NASA SBIR 2005 Phase I Solicitation

S6  Earth-Sun System Instrument and Sensor Technology

NASA's Earth-Sun Systems (ESS) Division is committed to studying how our global environment is changing. Using the unique perspective available from spaceborne and airborne platforms, NASA is observing, documenting, and assessing large-scale environmental processes with emphasis on atmospheric composition, climate, carbon cycle and ecosystems, the Earth's surface and interior, the water and energy cycles, and weather. A major objective of ESS instrument development programs is to implement science measurement capabilities with small or more affordable spacecraft so development programs can meet multiple mission needs and therefore make the best use of limited resources. The rapid development of small, low-cost remote sensing and in situ instruments is essential to achieving this objective. Consequently, the objective of this SBIR topic is to develop and demonstrate instrument component and subsystem technologies that reduce the risk, cost, size, and development time of Earth observing instruments and to enable new Earth observations measurements. The following subtopics are concomitant with this objective and are organized by measurement technique.

Subtopics

S6.01 Passive Optics

Lead Center: LaRC
Participating Center(s): ARC, GSFC, MSFC

The following technologies are of interest to NASA in the remote sensing subtopic "passive optics." Passive optical remote sensing generally requires that deployed devices have large apertures and large throughput. NASA is interested primarily in instrument technologies suitable for aircraft or space flight platforms, and these inherently also prefer low mass, low power, fast measurement times, and a high degree of robustness to survive vibrations in flight or at launch. Wavelengths of interest range from ultraviolet through the far infrared. Development of techniques, components and instrument concepts that can be developed for use in actual deployed devices and systems within the next few years is highly encouraged.

Technologies and components that are not clearly suitable for use in high throughput remote sensing instruments are not applicable to this subtopic. Technical and scientific leads at NASA have given careful consideration to the technology areas described below; responses are solicited for these topics.
• Technology leading to visible/NIR narrowband optical filters exhibiting greatly improved degradation properties over existing filters and minimal spectral drift for long-term space-based applications;

• Technology leading to significant improvements in capability of large format (>1 inch diameter), very narrow band (FWHM less than 2 cm⁻¹) optical filters; and

• Large format (>1 inch diameter), high-transmission, far infrared filters. Technology and techniques leading to filters operating at wave numbers between 500 and 5 cm⁻¹ with FWHM less than 2 cm⁻¹ are of immediate interest, though technology leading to very high transmission edge filters (long and short pass) is also solicited. The filters must be capable of operating in a vacuum at cryogenic temperatures; and

• High-performance, four-band two-dimensional (2D) arrays (128x128 elements) in the 0.4 - 2.5 µm wavelength range with high quantum efficiencies (60%-80% or higher) in all spectral bands, low noise, and ambient temperature operation.

S6.02 Lidar Remote Sensing

Lead Center: LaRC
Participating Center(s): GSFC

High spatial resolution, high accuracy measurements of atmospheric parameters from ground-based, airborne, and spaceborne platforms, require advances in the state-of-the-art lidar technology with emphasis on compactness, reliability, efficiency, low weight, and high performance. Innovative technologies that can expand current measurement capabilities to airborne, spaceborne, or Unmanned Aerial Vehicle (UAV) platforms are particularly desirable. Development of components that can be used in actual deployed systems within the next few years is highly encouraged. Technologies and components that are not clearly suitable for effective lidar remote sensing or field deployment are not applicable to this subtopic. This subtopic considers components that enable Earth-sun system measurements such as:

• Cloud and aerosols with emphasis on aerosol optical properties;
• Wind profiles using direct-detection lidar, or coherent-detection (heterodyne) lidar, or both;
• Land topography (vegetation, ice, land use); and
• Molecular species (ozone, water vapor, and carbon dioxide).

Innovative component technologies that directly address the measurement needs above will be considered. Dual-use technologies addressing Planetary Exploration are highly desirable (see subtopics X1.03 and S1.04). For the PY05 SBIR, we are soliciting component technologies described below.
Pulsed, single frequency, diode-based seed laser MOPA systems are desired due to inherent robustness, efficiency, thermal and alignment stability. If the cost per unit is reasonable, and the size is small, then many of these can be installed on a spacecraft for either parallel operation or as backup units to lengthen the life of the mission. Systems with the following specifications are solicited:

- Single frequency 1064 nm operation.
- Small, pinned package(s) that can generate CW powers in the 100's of mW and higher pulse powers yielding at least 10 nJ pulse energies.
- Gaussian pulsewidths between 100 ps and 5 ns.
- MOPA design configuration is desired where the pulse production cavity is short and more readily impedance matched for the fast rise times, gain switching, etc.
- A semiconductor amplifier, or possibly a small cm-scale Yb:fiber amplifier, can be coupled to the oscillator chip's output, itself contained in a hermetic butterfly or similar package.
- Repetition rates as low as 100 Hz and as high as 10 kHz is needed, with pulsed lifetimes in the trillion shot regime ($10^{12}$).
- Single mode, PM fiber output is needed.
- Short term drift less than 1 MHz.

