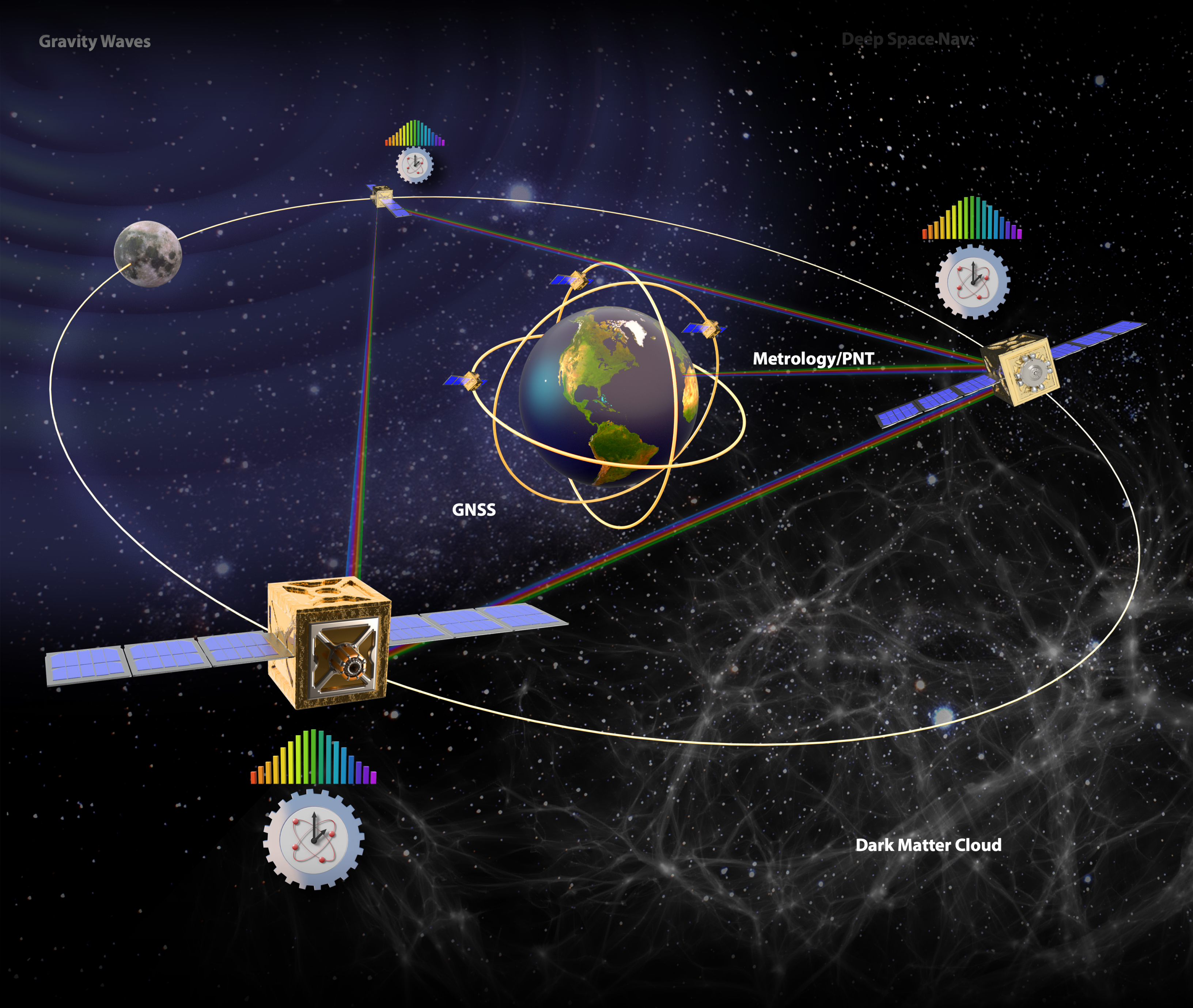
Optical Frequency Combs for Space Applications

Final Report for the Keck Institute for Space Studies



Keck
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Optical Frequency Combs for Space Applications

Final Report prepared for the Keck Institute for Space Studies (KISS)
Jet Propulsion Laboratory, California Institute of Technology
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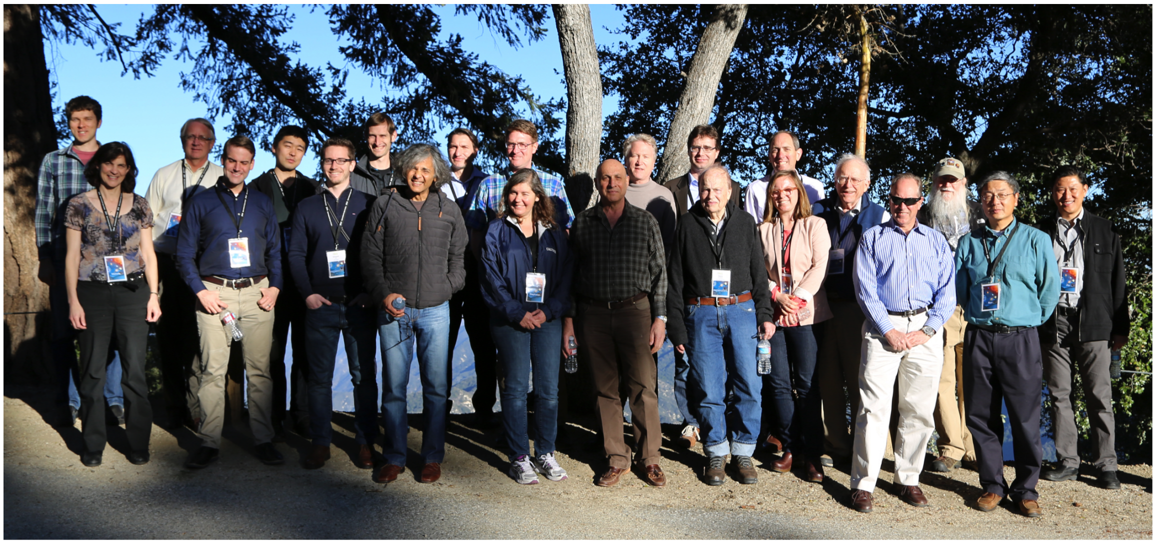
Participants of the Optical Frequency Combs for Space Applications First Workshop at the Keck Institute for Space Studies, California Institute of Technology, November 2015.

From Left: Carl Weimer (Ball Aerospace), Nan Yu (JPL), Ivan Grudinin (JPL), Gregg Hallinan (Caltech), Tobias Kippenberg (EPL), Scott Diddams (NIST), Debra Fischer (Yale), Ronald Holzwarth (Menlo Systems), Alex Gaeta, (Cornell), Kerry Vahala (Caltech), John Burke (AFRL), Pin Chen (JPL), Scott Papp (NIST), Geoffrey Blake (Caltech), Mike Shao, (JPL), Gautam Vasisht (JPL), Dimitri Mawet (Caltech), John Hall (JILA), Ethan Elliott (JPL), Lute Maleki (OEWaves), Kerri Cahoy (MIT), Stephanie Leifer (JPL), Nathan Newbury (NIST), Holly Lepardi (U. Colorado), Christian Frankenberg (Caltech), Tyler McCracken (Yale), William Loh (NIST), Slava Turyshev (JPL), Xu Yi (Caltech), Massimo Tinto (JPL), Qifan Yang (Caltech).
Not pictured: Mitchio Okumura (Caltech).



Participants of the Optical Frequency Combs for Space Applications Second Workshop pictured at the Mount Wilson Observatory Tour, February 2016.

From Left: Ivan Grudinin (JPL), Michelle Stevens (NIST), Carl Weimer (Ball Aerospace), Tyler McCracken (Yale), Yoshi Okawachi (Columbia), Vincent Huet (JPL), John Burke (AFRL), Gautam Vasisht (JPL), Andre Derevianko (U. Nevada), Scott Diddams (NIST), Stephanie Leifer (JPL), Lute Maleki (OEWaves), Kerry Vahala (Caltech), Ronald Holzwarth (Menlo Systems), Hans Schuessler (TAMU), Holly Lepardi (NIST), Scott Papp (NIST), John Hall (JILA), Steven Wilkinson (Raytheon), Mount Wilson Tour Guide, Nan Yu (JPL), Pin Chen (JPL).
Not Pictured: Mahmood Bagheri (JPL), Charles Beichman (NExScI), Ian Coddington (NIST), Alexander Kusenko (UCLA), Ed Wishnow (U.C. Berkeley).

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We feel deeply indebted to Dr. John Hall, the father of optical frequency combs, who graciously participated in both workshops and gave an engaging talk on his life-long efforts to push time and frequency metrology to new limits. Without his Nobel Prize-winning development of the optical frequency comb technique with Theodor Hänsch, we would never have been able to imagine the exciting missions and applications that were envisioned at these workshops, let alone conceive of the study itself.

Much gratitude is due the staff at the Mount Wilson Observatory, Theo ten Brummelaar of the CHARA facility, and Dr. Ed Wishnow of the UC Berkeley Infrared Spatial Interferometer observatory for their tours during the second workshop.

The artwork representing the four mission concepts derived from these workshops was illustrated by Charles Carter. Chuck patiently produced multiple iterations of each picture in attempting to capture and convey the ideas behind each venture.

We thank all of the workshop participants for their time, enthusiasm, and contributions to the workshops and this report. These workshops on Optical Frequency Combs for Space Applications have been a memorable experience and have set the stage for fruitful collaborations between talented scientists and engineers whose paths may never have crossed had it not been for the Keck Institute for Space Studies.

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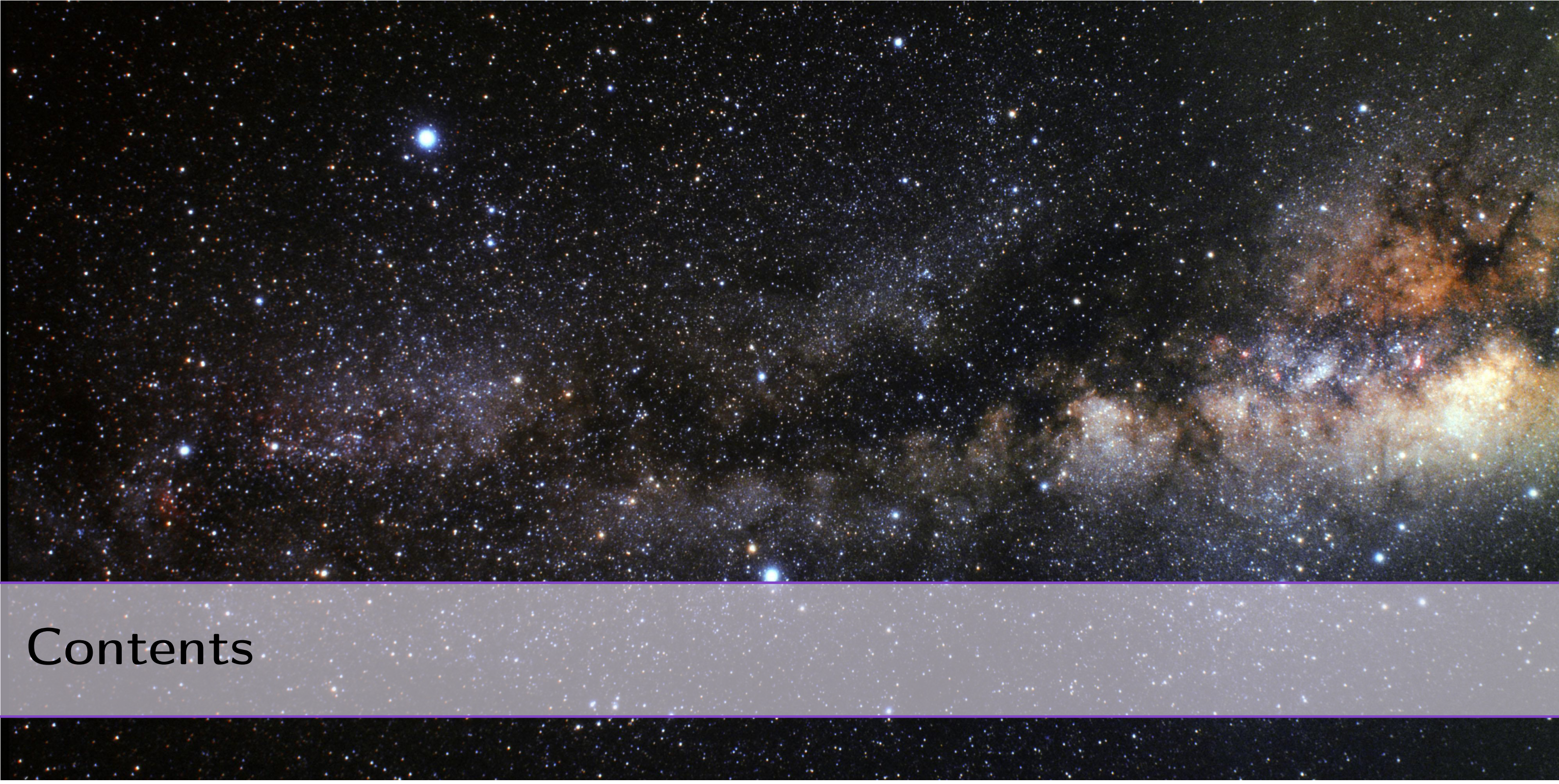

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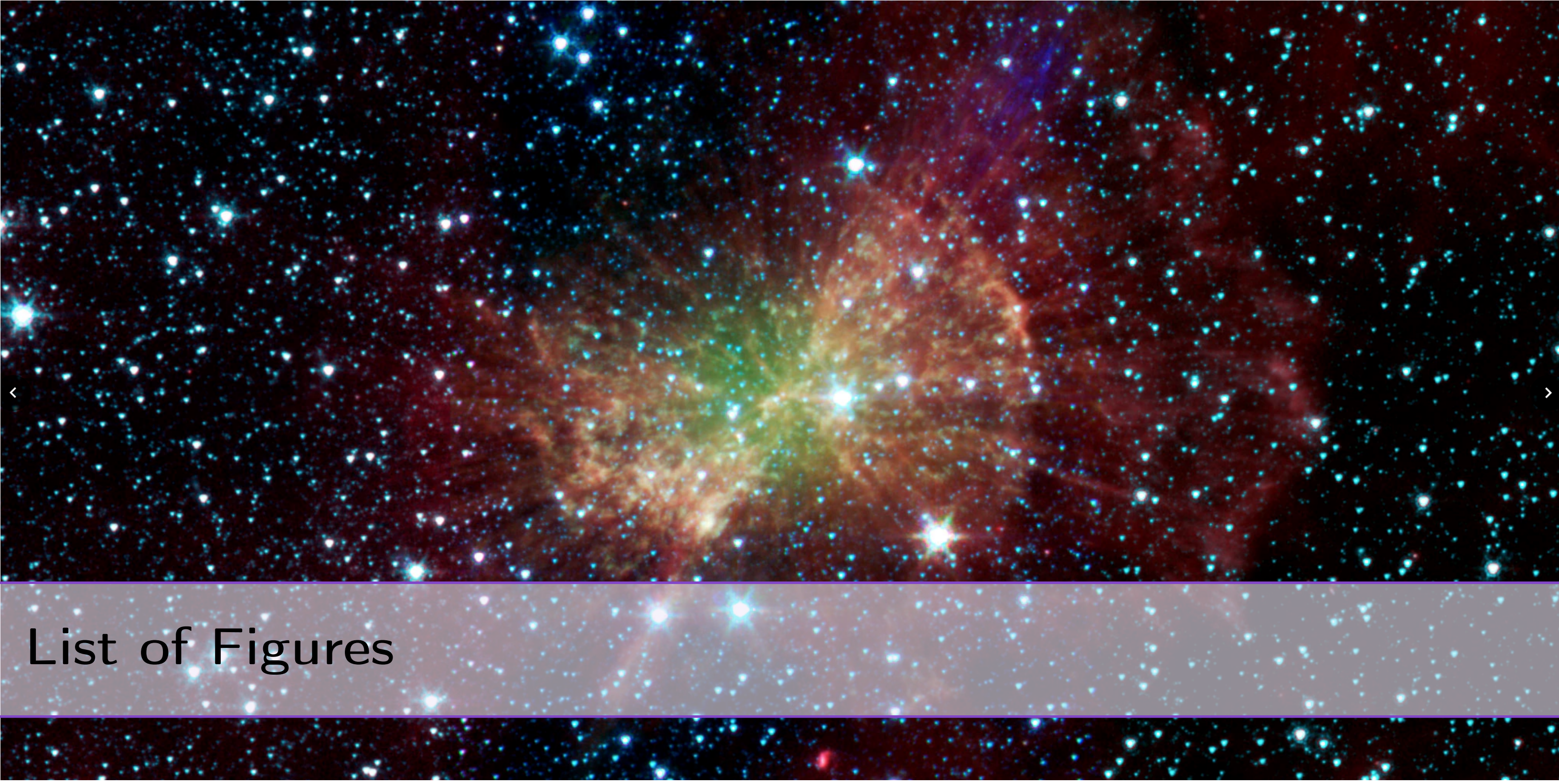

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Executive Summary

An Optical Frequency Comb (OFC) is an optical spectrum consisting of uniformly spaced lines. The stability of the line spacing is controlled by a radio frequency or microwave source. Moreover, if the comb is spectrally broadened to encompass an octave of bandwidth, it is also possible to "self-reference" the comb, endowing it with absolute frequency stability at a Hertz level. It is accordingly a very precise spectroscopic tool for measuring different frequencies of light and is sometimes referred to as an optical ruler. Additionally, comb lines are phase coherent so that phase information can be transferred or measured across a very broad band of optical frequencies. OFCs are also sometimes referred to as optical clockworks because they can relate an optical frequency standard to an electronic one, enabling signal processing with fast electronics, yet with the precision afforded by optical frequencies. OFCs are now central to a new generation of optical clocks that are 100 times more accurate than today's best time-keeping systems, enabling new capabilities in communication, navigation, and advancement of fundamental science.

Because of the unique and powerful features of OFCs, the Keck Institute for Space Studies sponsored two workshops on Optical Frequency Combs for Space Applications at the California Institute of Technology in November of 2015 and February of 2016. The purpose of these workshops was to formulate space applications and mission concepts enabled by optical frequency comb technology and to identify high priority technology challenges and gaps that need to be addressed to implement these missions. This was accomplished by bringing together a diverse group of experts in OFC technology, space application specialists, and potential customers in the areas of astronomy and astrophysics, navigation, laser interferometry, Earth and planetary science, and instrumentation development.

Workshop participants suggested 29 applications potentially enabled or significantly enhanced by the use of OFCs. These concepts spanned four general categories in the areas of spectroscopy, fundamental physics, astronomy, and technology. Four specific mission concepts were explored in more depth during the second workshop because of their potential science return. These concepts were 1) a Space-Time Observatory designed around a distributed network of optical clocks for use in gravitational wave detection, Dark Matter experiments, and a worldwide time standard for laboratory science; 2) The Alpha Centauri Reconnaissance Mission to demonstrate OFC technology on a small explorer-class spacecraft to achieve the highest possible Doppler shift measurement precision for radial velocity determination of exoplanetary mass and cosmological expansion, and also serve as a critical pathfinder for either a LUVOIR or HabEx observatory[1]; 3) a Comb Occultation Cubesat Observatory (COCO) for performing CubeSat-scale planetary atmospheric occultation measurements at Earth, Mars, and other solar system targets, thereby enabling fast, broadband, simultaneous measurement of multiple gas species with either active or passive illumination; and 4) Comb-enabled High Angular Resolution Imaging (CHARLI), a ground-based application using OFC-local oscillators for heterodyne detection and interferometry in the mid-infrared to allow imaging of complex scenes in astronomy on scales never imaged before.

There are multiple methods for generating OFCs. Thus, we considered the comb technologies that could best address these missions' requirements. Microcombs—chip-scale resonant cavity optical devices—were heavily favored for space-based applications due to their inherently small Size, Weight, and Power (SWaP). Electro-Optic Modulation (EOM) combs were also considered because they are robust and relatively simple to construct from commercially available telecommunications components. Quantum Cascade Laser (QCL) and Interband Cascade Laser (ICL) combs and fiber laser combs, the latter of which have been deployed on sounding rocket flights, were also examined. To achieve spectral coverage in various bands of interest ranging from the visible through the mid-IR, each comb technology presents various benefits and challenges. While an investment is being made in comb technology by several institutions internationally, notably including DARPA in the U.S., the targeted applications result in somewhat varying goals for comb performance and features. To achieve the goals of the four missions outlined in this report, as well as to enable some of the other space applications identified, the recommendations for OFC technology development for space missions include the following:

1. Soliton microcombs, which offer low SWaP and geometry-tailored repetition rates, should be integrated with on-chip coupling waveguides, connectorized, and subjected to space environmental testing. For applications requiring broad comb spans, high repetition rates, and spectral flattening, broadening stages that require integrated non-linear waveguides,

[1] Please note that the information in this report is predecisional and is provided for planning and discussion only. The decision to implement HabEx and LUVOIR will not be finalized until NASA's completion of the NEPA process.

fiber amplifiers, and spectral wave shapers will be necessary. Long life, ultra-narrow line width pump lasers should be included in development activities.

2. Self-referenced EOM combs offer both high stability (*Carlson et al.*, 2017) and broad spectral coverage in the NIR. However, they require filtering of RF oscillator and amplifier phase noise in the wings of the comb, rendering them more complex than line-referenced EOM combs. Ultra-low phase noise oscillators and amplifiers in conjunction with Fabry-Perot cavities are desirable to mitigate this problem, and the availability of narrow line width, high-stability rubidium D2 line-referenced CW pump lasers at 1550 nm would provide line-referenced combs with a stability adequate for many space science applications. As with soliton microcombs, nonlinear spectral broadening stages, narrow line-width pump lasers, and broad spectral flattening should be included in development activities.

3. Quantum Cascade Lasers and Interband Cascade Lasers (QCLs and ICLs) offer direct generation of frequency combs from the mid-IR (ICLs) through terahertz spectral regions (QCLs). They are low power devices and dramatically more efficient than difference frequency generated (DFG) mid-IR combs, and thus are well suited for the development of compact spectrometers. QCL devices have been commercialized, but broad spectral coverage remains a challenge, and careful dispersion engineering to minimize group velocity dispersion would improve this performance parameter. Also, self-mode locking of ICLs has recently been reported (*Bagheri et al.*, 2018). DFG-generated combs offer broad spectral coverage and can be generated with fiber laser comb technology; increasing the power of the output combs of these systems remains a goal.

4. Self-referenced fiber laser combs have been developed in small packages (volumes of <1 liter and power consumption of <50 W) (*Sinclair et al.*, 2015) providing mode spacing in the ~100–200 MHz repetition rate regime. These devices are promising for numerous applications in the field.

5. Hybrid systems that combine multiple frequency comb generation stages can overcome some limitations of individual comb technologies. For example, soliton microcombs pumped with an electro-optically modulated pump source (*Obrzud et al.*, 2017) allows the microresonator to self-lock to the driving laser so that no active feedback-loop is required.

Further recommendations regarding the approach to incorporating comb technology into space science missions include:

6. Establish ground-based astronomy implementations of frequency combs as testbeds for OFC component technologies extensible to flight, starting predominantly with electro-optic modulation frequency combs due to the relatively low cost and availability of components, and fiber laser combs due to commercial availability and technical maturity, with near-IR comb implementation first, followed by extension into visible wavelengths;

7. Advance soliton microcomb Technology Readiness Level (TRL) through introduction at established ground-based frequency comb implementations;

8. Advance dual-comb spectroscopy TRL in ground-based applications, followed by airborne-to-ground, airborne-to-airborne, and space-to-ground demonstrations.

9. Demonstrate ground-based heterodyne detection with mid-IR frequency comb local oscillators with concurrent advancement of fast detector capability.

Since the second KISS Workshop in February of 2016, progress has been made in implementing frequency comb technology for some of these mission concepts:

1. Alpha Centauri Reconnaissance Mission, or Space-based precision radial velocity detection of exoplanets:
   - In November of 2016, a proposal for an OFC-calibrated, diffraction-limited, single mode fiber-fed, extreme resolution PRV spectrometer in space was submitted to a NASA ROSES call for probe mission studies for input to the 2020 Decadal Survey. The concept, dubbed EarthFinder, was selected in March of 2017 with partial funding to support an 18-month study in simulating the precision radial velocities obtainable by removing Earth's atmospheric contributions to the error budget. The goal of the study is to better elucidate the science case for a space-based PRV mission.

