Keck Institute for Space Studies

Optical Frequency Combs for Space Applications

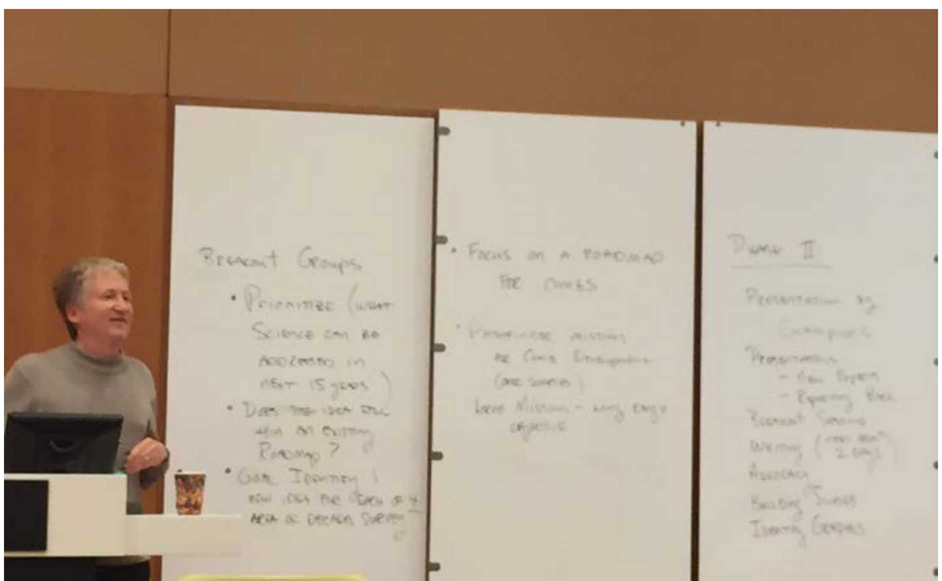
Second Workshop

February 8-11, 2016

Pasadena, CA

Action Items from Workshop #1

1. Prioritize: What science can be addressed in next 15 years?
2. Find correlation between concepts and ideas in existing roadmaps.
   – Goal: identify 1 new idea for each Decadal Survey.



3. Focus on roadmap for combs
   - Pathfinder missions for comb development (OFC sources)
   - Large missions – long term objectives

1. Prioritize: What science can be addressed in next 15 years?

WS#1 Concepts:

A. Spectroscopy	B. Fundamental physics	C. Astronomy	D. Technologies

• remote or in-situ planetary atmospheric sensing
  ◦ Earth, Mars, Venus, Moons
  ◦ passive (sunlight) or active
  ◦ measurement of bio-signatures (e.g. chirality) on primitive bodies
• ground based comb for atmospheric spectroscopy
• fast-flyby spectroscopy (e.g. Kuiper Belt object), on-the-fly comet tail spectroscopy
	• Gravity waves
	• general relativity tests: extra digits from combs.
	• dark matter test: enable by comb
	• short time-scale astronomical events
	• Vacuum fluctuations measurements with combs- ref: "Direct Sampling of Electric-Field Vacuum Fluctuations"
		• high-resolution IR spectrograph in space
		  ◦ PRV for exoplanet detection
		  ◦ exoplanetary magnetosphere (aurora?)
		  ◦ cosmic acceleration
		• PFI
		  ◦ squeezed comb light
		• dispersion from interplanetary media
		• 550 AU solar gravity focus
		• Ranging radar - asteroids
			• ISS experiments
			• cold atom experiment
			• self-referenced optical clocks
			  ◦ general relativity tests
			  ◦ dark matter test
			  ◦ global time standard
			• navigation/time transfer
			• mass marketing
			• high res- 3D imaging
			• Ranging radar - satellites
			• New Comb Functionality for Radar (e.g., Waveform Synthesis)
			• imaging GEO satellites from the ground (15 cm resolution)
			• "atomless" clocks in space
			• Planetary GPS
			• Super Oscillator
			• Precision Formation Flying
			• Universal System (Navigation, Communication, Timing)

