EXPLORESPACE TECH

TECHNOLOGY DRIVES EXPLORATION

EXPLORE: Sensors, Instruments, and Observatories
NASA Space Technology Mission Directorate

This Envisioned Future Priorities package is being released as a DRAFT for the NSTGRO solicitation.

STMD welcomes feedback on this presentation. Please visit https://techport.nasa.gov/framework/feedback if you have any questions or comments regarding this presentation.

SENSORS AND INSTRUMENTS Envisioned Future Priorities
Introduction

What Guided the Development of Recommended Priorities?

- STMD, as SMD's frontier, should invest in lower TRL, higher risk technologies
- High impact, paradigm-shifting technologies
  - Seed-corn for next Decadal science missions
  - Enable performance leaps for current Decadal missions and beyond
- Earth/climate technologies guided by extensive collaborations with NASA HQ and Center scientists across 14 specific science areas
  - Major themes tapped for recommending technologies
- Preference for technologies that are cross-cutting across NASA, spanning multiple mission classes or science themes and/or having relevance to the NASA Moon to Mars Objectives, as well as other domains such as planetary science, heliophysics, and astrophysics
- Cognizant of OGA landscape & partnership opportunities, but focus on tech development that meets NASA's needs

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STMD Strategic Framework: Areas Influenced by Advanced Sensors

STMD rapidly develops, demonstrates, and transfers revolutionary, high pay-off space technologies, driven by diverse ideas

Advanced Sensors enable missions through unprecedented measurements and improve safety with real-time warnings.

Thrusts	Outcomes	Sensors and Instruments Capability Area Potential Technologies
Go Rapid, Safe, and Efficient Space Transportation	• Develop nuclear technologies enabling fast in-space transits. • Develop cryogenic storage, transport, and fluid management technologies for surface and in-space applications.	Advanced plasma diagnostics; sensors for sensitive magnetic and electric fields; multi-sensor tomography (TX08)
	• Develop advanced propulsion technologies that enable future science/exploration missions.	Covered in other capability areas
Land Expanded Access to Diverse Surface Destinations	• Enable Lunar/Mars global access with ~20t payloads to support human missions. • Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies. • Develop technologies to land payloads within 50 meters accuracy and avoid landing hazards.	Covered in other capability areas

Live
Sustainable Living and Working Farther from Earth
	• Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities.
	  • Sustainable power sources and other surface utilities to enable continuous lunar and Mars surface operations.
	  • Scalable ISRU production/utilization capabilities including sustainable commodities on the lunar & Mars surface.
	  • Technologies that enable surviving the extreme lunar and Mars environments.
	  • Autonomous excavation, construction & outfitting capabilities targeting landing pads/structures/habitable buildings utilizing in situ resources.
		Active optical materials and sensors that respond to changing environmental conditions (TX08.2.2, 08.X); augmented reality displays for solar storm warnings (TX06.5.4, 11.2.3); Rad-hardened high-temperature sensors/instrumentation for surface power plant health monitoring (TX08.3.6)

	• Enable long duration human exploration missions with Advanced Habitation System technologies. [Low TRL STMD; Mid-High TRL SOMD/ESDMD]	Holographic imaging and microscopy to support Earth controlled surgery (TX05.X); advanced radiation protection and augmented vision systems (TX06.5.3); Advanced plant sensors to autonomously and non-invasively detect and mitigate early stress responses and ensure food safety (TX6.3.5)
Explore Transformative Missions and Discoveries	• Develop next generation high performance computing, communications, and navigation.	Quantum networks that integrate sensors, communication, quantum and supercomputing (TX11.X, 05.5.2)
	• Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions.	Compact extreme multi-function instrumentation for rover payloads, machine vision, and autonomous decision-making (TX08, 11.4.8)
	• Develop technologies supporting emerging space industries including: Satellite Servicing & Assembly, In Space/Surface Manufacturing, and Small Spacecraft technologies. • Develop vehicle platform technologies supporting new discoveries.	Covered in other capability areas
	• Develop technologies for science instrumentation supporting new discoveries. [Low TRL STMD/Mid-High TRL SMD. SMD funds mission specific instrumentation (TRL 1-9)] • Develop transformative technologies that enable future NASA or commercial missions and discoveries.	Advanced sensors (TX08)