   - Space-based frequency combs for spectrograph calibration were placed on the 2018 NASA Exoplanet Exploration Program prioritized technology needs and gap list: `https://exoplanets.nasa.gov/exep/technology/gap-lists/`.

   - For PRV detection of exoplanets at ground-based observatories, two groups have now demonstrated microresonator frequency combs for astronomical spectrograph calibration. The pump laser for one of these demonstrations was locked to a 100 MHz fiber laser comb, and the other was a HCN-line referenced laser. Soliton microcombs offer the benefit of comb line generation with a mode spacing desired for astronomical spectrographs in contrast with fiber laser combs, which require mode filtering to achieve a resolvable line spacing, and broad EOM combs that suffer from phase noise amplification in the wings that must also be filtered to accomplish self-referencing.

   - The Keck Institute for Space Studies is supporting a collaborative effort between the National Institute for Standards and Technology (NIST) and NASA's Jet Propulsion Laboratory (JPL) to build a self-referenced electro-optic modulation frequency comb through JPL's Strategic Research and Technology Development Program. The completed comb will be used for spectrograph calibration at Palomar Observatory for a new PRV capability dubbed PaRVI (**Pa**lomar **R**adial **V**elocity **I**nstrument). With a scheduled commission date in the fall of 2018, PaRVI will perform RV measurements of exoplanet-hosting stars in the astronomical J and H bands from 1200 nm to 1800 nm.

- Another EOM comb, with the pump laser referenced to a self-referenced fiber laser frequency comb and spanning 800 nm–1300 nm will be used for spectrograph calibration of the Habitable-zone Planet Finder (HPF) instrument at the Hobby-Eberly telescope at the McDonald Observatory through a cooperative effort between the National Institute of Standards and Technology (NIST) and Pennsylvania State University.

2. CHARLI, or high-angular resolution imaging in the mid-IR:
   - Frequency combs that operate in the mid-IR portion of the spectrum, particularly around 10 microns, have become more available. Commercial vendors such as Alpes Laser and IRSweep are now offering QCL-based mid-IR frequency combs.

   - High speed detectors in the 10-micron regime have typically been HgCdTe-based; the detectors in use at the Infrared Spatial Interferometer on Mount Wilson are characterized by a 2–3 GHz bandwidth. Previous attempts to use QWIPs for heterodyning have been reported (*Hutchinson et al.*, 1999) as QWIPs offer high speed, but historically, their low quantum efficiency (QE) made this route unattractive. However, resonant QWIPs developed at the Army Research Laboratory (*Choi et al.*, 2017) have been engineered to deliver high QE, making them an exciting potential option for a mid-IR heterodyne receiver system. Importantly, *Palaferri et al.* (2018) has recently reported measuring the heterodyne signal of two QCLs in the 9 μm band using "photonic metamaterial" QWIPs at frequencies up to 4.2 GHz at room temperature.

   - Another potential avenue for fast mid-IR heterodyne detection is adapting hot electron bolometers (HEB) (*Cunnane et al.*, 2015), which have demonstrated very high speed capability in the far-IR, for use around 10 microns.

Frequency comb technology has continued to advance rapidly in the two years since the end of the second KISS workshop. While we are not able to capture all of the developments in this burgeoning field, it is fair to say that this study marks only the beginning of space applications for optical frequency combs.

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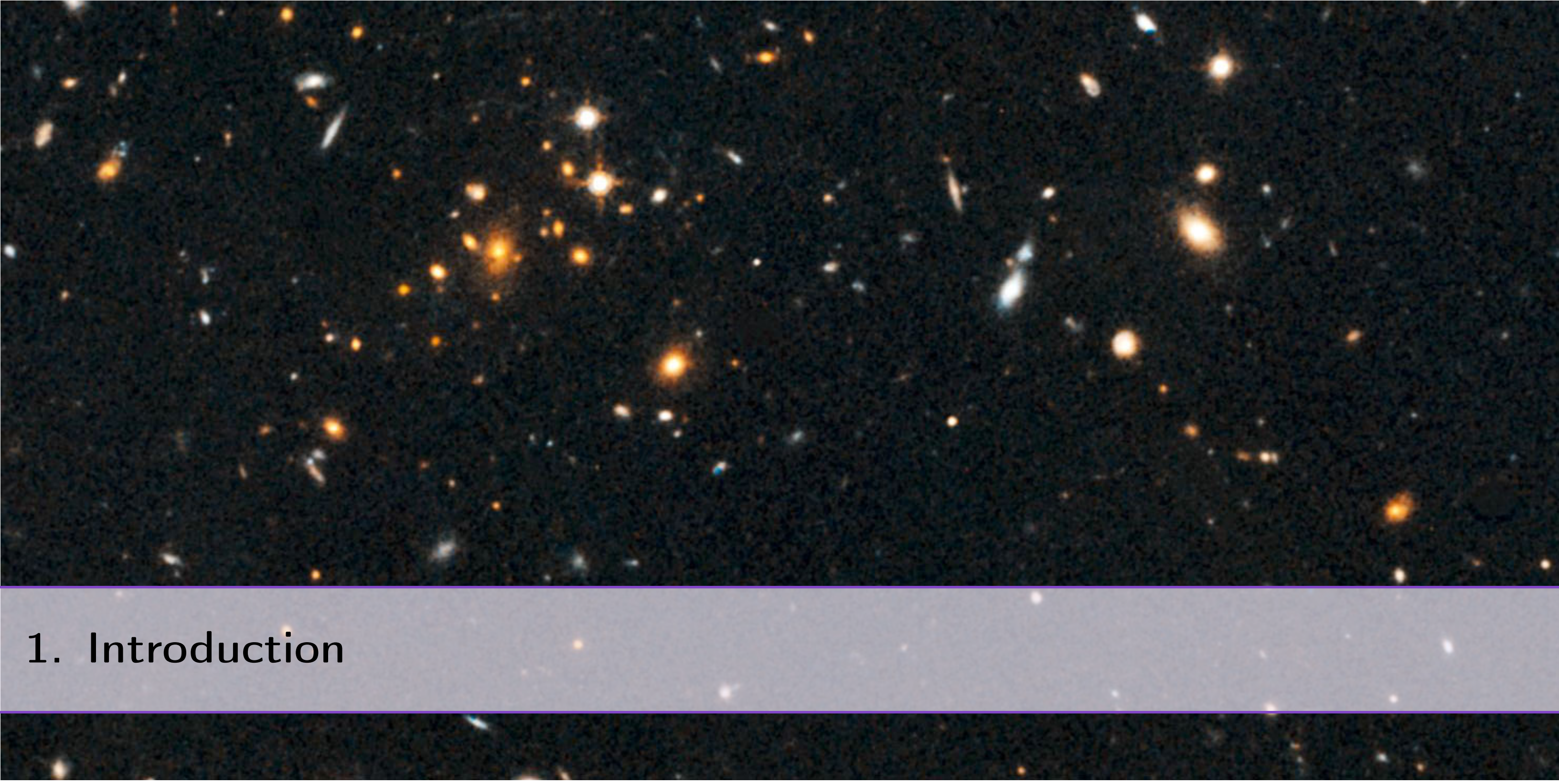

1. Introduction

The development of Optical Frequency Combs (OFCs) is a significant advancement in time and frequency metrology. This new technology offers the promise of answers to some of the most pressing scientific questions of the day; when we embarked on this study effort, it was apparent that the dramatic new capabilities in frequency metrology and timekeeping enabled by OFCs make them tantalizingly ripe for use in exciting space mission applications.

1.1 Background

An Optical Frequency Comb (OFC) is an optical spectrum consisting of uniformly spaced lines. The stability of the line spacing is controlled by a radio frequency or microwave source. Moreover, if the comb is spectrally broadened to encompass an octave of bandwidth, then it is also possible to "self-reference" the comb, endowing it with absolute frequency stability at a Hertz level. It is accordingly a very precise spectroscopic tool for measuring different frequencies of light and is sometimes referred to as an optical ruler. Additionally, comb lines are phase coherent so that phase information can be transferred or measured across a very broad band of optical frequencies. OFCs are also sometimes referred to as optical clockworks because they can relate an optical frequency standard to an electronic one, enabling signal processing with fast electronics, yet with the precision afforded by optical frequencies. OFCs are now central to a new generation of optical clocks that are 100 times more accurate than today's best time-keeping systems, enabling new capabilities in communication, navigation, and advancement of fundamental science.

Increasingly, OFCs are significantly impacting many other areas, including high-resolution broad range spectroscopy in chemical detection, precision wavelength calibrations in exoplanet detection, coherent control in studies of ultrafast dynamics, and measurement improvements in space interferometry, reflectometry, and LIDAR. In addition, the promise of miniaturization of OFC technology offers a slew of possibilities for instruments on landers, distributed spacecraft, and CubeSat-scale spacecraft in the next decade.

Because of the unique and powerful features of OFCs, the Keck Institute for Space Studies sponsored two workshops on Optical Frequency Combs for Space Applications at the California Institute of Technology from November 2nd through 5th, 2015, and February 8th though 11th, 2016. The purpose of these workshops was to formulate space applications and mission concepts enabled by optical frequency comb technology and to identify high priority technology challenges and gaps that need to be addressed to implement these missions. This was accomplished by bringing together a diverse group of experts in OFC technology, space application specialists, and potential customers in the areas of astronomy and astrophysics, navigation, laser interferometry, Earth and planetary science, and instrument development.

During the first workshop, a short course covering optical frequency comb technology, general applications of frequency combs, and considerations for preparing and qualifying optical hardware for spaceflight were presented to provide all workshop participants with a common basis for discussion.

Specific goals for the program were to:

1. Clearly identify 2–3 high-payoff mission concepts with enough fidelity to allow the Jet Propulsion Laboratory's concurrent engineering design teams (Team X for missions or Team I for space instruments) to conduct a follow-on study where a mission (or instrument) point design could be detailed,
2. Prioritize critical areas for frequency comb subsystem technology development needed for space applications and not currently being addressed by other agencies, make recommendations for follow-on studies, and
3. Create lasting, productive collaborations between frequency comb technologists and space science and technology specialists.

1.2 Space Science and Mission Applications Identified

In the first workshop, participants suggested 29 applications potentially enabled or significantly enhanced by the use of OFCs. These concepts spanned the four general categories of Spectroscopy, Fundamental Physics, Astronomy, and Technology. The concepts are:

- Spectroscopy
  - Remote or in-situ planetary atmospheric sensing with fast, broadband detection enabled by OFC:
    - At Earth, Mars, Venus, and large moons
    - Through either passive (sunlight) illumination or active illumination through the use of dual combs
    - For measurement of bio-signatures (e.g. chirality) on primitive bodies
  - Ground-based OFCs for atmospheric spectroscopy
  - Fast-flyby spectroscopy such as for Kuiper Belt objects or comet tails
- Fundamental Physics
  - OFC-enabled precision formation flying constellation for:
    - Detection of gravitational waves
    - Dark Matter tests
  - General relativity tests: higher precision enabled by OFCs
  - Observation of short time-scale astronomical events
  - Vacuum fluctuation measurements with combs, e.g., "Direct Sampling of Electric-Field Vacuum Fluctuations" (*Riek et al.*, 2015)
  - Worldwide precision timekeeping standard for laboratory science
- Astronomy
  - OFC-calibrated, high-resolution spectrograph in space to conduct Extreme Precision Radial Velocity (EPRV) measurements for:
    - Detection of Earth-sized exoplanets orbiting sun-like stars
    - Observations of exoplanetary magnetospheres through auroral emissions
    - Determination of cosmic acceleration
  - High angular resolution imaging of cool objects from the ground using OFC local oscillators for heterodyne detection interferometry:
    - Planet Formation Imager (PFI), Geostationary Satellites, and Near-Earth Objects (NEOs)
    - Utilization of squeezed comb light to improve upon detector quantum noise limit

  - Measurements of dispersion from the interplanetary medium (zodiacal dust)
  - 550 AU solar gravity focus mission use of OFCs
  - OFC-based ranging radar of asteroids
- Technologies
  - International Space Station experiments:
    - Cold atom experiment
  - Self-referenced optical clocks for
    - General relativity tests
    - Dark Matter tests
    - Global time standard
    - Navigation/time transfer
  - Mass marketing of OFCs in consumer devices (i.e., "iComb")
  - High resolution 3D imaging
  - Ranging radar of satellites
  - New Comb Functionality for Radar (e.g., Waveform Synthesis)
  - "Atomless" clocks in space
  - Planetary GPS
  - OFC-based super oscillator
  - Precision formation flying
  - Universal spacecraft system (navigation, communication, and timing functionality) in small SWaP

While many of these OFC applications merit further investigation, several of them have the potential to return science not easily achievable with any other known method. Thus, these concept areas were explored and developed in more detail during the second workshop and resulted in four exciting mission and application concepts that could yield ground-breaking science and discovery. These four concepts are:

1. **The Space-Time Observatory:** a constellation of spacecraft with on-board OFC-based optical clocks to enable precision timing and navigation for use in gravitational wave detection, Dark Matter experiments, and a worldwide time standard for laboratory science.

2. **The Alpha Centauri Reconnaissance Mission:** a precursor mission that demonstrates OFC technology on a small explorer class spacecraft and provides unprecedented extremely high-resolution, telluric-contamination-free, broadband spectra of the closest stars. Such a mission would have a significant impact on fundamental stellar astrophysics by providing a better understanding of the wavelength dependence of phenomena in stellar photospheres—spots, faculae, and granulation—across many spectral types and evolutionary stages. It would provide the needed breakthrough to reach the highest possible Doppler precision for extreme precision radial velocity determination of exoplanetary mass and thereby planet density and bulk composition, serve as a critical pathfinder for either a LUVOIR or HabEX observatory, and potentially provide a means to directly measure cosmological expansion.

3. **Comb Occultation CubeSat Observatory (COCO):** a CubeSat-scale, OFC-based planetary atmospheric occultation instrument for broadband, fast determination of atmospheric species at Earth, Mars, and other solar system targets. Measurements could be performed with active illumination, allowing for night-time observations, as well as polar observations during winter months.

4. **Comb-enabled High Angular Resolution Imaging (CHARLI):** a ground-based application using OFC-local oscillators for heterodyne detection and interferometry in the mid-infrared. It could allow imaging of complex scenes in astronomy on scales never imaged before, including: (1) direct imaging of planets in the act of formation in the disks around the nearest protostars, addressing one of the great, unsolved problems in both astrophysics and planetary science; (2) imaging of the surfaces of the nearest stars to unprecedented resolution, providing a new boost to stellar astronomy; (3) a new method of imaging mature planets, including those that are very close to the host star; (4) imaging of the morphology of Near Earth Object (NEOs), leading to better understanding of the surface and composition of these enigmatic objects and a more direct measurement of their diameters; and (5) imaging of geosynchronous satellites from the ground at high resolution.

1.3 Multi-agency Optical Frequency Comb-related Technology Needs

As part of this study, we examined the roadmaps and reports issued across government agencies to identify overlapping science goals or capabilities that could be addressed by OFC technology development. The reports reviewed include National Research Council Decadal Surveys for Astronomy and Astrophysics, Planetary Science, Earth Science, and Biological and Physical Sciences in Space; the NASA 2015 Technology Roadmap; and Department of Defense agency reports from the Air Force, Office of Naval Research, and the Defense Advanced Research Projects Agency (DARPA). The tables in Appendix A show the applicable excerpts from those reports. Uniformly across all agencies, chip-scale optical clocks for precision timekeeping was named as a high-priority technology goal. Advanced LIDAR and spectroscopic sensing tools were also called out by several agencies.

1.4 Organization of this Report

This report is a summary if the findings of the two KISS workshops on Optical Frequency Combs for Space applications. It begins with a description of the state-of-the-art in frequency comb technology; we describe comb generation techniques, comb operating parameters and performance, and current challenges to implementation. The status of commercial OFC availability is provided. Second, we explore general areas of comb application and investigate whether combs provide a notable advantage over other technologies for space platforms.

The next four chapters provide an overview of each of the four mission concepts named in Section 1.2, the potential science return OFCs enable for these missions, and the OFC technology development roadmaps to achieve them. Finally, we conclude by making recommendations for future OFC technology development that can most impact its role in space science applications.

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2. Introduction to Comb Technology

2.1 Background

The origin of the development of optical frequency combs can be traced to the 1964 demonstration of an actively mode-locked laser for ultrashort pulse generation (*Diddams*, 2010), and subsequently found in the work of Theodor Hänsch (*Udem et al.*, 2002) and John Hall (*Hall*, 2000) whose research in improved frequency standards and metrology tools led to their 2005 shared Nobel Prize for the optical frequency comb technique.

In this chapter, we describe the various methods for producing and stabilizing optical frequency combs, as well as the characteristics of the combs produced by these methods. We also provide an overview of the commercial availability of frequency comb sources and discuss extensibility to space flight.

2.2 Principle of Frequency Comb Generation

In a mode-locked laser, the laser's resonant cavity is formed by two opposing mirrors with a gain medium in between. Within this cavity, light will constructively and destructively interfere with itself, leading to the formation of a discrete set of frequencies—the longitudinal modes of the cavity. When a fixed phase relationship is induced between these modes, they can all constructively interfere with one another periodically, causing the laser light to be produced as a train of pulses with a repetition period corresponding to the resonator round-trip time. The process of inducing the fixed phase between pulses is called phase-locking or, more commonly, mode-locking. Mode-locking can be accomplished either passively, by placing some element into the laser cavity that causes self-modulation of the light, or actively, with an external signal.

An optical frequency comb is an optical spectrum that consists of lines with uniform spacing determined by the repetition rate of such ultrashort optical pulses (see Figure 2.1). The shorter the laser pulses are, the broader the range of frequencies in the comb. Mode-locked lasers emit femtosecond-range pulses resulting in comb spans of several hundred thousand frequencies, or teeth.

The first optical frequency combs were developed using mode-locked lasers where the output of the laser is described by the simple formula $\nu_n = n \cdot f_r + f_o$, where n is an integer, ν_n is the frequency of the nth comb "tooth," f_r refers to the pulse repetition frequency, and f_o is the carrier envelope offset frequency—a frequency spacing that results from the difference between the group and phase velocity in the optical cavity (Figure 2.2).

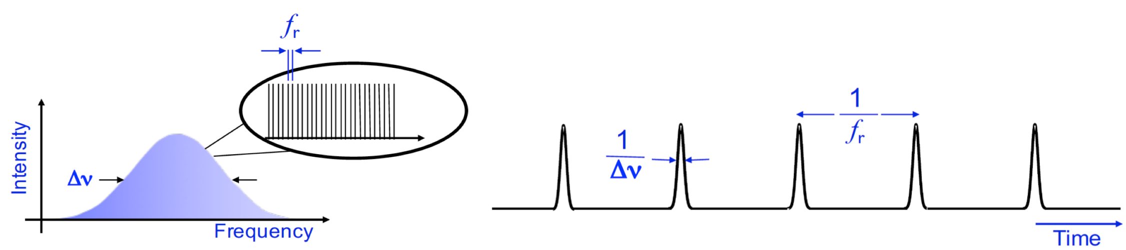


Figure 2.1: Optical Frequency Combs can be thought of as optical rulers (left), or in the time domain, as a perfectly spaced train of optical pulses (right). Here, f_r is the mode spacing and its reciprocal is the pulse repetition frequency, $\Delta\nu$ is the bandwidth, and its inverse yields the optical pulse width.

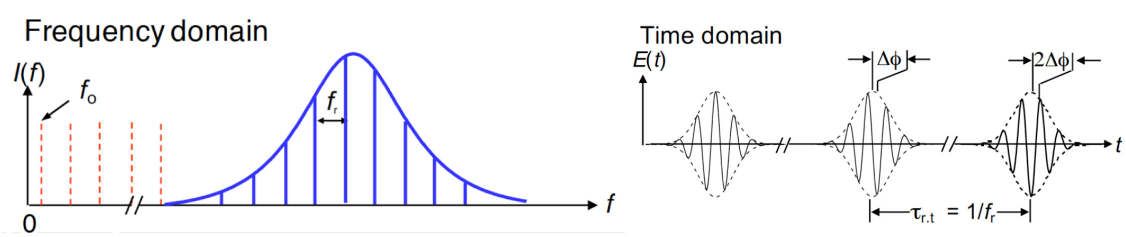


Figure 2.2: Carrier Envelope Offset (CEO) frequency, f_o, results from the difference between group and phase velocity in the optical cavity.

2.3 Comb Stabilization

Frequency combs inherently have two independent degrees of freedom: the repetition rate (f_r), which determines the spacing between comb lines, and the carrier envelope offset frequency (f_o), which determines the absolute position of the comb lines in frequency space.

Stability of the comb repetition frequency, f_r, can be accomplished by referencing to an RF standard (e.g., a GPS-disciplined atomic clock). Stabilization of f_o, or the absolute position of the comb in frequency space, is primarily accomplished through f–$2f$ self-referencing. In this technique, if the comb span is broad enough to encompass an octave or more of bandwidth, then using an interferometric scheme where a beat note generated between the frequency-doubled lower frequency end of the comb spectrum and the higher frequency end produces a measure of f_o. Self-referencing can provide absolute comb stability at the Hertz level.

If a full octave of comb span is not possible, but 2/3 of an octave is, then $2f$–$3f$ self-referencing may be possible; this has been accomplished in several different comb devices (*Jost et al.*, 2015; *Brasch et al.*, 2017; *Hitachi et al.*, 2014). From a practical standpoint, self-referencing requires that the heterodyned comb lines have low phase noise, and that there be enough power to produce a strong enough signal from the second (or third) harmonic generated in a nonlinear crystal to produce a detectable beat-note for the determination of f_o.

Comb stabilization can also be provided by using a laser pump source referenced to an atomic transition (line-referenced laser), or a comb tooth of another stabilized comb. In the case of the former, such comb stabilization is only as good as the stability of the pump laser, which is tied to the technique used by the electronics to track the centerline of the referenced atomic or molecular absorption feature, and the width and strength of that feature. For commercially available line referenced lasers, this on the order of 10^{-9} to 10^{-10} Allan deviation for acetylene or HCN referenced lasers (*Yi et al.*, 2016). Doppler-free Rubidium D2 line referenced lasers have shown better than an order of magnitude better stability (10^{-10} to 10^{-11}) over similar integration times (*Matthey et al.*, 2015). While not as stable as self-referenced combs, line-referenced combs are still useful for many applications. In some bands, where octave-spanning combs may be more difficult to produce, locking the pump laser to a tooth of a self-referenced comb can be useful.

2.4 Spectral Broadening

As octave-spanning frequency combs are needed for f–$2f$ self-referencing, one of the important components of a frequency comb assembly is the spectral broadener (i.e., supercontinuum generator). Comb broadening can be achieved when high power pulses propagate through various nonlinear media. The physical processes behind supercontinuum generation vary depending upon the optical pulse characteristics and dispersion properties of the nonlinear medium and are a result of a combination of processes including four-wave mixing, Raman scattering, or soliton formation at very high intensities. The largest broadening occurs when the pump source is close to the zero-dispersion point of the nonlinear medium. Supercontinuum generation is accomplished with the use of commercially supplied photonic crystal fiber (PCF) or highly nonlinear fiber (HNLF), or silicon nitride waveguides. The waveguides are in early commercialization phase, with the Swiss company Ligentec producing unpackaged devices. Pigtailed versions are not yet available but would be necessary for future implementations requiring robust assemblies (e.g., spaceflight). For high repetition rate combs this is challenging due to the high average power entering the waveguide, making alignment crucial.

2.5 Pulse Shaping

Some frequency comb applications require a flat power profile. Techniques for nonlinear broadening of the comb do not provide this, so the ability to perform line-by-line pulse shaping may be necessary. Pulse shaping can be accomplished using a programmable two-dimensional (2D) liquid crystal on silicon Spatial Light Modulator (LCOS-SLM) display in a reflective configuration (*Roelens et al.*, 2008). Commercial spectral "waveshapers" are available for ~70 nm spectral spans, but at present custom devices are required for wider combs.

2.6 Frequency Comb Generation Techniques and Characteristics

Since the development of mode-locked lasers, OFCs have been generated by other methods such as four-wave mixing in photonic crystal fibers, four-wave mixing in Kerr microcombs—optical "whispering gallery mode" resonant cavities, electro-optic modulation, and with Quantum Cascade Lasers (QCLs) and Interband Cascade Lasers (ICLs). Each of these comb generation techniques is described in the following sections, along with characteristic performance parameters.