Concepts flow down into 3 main theme areas for near-term development:

1. Comb flight demo on a small-sat	2. Ground-based High Angular Resolution Imaging	3. Combs and clocks for precision timing, navigation, and basic science

• Increase the technical maturity of comb technology by flying a comb on a small satellite platform.
  ◦ For eventual use in space-based PRV observatory
• Demonstrate the utility of the comb
  ◦ telluric line calibrator
  ◦ atmospheric column measurements
  ◦ "Formation flying" with multiple linked combs.
	• Of GEO-sats and for astronomy
	• With ground based, 10 micron heterodyne interferometry and combs as LOs
	  ◦ Squeezed comb light
	• For atmospheric ranging from ground-based telescopes to enable direct detection interferometry in the NIR (comb guide-star)
		• Continued development of "clock on a chip"
		• comb as a stand-alone oscillator or as a sub-system on a clock mission with either
		  ◦ atom or a stable cavity as a reference, or
		  ◦ comb output as a stable oscillator ("atomless clock") on the shortest time scales.
		• wide range of technical, military and scientific missions, including experiments focused on dark matter detection and physics beyond the standard model.

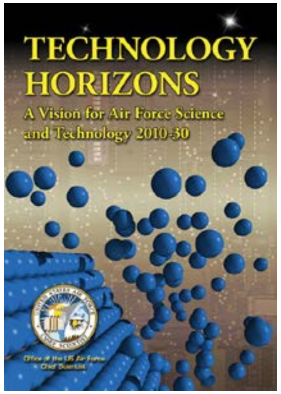
2. Correlation Between OFC Workshop #1 - Identified Applications and Multi-Agency Roadmaps and Strategic Plans

Roadmaps and reports examined:

- NRC Decadal Surveys for:
  - Astronomy and Astrophysics – New Worlds, New Horizons in Astronomy and Astrophysics 2010
  - Planetary Science – Vision and Voyages for Planetary Science in the Decade 2013-2023
  - Earth Science 2017-2027 NRC Decadal Survey for Earth Science and Applications from Space (2007)
  - NRC – Decadal Survey on Biological and Physical Sciences in Space - Recapturing a Future for Space Exploration: Life and Physical Sciences Research for a New Era (2011)
- Air Force “Technology Horizons” 2010-2030
- NASA Technology Roadmaps
  - TA5: Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
  - TA8: Science Instruments, Observatories, and Sensor Systems
- ONR
- (NOAA)
- DARPA

Summary of KISS OFC Applications and Multi-Agency Roadmaps and Strategic Plans

Agency	Technology Area	KISS OFC Focus Area
NASA		
Astronomy and Astrophysics	PRV, High angular resolution imaging, precision timekeeping, formation flying	1,2,3
Planetary Science	Spectroscopy, autonomous nav, timekeeping	1,3
Earth Science	Spectroscopy	1
Biological and Physical Sciences in Space	Optical Clocks	3
DARPA	High Angular Resolution Imaging; chip-scale comb technology, spectroscopy	1,2,3
Air Force/ONR	Precision Time, Navigation	3



Air Force Science and Technology 2010-2030

Chip-scale atomic clocks:

- Identified as key technology area
- Named for Potential Capability Areas (PCA) 7-15, 20, 22, 23, 25
- 13 out of all 30 PCAs!

PCA7: Frequency-Agile Spectrum Utilization

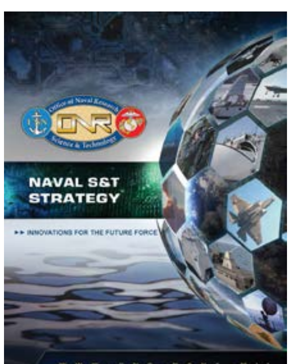
*PCA9: Precision Navigation/Timing in **GPS-Denied Environments**