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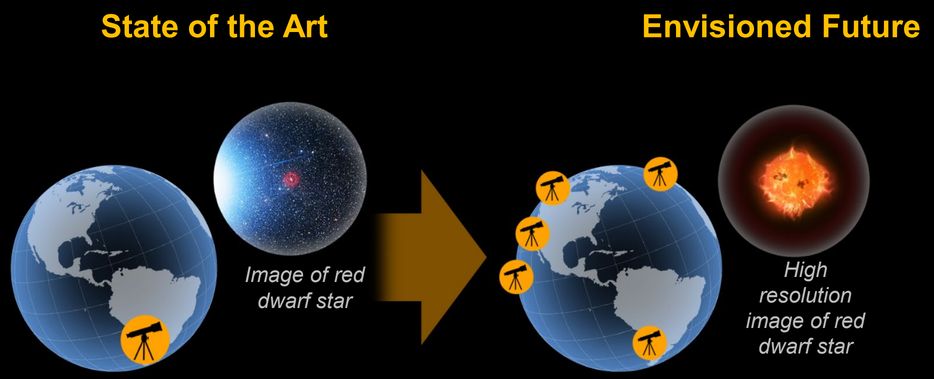
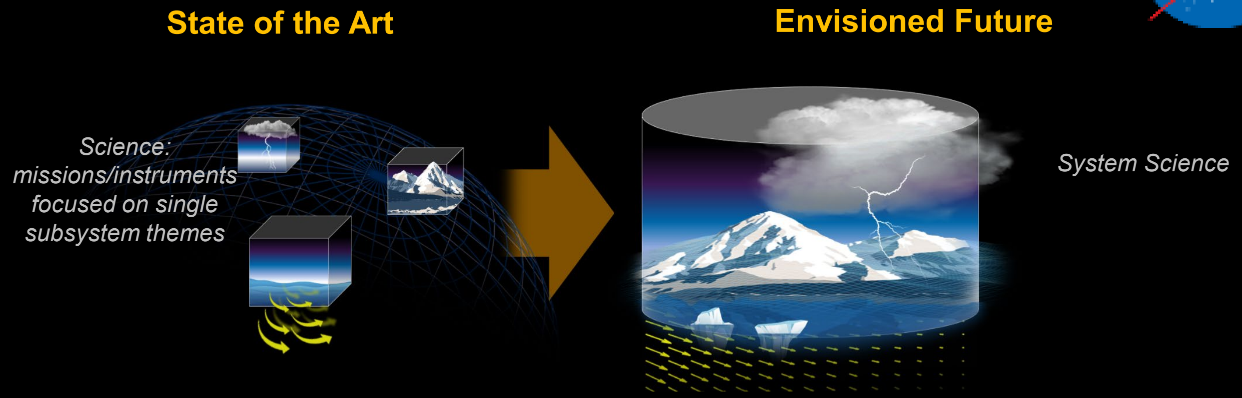
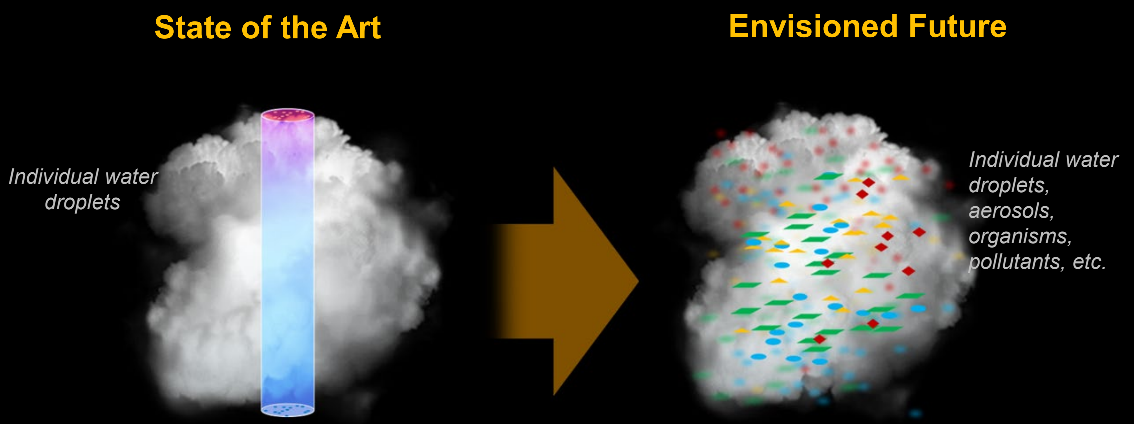
Envisioned Future Priorities Overview