The principle parameters and characteristics of OFCs relevant to this report are:

- **Span:** the bandwidth encompassed by the comb, inversely related to the pulse width. Often, additional spectral broadening stages must be used to increase a comb span.
- **Mode spacing:** the free spectral range between comb lines, f_r; in the time domain, the reciprocal of f_r is the pulse repetition frequency. Depending upon the comb generation technique, mode spacing may be a natural consequence of the comb geometry, or of an externally applied reference signal.
- **Power:** may refer to the overall power of the comb distributed among all modes, or the power per comb line.
- **Stability:** degree of invariance of both comb line relative spacing (f_r) and the absolute position of the comb in frequency space (the carrier envelope offset frequency, f_o).
- **Dynamic Range:** the flatness or variation of power per comb line across the full comb spectrum.
- **Efficiency:** comb output optical power versus input electrical power
- **Center (pump) wavelength:** the center wavelength of the pump laser seeding the comb

2.6.1 Mode-locked Laser Frequency Combs

2.6.1.1 Ti:Sapphire Combs

Ti:Sapphire femtosecond lasers were the original platform for the development of OFCs. These solid-state lasers are pumped by CW lasers (e.g., argon ion), are a widely commercially available mature technology, and offer inherently broad spectral coverage. They have mode spacing in the 100s of MHz regime and can generate octave-spanning combs for self-referencing without the need for additional nonlinear broadening. However, Ti:Sapphire lasers are heavy and have a large footprint—i.e., they are not conducive to flight hardware.

2.6.1.2 Fiber laser combs

Passively mode-locked fiber laser combs, such as those made with erbium, ytterbium, thulium, or praseodymium-doped fiber as the gain medium, emerged as a much lower cost and compact alternative to Ti:Sapphire combs. Pumped by fiber-coupled diode lasers, they can be operated continuously for longer periods of time and use a telecommunications band wavelength of 1.5 microns for pumping, opening up access to hardware developed for that industry. There are a number of different designs (*Newbury et al.*, 2007), but regardless of the design, the repetition rate is on the order of 100 MHz. Fiber laser combs require spectral broadening to attain a full octave for self-referencing; this is accomplished first with pulse amplification and then injection into highly nonlinear fiber (HNLF).

The fiber laser comb has become a mainstay in the frequency comb research, development and applications communities. Fiber laser combs were used in the first flight demonstrations of OFCs on a year-long flight in low Earth orbit launched in 2013 (*Lee et al.*, 2014) and in sounding rocket launches in 2015 and 2016 (*Lezius et al.*, 2016). Radiation testing of a fiber laser comb has been performed (*Buchs et al.*, 2015) to explore suitability for longer-term space missions.

2.6.2 Microcombs

An OFC technology with the greatest promise for delivering very compact size, low mass, low power, broad spectral coverage, and high repetition rate is the Kerr microresonator-based OFC, or microcomb. The majority of comb technology presentations given at the KISS workshops pertained to the development of these chip-platform devices—a reflection of the large effort by multiple institutions in this area at present.

Microcombs use laser light coupled into and confined in small, resonant cavity structures known as whispering gallery mode (WGM) resonators. These devices have a unique combination of millimeter dimensions and ultrahigh optical Q factors—a measure of the ability of the device to confine light without loss. In a WGM resonator, light is trapped by total internal reflection

	Ti:Sapphire (*Jones*, 2000; *Apolonski*, 2000)	Cr:LISAF (*Holzwarth*, 2001)	Er:fiber (*Washburn*, 2004)	Cr:forsterite (*Kim*, 2005, 2006)	Yb:fiber (*Hartl*, 2007)	Yb:KYW (*Meyer*, 2008)	Er:Yb Glass (*Stumpf*, 2009)	Tm:fiber (*Phillips* 2011)
Center Wavelength	800 nm	894 nm	1560 nm	1275 nm	1040 nm	1030 nm	1560 nm	1950 nm
Pulse Length	10–50 fs	~50 fs	80–200 fs	30 fs	70–100 fs	290 fs	170 fs	70 fs
Pump Source	532 nm, doubled Nd:YVO	650 nm diode	980 or 1480 nm diode	1075 nm fiber laser	976 nm diode	980 nm diode	976 nm diode	793 nm diode
Repetition Rate	0.1–10 GHz	93 MHz fs	50–300 MHz	420 MHz	0.1–1 GHz	160 MHz	75 MHz	72 MHz
Spectral Span	500-1200 nm; direct or in MSFc	550–1100 nm in PCF	1000–2000 nm in HNLF	1000-2000 nm in HNLF	700-1400 nm in PCF	700-1400 nm in PCF	1000–2000 nm in HNLF	In PPLN
Electrical-to-Optical Efficiency	0.1%	1–2%	1%	0.5%	1–2%	2–3%	2–3%	??
Average Optical Power	1000mW	150 mW	25–100 mW	500 mW	100–200 mW	>200 mW	>100 mW	??

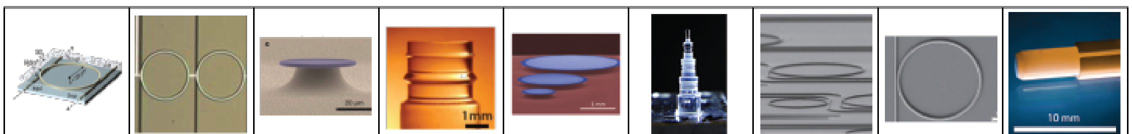
Table 2.1: Characteristics of self-referenced optical frequency combs from (*Diddams*, 2010), and KISS workshop on Optical Frequency Combs for Space Applications presentation, 2015.

from the dielectric-air boundary along which it travels. In 2004 experiments by *Kippenberg et al.* (2004) and *Savchenko et al.* (2004), light was coupled into WGM resonators and, through a process known as degenerate four-wave mixing—also referred to as optical parametric oscillation and modulation instability (*Pasquazi et al,*, 2018)—multiple comb-like modes were generated. This was a consequence of the Kerr effect, a nonlinear change in the refractive index of a material in response to an applied electric field. In the case of the optical Kerr effect, the electric field is due to the light itself. Thus, the variation in refractive index induced by a high intensity pump laser results in two new frequencies (one higher and one lower) being created from a single pump frequency. This occurs when two photons of the optical pump annihilate to generate two photons symmetrically-distributed (because of energy conservation) with respect to the central pump frequency. After these new frequencies of light appear in the resonator, they interact with the original pump light and among themselves through nondegenerate four-wave mixing in a cascading process to create even more optical frequencies. This cascade of frequencies forms a Kerr comb or microcomb. To emit a series of short pulses like those produced in mode-locked lasers, the microcomb must form solitons, which are unchanging wave packets formed when nonlinear and dispersive effects in the resonator exactly balance.

Unlike mode-locked lasers that have repetition rates in the 100 MHz (up to ~1 GHz) regime, microcombs have mode spacing intrinsically at ~1 GHz to terahertz regimes, depending upon the architecture of the resonator. Laser pump power required for comb generation is on the order of 100 mW. These chip-platform devices have been fabricated from silica, silicon nitride, and crystalline materials (See Figure 2.3). In a recent development, novel single-mode optical fiber-based high-Q Fabry-Perot microresonators were formed using a mm-scale optical fiber with mirror-coated end facets (*Herr at al.*, 2016). A recent review article on microcombs (*Pasquazi et al.*, 2018) provides a good summary of microcomb physics and fabrication techniques.

Microcombs leverage advances in heterogeneous photonic integration techniques for active, passive, and nonlinear devices on silicon. Hence, an entire frequency comb system can conceivably be fabricated on a silicon chip using current technology by the late 2020s. Currently, there are multiple microcomb development projects being funded by DARPA, namely for the ACES, SCOUT, and DODOS programs (See Table A.1 in Appendix A).

Presently, the challenges to microcomb development and implementation include reaching an octave span for self-referencing and deterministic operation in the low noise, soliton regime. Stabilization of line positions is challenging due to intrinsically high sensitivity to temperature fluctuations in all existing microdisk resonators. Also, the microcomb spectrum is usually generated with a rather high dynamic range. Full chip-scale integration of microcombs including the pump laser, coupling mechanism, PPLN, and nonlinear spectral broadening medium to permit self-referencing all in a fiber-pigtailed device is the ultimate goal.



Hydex (*Razzari et al.*, 2010)	Si:Nitride (*Levy et al.*, 2010; *Ferdous et al.*, 2011)	Silica toroid (*Del'Haye et al.*, 2007)	Crystals (*Savchenkov et al.*, 2008)	Silica wedge (*Lee et al.*, 2012)	Quartz (*Papp & Diddams*, 2011)	Diamond (*Hausmann et al.*, 2013)	Al:Nitride (*Jung et al.*, 2013)	SM fiber-based Fabry-Perot (*Obrzud et al.*, 2016)
RMIT	Cornell, Purdue, NIST Gaithersburg, EPFL, UCLA	MPQ, EPFL, Caltech	OEWaves JPL EPFL	Caltech	NIST	Harvard	Yale	CSEM

Figure 2.3: Various microresonator designs for generation of optical frequency combs.

2.6.3 Electro Optic Modulation Frequency Combs

Another method of generating OFCs is the electro-optic modulation technique (*Murata*, 2000). In this scheme, a chirped pulse train is produced from a CW pump laser using cascaded electro-optic phase and intensity modulators driven by a microwave oscillator at the desired pulse repetition frequency. The pulse train is dispersion compensated and then optically filtered by a Fabry-Perot cavity to suppress phase noise. Practical limitations of power handling and efficiency in electro-optic materials allow only a narrow bandwidth of 10–20 nm. Still, the generation of sub-picosecond duration optical pulses enables further spectral broadening of the EOM comb in nonlinear media following amplification. Through stepwise increases in the EOM comb bandwidth by first utilizing self-interaction of the optical pulses in a ~10-meter scale length of highly nonlinear fiber (HNLF), followed by supercontinuum generation in either a chip-based nonlinear waveguide second stage or more segments of appropriate dispersion HNLF, greater than octave spans can be produced, permitting self-referencing (see, for example, *Beha et al.*, 2014; *Carlson et al.*, 2017). The microwave source that provides the modulation frequency (which is typically ~10 GHz to 40 GHz) can be stabilized when synchronized with a GPS-disciplined Rb clock.

In an EOM comb, the f-$2f$ beat note that provides a measure of the comb carrier envelope offset frequency, f_o, is exactly the difference of the CW pump laser frequency and an integer multiple of the EOM pulse repetition frequency, f_r. The f_o signal is fed back into a servo controller to stabilize the CW pump frequency. EOM comb stabilization using a similar technique (but with additional filtering steps and a fiber laser comb-stabilized pump laser) has been demonstrated at NIST with an Allan deviation of an astonishing ~3^{-17} at 2000 s averaging time for a repetition rate of 10 GHz (*Carlson et al.*, 2017).

Stabilization of EOM combs can also be accomplished through the use of a CW laser source that has been referenced to an atomic or molecular reference (so that $f_o = f_{atom}$) and is thus dubbed a line-referenced EOM frequency comb (see Section 2.3). Such an arrangement has been demonstrated for astronomical spectrograph calibration, providing ~30 cm/s RV instrument precision for 100s integration times (*Yi et al.*, 2016). Figure 2.4 below shows lines from this 1560 nm line-pumped comb on the NIRPSEC spectrograph at the Keck Observatory. Line-stabilized microcombs have been used as well (*Suh et al.*, 2017). Habitable Planet Finder (HPF) is a new RV instrument being installed at the Hobby-Eberly telescope that uses an EOM comb spanning 800 nm–1300 nm; the comb pump laser is stabilized by locking its second harmonic to a line in a self-referenced fiber laser comb with ~250 MHz line spacing.

Although EOM combs are not currently commercially available, large scale development, manufacturing, and refinement of telecommunications industry components in the NIR (particularly at 1.5 microns) has provided for low cost, off-the-shelf access to most of the components needed for the construction of an EOM frequency comb, making it one of the most low-cost comb technologies. Further, some of these components have been qualified for space flight (see, e.g., *Ott*, 2006). However, broad EOM combs require tens of watts to generate, detracting from their usefulness in power-restricted situations.

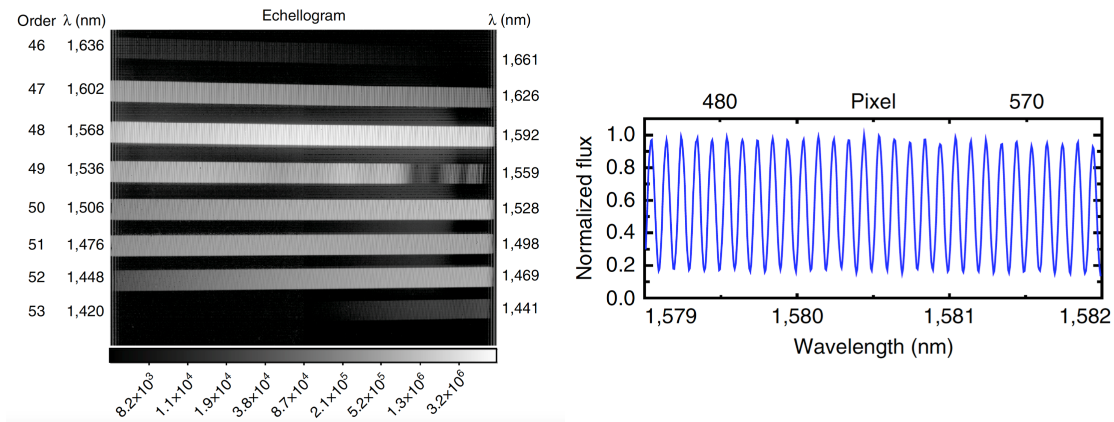


Figure 2.4: Left: 12 GHz EOM frequency comb lines on the NIRPSEC spectrograph at the Keck Observatory; Below: A portion of the extracted comb spectrum from order 48 is plotted versus wavelength.

2.6.4 Semiconductor Laser-based MIR Optical Frequency Combs

2.6.4.1 Quantum Cascade Laser Combs

To date, most attempts to realize frequency combs in the mid-IR spectral range have resorted to down-converting a mid-IR comb through optical parametric oscillation and difference frequency generation or CW optical pumping of a microresonator by an off-chip optical source. While these techniques provide optical combs over a wide range of optical frequencies with broad coverage, practical shortcomings include very low in-band output powers, relatively low total efficiencies, and inconvenient integration with other optical components.

Quantum cascade lasers (QCLs) frequency combs have emerged as efficient chip-scale devices capable of generating comb radiation in the MIR and THz regions (*Barbieri*, 2011; *Hugi*, 2012). This class of optical combs enables frequency spacing of sub-GHz up to 100 GHz with Schawlow-Townes limited phase noise.

Quantum Cascade Laser (QCL) frequency combs are generated when the different longitudinal modes of a Fabry-Perot laser use four-wave-mixing as a phase locking mechanism. This is very similar to the operation of microresonator combs. Combining mode proliferation based on four-wave mixing with gain provided by the quantum cascade laser leads to a phase relation similar to that of a frequency-modulated laser in which the amplitude remains constant.

Figure 2.5a shows an optical spectrum of an MIR optical frequency comb emitted from a QCL laser in the 7.5 μm range. The RF spectrum is also shown in Figure 2.5b, which demonstrates a single and narrow RF beat note (FWHM < 30 kHz) which denotes comb operation (*Villares*, 2015).

Figure 2.6 gives an overview the recent published work on MIR-THz QCL-combs. It shows that more than 100 mW integrated output power for mid-infrared combs is possible; that translates into μW level output power per comb line. It also shows the frequency coverage of the frequency comb in different bands (*Faist*, 2015).

The recent progress in broadband gain active regions in the mid-infrared and THz show that an octave-spanning QCL comb is feasible. Quantum cascade amplifiers can be used to boost the power of the MIR combs especially in applications where one single comb will be used to synchronize a network of subsystems. Moreover, due to ultrafast transport in the active region, QCLs can be used as high-speed detectors that can find potential applications in heterodyne systems.

2.6.4.2 Interband Cascade Lasers Combs

Interband Cascade Lasers (ICL) are another class of devices that have been used to produce frequency combs. Like QCLs, ICLs are semiconductor heterostructures. However, in ICLs, photons are generated with interband transitions, rather than the intersubband transitions utilized in QCLs. The resulting longer upper state lifetimes have enabled a recent demonstration of passively-mode locked ICLs (*Bagheri et al.*, 2018). ICLs operate at lower electrical input powers than QCLs and have undergone a continual improvement in wall plug efficiency and output power since the first CW demonstration at ambient temperatures in 2008 (*Canedy et al.*, 2014). ICLs' low-threshold drive power (29 mW) and high wall-plug efficiency ($\leq$18%) make them particularly well suited for power-constrained sensing applications—e.g., battery-operated devices. NASA's selection of a single-mode ICL for methane sensing on its Mars Curiosity Mission is a testament to this (*Sterczewski et al.*, 2017).

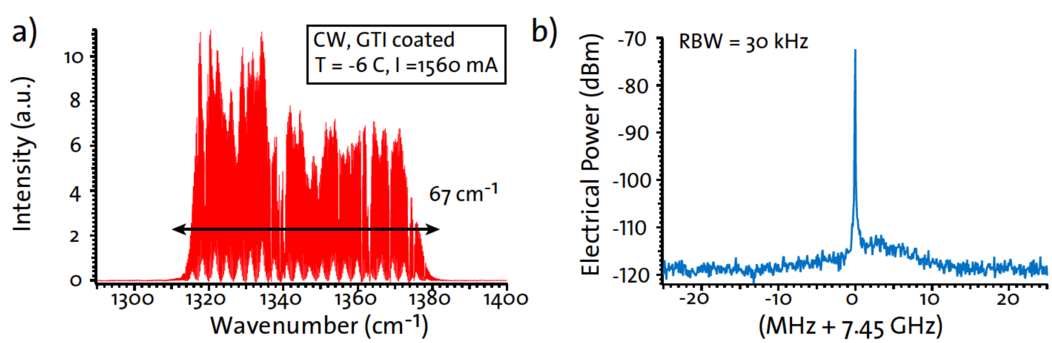


Figure 2.5: a) Optical spectrum of a QCL-comb; b) the measured RF spectrum. The RF spectrum shows a narrow beat note which denotes comb operation.

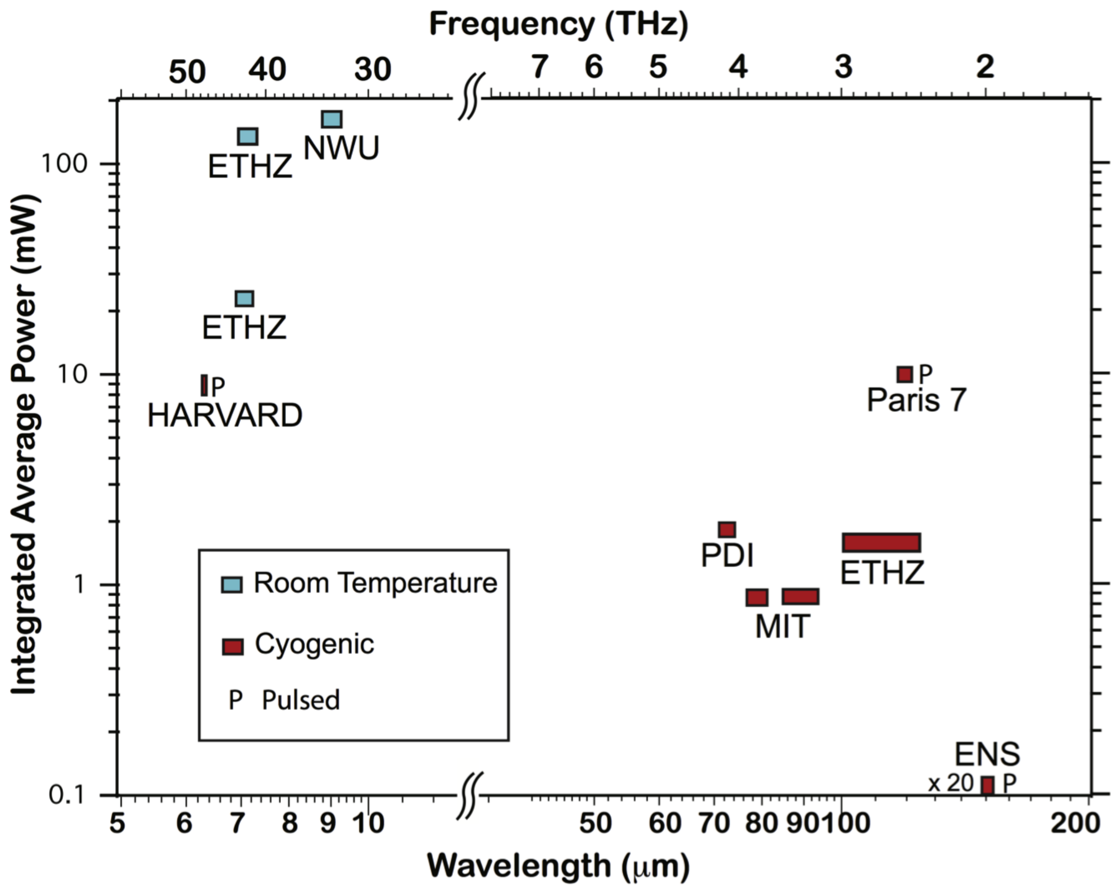


Figure 2.6: Average emitted power as a function of frequency coverage for published QCL-based comb sources. Rectangle width indicates the frequency coverage and the average power refers to the integrated laser output on all the emitted wavelengths. Data from the following groups: ETHZ (*Hugi et al.* 2012; *Rösch et al.*, 2015), NWU (*Lu*, 2015), Paris 7 (*Barbieri et al.*, 2011), PDI (*Wienold*, 2014), Harvard (*Wang*, 2009), ENS (*Freeman*, 2012), MIT (*Burghoff*, 2014).

ICL technology offers a low-power, chip platform source for direct generation of frequency combs in the mid-infrared portion of the spectrum. The spectral grasp of ICLs is still rather narrow, but could improve with appropriate dispersion engineering.

2.6.5 Hybrid Combs

Hybrid systems that combine multiple frequency comb generation stages can overcome some limitations of individual comb technologies. For example, soliton microcombs pumped with an electro-optically modulated pump source (*Obrzud*, 2017) allow the microresonator to self-lock to the driving laser so that no active feedback-loop is required. Phase and amplitude modulation of the CW laser can overcome some of the challenges associated with the formation of solitons.

2.7 Properties and Performance of Optical Frequency Combs

One may ask what is the "best" comb. In attempting to compare comb technologies in terms of their performance, it is important to note that different combs are best suited for different target applications. This is well illustrated in Figure 2.7 (*Kippenberg*, 2015), in which the ranges of mode spacing and bandwidth for various comb generation techniques are shown.

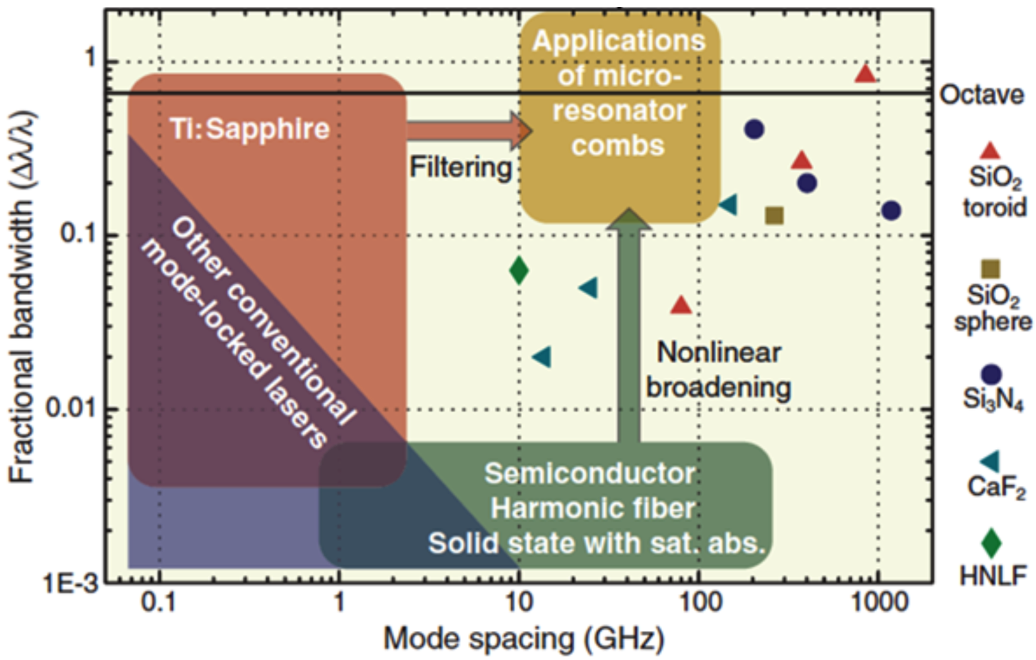


Figure 2.7: Characteristic performance of various comb generation techniques (Kippenberg, KISS presentation 2015[a]).