CW, dual frequency, diode-based seed laser systems are desired for high power solid-state laser cavity feedback and locking at 1064 nm. If two wavelengths are produced, one must be 1064 nm and another single wavelength 5 nm or more offline (in either direction). Systems with the following specifications are solicited:

- Simultaneous dual frequency operation; 1064 nm and a second wavelength at least 5 nm (either plus or minus) from 1064 nm.
- Small, pinned package(s) that can generate CW powers in the 100s of mW and higher pulse powers.
- CW output powers of >10 mW in each wavelength. Individual tunability is not required, but tunability of the 1064 nm output is required.
- Dual PM, single mode fiber output is desired, but not absolutely required.
- 5 MHz or less short term drift over 30 sec.

Efficient and compact single frequency solid state or fiber lasers operating at 1.5 and 2.0 micron wavelength regimes. Suitable for coherent lidar applications, these lasers must meet the following general requirements: pulse energy 2 mJ to 100 mJ, repetition rate 10 Hz to 200 Hz, and pulse duration of approximately 200 nsec.

Shared aperture, angle-multiplexed holographic or diffractive optical elements having several fields of view, each with angular resolution of 50 µrad or better for the Nd:YAG or Nd:YLF laser harmonics, and diffraction limited resolution for the Ho:YLF fundamental wavelength. Wide, flat, focal planes with low off-axis aberrations is of importance to terrain and vegetation mapping lidar applications. Hybrid designs using both 2053 nm or 1064 nm and 355 nm simultaneously are needed for dual wavelength Doppler wind lidar applications. Materials and technologies are needed that can be scaled up to 1 m apertures and larger and
space qualified. Designs using lightweight materials, such as composites or membranes and deployable folded architectures, are also desired to decrease system size and weight.

- Novel, high-power laser diodes capable suitable for pumping Holmium-based solid state lasers:
  
  - Quasi-CW laser diode arrays operating in 1939 nm or 1906.8 nm wavelengths with pulse duration of at least 1 msec, peak power in 10s watts regime, and duty cycle of greater than 2%;
  
  - Quasi-CW fiber-coupled laser diode pump arrays operating in 785 nm or 792 nm wavelengths with pulse duration of at least 1 msec, peak power in 100s watts regime, and duty cycle of greater than 2%; and
  
  - CW fiber-coupled laser diode pump arrays operating in 1939 nm or 1906.8 nm wavelengths.

- Lightweight, compact lidar telescopes operating at one or more of the primary laser wavelengths in 1.0 to 2.0 micron wavelength region. The general requirements are: optical quality better than 1/6 wave at 632 nm, mass density less than 12 kg/m$^2$, and aperture diameter from 10 cm to 30 cm. Proof of scalability to 0.5-1.0 m diameter for deployment in space is required.

- Laser beam steering and scanning technologies (such as dual-wedge, diffractive optical elements, and liquid crystal) operating at 1.5 or 2.05 micron with 2 cm to 25-cm aperture diameter meeting the following requirements:
  
  - 60 deg. field of regard.
  
  - 90% optical throughput.
  
  - 1/4-wave single pass optical quality at 632 nm.

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**S6.03 Earth In Situ Sensors**

**Lead Center:** GSFC  
**Participating Center(s):** ARC

Proposals are sought for the development of *in situ* measurement systems that will enhance the scientific and commercial utility of data products from the Earth Science Enterprise program and that will enable the development of new products of interest to commercial and governmental entities around the world. Technology innovation areas of interest include:

- Autonomous Global Positioning System (GPS)-located platforms (fixed or moving) to measure and transmit to remote terminals upper ocean and lower atmosphere properties including temperature, salinity,
momentum, light, precipitation, and biogeochemistry;