PCA10: Next-Generation High-Bandwidth Secure Communications

*PCA12: Processing-Enabled Intelligent ISR Sensors

*PCA27: Rapidly Composable Small Satellites

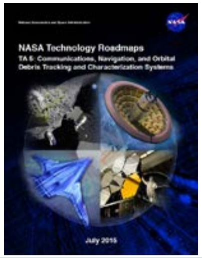
* Highest Priority PCA



Office of Naval Research

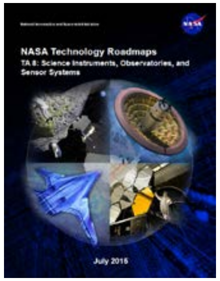
Naval Science and Technology Strategy 2015

- Precision time and navigation



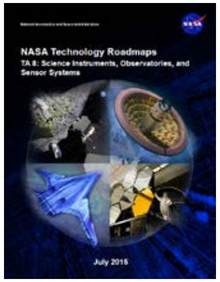
NASA 2015 Technology Roadmap:
TA 5: Communications, Navigation, and Orbital Debris Tracking and Characterization Systems

Optical Communication and Navigation	
5.1.5 Atmospheric Mitigation	Measurement and modeling of the atmospheric channel and its effects on optical propagation, and techniques and technologies for mitigating atmospheric effects.
5.1.6 Optical Tracking	Optical techniques for ranging and Doppler measurement derived from the optical communications signal.
Position, Navigation, and Timing	
5.4.1 Timekeeping and Time Distribution	Integrated, space-qualified systems with ultra-high time accuracy and frequency stability, as well as technologies and architectures for distributing precise time and frequency signals or information to distributed points in a network.
5.4.2 Onboard Auto Navigation and Maneuver	Technologies to implement autonomous onboard navigation and maneuvering to reduce dependence on ground-based tracking; ranging; trajectory, orbit, and attitude determination; and maneuver planning support functions.
5.4.3 Sensors and Vision Processing Systems	Technologies include optical navigational sensor hardware (such as high resolution flash Light Detection and Ranging (LIDAR) sensors, visible and infrared cameras), radar sensors, radiometrics, fine guidance sensors, laser rangefinders, high-volume and high-speed electronics for LIDAR and other imaging sensor data processing, sensor measurement processing algorithms, synthetic vision hardware and software, and situational awareness displays.
5.4.4 Relative and Proximity Navigation	Technologies include those that enable the ability to perform multi-platform relative navigation (such as determine relative position, relative velocity, and relative attitude or pose), which directly supports cooperative and collaborative space platform operations.
5.4.5 Auto Precision Formation Flying	Technologies to enable precision formation flying requirements imposed by envisioned distributed observatories, such as planet-finding interferometers. Technologies include differential (relative) navigation, sensors and vision processing systems, space clocks and time or frequency distribution systems, onboard system navigation, and autonomous orbit and attitude maneuvering.



NASA 2015 Technology Roadmap:
TA 8: Science Instruments, Observatories, and Sensor Systems

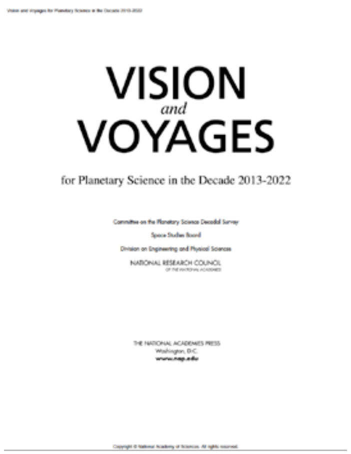
8.1 Remote Sensing Instruments and Sensors	
8.1.3 Optical Components	High-throughput optics with large fields of view<u>**, high stability, spectral resolution,**</u> and uniformity at many different temperatures.
8.1.3.9 Quantum Optical Interferometry	Interferometry with sensitivity significantly better than the quantum shot noise limit.
8 .1 .5 Lasers	Reliable, highly stable, efficient, radiation hardened, and long lifetime (> 5 years).
8.1.5.4 Three-Dimensional (3D) Imaging Flash Light Detection and Ranging (LIDAR) :	LIDAR to produce surface elevation maps on centimeter scales at distances of 2 km for uncooperative targets and 5km for cooperative targets.
8.1.5.6 Seed Laser:	Continuous wave (CW) diode or fiber seed sources used **to tune lasers over a range of wavelengths.**
8.1.5.8 Pulsed Tunable Near Infrared/Infrared Laser (Gas Detection)	In-situ source for gas detection and typing, IR lasers proposed for LIDAR detection or entry, descent, and landing (EDL) application.
8.1.5.9 Continuous Wave Tunable Near Infrared/Infrared for Gas Detection	In-situ laser source for gas detection and characterization.
8.1.5.10 1.65 μm Pulsed Light Detection and Ranging (LIDAR)	Lasers operating in this wavelength band have been identified as good candidates for remote methane sensing.
8.1.5.13 Laser Interferometer	Space-based lasers for interferometry.