[a]http://www.kiss.caltech.edu/workshops/optical/ optical_presentations/2015_Caltech_Kiss_Workshop _Kippenberg%20EPFL.pdf

2.7.1 Extension to Other Spectral Regions

Using a combination of harmonic generation, difference frequency generation and supercontinuum generation, frequency combs have been extended from the UV to the mid-infrared (Figure 2.8).

Fiber laser combs are readily generated from the visible through NIR spectral regions. EOM combs have typically been centered around telecom wavelength pump lasers at 1 micron and 1.5 microns and broadened from the far-red through ~2.4 microns (although a few lines can be produced through 3rd harmonic generation in the visible). Microcombs are similarly pumped. QCL and ICL combs lend themselves well to direct comb generation in the near to mid-IR (~3 to 200 microns). Difference frequency generation (or upconversion) can enable OFCs to produce lines in the mid-IR to terahertz regimes with a notable benefit that the offset frequency cancels in this process when the two wavelengths are coherently derived from the same femtosecond oscillator.

2.8 Availability of Frequency Combs

While frequency comb development is being conducted in research laboratories worldwide, several commercial suppliers of more mature comb technology have been established. Menlo Systems in Germany—co-founded by Theodor Hänsch, one of the developers of the frequency comb technique—was the first company to offer commercially available self-referenced optical frequency combs. Menlo Systems produces fiber laser combs and developed a mode-filtered "astrocomb" to bring the mode spacing in line with the resolution of astronomical spectrographs. Menlo Systems astrocombs have been deployed at several observatories, including the HARPS planet-finder instrument on ESO's 3.6-metre telescope at La Silla in Chile. Menlo is also the source of the fiber laser combs flown on two sounding rocket demonstrations in 2015 and 2016 (*Lezius*, 2016).

In 2017, Toptica Photonics, another German company, entered into a license agreement with Menlo systems; the agreement allows Toptica to commercialize OFC technology based on difference frequency generation (DFG). They produce erbium fiber laser combs with nonlinear broadening.

Laser Quantum is a British company that began selling their 1 GHz repetition rate Taccor laser frequency comb in 2016. The comb is a Ti:Sapphire-based laser system with integrated dispersion compensation, supercontinuum generation, and f–$2f$ interferometer for stabilization. Power per line in the Taccor is ~1 μW.

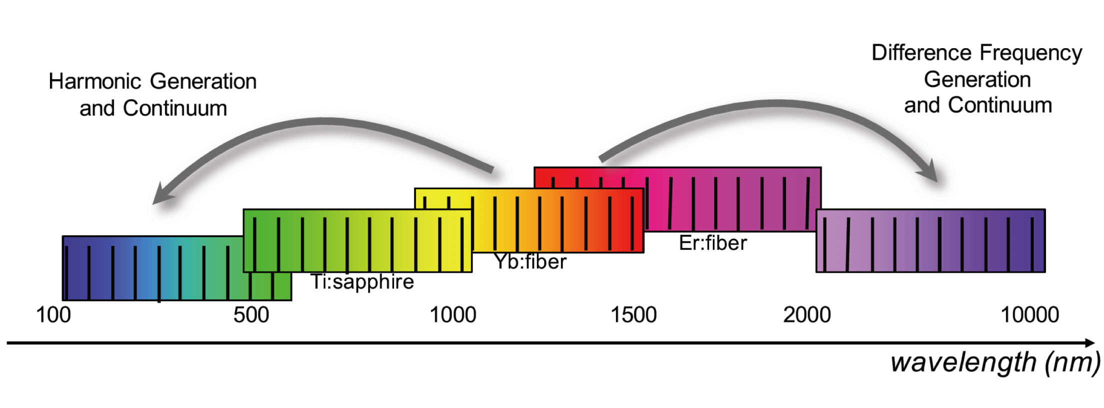


Figure 2.8: Extension of frequency comb spectra through difference frequency generation, harmonic generation, and supercontinuum generation (Diddams, KISS presentation 2015[a]).

[a]http://www.kiss.caltech.edu/workshops/optical/optical_presentations/Diddams_KISS_Short _Course_2015_v3.pdf

Alpes Laser and IRSweep are two Swiss companies now producing QCL combs. Alpes offers combs covering ~4 µm out to 200 µm. For bands at 5 µm or less, the devices are available pigtailed. IRSweep offers their QCL combs in a dual comb spectroscopy apparatus.

Small Business Innovative Research (SBIR) and Small Business Technology Transfer (STTR) awards made for frequency comb related technology since 2009 are shown in Appendix B.

Aerospace entities, both NASA and corporate, have embarked on frequency comb development work specific to space applications. An all PM-fiber, 1480 nm pumped, passively mode-locked femtosecond soliton fiber laser comb is being use to explore optical wave-front measurement, control of adaptive optics, precision ranging, and reference frequency stabilization at Ball Aerospace (*Wachs et al.*, 2016). NASA is supporting electro-optic modulation frequency combs for radial velocity experiments at ground-based observatories (*Yi et al.*, 2016). NASA is supporting electro-optic modulation frequency combs for radial velocity experiments at ground-based observatories (*Yi et al.*, 2016; *Metcalf et al.*, 2018) and QCL and ICL combs for gas detection (*Bagheri et al.*, 2018).

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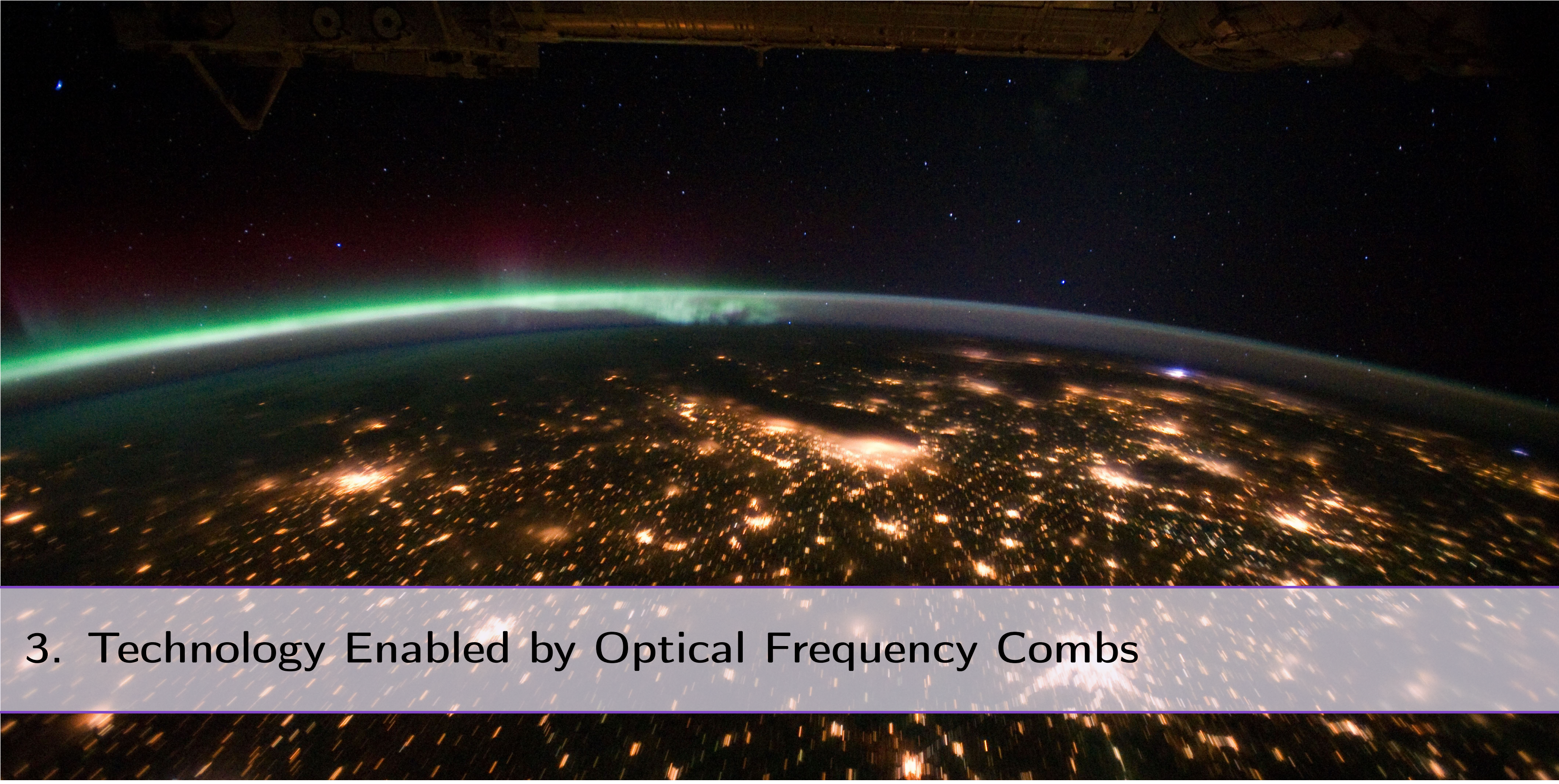

3. Technology Enabled by Optical Frequency Combs

Optical frequency combs have found application in a broad range of time and frequency measurements on Earth. They may provide a compelling solution for myriad outstanding challenges in space science as well. In this this chapter, we examine the role OFCs may play in technology areas important for spacecraft operations and space science instrumentation.

3.1 Optical Calibration and Referencing with OFCs

3.1.1 Spectroscopy

A general limitation of today's standard spectroscopic analyses is that it is necessary to choose between sensitivity, coverage, resolution, and acquisition time for any given measurement. The unique strength of frequency comb-based spectral analysis is that it allows for all at once. The simultaneous spectral coverage and high spectral resolution provided by OFCs allows sensitive detection of multiple molecular and isotopic species through broadband, "gratingless" absorption spectroscopy from UV through Terahertz spectral regions where gratings are large and difficult. The most generally applied spectroscopic analysis technique with OFCs is called Dual Comb Spectroscopy (DCS), but it is also referred to as multiheterodyne spectroscopy, linear optical sampling, coherent Fourier-transform spectroscopy (FTS), and terahertz (THz) asynchronous optical sampling (ASOPS) (*Coddington et al.*, 2016).

A thorough review of dual-comb spectroscopy is presented by *Coddington, et al.* (2016). In the most general technique, a sample is illuminated by a frequency comb laser source. The interrogating comb, now carrying the encoded spectral data, is then heterodyned with a second

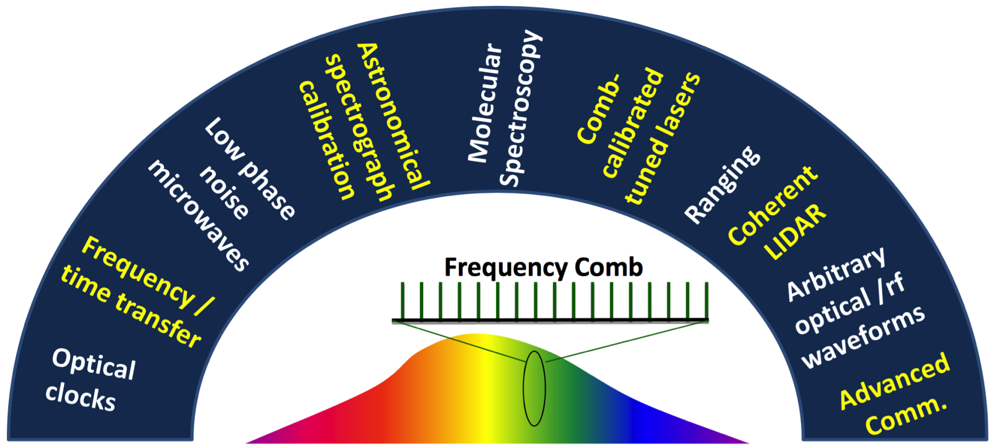

Figure 3.1: Applications of optical frequency combs as spectral or temporal rulers for laser-based metrology and sensing systems (*Newbury*, 2011; *Diddams*, 2010)

comb of slightly offset repetition rate. A resulting RF signal is produced by a fast photodetector at a frequency determined by the offset between the two combs and can be processed by fast digital electronics. DCS has a number of advantages over conventional spectrometers in the basic performance metrics of frequency resolution, accuracy, acquisition speed, and SNR, as well as in the potential for a compact system, since its performance is not fundamentally limited by the instrument optical path length as in grating or FTIR spectrometers (*Coddington, et al.*, 2016).

The DCS technique provides simultaneous and accurate access to a broad spectral bandwidth within a short measurement time. In space mission applications, this could be important where fast broadband measurements are critical, such as comet tail flybys, sampling of plumes from Enceladus, and analysis of volatile species formed by ablation of material from, e.g., primitive bodies. It also allows for active quantitative atmospheric compositional analysis, enabling continuous monitoring of species at nighttime or in polar regions of Earth, Mars, Venus, and Titan, for example. Zodiacal light measurements were also identified by workshop participants as an interesting target for OFC-based spectroscopy.

Various spectral regions are accessible—from the UV through terahertz regions—with different comb technologies (see Figure 10 from *Coddington et al.*, 2016). In the "molecular fingerprint" (mid-IR) spectral region, difference frequency generation (DFG) in, e.g., optical parametric oscillators (OPOs), as well as direct comb generation by quantum cascade laser (QCL) and interband cascade laser (ICL) combs (*Sterczewski et al.*, 2017), all provide the appropriate spectral coverage. Of these technologies, QCLs and ICLs have the inherent low SWaP most attractive for space-based platforms, but to date, have limited bandwidth. DFG provides for very broad bandwidth (*Timmers, et al.*, 2017), but is an inefficient process with relatively low conversion efficiency. Fiber laser combs provide access to the NIR and visible portions of the spectrum, with second (or higher) harmonic generation yielding combs at shorter wavelengths.

A space-based dual comb spectroscopy mission concept, the Comb Occultation CubeSat Observatory for performing atmospheric studies, became one of the products of the workshop deemed worthy of further study, and is the subject of Chapter 5.

3.1.2 Coherent Heterodyne Detection

High angular resolution imaging requires multi-telescope interferometers because it is not possible to build single telescopes of the necessary size (several kilometers across). Direct detection interferometers on these scales are prohibitive because of the scale of the infrastructure required

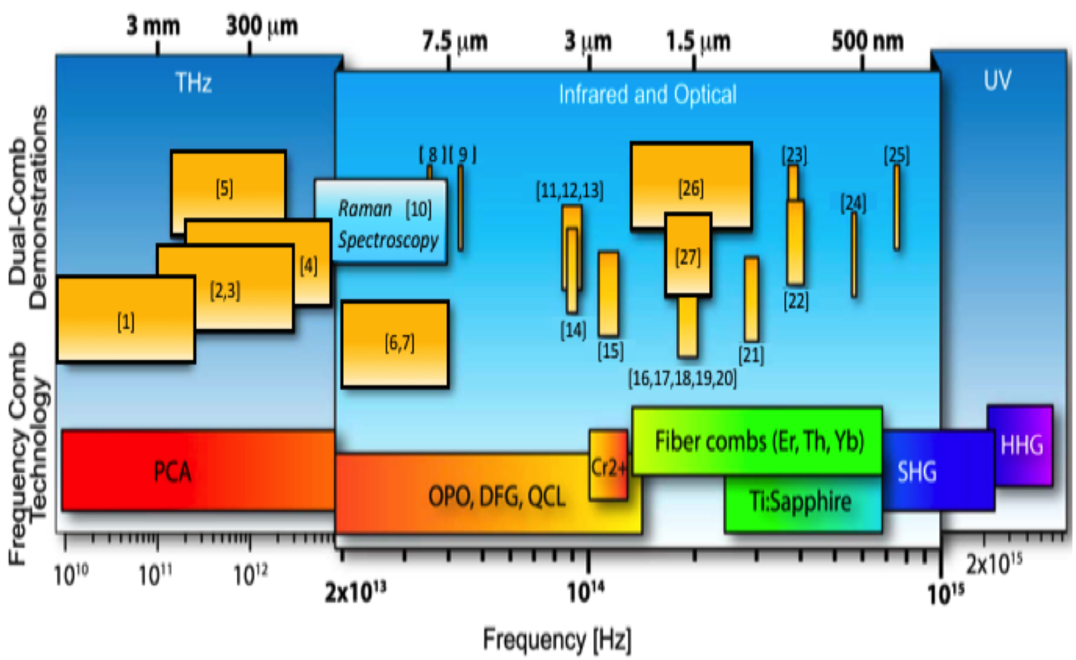

Figure 3.2: Frequency comb technologies used for dual comb spectroscopy adapted from *Coddington et al.* (2016). References: [1] *Yasui et al.*, 2006; [2] *Von Ribbeck et al.*, 2008; [3] *Yasui et al.*, 2010; [4] *Klatt et al.*, 2011; [5] *Finneran et al.*, 2015; [6] *Keilmann et al.*, 2004; [7] *Schliesser et al.*, 2005; [8] *Wang et al.*, 2014; [9] *Villares et al.*, 2014; [10] *Ideguchi et al.*, 2013; [11] *Zhang et al.*, 2012; [12] *Jin et al.*, 2015; [13] *Zhu et al.*, 2015; [14] *Baumann et al.*, 2011; [15] *Bernhardt et al.*, 2010; [16] *Coddington et al.*, 2008; [17] *Giaccari et al.*. 2008; [18] *Zhu et al.*, 2013; [19] *Ideguchi et al.*, 2014; [20] *Cassinerio et al.*, 2014; [21] *Bernhart et al.*, 2010; [22] *Potvin & Genest*, 2013; [23] *Hipke et al.*, 2014; [24] *Ideguchi et al.*, 2012; [25] *Hipke et al.*, 2014; [26] *Okubo et al.*, 2015; [27] *Zolot et al.*, 2012.

for beam combination and optical delay; the beam transport can be expensive and lossy, especially at thermal infrared wavelengths. Heterodyne systems have long been known to become attractive at these thermal wavelengths (8–14 microns), due to signal-to-noise properties, and where the atmospheric window is quite wide (*Teich*, 1968; *Ashcom*, 2015). The ability to amplify, digitize, and record the incoming electric field also allows perfect ${}^{N}C_2$ pairwise cross-correlations, which are not possible in direct detection Michelson or Fizeau interferometry.

Traditionally, heterodyne systems at optical wavelengths suffer from low SNR relative to direct detection (homodyne) interferometry due to small optical bandwidths ($d\nu/\nu$ ~10^{-4}). In the visible and NIR portions of the spectrum, where shot-noise-limited detectors are available, this remains the case (*Ashcom*, 2015). However, optical frequency combs used as the Local Oscillators (LOs) in these heterodyne systems at mid-IR wavelengths offer game-changing wide bandwidth ($d\nu/\nu$ ~1) and radical simplification of the required infrastructure. For example, using a 1000-line comb LO is the equivalent of having 1000 interferometers running in parallel, and should improve the SNR by $\sqrt{1000}$. Also, because each comb line is so narrow, the optical paths only need to be made equal for that narrow bandpass; at 1 GHz bandwidth, the electrical paths have to match to $<$30 cm, compared to a fraction of a micron for optical direct combination of the light.

Another advantage is that when multiple telescopes are used, the heterodyned signal from one telescope can be combined with every other one digitally, as is done with radio astronomy, while optical combination needs to split the light. With a large number of telescopes, this is an advantage of $\sqrt{(M\text{-}1)}$, where M is the number of telescopes.

Not only do OFCs used as LOs in heterodyne receivers provide dramatically improved SNR in electric power, they also make mobile systems possible, where telescopes might be locally or regionally transported, and greatly simplify the infrastructure associated with interferometry; evacuated beam transport, precision delay lines, and related optics and cryogenic systems become unnecessary.

Thermal IR OFCs may enable multi-element interferometers to achieve resolution ($<10^{-9}$ radians) that would allow for imaging of complex scenes in astronomy on scales never before achieved: (1) direct imaging of planets in the act of formation in the disks around the nearest protostars, addressing one of the great unsolved problems in both astrophysics and planetary science; (2) imaging of the surfaces of the nearest stars to unprecedented resolution, providing a new boost to stellar astronomy; (3) a new method to image mature planets, including those that are very close to the host star; (4) imaging the morphology of Near Earth Object (NEOs), leading to better understanding of the surface and composition of these enigmatic objects and a more direct measurement of their diameters; and (5) imaging of geosynchronous satellites from the ground. Thermal IR heterodyne receivers developed for these applications could also be used for high-resolution spectroscopy using just a single telescope element, with potential applications in Earth and planetary atmospheric science.

Mid-IR heterodyne detection using frequency comb local oscillators near 10 μm is a powerful technique that merits further study. Challenges to its implementation include extremely high data rates, mid-IR frequency comb generation of the desired mode spacing, power, phase coherence, synchronization, and commensurate high speed mid-IR detector technology. These technology needs are discussed in Chapter 7, Comb-enabled High Angular Resolution Imaging (CHARLI).

3.1.3 Spectrograph Calibration

The fundamental question of whether life exists on other planets has brought huge interest in searching for Earth-like extrasolar planets (exoplanets), especially in the 'habitable zone' where the orbital separation is suitable for the presence of liquid water at the planet's surface. In this quest, the radial velocity (RV) method employs high-precision spectroscopic measurements of periodic Doppler shifts in the stellar spectrum to infer the presence of an orbiting exoplanet. Importantly, the RV technique provides information about the exoplanet mass, which is unavailable with the complementary technique of transit photometry. However, RV detection of an Earth-like planet in the habitable zone requires extreme spectral precision of about 3×10^{-10}, equivalent to a recoil velocity of the star of only about 10 cm/s!

Paramount, therefore, to RV measurements is a precisely-calibrated astronomical spectrometer. In a detailed review of state-of-the art RV measurement techniques provided by *Fischer et al.* (2016), optical frequency combs are identified as a powerful calibration tool for providing broad spectra of precisely stabilized optical frequencies. For RV detection of exoplanets, OFCs, or so-called astrocombs, have enabled RV instrument precision at the cm/s level. This is well below requirements for detection of Earth-like planets in the habitable zone of sun-like stars, and also is at a level not achievable by conventional calibration methods using the emission lines of hollow-cathode gas lamps. At the level of ~1 cm/s over several decades, OFCs may enable direct measurement of the acceleration of the expansion of the universe (*Loeb*, 1998), or aid in determining systematic effects in observations geared at studying whether there have been changes in the values of fundamental constants by comparing relative positions of absorption lines in the spectra of high red-shifted distant quasars with the same lines on Earth (*Lopez*, 2008).

The astrocombs used in the earliest RV detection experiments are derived from femtosecond mode-locked lasers that feature a comb line frequency spacing not resolvable by most astronomical spectrographs—typically in the range of 0.1–1 GHz. As a result, the output spectrum of the comb must be spectrally filtered, as demonstrated by *Ycas et al.*, (2012). The added complexity of this filtering step has created interest in frequency comb generation by other means that can intrinsically provide readily resolvable line spacing. For example, electro-optical (EO) modulation provides an alternative approach for direct generation of >10 GHz comb line spacing. Line referenced EO-astrocomb devices (*Yi et al.*, 2016) and, more recently, self-referenced EO-combs (*Beha et al.*, 2016) have been demonstrated. However, these latter devices also require optical filtering to remove amplified phase noise in the wings of the broadened comb to achieve self-referencing. Another optical source that produces wider comb line spacing is a Kerr microresonator-based comb driven by parametric oscillation and four-wave-mixing. The recent demonstration of soliton mode-locking in microresonators represents a major turning point for applications of microcombs; soliton formation ensures highly stable mode-locking and reproducible spectral envelopes. Microcombs for astronomical spectrograph calibration have recently been demonstrated by two groups (*M. Suh et al.*, 2017; *E. Obrzud et al.*, 2017).