- Dynamic stabilization systems for small instruments mounted on moving platforms (e.g., buoys and boats) to maintain vertical and horizontal alignment. Systems capable of maintaining a specified pointing with respect to the Sun are preferred;

- Small, lightweight instruments for measuring clouds, liquid water, or ice content (mass) designed for use on radiosondes, dropsondes, aerosondes, tethered balloons, or kites;

- Wide-band microwave radiometers capable of high-speed characterization of cloud parameters, including liquid and ice phase precipitation, which can operate in harsh environmental conditions (e.g., onboard ships and aircraft);

- Autonomous, GPS-located airborne sensors that remotely sense atmospheric wind profiles in the troposphere and lower stratosphere with high spatial resolution and accuracy;

- Systems for in situ measurement of atmospheric electrical parameters including electric and magnetic fields, conductivity, and optical emissions;

- Systems to measure line- and area-averaged rain rate at the surface over lines of at least 100 m and areas of at least 100x100 m;

- Lightweight, low-power systems that integrate the functions of inertial navigation systems and GPS receivers for characterizing and/or controlling the flight path of remotely piloted vehicles;

- Low-cost, stable (to within 1% over several months), portable radiometric calibration devices in the shortwave spectral region (0.3 to 3 Åμm) for field characterization of radiance instruments such as sun photometers and spectrometers;

- Miniaturized, low-power (12V DC) instruments especially suited for small boat operations that are capable of adequately resolving, at the appropriate accuracy, the complex vertical structure (optical, hydrographic, and biogeochemical) of the coastal ocean (turbid) water column. Sensors that can be easily integrated within a digital (serial) network to measure the apparent and inherent optical properties of seawater are preferred; and

- Aircraft or UAV instruments for in situ measurements of physical and optical properties of clouds and aerosols with instantaneous measurement volumes ranging from cubic meters up to a maximum of a cubic kilometer, the purpose being to furnish validation for satellite remote sensing at the spatial scales satellites actually provide.

S6.04 Passive Microwave

Lead Center: GSFC

Proposals are sought for the development of innovative passive microwave technology in support of Earth System Science measurements of the Earth’s atmosphere and surface. These microwave radiometry technology innovations are intended for use in the frequency band from about 1 GHz to 1 THz. The key science goal is to increase our understanding of the interacting physical, chemical, and biological processes that form the complex Earth system. Atmospheric measurements of interest include climate and meteorological parameters-including temperature, water vapor, clouds, precipitation, and aerosols; air pollution; and chemical constituents such as ozone, NOX, and carbon monoxide. Earth surface measurements of interest include water, land, and ice surface temperatures, land surface moisture, snow coverage and water content, sea surface salinity and winds, and multi-
Technology innovations are sought that will provide the needed concepts, components, subsystems, or complete systems that will improve these needed Earth System Science measurements. Technology innovations should address enhanced measurement capabilities such as improved spatial or temporal resolution, improved spectral resolution, or improved calibration accuracies. Technology innovations should provide reduced size, weight, power, improved reliability, and lower cost. The innovations should expand the capabilities of airborne systems (manned and unmanned) as well as next generation spaceborne systems. Highly innovative approaches that open new pathways are also an important element of competitive proposals under this solicitation.

Specific technology innovation areas include:

**Electronics Technologies**

- Imaging radiometers, receivers, or receiver arrays on a chip;
- Microwave and millimeter-wave frequency sources as an alternative to Gunn diode oscillators. Compact (100 mW), and low power consumption (100 mW), low power consumption;
- Wideband and ultra-wideband sensors with >15dB cross-pole isolation across the bandwidth;
- Low noise (15dB)
  - Undersampling, multibit, analog-to-digital converters with Multigigahertz RF input bandwidth, low power consumption, and associated digital signal processing logic circuit;
- Low power, lightweight microwave with DC power consumption of less than 2 W;
- Electronic design approaches and subsystems that can be incorporated into microwave radiometers to detect and suppress RFI within or near the reception band of the radiometer, thus insuring higher data quality;
- Innovative new designs for highly stable noise-diode or other electronic devices as additional reference sources for onboard calibration. Of particular interest are variable correlated noise sources for calibrating correlation-type receivers used in interferometric and polarimetric radiometers;
- Monolithic microwave integrated circuit (MMIC), low-noise amplifiers (LNA). Of particular interest are LNAs covering the frequency range of 165 to 193 GHz with low 1/f noise, and having a noise figure of 6.0 dB or better; and
- GPS receiver systems for application as bi-static altimeters and scatterometers.