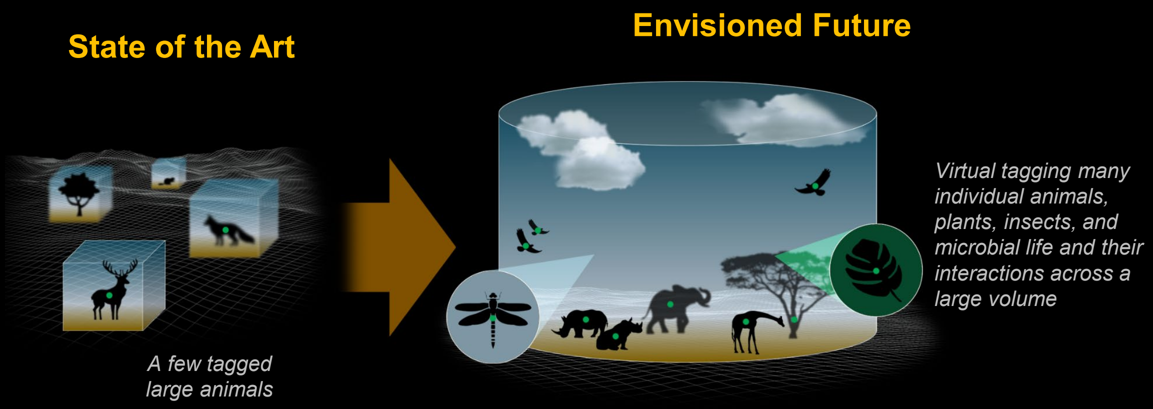
Orders of Magnitude Improvement in Sensitivity & Resolution



Larger Numbers of Simultaneous Observations for System Science



3D, 4D, 5D Visualization with Composition



Large-Volume Whole-Ecosystem Observation

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Challenges and State of the Art
ORDERS OF MAGNITUDE IMPROVEMENTS IN SENSITIVITY & RESOLUTION

Challenge:

Develop paradigm-shifting sensors & sensor networks that can detect phenomena, features, and/or parametric details never detected before. Enable new scientific insights that are stunning/unexpected. Achieve deterministic time and resolution scales of observables in 3D+.

Potential Applications:

- More timely climate predictions (with dramatically tighter error bars) for policymakers; Turbocharge modeling capabilities.
- Improved, timely measurements of the changes to the Earth's mass distribution. Better, more accurate ground water aquifer level & depletion rates; coastal inundation warnings for cities due to ice sheet melt; forecasts of natural hazards such as volcanic eruptions; seismology.
- Unprecedented, detailed images of nearby bright stars with high angular resolution by developing the first long-baseline optical phased arrays; understanding exoplanet stellar environments & habitability.
- More timely space weather predictions (with dramatically tighter error bars) for Earth and astronaut safety.
- Understanding the nature & properties of dark matter.

SoA:

- GRACE-FO measures Earth's mass change at 300-400 km. 2017 Earth Science Decadal calls for 100-200km. Atom interferometer gravity gradiometer with micro-Eotvos sensitivity could reach that with one spacecraft instead of two.
- Radio telescope phased arrays are quite powerful, optical telescopes barely exist. (Event Horizon Telescope) performs with planet-scale (1000's kilometers) baseline, imaging supermassive black holes at galaxy centers, but optical telescope phased arrays are currently far less capable:
  - Six 1-meter telescopes, 330-meter baseline (Mt Wilson); four 8-meter telescopes, 130-meter baseline (Chile ESO).
  - No space-based astronomical interferometry has been done

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Challenges and State of the Art
LARGER NUMBERS OF SIMULTANEOUS MEASUREMENTS ENABLING NEW SYSTEM SCIENCE

Challenge: Develop technologies to enable scientists to characterize how Earth or planetary subsystems (e.g., atmosphere, ocean, land, biosphere, space weather) interact & influence one another, improving our understanding of coupled processes. Enable larger numbers of simultaneous, diverse remote sensing & in situ measurements on multiple temporal & spatial scales while reducing information processing burden & electrical power demands.