The main technology hurdle for any OFC calibration system for astronomy is the long duration over which comb stability must be maintained; observation of exoplanets throughout the course of their orbits may require many Earth-months or even years for careful characterization, placing demands on the longevity of comb components. OFC-calibrated spectrographs for cosmological expansion determination is more ambitious still. Furthermore, instrument stability as characterized by the OFC is but one contribution to the uncertainty in RV measurements; telluric line contamination of spectral features in ground-based observations, particularly in the near infrared portion of the spectrum, stellar jitter of the host star, and detector noise all factor into the overall RV error budget. Space-based RV missions could address the telluric line contamination, as well as provide a means for studying stellar phenomena with a better observational cadence than would available from the ground.

3.2 Precision Metrology Enabled by OFCs

To date, the most precise clocks, now at the 10^{-18} instability level (*Hinkley, et al.*, 2013), rely on single frequency lasers stabilized to electronic transitions in atoms, ions, or molecules. The standard must be of a frequency that enables conversion to other desired frequency domains. The conversion is accomplished through what is termed an optical clockwork—a device that phase-coherently relates a high and a low frequency; when the higher frequency is an optical frequency, (e.g., hundreds of terahertz) and the lower frequency is typically in the microwave region (between 1 and 100 GHz), the clockwork forms the basis of an optical clock. Thus, the superior stability of the optical frequency standard—a natural consequence of dividing a second into smaller and smaller partitions—can be "translated" to lower frequencies and processed with fast electronics.

The development of optical frequency combs has provided the much-needed clockwork for optical clocks. *Papp et al.* (2014) have demonstrated an optical clock based on a microresonator frequency comb (microcomb). This architecture provides the framework for what might be envisioned on future space-based optical clocks needed for a Space-Time Observatory constellation of satellites discussed in Chapter 4. At the first workshop, the idea of "atomless" optical clocks was suggested—perhaps in the future yielding optical clocks that need not rely on atomic transitions and the associated infrastructure required to cool and shield the atomic species being interrogated.

Required instead might be high-Q reference cavities. However, achieving long-term stability with such cavities is a challenge. Recent efforts are making progress on that front; Jun Ye and colleagues (*Zhang et al.*, 2017) have shown remarkable stability near 10^{-16} with Si reference cavities. Some applications could benefit from this if the free running cavity could be stable on the timescale of the orbital period, or if good stability but not accuracy is required.

Another method suggested for high precision timekeeping for space applications is the use of pulsars. X-ray navigation (XNAV) is a technique explored by the Navy Research Lab and through various DARPA programs (*Mitchell and Gendreau*, 2017) that uses the X-ray flashes emitted by pulsars as they rapidly rotate with a remarkably repeatable period; these natural clocks are known to be stable with an Allan deviation in the 10^{-15} regime over decade-long time scales (*Hartnett and Luiten*, 2010). More recently, a pulsar-navigation experiment—the Station Explorer for X-ray Timing and Navigation Technology (SEXTANT)—makes use of the 52 small X-ray telescopes for the Neutron-star Interior Composition Explorer NICER experiment installed on the International Space Station in 2017[1]. China launched its own experimental pulsar-navigation satellite, XPNAV-1, in November of 2016 that uses pulsars similarly (*Zhang et al.*, 2017). The timing stability of pulsars has also been examined for the prospect of their use for gravitational wave detection (e.g. *Verbiest et al.*, 2009).

However, *Hartnett and Luiten* (2010) point out that atomic clocks are still a more capable technology for high-precision time-keeping for short integration times. Furthermore, the mass of a single X-ray telescope dedicated for this purpose might be on the order of 5 kg[2] and cannot rival projected miniaturization in OFC technology. The use of an OFC for precision timing also obviates the pointing requirements needed for XNAV.

3.2.1 Time and Frequency Distribution

3.2.1.1 Introduction

Frequency combs can enable future optically based network of clocks with three orders of magnitude greater timing precision and coherence than current RF-based networks. Researchers have been quick to realize the potential of such a network to support different applications that include:

- Redefinition of the time standard, including a new SI second (*Grebing et al.*, 2015; *Le Targat et al.*, 2013; *Margolis*, 2014; *Riehle*, 2012)
- Clock-based geodesy (or chronometric leveling) where the gravitational redshift between clocks is used to compare their local gravitational potentials (*Bondarescu et al.*, 2012; *Chou et al.*, 2010; *Delva and Lodewyck*, 2013; *Grotti et al.*, 2018)

[1] https://www.nasa.gov/sites/default/files/atoms/files/session_3_-_2_x-ray_pulsar_navigation_for_deep-space_autonomous_applications_jason_mitchell_0.pdf

[2] https://www.nature.com/articles/d41586-018-00478-8

- Tests of general relativity (*Altschul et al.*, 2015; *Müller et al.*, 2008; *Schiller et al.*, 2009; *Will*, 2006; *Wolf et al.*, 2009; *Wolf and Blanchet*, 2016)
- Searches for dark matter (*Derevianko and Pospelov*, 2014; *Van Tilburg et al.*, 2015)
- Searches for gravitational waves (*Loeb and Maoz*, 2015)
- Distributed sensing across a coherent spatial array (e.g., to enable a large synthetic aperture)

The timing/frequency precision across the network is limited by both the absolute timing uncertainty associated with the master clocks and the residual timing uncertainty associated with the distribution of their timing signals between nodes. The absolute timing uncertainty of optical clocks/oscillators has improved dramatically in recent years with optical clocks that can reach absolute accuracies approaching 10^{-18} and optical oscillators (e.g., cavity-stabilized laser) that can reach sub-femtosecond timing stability over seconds (*Ludlow et al.*, 2015; *Poli et al.*, 2013). These results are currently achieved with large laboratory systems, but there is a concerted effort to transfer this performance to mobile or even space-based clocks (*Bongs et al.*, 2015).

The residual timing uncertainty associated with the distribution of these signals across a network must keep pace with these advancements. Existing RF-based distribution systems, either through Global Navigation Satellite System (GNSS) (GPS-like) systems or via two-way satellite transfer (*Bauch*, 2015; *Droste et al.*, 2015; *Fujieda et al.*, 2014; *Piester et al.*, 2005), have residual timing noise that is orders of magnitude worse than the best optical clocks/oscillators. Even the most advanced microwave link (MWL) developed to connect ground stations to the International Space Station under the ACES mission is limited to 0.3 ps at 300 s integration time and <6 ps after 1 to 10 days of integration (*Delva et al.*, 2012; *Laurent et al.*, 2015).

Future networks of optical clocks/oscillators will require analogous optical time-frequency distribution for the simple reason that the higher bandwidth afforded by optical transmission will permit a reduced timing jitter. Moreover, for the highest performance, this distribution will inevitably involve a frequency comb as it can faithfully translate, or "reformat," the output of the optical clock/oscillator into a transmission signal without incurring any additional timing penalties in the distribution. For space-based systems, we will need the ability to distribute the frequency/timing signals both from the ground-to-satellite and from satellite-to-satellite over free-space (and possibly turbulent) links.

While many of the applications listed above rely on the unprecedented absolute timing that will eventually be achievable by fielding the highest performance cold atom/ion optical clocks (*Bongs et al.*, 2015), other applications could exploit high performance optically based time-frequency distribution even without the highest performance cold-atom clock. For example, the first space-based optical clocks will certainly not have the high accuracy possible with laboratory clocks because of the complexity involved in lattice clocks or cold ion clocks. However, "simpler" optical clocks can still have advantages over the heritage RF clocks in terms of systematics and can provide staged improvements in performance for future GNSS. As another example, optical time-frequency distribution can have much higher bandwidth and lower residual noise. These features can enable tight real-time synchronization across a network (*Bergeron et al.*, 2016), regardless of the absolute timing noise of the network master clock. This ability could enable coherent distributed sensing with the corresponding increase in resolution.

As a final comment, thus far we have somewhat loosely discussed time-frequency distribution. However, in any system we must distinguish between frequency comparisons (possibly in post-processing), frequency syntonization (i.e., real-time feedback to force all nodes to the same frequencies), time comparisons (again possibly in post-processing, as is done now), and full-time synchronization (real-time feedback to force all nodes to the same time).

3.2.1.2 Optical time-frequency distribution over free-space: Challenges

As with RF-based time-frequency distribution, optically based time-frequency distribution must suppress both statistical and systematic uncertainty. The statistical uncertainty is set by the ratio of BW/SNR, where BW is the bandwidth and SNR is the signal-to-noise ratio. The systematic uncertainty is more complicated but can be broken down into two categories: systematics associated with the generation/detection of the transmitted timing signals within the transceiver and systematics associated with the transmission over the free-space link between the nodes.

With regard to the statistical noise, the optically based distribution can utilize much higher bandwidth than the RF distribution, either through the direct transmission of short optical comb pulses or high-bandwidth RF modulation of an optical carrier (both of which are discussed below). In contrast, RF distribution uses limited bandwidth for the simple reason that RF bandwidth is expensive for satellites. (Part of the improved performance of the ACES microwave link is due to the use of higher bandwidth.) The SNR also differs between optical and RF distribution because of the shorter optical wavelengths; any laser link will have a much narrower beam than an RF link. As a result, the effects of platform motion and turbulence are much stronger and the requirements on the pointing and tracking considerably harder. Furthermore, these issues become even more pronounced for a coherent single-mode spatial laser link than a multi-mode optical link. However, there has been considerable work done in this area as part of free-space optical communications and it is possible to transmit laser light a very long distance with reasonable SNR, even to moving platforms (*Chiodo et al.*, 2013; *Juarez et al.*, 2012; *Stotts et al.*, 2009; *Takenaka et al.*, 2012), which bodes well for distributed spacecraft mission architectures such as the European Space Agency's Laser Interferometer Space Antenna (LISA) mission for space-based detection of gravitational waves. Of course, for any terrestrial link, the optical system will ultimately be limited by weather (clouds, rain, etc.) and will therefore always be more intermittent than an RF-based system.

The dominant potential systematic error, as with any time transfer, arises in the transmission between nodes because of variations in the time-of-flight due to platform motion and turbulence. The turbulence effect appears as a piston-like mode and has been measured experimentally and reported in several papers (*Djerroud et al.*, 2010; *Ridley*, 2011; *Sinclair et al.*, 2014). These time-of-flight variations are removed by use of the two-way approach; signals are sent bi-directionally between nodes to cancel out the time-of-flight variations. This approach rests on the reciprocity of atmospheric transmission (*Shapiro*, 1971; *Shapiro and Puryear*, 2012). Reciprocity will break down in long-distance ground-to-satellite links because of the long times associated with the long paths and because of point ahead effects (*Shapiro*, 1975). However, a careful analysis shows the two-way approach should still suppress the turbulence-induced piston noise to negligible levels (*C. Robert et al.*, 2015; *Robert et al.*, 2015). For RF-based distribution, the reciprocity can break down due to dispersion in the ionosphere, but analogous dispersive effects are calculated to be quite low for optical two-way transmission.

With the implementation of a two-way approach, the systematic uncertainties are associated with the transceivers themselves, in either the generation or detection of the transmitted timing signals. As discussed below, there are a number of different approaches for two-way optical transfer with very different transceiver architectures and performance.

3.2.1.3 Optical time-frequency distribution: Approaches

It is possible to establish a network of terrestrial clocks connected via optical fiber (*Droste et al.*, 2013; NEAT-FT project, n.d.; *Predehl et al.*, 2012; *Raupach et al.*, 2015; *Williams et al.*, 2008). However, in this approach, the clock locations are fixed and there must be a bidirectional fiber link that connects the network nodes. Clearly, space-based systems and flexible terrestrial systems require the ability to distribute time-frequency across free-space links. Three different classes of approaches for free-space optical time-frequency distribution have appeared thus far in the literature.

The T2L2/Jason 2 experiment has successfully demonstrated time transfer by laser link. Its goal is to synchronize remote clocks over intercontinental distances (*Exertier et al.*, 2010, 2014; *Samain et al.*, 2014). Its basic implementation is as follows: two ground stations send time-tagged light pulses to the satellite platform. In order to achieve a high enough signal intensity at the satellite, the light pulses are transmitted from existing satellite laser ranging stations. Their arrival is time-tagged and a portion of the light retro-reflected back to the ground station in order to measure and cancel the time-of-flight. A compact stable quartz oscillator onboard the satellite is used to track the relative timing. The different time-tags are combined to yield the time offset between the two ground clocks (or eventually between a ground clock and space clock). The T2L2 system is designed to reach better than 1 ps over 1000 s integration and an accuracy of better than 100 ps and has undergone testing both across a ground link and with actual satellite data. The basic concept of the T2L2 system has been extended to the laser-transfer system

(ELT) to be used as part of the ACES mission as an alternative to the MWL (*Laurent et al.*, 2015). Again, picosecond laser pulses are transmitted from ground-based satellite laser ranging stations to the ACES platform, detected, time-tagged, and simultaneously retro-reflected via a corner cube. Unlike T2L2, the ELT system will detect the pulse arrival with single-photon counting detectors. Ground testing has shown excellent performance that is at a few picoseconds over a single pass (300 s) and <7 ps over several days, matching the ACES MWL. Finally, this same "T2L2" approach has been modified using available compact oscillators so that it can fit within roughly 1U of a CubeSat mission and achieve a short term accuracy of ~300 ps with a long term error of 6 ns (*Conklin et al.*, 2014). These systems do not make use of frequency combs and require photo-detection of the launched and received pulses for the time-tagging.

In a different method, researchers explored frequency transfer over free space using the basic approach used in fiber-based transfer. In the basic implementation, a CW laser beam is transmitted out to the receiver and retro-reflected back to the transmitter. A heterodyne measurement of the return light versus the transmitted light then yields the round-trip Doppler shift. Half this shift is applied to the outgoing light to compensate for any Doppler shift at the remote end. *Djerroud et al.* (2010) explored this technique through turbulent atmosphere using a retroreflector at the far end with the goal of understanding the effects of turbulence. In further work, the same group designed a Doppler ranging system for ground-to-satellite measurements (*Chiodo et al.*, 2013). The problem with this CW-laser heterodyne approach for frequency transfer is the strong and frequent signal fading incurred by turbulence and platform motion. As a result of these fades, the frequency transfer averages down slowly and there are systematic errors due to unrecognized phase slips at low SNR.

The final approach uses a coherent laser link to implement a two-way time-interval comparison of remote clocks, as opposed to a frequency comparison between the clocks. Here, the basic approach mirrors RF systems in that it compares time intervals at the two sites via a two-way link, which also yields their relative frequencies after normalizing by the measurement time. A loss of signal during the time interval does not cancel the measurement, so it is very robust to the effects of turbulence. The transmitted signals are the pulses of a frequency comb and therefore have femtosecond-level jitter with respect to the underlying clocks. To maintain that femtosecond jitter in the effective time-tagging of the received pulses, the system uses linear optical sampling—i.e., heterodyne detection—of the incoming frequency comb pulse train by a local frequency comb pulse train. In this way, the time intervals measured by remote clocks can be measured with femtosecond, or even sub-femtosecond, precision.

In the initial demonstration, the system targeted direct frequency comparison of two clocks via a measurement of relative time intervals across a 2 km link (*Giorgetta et al.*, 2013). The next generation system showed full time synchronization between two remote optical clocks across a longer 4 km link. This time synchronization is considerably more complicated and required the introduction of a third transfer comb, a coherent communication link, and a second layer of optical two-way time-frequency transfer via a coherent optical link. This system achieved synchronization to within ~1 fs over 10,000 s for a 4 km air path parallel to ground at an altitude of 2 km (Boulder, Colorado), corresponding to 2 $\times$ 10^{-19} time interval/frequency comparison inaccuracy within 3 hours (*Deschenes et al.*, 2015). This 4 km link is, of course, far shorter than a ground-to-satellite link. However, the 4 km horizontal air path is roughly equivalent to the thickness of atmosphere that will have to be traversed by a laser beam going from ground to space because the density of the atmosphere has a $1/e$ length scale of 9 km and in addition, turbulence decreases strongly with height above ground. Furthermore, recent experiments indicate that the system can operate well over even 11.7 km horizontal turbulent paths (*Bergeron et al.*, 2016). Finally, while the original system demonstrated synchronization between optical clocks, a second experiment showed that the same tight femtosecond-level synchronization is possible between an optical clock and a microwave quartz-oscillator-based clock (*Bergeron et al.*, 2016). This capability opens up the possibility of a master optical atomic clock whose signal is distributed to an array of remote simpler microwave-based clocks to support a next generation GNSS navigation system or a coherent passive/active microwave sensing array.

It remains an open question as to how well this comb-based two-way time-frequency transfer can work with moving platforms and whether it can reach the distances required for ground-to-satellite links. However, this comb-based transfer is the only method to reach the femtosecond level of frequency-timing distribution that is commensurate with the next generation of optical clocks/oscillators and that should enable interesting future science experiments.

3.2.2 Ranging LIDARS enabled by OFCs

3.2.2.1 Topographic LIDAR

Topographic LIDARs (laser radars for surface mapping) have been used extensively to study different planetary bodies, including the Earth, Mars, Mercury, and the Moon, with the future holding the possibility of mapping the outer "icy moons" and the Earth to even higher resolution (*Board & NRC*, 2007). Some commonalities make the use of currently demonstrated OFC-based LIDARs to be at a disadvantage compared with traditional systems. The extensive development programs for these traditional LIDARs have resulted in the exploration of a wide range of system design trades and identification of the systematic error sources in subsequent systems. The work preparing for the ICESat II mission provides an excellent case for studying an OFC-based ranging mission (*Abdalati*, 2008, 2010). Most of the challenges do not appear to favor the use of OFC-based ranging for this application.

In order to get extended coverage of the surface, higher orbits are used that provide adequate mission lifetime. The long range to the surface and high speed of the orbits places a premium on high SNR with minimal averaging time to prevent smearing along the surface. The measurement has to be made with some level of background light interfering with the signal. This can require narrowband filters which are problematic for the broad OFC spectra sometimes used. However, this is less of a problem at longer wavelengths or farther from the Sun. The long range also places a premium on photon efficiency. Both lower repetition rate (40 Hz)/high peak energy and higher repetition rate (5 kHz)/lower pulse energy have been utilized. However, this does not scale well to higher repetition rates, where having multiple pulses "in the air" at once can lead to ambiguity. Intervening cloud or aerosol layers can cause ambiguity as to the origin of a scattered photon. Interfering layers are especially difficult for continuous-wave types of LIDARs for altimetry. These problems appear to put OFC-based ranging at a severe disadvantage to traditional time-of-flight ranging from orbit.

3.2.2.2 Asteroid Redirect Mission Requirements

The Asteroid Redirect Mission Concept included a baseline sensor suite for different relative navigation/docking applications that included both satellite-to-satellite ranging as well as satellite-to-asteroid ranging (NASA, "Asteroid Redirect Mission Broad Agency Announcement," 2014). The two competing approaches for the LIDAR part of the sensor suite were the "Flash" LIDAR that uses a CMOS-based focal plane that both images and ranges a laser pulse, and the more traditional scanned LIDAR that utilizes a single pixel. The flash LIDAR has the advantage of making a multi-point measurement on every laser pulse, freezing out rotation (*Miller et al.*, 2012). The scanned LIDAR has the advantage of greater range (the light is concentrated on a single pixel) (*Kolb et al.*, 2015). The Flash LIDAR has the complexity/risk of the CMOS based focal plane while the scanned LIDAR has the complexity/risk of the scanning mechanism. Both ranging to corner cubes and to natural scenes (asteroids) are considered as part of the requirements.

The OFC-based techniques would appear to work well with the mechanically scanned approach. It could give much higher range precision and accuracy. However, the traditional approaches seem to adequately cover the current applications. Possible future applications, like high 3D resolution space situational awareness or very fine-scale 3D imaging of remotely collected samples, would require an OFC approach. Because of the importance of low-power operation, it would be critical to use the most "photon efficient" approach. With this in mind, a ranging system based on direct illumination of the surface by the frequency comb light (*Coddington et al.*, 2009) is not as attractive as a comb-calibrated swept laser ranging system (*Baumann et al.*, 2013, 2014). In this case, the purpose of the comb is simply to calibrate the swept frequency of the transmitted CW laser. This comb-assisted LIDAR approach combines shot-noise limited sensitivity with high resolution and accuracy. Furthermore, it could eventually be realized in a compact, low-power, chip-based system. As is generally the case, the crossover from a conventional LIDAR to a comb-assisted LIDAR would be driven by the need for higher performance, or specifically in this case, the need for higher bandwidth modulation of the CW laser light than can be achieved by conventional RF modulators.

3.2.2.3 Differential Absorption

Differential absorption to identify molecular content of a material is a powerful spectroscopic approach, and critical to remote sensing. Laser-based methods in space are used for both remote sensing (e.g., Differential Absorption LIDARs—DIAL) (*Riris*, 2011), and for more in-situ types of instruments, as on the Mars Science Lab (*Webster*, 2015). The distinction between these types of measurements is whether they are single-ended (requiring a target to reflect or scatter from) or double-ended (a direct transmission measurement), with the key difference between the two lying in the required laser power levels.

Optical frequency combs have the advantage of being able to create a precise set of frequencies that can cover a very broad spectral region where a large number of atomic or molecular species are absorbing (*Adler*, 2010), and they have the ability to create a concentrated beam that thermal sources cannot. The broad spectral coverage is superior to more traditional laser-based sensing where a laser is dedicated to a single (or small number) of species depending upon its tunability. The ability to create beams of light enhances different system designs, for example by increasing SNR when background light is limited, and by utilizing multi-pass cells to increase effective path length. The primary disadvantage of the use of combs is overall photon efficiency. Much of the light that is generated will likely not be used in the final measurement because it will not fall on or near an absorption feature. This can be offset by tailoring a comb to specific spectral regions rich in absorption features. This tailoring will be needed to offset the comb's lower "wall-plug efficiency" (electrical to-optical) which is a key parameter in most instrument designs for space. Rarely is there an "excess" in power to run instruments. This is especially true for the higher powers needed for long range DIAL types of measurements. Here the OFC might best be used as a reference that could complement or replace gas reference cells and offset locking schemes.

The photon efficiency problem tends to favor the use of combs for transmission-based absorption measurements, especially when longer averaging times are possible. With the advent of microcomb-based designs, it is conceivable that miniaturized gas "fingerprinting" sensors could be achieved that would enable their implementation on all future "rovers" or other in-situ types of measurements where the highest sensitivity (made with a few lines) might be traded for a broad range of species detections that might help identify chemical interactions in progress. Another example is the "active occultation" transmissive measurement described in Chapter 6.

3.2.2.4 Doppler LIDAR

Different types of measurements required in space utilize Doppler shifts in laser light to infer the relative velocity. Two examples are measuring range-resolved atmospheric winds from orbit and measuring the relative speed of a landing spacecraft.

Different instrument configurations have been explored for measuring atmospheric winds from space with LIDARs, both for Earth and Mars. Loosely, there are two approaches that have been used: direct detection methods, in which the Doppler shift is detected in the optical domain by the use of interferometers, and coherent detection, in which heterodyne methods are used to detect the Doppler shift electronically. Both methods are successfully used in ground- and aircraft-based instruments. However, a key problem for space applications in both cases is adequate SNR. Mission architectures typically require range-resolved measurements of $<$1 km vertical extent and 100 km or less along-track averaging, limiting the volume of scatterers that can be used. This is compounded by the weak scattering cross sections of atmospheric aerosols and molecules as compared with hard surfaces. These challenges appear to limit the value of OFCs to on-board calibration. An example would be in helping to address the impact of Doppler shifts due to platform motion on heterodyne LIDAR designs. The high platform motion, combined with the changing relative pointing direction, requires high bandwidth system design in the heterodyne receivers (*Hale et al.*, 2003). A system design that could reduce the bandwidth requirements by utilizing different phase coherent comb teeth could potentially greatly simplify the receiver and reduce the noise bandwidth, improving the overall sensitivity.

Autonomous Landing and Hazard Avoidance Technology (ALHAT) is a new capability necessary for future planned NASA missions where powered descent and landing will be required. Past missions have used radar systems, but the lower SWaP and additional capabilities of LIDAR systems offers engineers more capability that could enable higher autonomy. Doppler LIDARs based on Frequency Modulation Continuous Wave (FMCW) have been developed for future missions.

3.2.2.5 GRACE

The GRACE mission mapped Earth's gravity field for 15 years by making accurate measurements of the distance between two satellites using GPS, a microwave ranging system, and sensitive onboard accelerometers (GRACE). As a GRACE spacecraft passed over a changing gravity field, it would accelerate or decelerate, and correspondingly be closer or farther from its companion spacecraft.