**Antenna Technologies**

- Sensor elements with low mutual coupling allowing close spacing within large arrays;
- Large format, millimeter wave, focal plane array modules for large-aperture passive imaging applications; and
- Large aperture, deployable antenna concepts. Such large apertures can be real or synthetic. Of particular
Calibration Technologies

- New technology calibration reference sources for microwave radiometers that provide greatly improved reference measurement accuracy. Of particular interest are high emissivity (near-black-body) surfaces for use as onboard calibration targets for microwave radiometers—which will significantly reduce the weight of aluminum core target designs, while reliably improving the uniformity and knowledge of the calibration target temperature; and

- New approaches, concepts, and techniques for microwave radiometer system calibration over or within the 1-300 GHz frequency band—which provide end-to-end calibration to better than 0.1K, including corrections for temperature changes and other potential sources of instrumental measurement drift and error.

S6.05 Active Microwave

Lead Center: JPL
Participating Center(s): GSFC

Active microwave sensors have proven to be ideal instruments for many Earth science applications. Examples include global freeze and thaw monitoring, soil moisture mapping, accurate global wind retrieval, and snow inundation mapping, global 3D mapping of rainfall and cloud systems, precise topographic mapping and natural hazard monitoring, global ocean topographic mapping, and glacial ice mapping for climate change studies. For global coverage and the long-term study of Earth’s eco-systems, space-based radar is of particular interest to Earth scientists. Radar instruments for Earth science measurements include Synthetic Aperture Radar (SAR), scatterometers, sounders, altimeters, and atmospheric radars. The life-cycle cost of such radar missions has always been driven by the resources—power, mass, size, and data rate—required by the radar instrument, often making radar not cost competitive with other remote sensing instruments. Order-of-magnitude advancement in key sensor components will make the radar instrument more power efficient, much lighter weight, and smaller in stow volume, leading to substantial savings in overall mission life-cycle cost by requiring smaller and less expensive spacecraft buses and launch vehicles. Onboard processing techniques will reduce data rates sufficiently to enable global coverage. High performance, yet affordable, radars will provide data products of better quality and deliver them to the users more frequently and in a timelier manner, with benefits for science as well as the civil and defense communities. Technologies that may lead to advances in instrument design, architectures, hardware, and algorithms are the focused areas of this subtopic. In order to increase the radar remote sensing user community, this subtopic will also consider radar data applications and post-processing techniques.

The frequency and bandwidth of operation are mission driven and defined by the science objectives. For SAR applications, the frequencies of interest include UHF (100 MHz), P-band (400 MHz), L-band (1.25 GHz), X-band (10 GHz), and Ku-band (12 GHz). The required bandwidth varies from a few megahertz to 20 MHz to 300 MHz to achieve the desired resolution; the larger the bandwidth, the higher the resolution. Ocean altimeters and scatterometers typically operate at L-band (1.2 GHz), C-band (5.3 GHz), and Ku-band (12 GHz). Ka-band (35 GHz) interferometers have applications to river discharge. The atmospheric radars operate at very high frequencies (35 GHz and 94 GHz) with only modest bandwidth requirements on the order of a few megahertz.
The emphasis of this subtopic is on core technologies that will significantly reduce mission cost and increase performance and utility of future radar systems. There are specific areas in which advances are needed.

- **SAR for surface deformation, topography, soil moisture measurements:**
  - Very large aperture L-band antennas (20 m x 20 m) for Medium Earth Orbit (MEO) or 30m diameter for Geosynchronous SAR applications.
  - Shared aperture, multi-frequency antennas (P/L-band, L/X-band).
  - Lightweight, deployable antenna structures and deployment mechanisms.
  - Rad-hard, high-efficiency, high power, low-cost, lightweight L-band and P-band T/R modules.
  - High-power transmitters (L-band, 50-100 kW).
  - L-band and P-band MMIC single-chip T/R module.
  - Rad-hard, high-power, low-loss RF switches, filters, and phase shifters.
  - Digital true-time delay (TTD) components.
  - Thin-film membrane compatible electronics. This includes: reliable integration of electronics with the membrane, high performance (>1.2 GHz) transistor fabrication on flex material including identifying new materials, process development, and techniques that have the potential to produce large-area passive and active flexible antenna arrays.
  - Advanced transmit and receive module architectures such as optically-fed T/R modules, signal up/down conversion within the module, and novel RF and DC signal distribution techniques.
  - Advanced radar system architectures including flexible, broadband signal generation and direct digital conversion radar systems.
  - Advanced antenna array architectures including scalable, reconfigurable, and autonomous antennas; sparse arrays; and phase correction techniques.
  - Distributed digital beamforming and onboard processing technologies.

