationships across subsets.
1. Multimodal Non-Rigid Image Registration
   with Veljko Jovanovic
   - A need to advance image matching algorithms to account for non-rigid deformation.
   - **Challenges:** Representing fluid deformation and discontinuous behavior of cloud motion.

2. Multispectral Multiframe Superresolution of Deforming Blurry and Noisy Scenes with Applications to Microwave Hurricane Imagery
   with Bjorn Lambrigtsen
   - **Challenges:** Information is not always shared between different bands.

3. Atmospheric Data Fusion and Data Deconvolution on Irregular Grids
   with Amy Braverman and Hai Nguyen
   - **Challenges:** No uniform grid assumption.

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Layers of Reflective Surfaces in Earth Remote Sensing Imaging Data: Multi-Angle Multi-Spectral Layer Separation and Cloud Tomography

with Veljko Jovanovic, Anthony Davis, David Diner

*Upper clouds*: vary slowly in space; strongly stratified and optically thin.

*Lower convective clouds*: optically thick, with relatively sharp boundaries.

**Challenges**: Computational efficiency; alternative methods for layer separation will be beneficial.