The GRACE Follow-On Mission launched in 2018 and continues the success of the first mission with a notable technology change: it utilizes heterodyne laser ranging instead of microwaves, which promises to improve the precision of separation distance measurements by a factor of up to 20 because of the laser's higher frequencies. This is be the first demonstration of active laser ranging between two spacecraft.

Early GRACE-Follow-on mission studies illustrated a number of difficult issues for realizing an improved gravity measurement that laser ranging enables. Improving the inter-spacecraft range-rate of change precision from the GRACE K-band (0.2 μm/s) to a laser-based (0.6 nm/s) system would provide some improvement, but not as much as might be expected from the higher precision. A number of factors go into the mission architecture that contribute to the gravity measurement precision and accuracy, including:

- The use of on-board accelerometers to remove non-conservative forces (e.g., radiation pressure and atmospheric drag) limits the precision at low frequencies (<10 mHz) . Drag-free approaches could improve this.
- Laser Frequency Noise, which was assumed to be 30 Hz/$\sqrt{\text{Hz}}$ in the initial modeling, limits precision at higher frequencies (*Sheard et al.*, 2012).
- Secondary measurements are used in the retrieval and contribute at a lower level. These include the startracker to help remove pointing-induced errors, GPS measured orbit accuracy, and the USO to generate the local oscillator (LO) for the heterodyne measurement (*Sheard et al.*, 2012; *Pierce et a.*, 2008).
- Several geophysical processes that cause temporal variations are modeled and removed as part of the gravity retrieval. Because of the sparse temporal-spatial gravity field sampling of GRACE, these temporal processes cause aliasing that leads to uncertainties if they occur at time scales faster than the approximate one month average for GRACE. This requires accurate models of the temporal mass changes due to the atmosphere, ocean, and land tides, and general hydrologic signals. This is a complex problem because of the regional and seasonal variations in those signals and how the ground-track of the satellites sample the gravity. This aliasing is the major contributor at this time to the limit on accuracy of the gravity measurement (*Loomis et al.*, 2013).

The geophysical aliasing problem has been shown to be significantly reduced if other spacecraft configurations are used. One example is to use multiple pairs of spacecraft with different orbital inclinations. A second example is to position the spacecraft offset across-track rather than "in-line" to add ranging in a separate dimension (*Elaska et al.*, 2014).

The use of an Optical Frequency Comb-based instrument has the potential to open up the mission architecture trade space to address the systematic errors that limit the current two-spacecraft approach. This would entail the following:

- An improvement in the laser frequency noise would improve the precision of the range measurement. Note that the shorter the wavelength, the more improved the measurement; GFO operates at 1.06 μm. The 30 Hz/$\sqrt{\text{Hz}}$ specification assumed in the earlier work is well above the frequency noise of laboratory-based cavity-stabilized lasers. A lower frequency cavity-stabilized laser is certainly technically possible. The frequency comb can easily then translate this lower frequency noise to a low timing jitter pulse train.

- The comb could also be used in conjunction with a high-quality RF oscillator. The timing of the RF oscillator is perfectly transferred to the timing of the very short optical comb pulses, which can then be transmitted across the link for ranging. In that case, the fundamental performance would still be limited by the RF oscillator rather than a higher performance optical oscillator (cavity-stabilized laser), but the transmission of the comb pulses might reduce overall systematics, provide a well-defined reference plane, and allow for lower overall SWaP (see below).

- Allowing for a greater dynamic range for the range-rates by using multiple comb teeth as part of the heterodyne detection would allow for other dual spacecraft configurations to be considered to reduce the aliasing. Some of the different configurations have higher and varying Doppler shifts that need to be accommodated by the laser ranging measurement (*Elaska et al.*, 2014).

- Reducing the SWaP of the laser ranging could enable smaller spacecraft to be used, which would make multiple pairs of spacecraft affordable. This also might enable multiple pairs to share a single launch. Note that precision pointing and attitude determination would still be required (*Bennett et al.*, 2013).

- As pointed out in (*Tinto & Yu*, 2015) for LISA, the optical frequency comb could also provide the USO needed for the heterodyne measurement, reducing complexity and improving overall precision if common-mode noise reduction could occur.

Optical frequency combs offer the possibility of enabling new constellation approaches towards making GRACE-like gravity measurements that would address key systematic errors in the measurement. Further evaluation would be needed to verify that a significantly lower SWaP could be achieved (as compared to GRACE FO) while achieving as good or better range performance with new constellation configurations.

3.2.2.6 Summary

Optical Frequency Combs offer new capabilities that could enhance a broad range of LIDAR measurements for space-based applications. The wide range of applications makes it challenging to have confidence identifying where the biggest impact could be, and the technology will need to mature in parallel with new trade studies and architectures being investigated. Many of the applications will likely be evolutionary; OFCs and their inherent stability and broad spectral coverage will make some measurements easier, for example in local optical references carried on board. There are a few possibilities for more revolutionary improvements by use of OFCs in LIDAR/lasers instruments. Two identified here are in making broad-spectrum, multi-constituent atmospheric measurements simultaneously in a one-way transmission measurement—either in-situ or between satellites. The second revolutionary change in a measurement would be a dramatic improvement in gravity measurements made if new constellation configurations could be enabled with OFCs. Both of these could be major advancements if realized.

3.3 RF Photonics: Low Phase Noise Microwaves Provided by an OFC

Optical frequency combs offer unique characteristics for emerging applications in RF photonics. These include high-performance filtering of microwave signals, ultra-broadband coherent wireless/optical communications, and high-fidelity synthesis of ultra-broadband waveforms (*Torres-Company*, 2014). In this section, we explore the potential benefits that OFCs bring to each of these application areas, with a particular emphasis on space mission implementation where OFC technology can dramatically enhance performance and reduce SWaP.

It should be noted that for optical communications and RF photonics applications, self-referencing of the OFCs is not required, but repetition rates at and above 10 GHz, simplicity, spectral flatness, robustness, and in some cases tunability are needed (*Torres-Company*, 2014).

Mission	Measurement	Range	Range Precision	Measurement time (bandwidth)
ICESat II follow-on/LIST or Europa	Surface Topography from Low Orbit	300–700 km	cm	$<$ 0.01 sec
Asteroid Redirect Mission	Asteroid Range and Bearing	1 m to 3 km	2 cm	0.1 sec
Lunar/Phobos Ranging	Range to planetary body	384 Mm; 78 Gm	mm/ps	250 sec
GRACE-like mission	Spacing between two inertial references on two satellites	50–220 km	nm	0.1–100mHz
LISA-Like Mission	Spacing between two inertial references on 3 satellites	5 Gm	pm	0.1–1 Hz

Table 3.1: Missions that could potentially benefit from implementation of OFC technology.

3.3.1 Radar

Radar instruments are widely used in space science applications. Various radar systems are employed to study earth and planetary features, terrain, and composition of large features. Important discoveries, such as the discovery of ice caps on Mercury, were made with Earth-based planetary radar. Radar is also deployed onboard flying platforms and spacecraft. While radar is used for myriad applications in the military, civil and commercial sectors, it is a cornerstone technology in space science and exploration.

Optical frequency combs have found an important role in radar systems. Their application has great potential to enhance the performance of the radar and, in the near future, help with its size, weight, and power parameters. In particular, three important functions in radar—namely, the generation of the carrier on which the radar signal is modulated, the generation of the desired radar waveform, and digital processing of the radar data—have already been demonstrated with optical frequency combs to achieve significantly improved performance.

The first application is generation of highly spectrally pure signals as the radar carrier wave. Optical frequency combs are essentially an aggregate of a large number of coherent lasers separated by the comb repetition rate. When such a collection of lasers impinges on a fast photodetector, they beat and produce a signal at its output at the comb repetition frequency, which is at RF (microwave, or mm-wave). The generated signal is highly spectrally pure and represents a reduction of the noise of each of n lasers (comb elements) by a factor of $\sqrt{n}$. Such an oscillator based on a microcomb has been produced in a miniature package and is now commercially available. Furthermore, for a stabilized octave-spanning comb, the noise of the produced RF beat is the noise of the laser that stabilizes the comb divided by the ratio of frequency of the laser to the RF frequency. This large divisor leads to extremely high spectral purity. Such an approach has demonstrated the highest reported spectral purity for a 10-GHz signal. Since spectral purity of the signal that generates the radar carrier wave is the ultimate limitation in the sensitivity of the radar and the achievable signal-to-noise ratio, the optical frequency comb represents a major technology advancement in improving the radar capability and allowing it to "see farther."

The growing volume of data in space and ground-based systems is being fueled by a revolution in digital signal processing. This also applies to the case of radar, where digital signal processing is now an important component of any modern system. Nevertheless, further technological advances in this field are required to meet the needs of future systems. A key element determining the ultimate performance of digital signal processing systems is the analog-to-digital converter (ADC or A/D). As its name implies, ADC translates any analog waveform at its input to a digital copy by sampling and digitization. The efficiency of this process depends on the resolution with which the signal is converted from a continuous form to a discrete form (measured in bits of resolution) and the speed at which the digitization is accomplished. The latter function is limited by the noise and the speed of the clock in the ADC.

The advent of optical frequency combs has provided a powerful new tool to significantly improve the performance of the ADC. Optical frequency combs contribute to the development of advanced ADCs in a variety of ways, from replacing some of the components in the electronic ADC to completely replacing its architecture with photonic approaches. Since optical frequency combs have been demonstrated to provide the highest achievable spectral purity oscillator at speeds ranging from 10 to 100 GHz, their use in place of electronic clocks improves the performance of the electronic ADC by increasing the speed and lowering the jitter (clock noise) that in turn impacts both the sampling rate and resolution. At the other extreme, optical frequency combs are at the heart of an all-optical architecture that replaces all A/D functions with photonic components. In between the two extremes, optical frequency combs serve to realize photonic sampling with electronic quantization, and electronic sampling with photonic quantization. All these approaches enhance the ADC function beyond what is possible with solely electronic schemes. The most advanced ADCs demonstrated recently incorporated photonic schemes, with the optical frequency comb at their heart.

3.3.2 Communications

The demand for high speed optical communications has increased 1000-fold in the last 20 years. The predicted data rates in the next 5–10 years are driving the development of high speed digital systems; the industry is currently at a single line rate of 100 Gb/s with a strong push to obtain 400 Gb/s in the next few years. We could need petabit/s optical communications in the next decade to keep up with growth (*Kamiya et al.*, 2010). If our fastest component is 400 Gb/s, then we would need 2500 per transceiver unit to meet just the petabit demand, and we would need 1000 times as many for an exabit system. Obviously, 2.5 million 400G optical modulators, along with

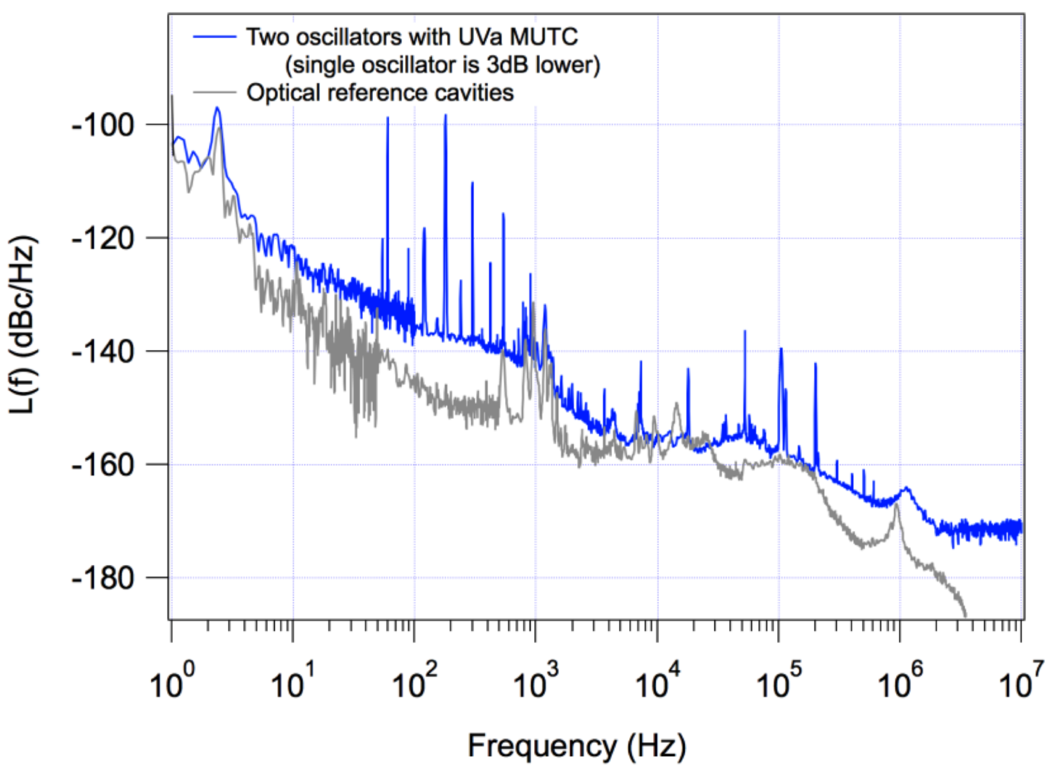

Figure 3.3: Record high spectral purity of a 10-GHz signal produced by an optical frequency comb. (Courtesy of NIST).

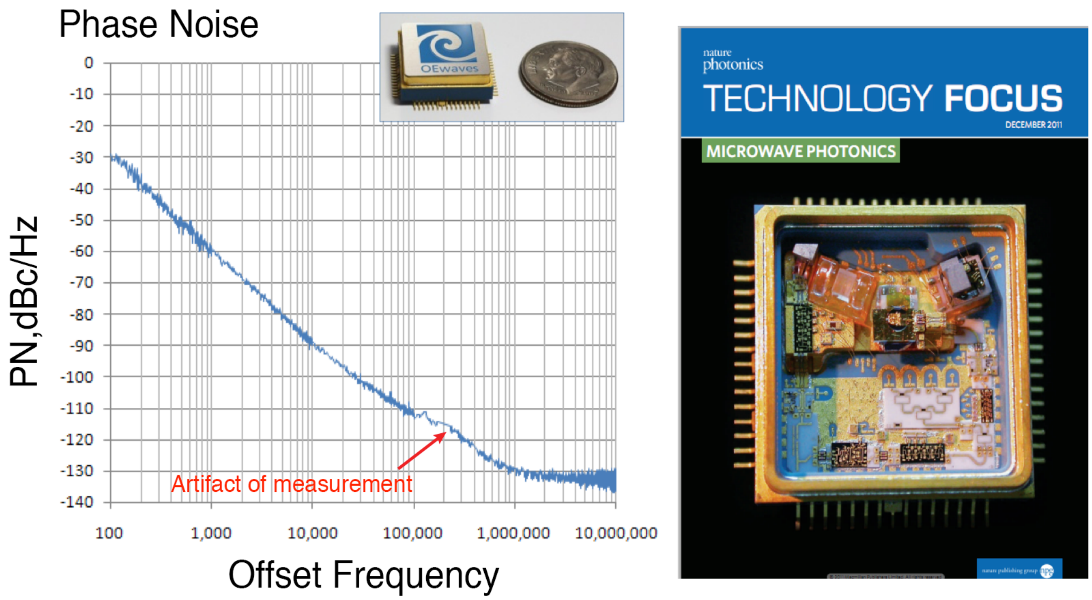

Figure 3.4: Chip-scale oscillator and its spectral purity at 40 GHz. (Courtesy of OEwaves, Inc.)

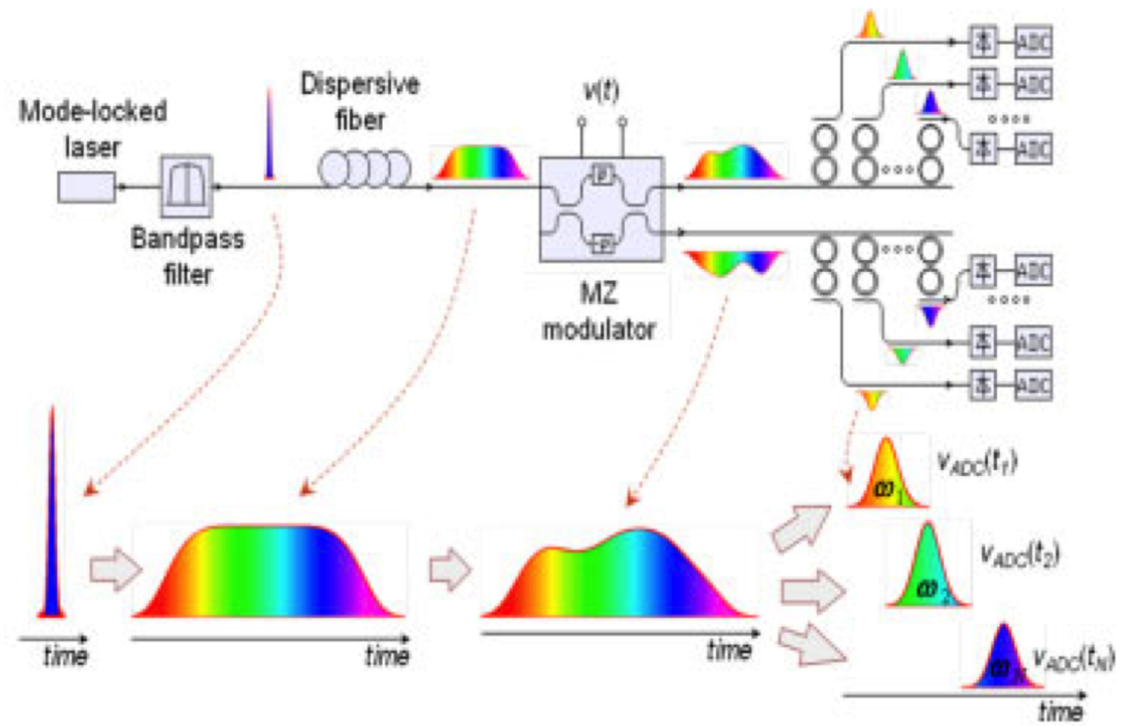

Figure 3.5: Scheme for a photonic assisted ADC. Here the mode-locked laser represents the frequency comb.

the lasers and other system components needed to meet this demand, becomes intractable very quickly! Reasons driving the demand come mainly from streaming HD video and the continued growth in mobile/wireless devices that are connecting to the global internet. Cisco predicts that the number of devices connected to the internet will be more than six times that of the global population by 2020 (*Afshar*, 2017).

Let's consider performance improvements and how to increase data rates in communication systems. There are two ways to increase the number of bits a communication system can transmit; the two knobs are higher order modulation and high baud (symbol) rates. The trade space that has to be considered includes transceivers and the propagation media (on Earth, atmospheric propagation provides natural windows around 90, 140, and 220 GHz (*Rosker & Wallace*, 2007; *Armstrong*, 2012), with a high frequency limit naturally imposed by atmospheric attenuation around 500 GHz), and we are beginning to reach limitations in each domain (See the Proceedings of the Optical Fiber Communications (OFC) 2015 and past years). Higher-order modulation techniques require more symbols to be packed together in a given bandwidth, thus increasing inter-symbol-interference (ISI). Since we are using digital transmission, the number of symbols $S = 2^k$ where k is the number of bits per symbol. Figure 3.6 shows the constellation pattern of a 16-QAM (Quadrature Amplitude Modulation) on the left and a 256-QAM constellation on the right. They are 4 bits and 8 bits per symbol, respectively.

The 256-QAM transmission is more susceptible to noise than the 16-QAM signal. The blue halo around each constellation point is due to phase noise and other impairments that cannot be compensated for in the receiver. 256-QAM represents 8 bits/symbol transmission and 16-QAM is 4 bits/symbol. Even though there is a 16-fold increase in the number of symbols, it only represents a $2\times$ increase in data rate if one keeps the same baud rate. The improvement is found in spectral efficiency that has units of bits/s/Hz. Thus, we can transmit more information over a given bandwidth. Optical communication over fiber is restricted to the L- and C-bands. Equipment restrictions such as the availability of high quality amplifiers have limited the growth to mainly the C-band for long range high capacity transmission.

The other way is to increase the baud rate or the bandwidth of the transmission. We are effectively reducing the spectral efficiency by just increasing the baud rate. But due to the issues associated with higher order modulation in the current infrastructure, another way is looking at transmitting 16-QAM (4 bits/symbol) and increasing the baud rate by two or higher, thus achieving a $2\times$ improvement or better. To see the issues associated with the higher baud rate, Figure 3.7 shows an eye diagram of a 16-QAM signal.

The horizontal axis is the symbol time, which is the inverse of the baud rate. As we increase the baud rate, the symbol period decreases, thus putting demands on the ability to synchronize to the decision points. The decision points are the locations where there are openings in the diagram. We can easily see four crossings that represent one of the four states in either the I (in-phase) or

Q (Quadrature) waveform. The system has two eye diagrams, one for I and one for Q. When properly aligned in time, the receiver can declare the amplitude of both I and Q waveforms, then be able to determine the bit pattern that is represented by that symbol. The area in between the decision points is affected by jitter and system noise. For the 256-QAM constellation, the eye diagrams would have 16 individual crossings that would have to be recognizable by the receiver. Thus, equipment limitations are harder to deal with when transmitting high order QAM as compared with lower orders.

In summary, as data rates increase in both the optical and wireless domains, the need for improving clock performance will be crucial to system operation. Higher order modulation depends on the frequency stability and phase noise of the oscillator, and higher baud rates require low jitter clocks.

Having outlined these challenges, we now consider optical frequency combs with their relatively broad optical bandwidth, compactness, and low noise level as a compelling route to providing solutions for growing demands on high speed communications (*L. Jiang et al.*, 2005; *Torres-Company and Weine*, 2014). As we explored with OFCs for Radar in section 3.3.1, reduced phase noise and frequency stability are inherent traits of this technology. For wireless communication, the broadband phase coherence of OFCs can allow for higher order modulation by implementing a hybrid photonic transmitter. In such a scheme, one line of a comb is modulated to encode data, heterodyned with another comb line, and then detected with a photodiode, thereby generating a

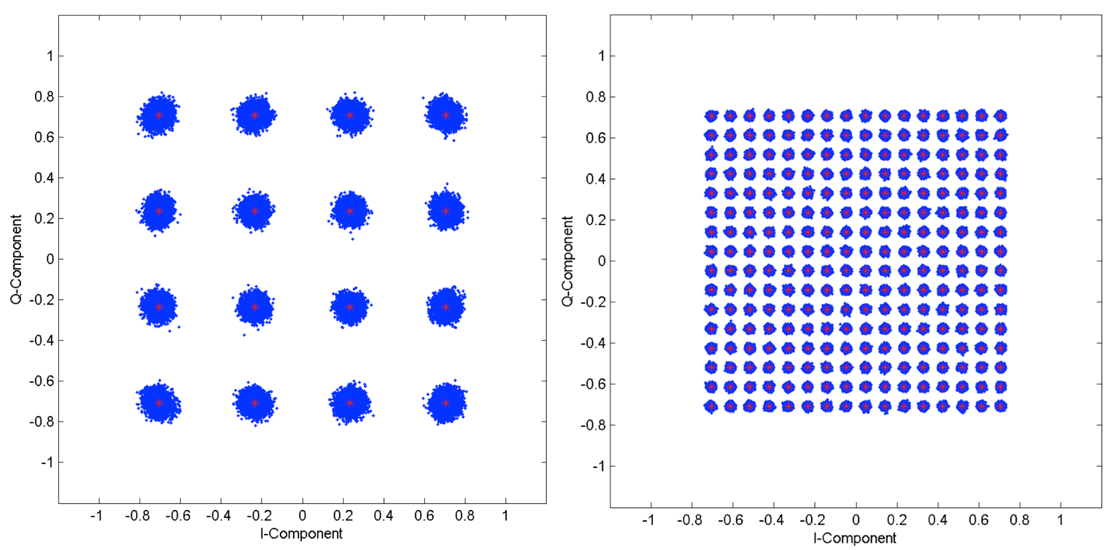

Figure 3.6: Right: A 16-QAM constellation; left: a 256-QAM constellation. The higher order QAM transmission on the right is more susceptible to impairments than the one on the left. The horizontal axis represents the amplitude of the I-symbol and the vertical represents the amplitude of Q-symbol. When measured together give the symbol location in the above constellations.

modulated high-frequency (potentially terahertz) carrier fixed by the spectral difference between the two comb lines. This technique allows for both the amplitude and phase of the photodetected RF signal to be independently modulated while covering a narrow spectral bandwidth. Importantly, this application requires preserving the phase coherence of the comb lines after manipulation.