NASA 2015 Technology Roadmap:

TA 8: Science Instruments, Observatories, and Sensor Systems Continued

8.2 Observatories	
8 .2 . Distributed Aperture	For extra-large apertures, a method to create the aperture via deployment, assembly, or formation flying — where formation-flying technology is an actively controlled virtual structure.
8.2.3.1 Ultra-Precise Absolute Ranging for Distributed Aperture	An inter-spacecraft sensor that precisely measures absolute ranges to sub-nanometer accuracy between spacecraft separated by up to kilometers.
8.2.3.6 Ultra-Long Range, Ultra-Precise Inter-Spacecraft Bearing Sensing.	A formation flying, inter-spacecraft sensor that precisely measures relative bearing between vastly separated spacecraft
8.3 In-Situ Instruments and Sensors	
8 .3 .3 In-situ (other)	In-situ sensor technologies (for chemical, mineralogical, organic, and in-situ biological samples) include sample handling, preparation, and containment**; chemical and mineral analysis;** organic analysis; biological detection and characterization; and planetary protection. These technologies need to be applied in extreme temperatures, pressures, and environments.



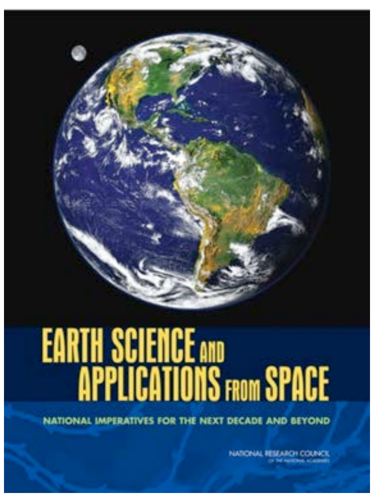
NRC Decadal Survey – Planetary Science 2013-2022

Core Multi-Mission Technology needs:

- Reduced mass and power requirements for spacecraft and their subsystems
- Increased spacecraft autonomy
- New and improved sensors, instruments, and sampling and sample preservation systems

Key capabilities for flight 2023-2033

- In-situ instruments/sample analysis



NRC Decadal Survey – Earth Science 2017-2027 (2007)

ASCENDS – like mission:

Mission objectives:

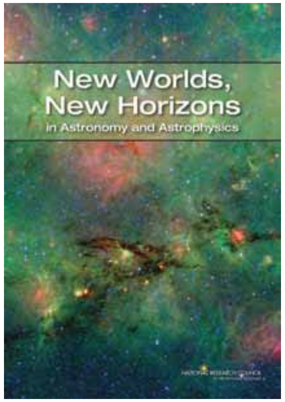
Measure the number density of Carbon Dioxide (CO2) in the column of air beneath the aircraft

Measure length of the column using a laser altimeter

Measure ambient air pressure and temperature.