Potential application (examples)

- Earth climate science; severe weather prediction; natural hazard forecasting; whole-ecosystem characterization; maintaining food and water security
- Titan's methane hydrology, Mars dust storms & climate; search for evidence of life on Mars, in atmospheres, and on water worlds

SoA: Earth science spacecraft have traditionally focused on a single scientific theme such as ocean, or atmosphere. Although scientists ultimately combine knowledge across missions into a more comprehensive view, technology development could change the paradigm and make interconnections a new, special priority.

Tech development might include:

- More (especially integrated cross-theme) capabilities per instrument, integrated instrument suite, sensor network
- Higher levels of multi-platform integration/coordination of air, space, ground in-situ and remote observations
- Smart sensing; use of artificial intelligence for real-time pattern recognition, decision-making, configuration selection, etc.
- More efficient, smarter information storage & processing
- Lower costs per instrument, payload, constellation enabling more affordable, more persistent observations

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Challenges and State of the Art
3D, 4D, 5D SENSING, VISUALIZATION & DISPLAY

Challenge: Develop a capability to sense, visualize, & display the complex-featured subjects or phenomena. Parameters of interest include three spatial dimensions, time, & other key parameters (depending on application) such as composition, temperature, etc

Potential/Desired Applications

- Imaging of changing Earth/planetary terrains
- Asteroid tomography & planetary defense
- Cloud microphysics; jet stream/boundary layer; 4D storm dynamics
- Natural hazards warning & monitoring their evolution (e.g., forest fires, volcanic eruptions)
- Medical imaging for astronauts on the Moon or Mars
- Advanced displays: augmented/virtual reality displays; 3D television

SoA:

Interferometric Synthetic Aperture Radar (InSAR): measures millimeter changes in surface deformation change over days to years

- ISRO-NISAR (to be launched 2023)

Cloud tomography- multi-angle scatter observed from aircraft; reconstructed into 3D using photogrammetry methods

Other examples include synthetic aperture radar (SAR), various types of lidar Imaging, Ground Penetrating Radar (GPR), muon tomography, hyperspectral imaging, synthetic aperture imaging lidar, compact x-ray computed tomography, nuclear magnetic resonance spectroscopy, multi-frequency microwave Doppler radar and polarization. Depending on the specific technique employed results can be ambiguous, hard to interpret, or lack desired temporal and/or spatial resolution

Challenges and State of the Art
Large-Volume Whole-Ecosystem Observation Integrating Multiple Temporal and Spatial Scales

Challenge: Develop a capability to observe a large-volume, whole ecosystem with a capability to identify & monitor constituent species & individual organisms on multiple temporal & spatial scales, noting interactions between them and with their environment. Particularly challenging environments include, but are not limited to dark ocean depths, hidden areas under forest canopies, soils, large ranges, obscured habitats, caves, crevasses.

- Potential Applications:
  - Biodiversity conservation, providing ways to assess health status of ecosystems and offering effective options to ensure species survival while minimizing adverse economic impact
  - Food security and safety through advanced plant health monitoring
  - Epidemiology of emerging infectious diseases. Tracking disease vector species, identifying new habitats, in order to aid in slowing or stopping the spread of disease. Possibly aid in identifying disease vector species for new, previously unknown diseases.
  - Astrobiology search for microbial/single-celled life on Mars, or Europa, & other water worlds. Reduce the ambiguity inherent in identifying life that might be different than terrestrial life. Including molecular biosignature detection and resolution.
  - Especially cross-cutting would be technology contributions for extending ranges of remote observation; overcoming obscurations & obstacles; combining/integrating multiplatform data, etc.

SoA: Physically tagging animals; limited numbers of ground observation stations; photo-traps; marine observations focus mostly on ocean photic & coastal zones rather than deep pelagic zones; limited numbers of expeditions and/or sampling buoys.