In fiber-optic communication, where wavelength division multiplexing (WDM) has revolutionized the technology, an optical frequency comb can replace the large number of lasers required in the transmitter by a single one and fix the channel separation across the bandwidth with great accuracy. This dramatic increase in WDM performance was recently demonstrated by *Marin-Palomo et al.* (2017) with microresonator soliton frequency comb sources that were used to transmit data on 179 individual optical carriers, completely covering the optical telecommunication C- and L-bands and allowing a transmission of data at a rate of 55 terabits per second over a distance of 75 kilometers.

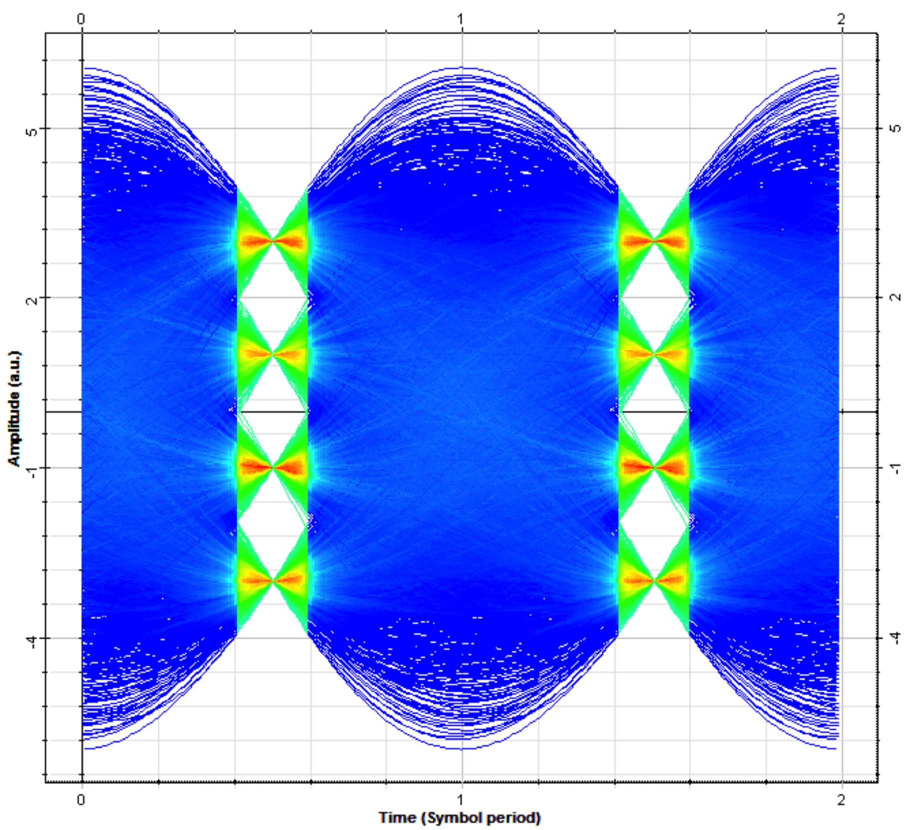

Figure 3.7: The eye diagram of a 16-QAM signal. The open areas represent the receiver decision points to declare what symbol was transmitted. As the symbol (baud) rate increases the symbol period decreases thus placing a demand on the stability of the clock to ensure the receiver is sampling the received signal at the proper time for data transfer.

For large-scale commercial applications, transitioning to OFCs requires that they be produced at a cost and reliability that justifies the challenges associated with integrating a new technology as compared with non-optical clock approaches. However, for space-based applications, where there is a lower demand for volume but a greater need for performance, OFCs may indeed provide a significant improvement.

On a final note, the Keck Institute for Space Studies held two workshops specifically on Optical Communication on SmallSats in July of 2016 and February of 2017. The interested reader is referred to the study report (*Carrasco-Casado et al.*, 2017).

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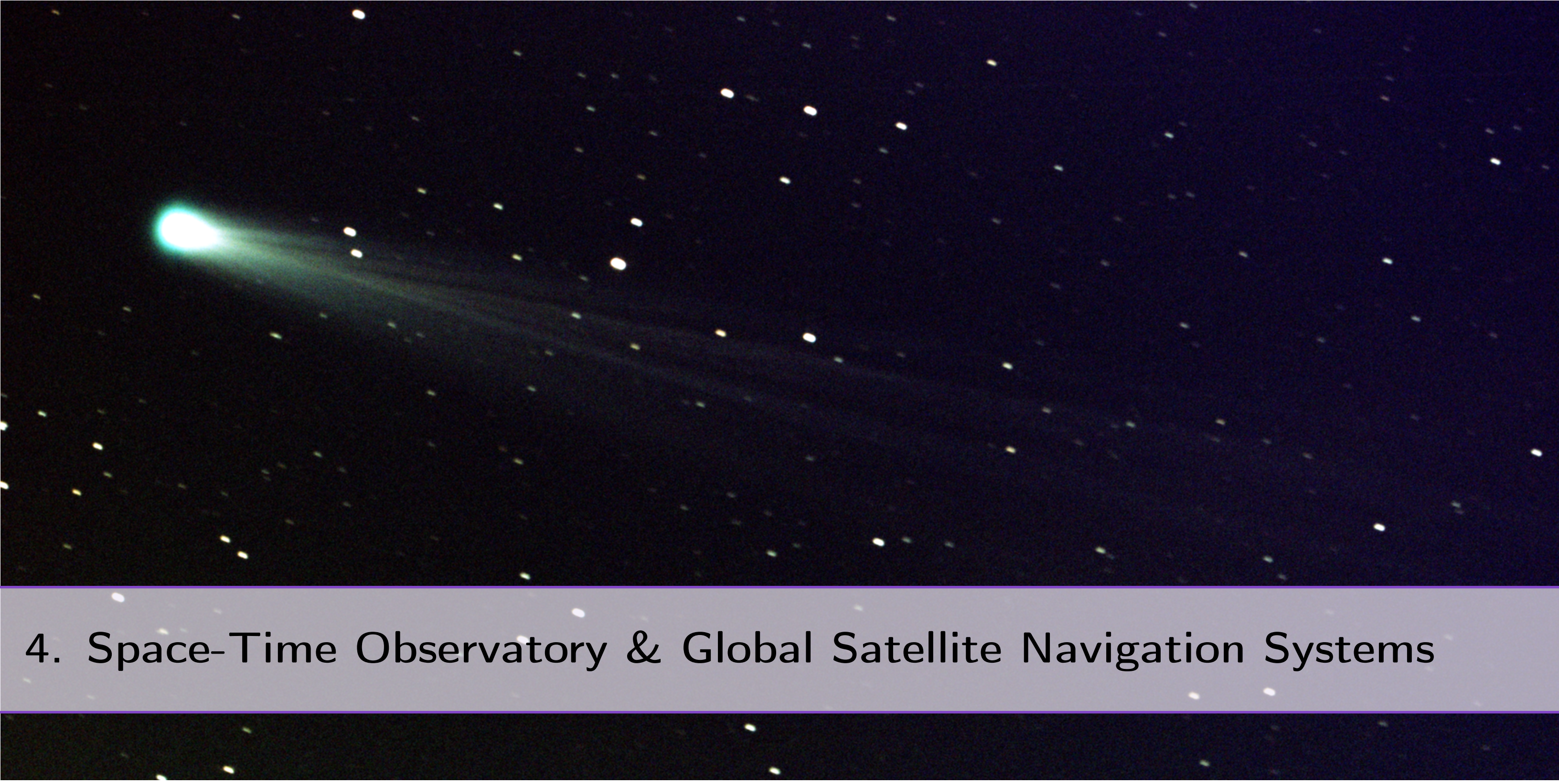

4. Space-Time Observatory & Global Satellite Navigation Systems

Frequency combs are a key enabling component of the most advanced atomic clocks that "tick" at optical frequencies and keep time on the femtosecond scale. These timing tools open unique opportunities to explore space-time and its properties at the highest accuracy and provide the technological underpinnings of next-generation communication and navigation systems. Because high performance clocks are affected by local gravity, it will be necessary for such clocks to become space-based. Such space optical clocks will offer opportunities to search for violations of general relativity, the standard model, and the Einstein equivalence principle, and have the potential to discover new physics. High performance atomic frequency standards and clocks have always been an integral part of the Deep Space Network (DSN), responsible for communication, navigation, and tracking. GPS reliance on atomic clocks is one familiar example. High accuracy clocks will be a central part of the interplanetary network system envisioned for the future. In such advanced communication and navigation, frequency combs would provide the means to seamlessly transfer the exquisite performance of optical clocks across the microwave, millimeter wave, or terahertz domains, as driven by the particular application. The same high accuracy clocks are also being proposed for relativistic geodesy, where clocks connected by frequency comb-based time transfer are used to measure gravitational potential. In these types of measurements, comparison of terrestrial clocks at different potentials via a space-borne clock or satellite transponder could enable mapping of the geoid and advance understanding of geophysical dynamics that shape our Earth.

The participants of the Optical Frequency Combs for Space Applications workshops considered the benefits of a constellation of satellites utilizing OFC-based clocks for precision timekeeping. In this chapter, we examine the implementation of such a network of spacecraft—designated the Space-Time Observatory—for gravitational wave detection, dark matter research, and as a world-wide time standard (Figure 4.1).

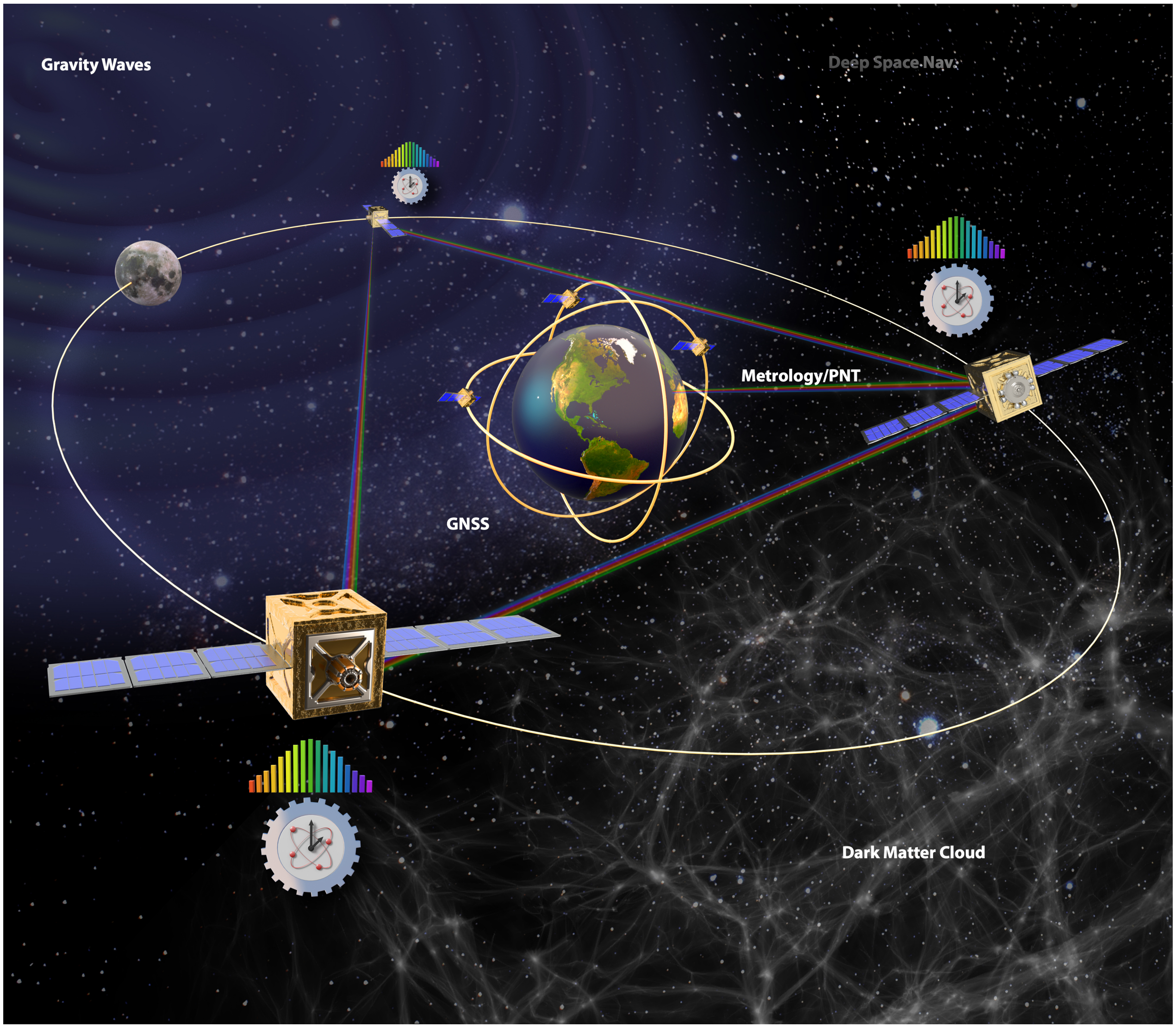

Figure 4.1: Space-Time Observatory and Global Satellite Navigation Systems concept.

4.1 Concept for a Super GPS

Global Navigation Satellite Systems (GNSS) like the Global Positioning System (GPS) utilize satellites that broadcast accurately timed beacons and their positions such that users can triangulate their location. For an order-of-magnitude understanding of how time accuracy translates to position accuracy, simply multiply the time error by the speed of light to find the User Range Error of Clock (UREC). For 1 meter accuracy, the timing accuracy must be within a few nanoseconds.

The satellites utilize atomic clocks to keep time. However, these clocks represent a compromise between timing accuracy and cost and can only hold nanosecond level timing for about a day. The ultimate timing accuracy is provided by a complicated network of monitoring stations, accurate ground clocks at the U.S. Naval Observatory (USNO), the GPS Master Control Station, and timing links between them all. See Figure 4.2, taken from *Mitchell and Powers* (2012).

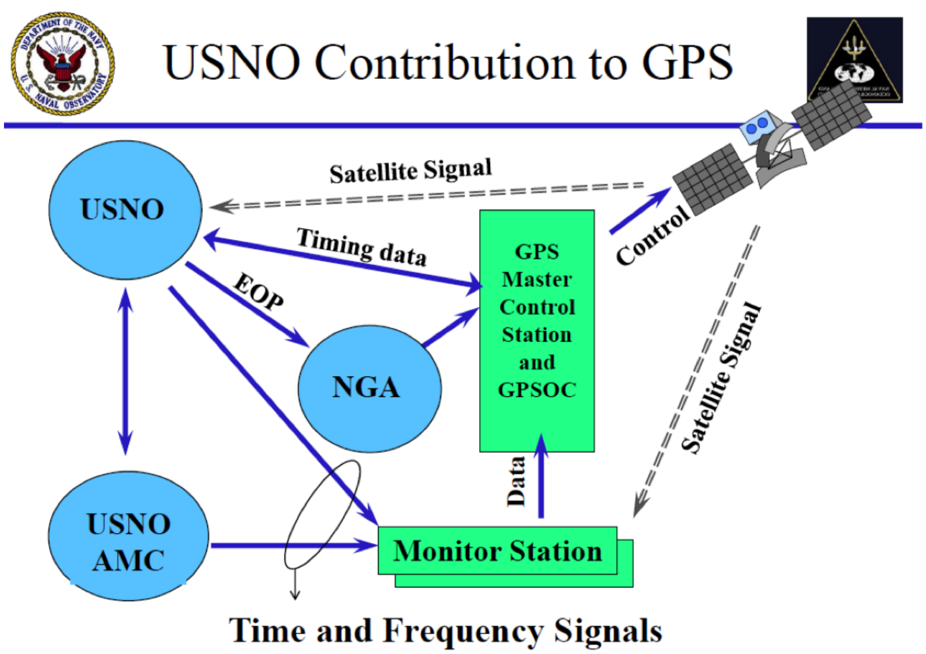

Figure 4.2: Global Navigation Satellite System (GNSS) interdependencies (*S. Mitchell and E. Powers*, 2012)

Today, frequency comb-based optical atomic clocks are approaching accuracies to a few parts in 10^{18} (*Bloom*, 2014; *Hinkley*, 2013; *Chou*, 2010). This is about 100 times better than the best fountain clocks, such as the NIST-F2 (*Giorgetta*, 2013). The question is what utility such optical atomic clocks would provide to the GNSS constellations. As of 2013, GPS Signals in space had an RMS position accuracy of about one meter, which corresponds to about one nanosecond of time error (see gps.gov). Thus, the clocks and time transfer network supporting the GNSS constellations have time accuracy to the nanosecond level. A clock that counts a frequency standard accuracy at the part per 10^{18} level, assuming flicker noise, would hold one nanosecond for about 50 years[1]. Satellites can last for decades.

[1] The time deviation σ_x for flicker frequency noise is $\sigma_x = \tau\sigma_y/\sqrt{3}$. For constant fractional frequency deviation (Modified Allan Deviation) σ_y of 1×10^{-18} and target time deviation of 1×10^{-9} seconds yields $\tau = 55$ years.

A constellation of super clocks could be used to supplement the ground observation system, and even provide a primary autonomous reference for GNSS. To accomplish this, other technical requirements must be met. First, the reference clocks need to connect to the GNSS clocks and relate time information to them. Fortunately, the same frequency comb technology used to transfer optical atomic clock laser stability to the RF domain can be used to execute a time transfer protocol at the required stability levels (*Giorgetta*, 2013). The mechanism can be used to determine the path length and time between two points in space-time, which also addresses the second major requirement that spatial information on the GNSS constellation also be monitored and updated. A constellation of three satellites that share a common reference time could be used to determine the position and time offsets of GNSS spacecraft relative to reference spacecraft. This only translates the spatial reference problem to the super clock satellites. The super clock satellites would need to be located in a highly stable orbit.

Stable orbits could be provided by the Lagrange points L4 and L5 for the Earth-Moon system. These points are full three-dimensional local minima of the gravitational potential between the two massive bodies that form the points. These points also have the advantage of stabilizing the gravitational clock shift. The symmetry of placing the third clock at L3 is appealing because this forms an equilateral triangle, however this point is a saddle point in the gravitational potential and therefore not stable. Objects placed at L5 would have a tendency to move along the axis of the two planets. However, the symmetry of this point to the other two in combination with a partial minimum should be enough to locate a spacecraft there. The spacecraft orbital radius could be measured by the two crafts at L4 and L5 while the out-of-plane motion is determined by the gravitational minimum. More analysis of the spatial stability of these orbits relative to the surface of the Earth is needed; ultimately GNSS is providing position information relative to Earth's habitable surface, and not a gravitational potential surface.

Lastly, one might ask: "Why have these augmentations in space at all?" Ground-based optical atomic clocks could provide benefits through the existing architecture if optical upgrades are made. However, the atmosphere provides significant challenges in this case.

Turbulence will challenge the time transfer link from ground to space and changes in the index of refraction will degrade the absolute ranging knowledge. This would limit the full capability provided by a space-based implementation. Furthermore, the Space-Time Observatory could provide some GNSS resiliency and robustness by providing laser-based one-way navigation aid to ground users should GNSS availability be challenged. According to the Air Force's 2013 Global Horizons report, "by the 2030 time-frame, multiple countries will have the ability to hold all US space services at risk via both physical and cyber attacks."[2] The fact that the Lagrange points L3 through L5 are an order of magnitude further away than geostationary orbit should provide some safety from human-based physical threats.

[2] `www.af.mil`, Appendix p. 8

4.2 Gravitational Wave Science Enabled by a Space-Time Observatory

During the second Optical Frequency Combs for Space Applications workshop on February 11th, 2016, there came an extraordinary scientific announcement; the first detection of gravitational wave waves had been made by the Laser Interferometer Gravitational-wave Observatories (LIGO) in Washington and Louisiana. Five more detections have been reported as of this writing, the last two of which were also observed at the Virgo interferometer near Pisa, Italy. At the workshop, conversation instantly shifted to this historic news, and discussion of OFC-enhanced gravitational wave detection naturally ensued. While groundbreaking discoveries continue to emerge from these ground-based observatories, gravitational waves at very low frequency, with wavelengths larger than Earth, will not be detectable with existing facilities. For a window into this realm, space-based gravitational wave detection is necessary to enable the very long baselines required.

The Laser Interferometer Space Array (LISA) mission is currently in line as a European Space Agency-led endeavor with the goal of formation-flying a three-spacecraft laser interferometer in an L3 orbit to continuously monitor gravitational wave activity by coherently measuring the stretching and squeezing of space-time, including frequency, phase, and polarization.[3]

The LISA spacecraft ranging system must eliminate the effects of laser frequency noise, which would otherwise couple to the science signal through the sizable armlength difference. The current plan is to provide stabilization to a reference cavity contained in the payload, with the remaining noise removed by "Time-Delay Interferometry" (TDI), which synthesizes a virtual balanced armlength interferometer in post-processing. This requires knowledge of the absolute armlengths to roughly 1 meter accuracy, measured with an auxiliary ranging phase modulation of the laser beam. A second modulation would be used to measure and remove noise caused by timing jitter of the ADC sampling clocks in the phasemeters.

However, *Tinto and Yu* (2015) have shown that using self-referenced optical frequency combs, it is possible to generate a heterodyne microwave signal that is coherently referenced to the onboard laser such that the microwave noise can be canceled directly by applying modified second-generation time-delay interferometric combinations to the heterodyne phase measurements. This approach avoids the use of modulated laser beams as well as the need for additional ultrastable oscillator clocks (USOs).

An alternative to the LISA mission architecture has been proposed by *Loeb and Maoz* (2015), who suggest using an array of atomic clocks, distributed along the Earth's orbit around the Sun to detect the time dilation effect of mHz gravitational waves. Simultaneous measurement of clock-rates at different phases of a passing gravitational wave provides a different approach to the interferometric detection of temporal variations in distance between test masses separated by less than a gravitational wave wavelength. Another advantage of this approach is that although a

[3] NASA LISA Mission Home Page, `https://lisa.nasa.gov`

minimum of two orbiting spacecraft equipped with atomic clocks is required, the timing precision will improve with the number of clock spacecraft. Here again, OFCs offer a technology path forward.

4.3 Dark Matter Science Enabled by a Space-Time Observatory

In their review article on dark matter, *Bertone, Hooper, and Silk* (2005) point out how the modern problem of Dark Matter is conceptually very similar to the old contrasting problems of unseen planets presented by the motion of Uranus, which led to the discovery of Neptune, versus Mercury's anomalous orbit that instead required Einstein's theory of general relativity to explain.

The theory of Dark Matter arises from our failure to explain anomalous behavior of large astrophysical systems, with sizes ranging from galactic to cosmological scales, assuming that there is no deviation from the known laws of gravitation and the theory of general relativity. As such, with current models predicting that Dark Matter—which does not interact with electromagnetic radiation but does interact gravitationally—constitutes 84.5% of all mass in the universe, our technological capability to help elucidate the nature of this enigmatic matter is of great importance; optical frequency combs may provide one tool for probing the nature of Dark Matter.

Derevianko and Pospelov (2014) have hypothesized that the precision clocks on a GPS-like network of spacecraft could be affected by 'topological defect dark matter (TDM)' interacting with our solar system (see Figure 16 from *Derevianko and Pospelov*, 2014). The time scale over which the clocks exhibit a change could provide a clue to the extent and nature of a TDM. Increasing the precision of the clocks on GNSS spacecraft by ~3 orders of magnitude could correspondingly increase the sensitivity to small deviations resulting from dark matter. Optical frequency comb-based optical clocks could provide this precision.

4.4 A Worldwide Time Standard for Fundamental Physics Studies

The OFC-enabled Space-Time Observatory would be beneficial to ground-based optical clock research groups as it would allow for comparisons between distant clocks that would be otherwise difficult to compare. At present, most state-of-the art optical clocks are scattered across the northern hemisphere in the United States, Europe, and Japan, making comparisons between them currently impossible. A link between these trans-continental optical clocks would also enable a global measurement of variations of fundamental constants, which could provide insight into fundamental physics, Dark Matter, and astrophysics, which require clocks to be separated at large distance scales to resolve the predicted effects. As the fractional uncertainty of these optical clocks is at the 10^{-18} level, local variations in the Earth's gravitational potential at the centimeter level and below will limit the accuracy of ground-based optical clocks. To overcome these limitations, optical clocks will need to be moved into space, where temporal variations of Earth's gravitational potential are reduced, to provide a reference timescale for optical clocks on the ground.