- **SAR data processing algorithms and data reduction techniques.**

- **SAR data applications and post-processing techniques.**

- **Low-frequency SAR for subcanopy and subsurface applications:**
  - Lightweight, large-aperture (30 m diameter) reflector and reflectarray antennas.
  - Large, electronically scanning P-band arrays.
  - Shared aperture, dual-polarized, multiple low-frequency (VHF through P-band, 50-500 MHz) antennas with highly shaped beams.
- Lightweight, low frequency, low-loss antenna feeds (VHF through P-band, 50-500 MHz).
- High-efficiency T/R modules and transmitters (50-500 MHz, 10 kW).
- Lightweight, deployable antenna structures and deployment mechanisms.
- Data applications and post-processing techniques.

- Polarimetric ocean/land scatterometer:
  - Multi-frequency (L/Ku-band) lightweight, deployable reflectors.
  - Large, lightweight, electronically steerable Ku-band reflectarrays.
  - Lightweight L-band and Ku-band antenna feeds.
  - Dual-polarized antennas with high polarization isolation.
  - Lightweight, deployable antenna structures and deployment mechanisms.
  - High efficiency, high power, phase stable L-band and Ku-band transmitters.
  - Low-power, highly integrated radar components.
  - Calibration techniques, data processing algorithms, and data reduction techniques.
  - Data applications and post-processing techniques.

- Wide swath ocean and surface water monitoring altimeters:
  - Shared aperture, multi-frequency (C/Ku-band) antennas.
  - Large, lightweight antenna reflectors and reflectarrays.
  - Lightweight C-band and Ku-band antenna feeds.
  - Lightweight, deployable antenna structures and deployment mechanisms.
  - High-efficiency, high power (1-10 kW) C-band and Ku-band transmitters.
  - Real-time onboard radar data processing.
  - Calibration techniques, data processing algorithms, and data reduction techniques.

- Ku-band and Ka-band interferometers for snow cover measurement over land (Ku-band), wetland, and river monitoring (Ka-band):
  - Large, stable, lightweight, deployable structures (10-50 m interferometric baseline).
  - Ka-band along and across-track track interferometers with a few centimeters of height accuracy.
  - Ku-band interferometric polarimetric SAR.
- Phase-stable Ku-band and Ka-band electronically steered arrays and multibeam antennas.
- Lightweight deployable reflectors (Ku-band and Ka-band).
- Shared aperture technologies (L/Ku-band).
- Phase-stable, Ku-band and Ka-band receive electronics.
- High-efficiency, rad-hard Ku-band and Ka-band T/R modules or >10 kW transmitters.
- Ku-band and Ka-band antenna feeds.
- Calibration and metrology for accurate baseline knowledge.
- Real-time onboard radar data processing.
- Data applications and post-processing techniques.

- Atmospheric radar:
  - Low sidelobe, electronically steerable, millimeter wave, phased-array antennas and feed networks.
  - Low sidelobe, multi-frequency, multi-beam, shared aperture millimeter wave antennas (Ka-band and W-band).
  - Large (~300 wavelength), lightweight, low sidelobe, millimeter wave (Ka-band and W-band) antenna reflectors and reflectarrays.
  - Lightweight deployable antenna structures and deployment mechanisms.
  - High power (10 kW) Ka-band and W-band transmitters.
  - High-power (>1 kW, duty cycle >5%), wide bandwidth (>10%) Ka-band amplifiers.
  - High-efficiency, low-cost, lightweight Ka-band and W-band transmit/receive modules.
  - Advanced transmit/receive module concepts such as optically-fed T/R modules.
  - Onboard (real-time) pulse compression and image processing hardware and/or software.
  - Advanced data processing techniques for real-time rain cell tracking, and rapid 3D rain mapping.
  - Lightweight, low-cost, Ku/Ka band radar system for ground-based rain measurements.
  - Light weight, wideband (>200 MHz), low-sidelobe (Low-power, high-speed, multi-channel single board digital receivers.
  - High-power, high-duty cycle solid state power amplifier from X through W-band.
Many NASA future Earth science remote sensing programs and missions require microwave to submillimeter wavelength antennas, transmitters, and receivers operating in the 1-cm to 100-Åµm wavelength range (or a frequency range of 30 GHz to 3 THz). General requirements for these instruments include large-aperture (possibly deployable) antenna systems with RMS surface accuracy of

For these systems, advancement is needed in primarily three areas: 1) the development of frequency-stabilized, low phase noise, tunable, fundamental local oscillator sources covering frequencies between 160 GHz and 3 THz; 2) the development of submillimeter-wave mixers in the 300-3000 GHz spectral region with improved sensitivity, stability, and IF bandwidth capability; and 3) the development of higher-frequency and higher-output-power MMIC circuits.