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Orders of Magnitude Improvement in Sensitivity & Resolution – STMD Strategy

	0-5 years	5-15 years	15+ years
ATOM INTERFEROMETRY: HIGHER RESOLUTION TIME-VARIABLE-GRAVITY			
• Mass movements of ground water, glaciers, ice sheets, sea level, ocean currents; seismology; volcanos • Goal: Order of magnitude better time variable gravity sensitivity over GRACE-FO • Achieve aquifer spatial resolution <100km and <1cm height	Cold atom gravity gradiometer integrated lab demo (TRL3-TRL4) STMD funded Cold atom gravity gradiometer engineering design unit development, vacuum/ microgravity drop tower test (TRL4-TRL6) STMD and/or SMD funded	Mass Change Pathfinder SMD funded	Mass Change Flagship 1 microeotvos sensitivity 10x Decadal performance goal SMD funded
DEVELOP NEW, POWERFUL SENSORS BY LEVERAGING THE "SECOND QUANTUM REVOLUTION" CURRENTLY UNDER WAY			
Develop new, specific quantum-enhanced NASA applications E.g., lidars, radars, scatterometers, imagers, sensor networks, PNT, motion, spectrometers, in-situ, remote sensing	STMD Early-Stage topic(s). Harness superposition, quantum entanglement, quantum squeezing for super-sensitivity, super-resolution, new observation capabilities	Scaled quantum physics demonstration based on early-stage findings	
PLANET-SCALE BASELINE QUANTUM-ENTANGLED OPTICAL TELESCOPE PHASED ARRAY			
Harness quantum entanglement to develop a telescope that can high angular resolution by phasing together smaller apertures. Also serves as pathfinder for quantum sensor networks.	Hundreds of meters to one kilometer baseline quantum-entangled optical phased array(s) • Entangled photon generation, quantum receiver processing, quantum memory	Hundreds of kilometers baseline • Advanced processing, long-term memory storage & reliable retrieval	Planet-scale quantum phased array optical telescope • World's largest ground-based telescopes 30-meter telescopes
DETECT DARK MATTER			
Develop super-sensitive detectors & detection schemes for detecting extraordinarily weak (single-quantum) signals derived from interactions with dark matter candidate particles.	STMD Early-Stage topic: Quantum sensors/components, including single photon counting schemes, processing/computing, clocks	Dark Matter particle detection experiments	Dark matter mapping?
DETECT GRAVITATIONAL WAVES			
Improve sensitivity for gravitational wave detection from space	No topic recommended. Funded outside STMD for LISA launch in 2037	Develop greater gravitational wave sensitivity , TBD spectral capabilities for post-LISA mission to launch >2050	

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Larger Numbers of Simultaneous Measurements for System Science– STMD Strategy

	0-5 years	5-15 years	15+ years
NEW SENSOR PARADIGMS TO CHARACTERIZE HOW EARTH (OR PLANET) SUBSYSTEMS (E.G. ATMOSPHERE, OCEAN, LAND) INTERACT AND INFLUENCE ONE ANOTHER			
New sensor & sensor design/control/integration paradigms that enable larger numbers of simultaneous, diverse observations on multiple temporal/spatial scales • Remote sensing • In-situ sensing • Sensor networks	STMD Early-Stage topic(s). Extreme multi-function instruments that can morph and shape-shift, enabling higher numbers of simultaneous measurements on demand & in real time Static & dynamic metamaterials, meta-optics, meta-surfaces, transform optics, nano-optics, plasmonics, photonic integrated circuits, multi-functions in small packages Neuromorphic cameras e.g., can efficiently stare for a long time & record data only when unpredictable sporadic events occur (relieving memory & power req'ts Smart sensors that use machine learning & artificial intelligence for decision-making, pattern recognition, etc.	High levels of dynamic sensor integration and adaptive sensing More instruments per platform; more platforms Affordable, persistent observations	

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3D, 4D, 5D Sensing, Visualization & Display - STMD Strategy