Orbit: LEO, SSO

Instruments: Multifrequency laser



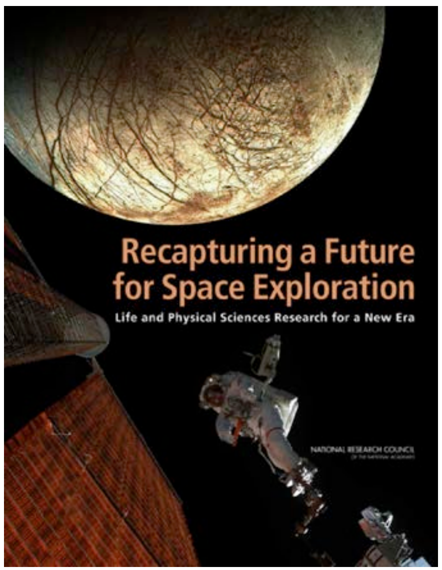
NRC Decadal Survey – Astronomy and Astrophysics 2010

The Big Questions:

- What Are Planetary Systems Like?
- How Do Stars and Planets Form?
- How Can We Detect Gravitational Waves? What Can They Tell Us?
- What Are Dark Matter and Dark Energy?

- NSF Mid-Scale Innovations Program - targets the design and development of instruments costing between $4 million and $135 million.
- New Worlds Technology Development for a 2020 Decade Mission: "… to lay the foundations in this decade for a dedicated space mission in the next to detect and characterize exoplanet atmospheres, … What systems contain Earth-like planets in the habitable zones around their parent stars? At what level does starlight scattered from dust in exoplanet systems hamper planet detection?

NRC – Decadal Survey on Biological and Physical Sciences in Space (2011)



Recommended Program Element 2: Research That Tests and Expands Understanding of the Fundamental Forces and Symmetries of Nature

Space offers unique conditions to address important questions about the fundamental laws of nature, with sensitivity beyond that of ground-based experiments in many areas. In particular, high-precision measurements in space can test relativistic gravity and fundamental particle physics and related symmetries in ways that are not practical on Earth. **Atomic clocks in space, probably optical but potentially microwave too, are useful in the study of time variation of the fundamental constants and have many more applications.**

DEFENSE ADVANCED RESEARCH PROJECTS AGENCY

- GEO-sat imaging
  - Space Surveillance Telescope (SST)
    - enable ground-based, broad-area search, detection, and tracking of faint objects in deep space for purposes such as space mission assurance and asteroid detection.
- Spectral Combs from UV to THz (SCOUT)
  - chip-scale optical frequency comb sources to enable trace-level chem-bio detection in real world environments.
- Direct On-Chip Digital Optical Synthesizer (DODOS)
  - octave-spanning microcombs, high-efficiency chip-scale lasers, high-efficiency on-chip frequency doubling, and CMOS-compatible integration technology.
- Atomic Clocks with Enhanced Stability (ACES)
  - The DARPA Microsystems Technology Office is soliciting research proposals for the development of high stability timekeeping instruments with suitably low size, weight, and power (SWaP) to enable widespread deployment in battery-powered portable applications.”

Workshop #2 Goals Defined at Workshop #1

- Presentations by Champions → Presentations for each theme area
- Presentations → Lightening talks to close knowledge gaps
- New ideas are still encouraged!
- Breakout sessions:
  - Develop straw-man concepts for each theme area
  - Focus on comb development roadmap needed to enable
- Writing
- Advocacy
- Building Slides
- Identify Graphics

Suggested breakout session discussion focus:

Session Co-Leads: Kerri Cahoy Michelle Stephens	Session Co-Leads: Gautam Vasisht Mike Shao	Session Co-Leads: John Burke Slava Turyshev
Comb flight demo on a small-sat	**Ground-based High Angular Resolution Imaging**	**Combs and clocks for precision timing, navigation, and basic science**

• Discuss what comb technology is needed for the application of PRV in space; wavelength coverage; required frequency stability; total power and power per line; volume and requirements of smallsat; mission life; what orbit.
• Discuss which atmospheric science applications could be demonstrated and what delta qual would be needed over PRV comb design.
• Consider prior instrument development programs – what are applicable lessons learned?
	• Discuss two possible approaches to ground-based high angular resolution imaging:
	  • Do in-depth analysis of SNR for 10 micron heterodyning with N comb lines; what are requirements on detectors?
	    • Quantitative impact if have squeezed comb light?
	  • 2nd approach – atmospheric turbulence compensation from ground using comb “guide star” for atmospheric ranging and direct NIR interferometry.
		• Discuss where current development programs will likely leave off and where new support will have to come in to bring chip-platform (microcomb) clocks to a high TRL.
		  • What specific further technology developments will be needed?
		• What are the mission scenarios for high precision timing-related physics (gravity wave, dark matter) experiments?