Specific innovations or demonstrations are required in the following areas:

- Heterodyne receiver system integration at the circuit and/or chip level is needed to extend MMIC capability into the submillimeter regime. MMIC amplifier development for both power amplifiers and low noise amplifiers at frequencies up to several hundred GHz is solicited. Integration of a local oscillator multiplier chain, mixer, and intermediate frequency amplifier is one example. There is also a specific need to demonstrate array radiometer systems using MMIC radiometers from 60 GHz to approximately 500 GHz;

- Solid-state, phase-lockable, local-oscillator sources with flight-qualifiable design approaches are needed with >10 mW output power at 200 GHz and >100 ÅµW at 1 THz; source line widths should be

- Stable local-oscillator sources are needed for heterodyne receiver system laboratory testing and development;

- Multi-channel spectrometers that analyze intermediate frequency signal bandwidths as large as 10 GHz with a frequency resolution of

- Compact and reliable millimeter and submillimeter imaging instrumentation that produces images simultaneously in multiple spectral bands;

- Schottky mixers with high sensitivity at $T = 100$ K and above;

- Low noise superconducting HEB mixers and SIS mixers;

- Receivers using planar diode or alternative reliable local oscillator technologies in the 300-3000 GHz spectrum;

- Lightweight and compact radiometer calibration references covering 100-800 GHz frequency range;

- Lightweight, field portable, compact radiometer calibration references covering frequencies up to 200 GHz. The reference must be temperature stable to within 1 K with a minimum of three temperature settings between 250 and 350 K;

- Low-cost, special purpose, ground-based receivers to detect signals radiated from active satellites that are in orbit for estimating rain rate, water vapor, and cloud liquid water; and

- Calibrated radiometer systems that can achieve accuracy and stability of 0.1 K.
Future instruments for NASA’s Science Mission Directorate will require increasingly sophisticated thermal control technology. Innovative proposals for thermal control technologies are sought in the following areas:

- Instrument Optical alignment needs, lasers, and detectors that require tight temperature control, often to better than +/- 1Å°C. Some new missions, such as LISA and TPF, require methods of temperature measurement and control to micro-Kelvin levels.

- Heat flux levels from lasers and other high power devices are increasing with some projected to go as high as 100 W/cm². They will require thermal technologies such as spray and jet impingement cooling. Also, high conductivity, vacuum compatible interface materials will be needed to minimize thermal losses across make/break interfaces.

- Future missions will utilize large, distributed structures such as mirrors and detector arrays at both ambient and cryogenic temperatures. These missions will require creative techniques to integrate thermal control functions and minimize weight. Some anticipated technology needs include: advanced thermoelectric coolers capable of providing cooling at ambient and cryogenic temperatures, high conductivity structural materials to minimize temperature gradients and provide high efficiency lightweight radiators, and advanced thermal control coatings such as variable emittance surfaces and coatings with a high emissivity at ambient and cryogenic temperatures.

- The push for miniaturization also drives the need for new thermal technologies towards the MEMS level. Miniaturized heat transport devices, especially those suitable for cooling small sensors, devices, and electronics, include miniaturized mechanical pumps, Loop Heat Pipes (LHPs), and Capillary Pumped Loops (CPLs) which allow multiple heat load sources and multiple sinks.

- The drive towards robotic missions and reconfigurable spacecraft presents engineering challenges for science instruments, which must become more self-sufficient. Some of the technology needs are:
  - Advanced analytical techniques for thermal modeling focusing on techniques that can be easily integrated into existing codes, emphasizing inclusion of LHPs, CPLs, and mechanically pumped system models;
  - Single and two-phase mechanically pumped fluid loop systems, which accommodate multiple heat sources and sinks, and long life, lightweight pumps for these systems; and
  - Efficient, lightweight vapor compression systems for cooling up to 2 KW.