	0-5 years	5-15 years	15+ years
INTERFEROMETRIC SYNTHETIC APERTURE RADAR (InSAR)			
Next generation InSAR: Larger, denser constellation of co-registered s/c; faster revisit time, higher bandwidth, higher power, larger aperture	Sensor web: Formation flying (collision avoidance, repeat-ground-track capability) clock synchronization techniques Antennas – lighter weight, higher power, thermal improvements, digital signal processing	Surface Deformation & Change space mission launch (TBD)	
ADVANCED SENSING, VISUALIZATION, & DISPLAY TECHNOLOGIES & METHODOLOGIES			
	STMD Early-Stage topic(s). Imaging, Sensing Tomography, Holography • New methodologies for larger and potentially more distant subjects of interest: Acquiring lidar data, transforming lidar point clouds along with targets of interest, into a display • Quantum lidars – e.g., polarization entangled lidar for clouds/aerosols; quantum-enhanced holography? • Advanced components – e.g., nano-optics, meta-mirrors • Advanced displays of scientific data – images & video • Next gen tomography, including algorithms • Other next gen active and passive sensing/imaging technologies	• Larger, more distant phenomenology • Larger lidar point clouds • Faster data acquisition • Advanced algorithms • Larger, more detailed displays, faster frame rates	

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Large-Volume Whole-Ecosystem Observation - STMD Strategy

	0-5 years	5-15 years	15+ years
CHARACTERIZE WHOLE ECOSYSTEMS AND QUANTIFY BIOLOGICAL LIFE IN 4D IN CHALLENGING ENVIRONMENTS			
Expand beyond conventional traditional sensing based on human sensory preferences & experiences. Detect life the way terrestrial organisms have learned to detect life during millions of years of evolution. • Remote & In situ instruments & detectors Large observation volumes & multiple spatial /temporal scales Expand volume and scope of observations on multiple scales including species, individual organisms	Small, challenging ecosystems & several species/ individuals STMD Early-Stage topic(s) : Direct Life Detection Sensor Development • Electric field (e.g., some fish detect nearby nervous systems in sediment-laden water where chemical scent & tactile pressure are not as useful clues to avoid predators, find food. • Chemical scent - extremely large numbers of molecular receptors (e.g., fractal ant antennae) • tactile pressure/motion sensing • Acoustics – broad spectrum, or specialized spectrum • Bio-inspired vision systems • Neuromorphic cameras (turn on only for events) • Non-Line-of-Sight Videography (e.g., under tree canopies or other obscurations); ghost imaging • Sensor networks – bio-inspired • Extreme multi-function instruments that can morph and shape-shift, enabling higher numbers of simultaneous measurements (tunable meta-lenses, etc)	Larger, challenging ecosystems & Larger numbers of species/individuals	Whole ecosystems in challenging environments

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Sensors and Instruments Envisioned Future Priorities
Top Gaps (Early-Stage Program Topics)

Gap	Investment Recommendation
Measure Aquifers At County Level Or Better From Space • Goal: Order of magnitude better time variable gravity sensitivity over GRACE-FO • Achieve aquifer spatial resolution <100km and <1cm height • Other applications: changes in glaciers, ice sheets, sea level, ocean currents, seismology, volcanos	Cold atom gravity gradiometer integrated lab demo (TRL3-TRL4) Cold atom gravity gradiometer engineering design unit development and vacuum/microgravity drop tower test (TRL4-TRL6)
Develop New, Powerful Sensors By Leveraging The "Second Quantum Revolution" Currently Under Way • Develop quantum sensors toward specific NASA applications • Discover new quantum advantages, understand limitations	Early-Stage topic(s). Harness superposition, quantum entanglement, quantum squeezing for super-sensitivity, super-resolution, new observation capabilities
Characterize How Earth (Or Planet) Subsystems (e.g. Atmosphere, Ocean, Land, Subsurface, Ice) Interact And Influence One Another • Extreme multi-function instruments that can morph and shape-shift, enabling higher numbers of simultaneous measurements	Early-Stage topic(s). Metamaterials, meta-optics, meta-surfaces, transform optics, plasmonics, photonic integrated circuits, neuromorphic cameras, machine learning
Characterize And Quantify Biological Life In 4D In Challenging Environments • Detect life the way terrestrial organisms have learned to detect life during millions of years of evolution. • Expand volume and scope of observations on multiple scales including species, individual organisms of flora and fauna	Early-Stage topic(s). Examples: electric field (nearby nervous systems), scent, tactile pressure/motion, sound signaling, low light, 3D mapping without imaging, others

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