Schedule

Breakout sessions are very important!

Monday, February 8, 2016 - Think Tank, Room 155 - Keck Center, Caltech		
Time	**Event**	**Speaker**
8:30 - 9:00	Coffee and Refreshments	
9:00 - 9:30	Logistics / Introductions	Michele Judd
9:30 - 10:15	Review of workshop 1 and to-do item reports, theme area description	Team Leads
10:15 - 10:45	Break	
10:45 - 11:15	Theme area #1 talk - Kerri Cahoy	
11:15 - 11:45	Theme ares #2 talk - Ed Wishnow	
11:45 -12:15	Theme area #3 talk - Andrei Derevianko	
12:15 - 12:30	Brief theme area discussion	All
12:30 - 2:00	Lunch at the Athenaeum	
2:00 - 2:30	**Discuss purview of breakout groups**	**Team Leads**
2:30 - 4:00	**Breakout groups**	
4:00 - 4:30	Break	
4:30 - 5:00	**Breakouts continue as needed**	**All**
5:00 - 5:45	**15 minute report outs from groups**	**All**
6:00	Dinner at the Rathskeller	

Schedule Continued

Tuesday, February 9, 2016 - Keck Center - Think Tank, Room 155		
Time	**Event**	**Speaker**
8:30 - 9:00	Coffee and Refreshments	
9:00 - 9:15	Logistics: Summary re-cap of day one and goals for day two	Michele Judd Team Leads
9:15 - 10:15	Topical Lecture by Alexander Kusenko	
10:15 - 11:30	**Breakout Groups resume**	**All**
11:30 - 12:30	Lunch at the Athenaeum	
12:30	Pick up from Athenaeum for Mount Wilson Tour (road conditions permitting)	All
1:30:4:30	Mount Wilson Tour	
4:30	Return to Campus	All
6:00	Optional no-host dinner in Pasadena (KISS pays for postdocs and students)	

Schedule Continued

Wednesday, February 10, 2016 - Keck Center - Think Tank, Room 155		
Time	**Event**	**Speaker**
8:30 - 9:00	Coffee and Refreshments	
8:30 - 8:45	Logistics: Summary re-cap of day two and goals for day three	Michele Judd Team Leads
9:00 - 10:30	Lightning talks to close any knowledge gaps as needed	All
10:30 - 11:00	Break	
11:00 - 12:30	**Breakout Groups**	**All**
12:30 - 2:00	Nobel Laureate Lunch with Young Investigators	
2:00 - 5:00	**Breakout Groups**	**All**
5:00 - 6:00	**Breakout Group Reports and Plenary Discussion**	**All**
6:15	Athenaeum Dinner with Guests	

Schedule Continued

Thursday, February 11, 2016 , 2015 - Keck Center - Think Tank, Room 155		
Time	**Event**	**Speaker**
8:30 - 9:00	Coffee and Refreshments	
9:00 - 9:15	Logistics: Summary re-cap of day three and goals for day four	Michele Judd Team Leads
9:15 - 10:30	**Final breakout group report outs and plenary discussion**	**All**
10:30 - 11:00	Break	
11:00 - 12:00	Writing assignments, outline of needed illustrations, plan for dissemination of information out to larger community	Study leads
12:00 -12:30	Workshop path forward	Michele Judd
12:30 - 1:30	Informal lunch at the Institute	
1:30 - 4:30	**WRITING SESSION (very important to stay and get as much of this done as possible before everyone leaves)**	
4:30	Workshop concludes, celebrating ensues	