In 2010, the 'Space-Time Explorer and Quantum Equivalence Principle Space Test' (STE-QUEST) project was proposed to ESA, which included a test of the gravitational redshift in the field of the Sun/Moon. Although not selected in a 2014 opportunity, the idea was to compare, via the STE-QUEST satellite, two clocks attached to the Earth and separated by intercontinental distances. The comparison would be made using microwave links in common-view mode. The test boils down to a search for a periodic signal with a known frequency and phase in the clock comparison data (*Wolf and Blanchet*, 2016).

For a test of general relativity, *Ashby et al.* (2009) suggested a space mission for improving the precision of measuring the parameter γ—the curvature of space—from the range of 10^{-5} to 10^{-8} using optical clocks. The value of this improved information about γ would directly limit the range of applicability of alternative gravitational theories. The major requirement for the mission is to fly an optical clock that has very high stability over a period of at least 8 days; it must

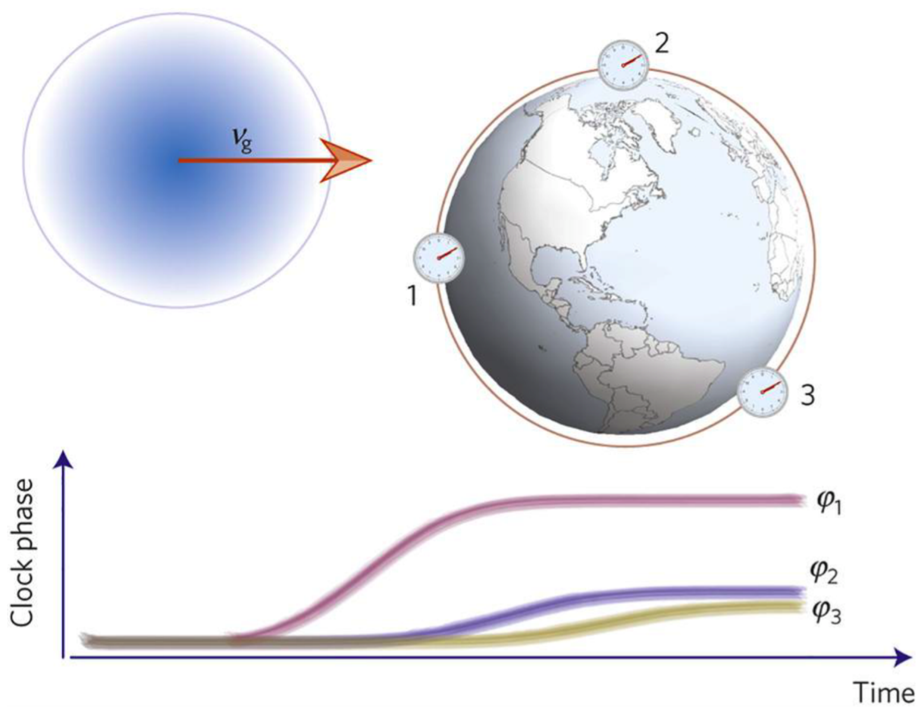

Figure 4.3: Interaction of a hypothesized Dark Matter cloud with clocks (from *Derevianko and Pospelov*, 2014)

achieve a fractional frequency noise power spectral density amplitude that is nearly equivalent to an Allan deviation of 5 $\times$ $10^{-15}/\sqrt{\tau}$ for times from 1 s up to 10^6 s.)

4.5 Optical Frequency Combs for a Space-Time Observatory

While fully integrated microcombs are a goal for space platforms, self-referenced fiber laser frequency combs have already been demonstrated in small, low-power packages in flight (*Lezius et al.*, 2016) and may provide the optical clockwork needed on GNSS satellites in the near future. The size of these devices has evolved, with packages now of ~1 liter total volume[4]. The U.S. Air Force has contracted with Honeywell Corporation to provide a Rubidium optical clock[5]. This is the type of optical clock that might soon find use on a "super GPS" spacecraft.

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[4] `https://www.nist.gov/news-events/news/2014/03/portable-frequency-comb-rolls-out-lab`
[5] `https://govtribe.com/contract/award/fa945317c0039`

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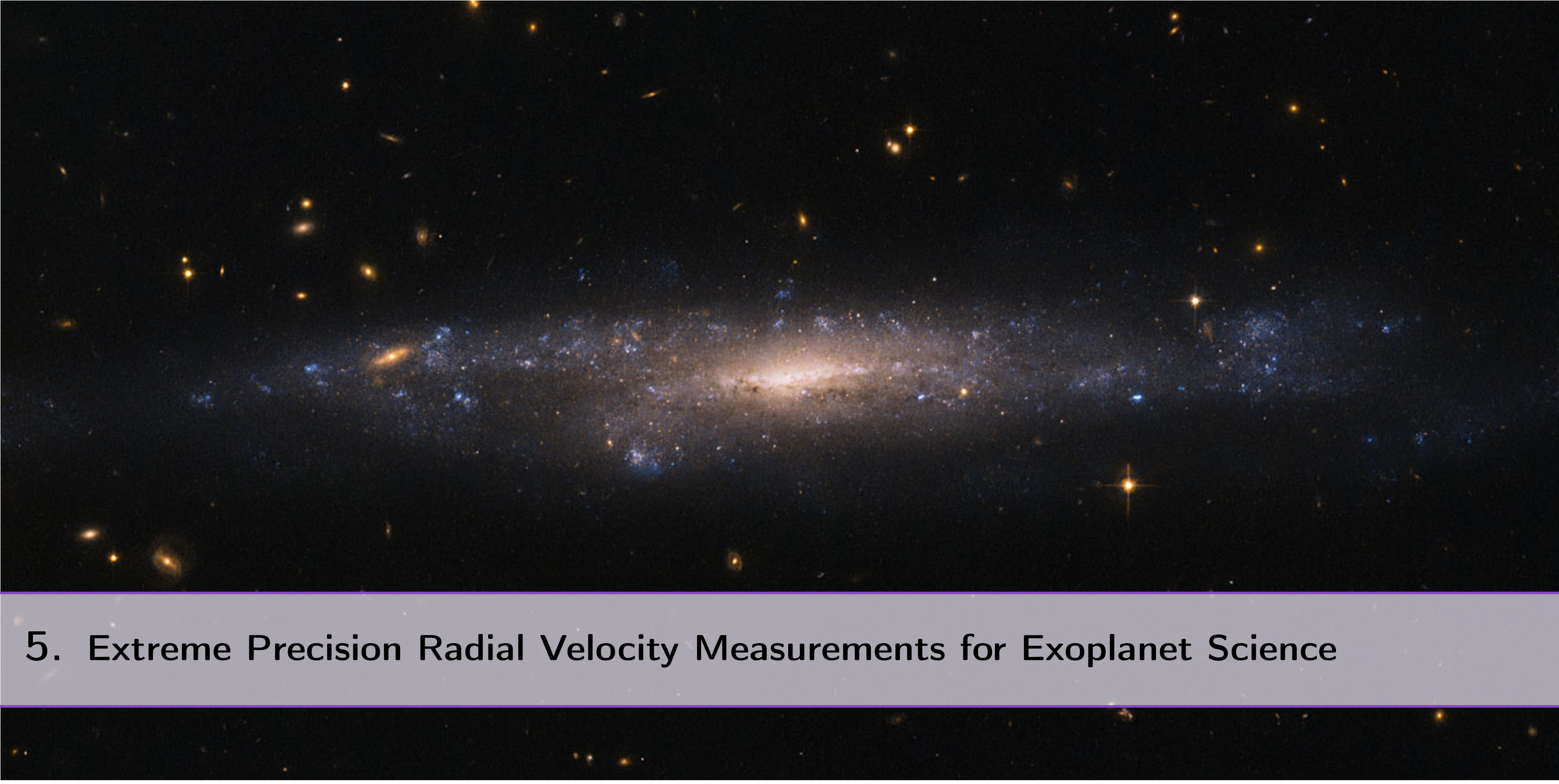

5. Extreme Precision Radial Velocity Measurements for Exoplanet Science

5.1 Executive Summary

One frequency comb application that has proven valuable in ground-based space science is the use of OFCs for calibration of astronomical spectrographs. The high precision afforded by OFCs for this purpose allows for unprecedented precision in the radial velocity detection technique. However, in both visible and NIR observations, even OFC calibration, which can provide spectrograph calibration at the sub-cm/s level, reaches a floor of about 1 m/s due to other factors. Dominant among these, and the most challenging to overcome, is uncertainty introduced by telluric lines in the spectra. It was the recognition of telluric line contamination of stellar spectra as the principle factor limiting the ultimate precision of future ground based extreme precision radial velocity measurements that led to the mission concept described in this chapter—a space-based telescope and fiber-fed OFC-calibrated spectrograph to avoid telluric line absorption entirely that would:

- Provide unprecedented extremely high-resolution broad band spectra of stars that are free from telluric contamination. A mission that could obtain high-cadence time series with high SNR, high resolution spectra spanning from 0.4 to 2 microns toward a large number of bright stars would have a significant impact on fundamental stellar astrophysics by providing a better understanding of the wavelength dependence of phenomena in stellar photospheres—spots, faculae, and granulation—across many spectral types and evolutionary stages.

- Provide the needed breakthrough to reach the highest possible Doppler precision for extreme precision radial velocity determination of exoplanetary mass, and thereby planet density and bulk composition.

- Be a critical pathfinder for a LUVOIR or HabEX observatory.

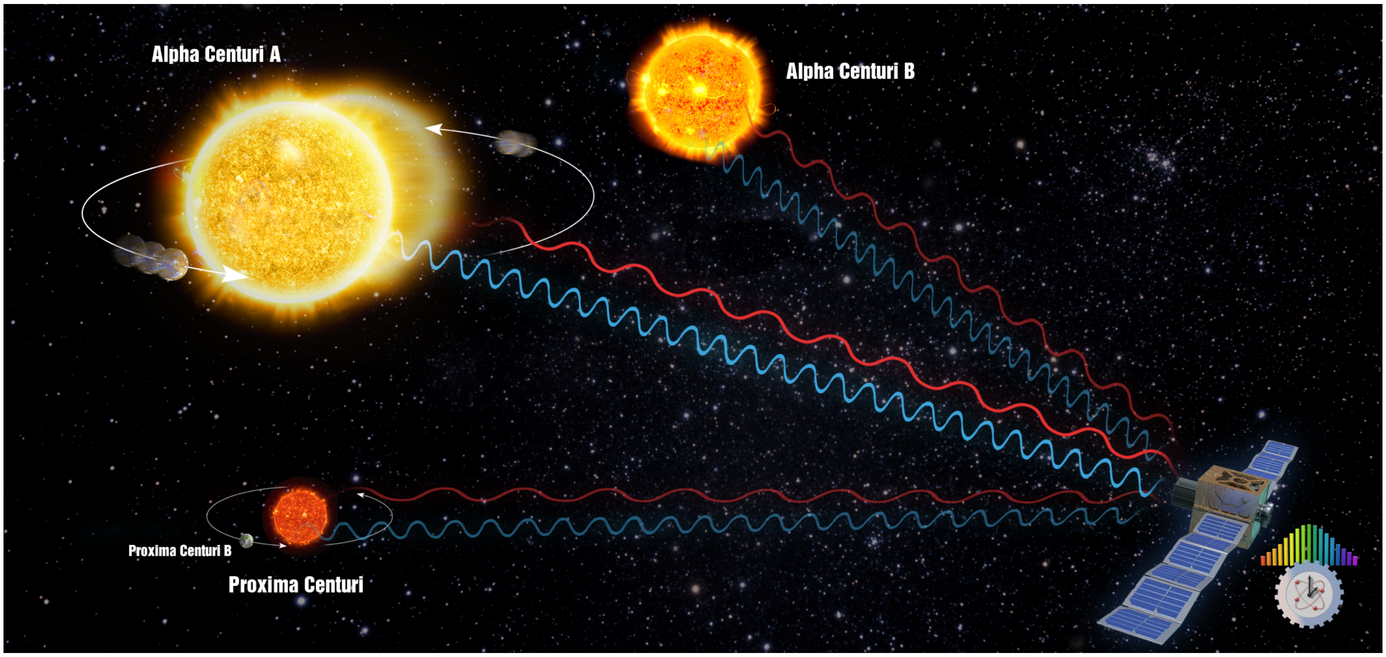

Figure 5.1: Extreme Precision Radial Velocity concept.

5.2 Science Motivation

Exoplanet science is a booming subfield of astronomy of enormous interest to both the astronomical community and the broad public. Yet the vast majority of exoplanets, even around nearby stars, have escaped detection. While the transit technique can detect earth-sized planets close to their host stars, the probability of detecting an earth in the Habitable Zone of a nearby solar type star is low due to the intrinsic geometry required by the technique. Astrometric measurements from space (the GAIA mission) are limited to the detection of gas and icy giants. Microlensing can probe planets in the Habitable Zone, but the detected planets will never be seen again for follow-up to reveal their physical properties. Thus only direct imaging and the Doppler or Precision Radial Velocity (PRV) technique hold the promise of detecting true earth analogs and searching for signs of life. The future of exoplanet science depends heavily on progress on both techniques and has very different trajectories depending on the Doppler precision that is ultimately achieved.

Extreme precision radial velocity (EPRV) measurements are the most promising discovery technique for measuring masses of potentially habitable worlds. The 2010 Decadal Survey listed the detection of Earth-like planets orbiting within the habitable zones of nearby stars as one of three top priorities. The New Worlds New Horizons report (*Blanford et al*,. 2010) specifically recommended improvement in the precision of the radial velocity (RV) technique as the highest priority for ground-based exoplanet research. The 2012 NSF Portfolio Review report (*Eisenstein et al.*, 2012) supported this priority, making extreme precision optical RV spectroscopy the number

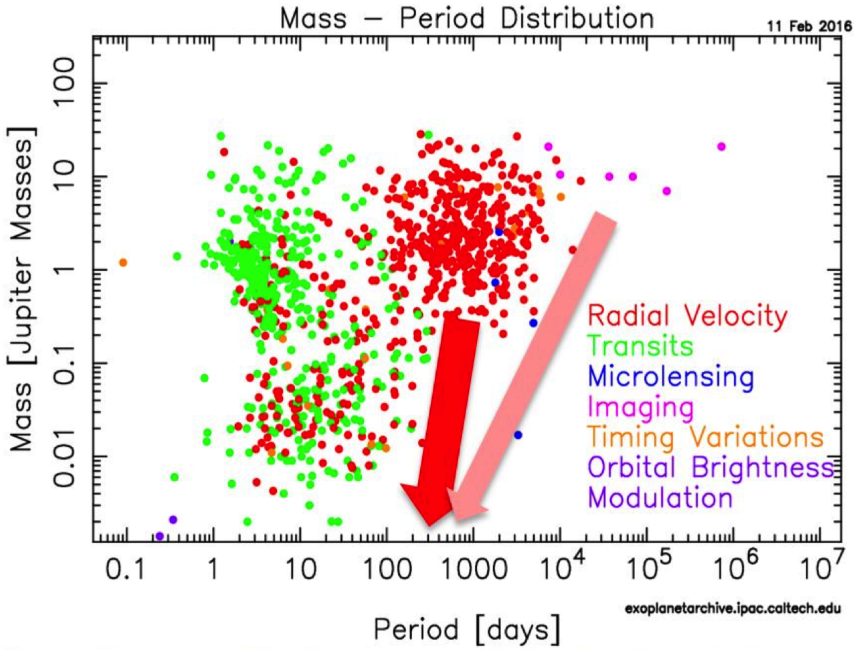

Figure 5.2: Census of confirmed planets with the detection technique color coded. The arrow shows the prospects for PRV and extreme PRV using specialized instruments on large telescopes that employ, in may cases, laser frequency combs. The secure detection of true earth analogs and the search for habitable planets may require high contrast direct imaging (lavender arrow) and extreme PRV, both from a large space-based telescope.

one priority for "Planets and Stars," emphasizing that the science drivers demand an instrumental precision of 0.1 m s^{-1} (10 cm s^{-1}). However, this is not a trivial goal. The capability to achieve 0.1 m s^{-1} is not currently available at any observatory in the world. While simulations show that the information content in the stellar spectrum is sufficient to recover a few cm s^{-1} precision with high SNR and high spectral resolution, current state-of-the-art RV spectrographs fall short of this precision goal by a factor of ten. Fortunately, the community has identified the required advances: precise wavelength calibration with laser frequency combs; environmentally stabilized spectrographs with resolution of at least 150,000; high fidelity spectra; and elimination of telluric contamination. The last of these requirements is particularly problematic—we cannot eliminate the Earth's atmosphere unless we observe from space. The consensus from the PRV community is that it should be possible to improve Doppler measurement precision to levels approaching 10 cm/s at visible wavelengths. However, there remain concerns that residual terrestrial atmospheric effects and residual noise in the photospheres of the host stars themselves may produce a noise floor at or below this level (*Fischer et al.*, 2016).

In this chapter we suggest that:

1. Laser frequency combs may play an important role in achieving these levels of sensitivity and that a robust technology plan is needed to achieve the desired properties of such combs in terms of broad wavelength coverage, line spacing, spectral flatness, etc;

2. Residual telluric effects at visible and especially at near-infrared (NIR) wavelengths may provide a fundamental floor to the sensitivity of PRV measurements, thus necessitating consideration of space-based measurements;

3. A technology roadmap for space qualified laser frequency combs is important;

4. One or more demonstrations of extreme precision radial velocity measurements from space may be required, perhaps necessitating a small telescope and spectrometer to measure one or a few extremely bright stars, such as alpha Centauri A and B;

5. Consideration should be given to an EPRV instrument on a future flagship mission to make EPRV measurements of stars being imaged with a coronagraph or starshade.

We first discuss how PRV measurements can complete the census of planets orbiting the nearest stars and then support upcoming space missions. We assess the sensitivity to reach the appropriate level to detect and characterize Earth analogs; laser frequency combs will play a critical role in obtaining the requisite precision. We then discuss whether on-going or planned ground-based experiments can ever reach the desired level of performance and suggest that there is a critical role for a space-based PRV instrument. Such an instrument could fly as a secondary payload on the direct imaging telescopes to achieve the sub-10-cm/s precision to detect and characterize the masses and orbits of the planets imaged by a future flagship. A precursor project could demonstrate the need for EPRV from space and the technology required to achieve the sensitivity goals.

5.2.1 A Search for the Nearest Planetary Systems

Transit searches rely on a careful alignment of the orbital plane of the planetary system with the line of sight to the Earth. Thus, by their nature, transits cannot find the closest planetary systems. The transit probability drops with increasing orbital separation, making the detection of planets in wide orbits, such as Earth analogs, difficult. Thus an unbiased PRV survey of nearby stars, from solar analogs to cool M stars, is an important part of exoplanet research. The omnipresence of planets discovered around distant M stars by the Kepler spacecraft (*Dressing and Charbonneau*, 2015) makes PRV measurements at very red visible wavelengths and at NIR wavelengths an important component of these searches. The detection of a triple planetary system orbiting Wolf 1016, an M star only 5 pc away (*Wright et al.*, 2016), highlights the opportunities for using PRV to find nearby planetary systems.

5.2.2 Critical Support for Space Missions

5.2.2.1 Transit Missions

New space missions (TESS, CHEOPS, PLATO) will soon measure the radii for thousands of new transiting exoplanets. Since the combination of mass and radius allows a straightforward calculation of bulk density, extreme precision radial velocity measurements allow astronomers to both confirm transit detections and model the internal composition and atmospheres of exoplanets. Extreme radial velocity precision (better than 10 cm/s) will confirm the planetary nature of these systems and provide masses for many Earth-sized planets.

5.2.2.2 Direct Imaging missions

The ultimate goal for exoplanet science and for the public's interest in this area of research is the observation of exoplanet atmospheres to detect spectroscopic bio-signatures. The intrinsic faintness of exoplanets (about 30th visual magnitude) will require the use of a large aperture space telescopes. Two exoplanet-friendly concepts that are currently under study are the 8–16-m LUVOIR (the Large Ultra Violet Optical and Infrared) telescope and the 4–8-m HabEx telescope. These missions aim to reach contrasts of 10^{-10} in order to image exoplanets by using coronagraphs or star shades.

Radial velocity measurements have directly measured the masses of planets detected by the transit technique, leading to the determination of planet density and bulk composition—gaseous, icy, water, rocky, metallic (*Weiss and Marcy*, 2014)—which is perhaps the prime factor in assessing the physical properties of a planet and its suitability as a abode for life. Similarly, radial velocity measurements will be critical to the physical characterization of the planets that will be imaged with a future flagship mission. The interpretation of the low-resolution spectra of exoplanet atmospheres will be richer and more robust if the spectra are coupled with a knowledge of the planet mass. While the radius of the directly imaged planet will not be known because of the unknown reflectivity (albedo) of the planet that could be either small and shiny or large and very dark, the mass-radius relationship inferred from transiting planets can be used to constrain the properties of newly imaged planets.

EPRV measurements will play a crucial role in supporting imaging space missions both before, during and after those missions. Precursor observations of the most favorable stars—perhaps 50 in number—over a decade or longer will be able to identify those stars with planets in few AU orbits with masses down to a few Earth masses, but the most critical need will be the detection of direct Earth analogs in the habitable zones of other solar type stars. It is this final step that we address and consider whether or not ground-based observations are capable of achieving the goal.

5.3 What RV precision is needed and how do we get there?

5.3.1 Precision Goals

The extreme precision radial velocity goal for next generation spectrometers like ESPRESSO (on the VLT) or EXPRES (on the DCT) is 10 cm/s. This is the solar reflex velocity induced by Earth for an edge-on orbit. For arbitrary viewing angles however, this amplitude is reduced by a factor of the sine of the inclination angle, statistically by a factor of two. The RV signal is reduced even more for the systems most favorable for direct imaging which are biased to be face-on. As a result of these factors, the desired precision for robust mass measurement of those Habitable Zone Earth-like planets orbiting solar type stars, and particular those likely to be imaged directly from space, is closer to 1 cm/s.

Beyond producing an instrument with inherent precision at the ~1 cm/s level and collecting enough stellar photons to achieve the signal to noise ratio (SNR) needed to make PRV measurements, there are two remaining hurdles for extreme PRV precision:

1. Distinguishing Doppler shifts due to planets of ever-lower masses on ever-wider orbits from systematic effects due to motions of material in the photospheres of the host stars. This is generically called "stellar jitter";
2. Eliminating the effects of telluric contamination in the spectra produced by ground-based instruments.

5.3.2 Stellar Jitter

The community is attacking the issue of stellar noise with very high-resolution spectrographs that provide high quality information about the spectral line depths and line profiles. Broad bandwidth spectra with high SNR with robust statistical techniques (like PCA; *Davis et al.*, 2017) will provide dramatic leverage for distinguishing between the Doppler shifts and photospheric velocities. These approaches collectively exploit two important properties of stellar jitter:

- While stellar jitter is not purely stochastic, it is also not a persistent Keplerian signal; it waxes and wanes, is not perfectly coherent, and varies on timescales that are different from center of mass (COM) radial velocities.
- The underlying physical phenomena that spawn jitter have detailed spectroscopic, photometric, wavelength dependencies, and polarization signatures that are in principle distinguishable from simple wavelength shifts due to Keplerian Doppler shifts (Figure 5.3).

A robust correction for stellar activity and photospheric velocities will require a broad spectral bandpass from blue wavelengths, ~0.4 μm out into the near-IR, ~2.4 μm, to leverage the different contrast of features as a function of wavelength. Currently, this is not possible because of telluric contamination.

5.3.3 Telluric Contamination

It is possible that telluric contamination will limit the precision of ground-based RV measurements to 30 cm/s or worse (*Cunha et al.*, 2014) at visible wavelengths, far above the hoped for 10 cm/s and even further away from the ultimate requirement of a few cm/s. Atmospheric lines are imprinted in all spectra acquired with ground-based spectrographs. The telluric spectrum (Figure 5.3) is comprised of weak lines from 442–576 nm and increasingly stronger and more saturated lines (Figure 5.4) beyond 600 nm. These lines shift across the stellar spectrum by ±30 km/s over one year because of the Earth's barycentric motion and their intensity varies with air mass.

There are many limitations in our ability to model out telluric contamination.

- Water vapor is particularly problematic because it shows a highly variable contribution to the telluric spectrum.
- The atmospheric HITRAN line database and the accuracy of molecular parameters are incomplete.

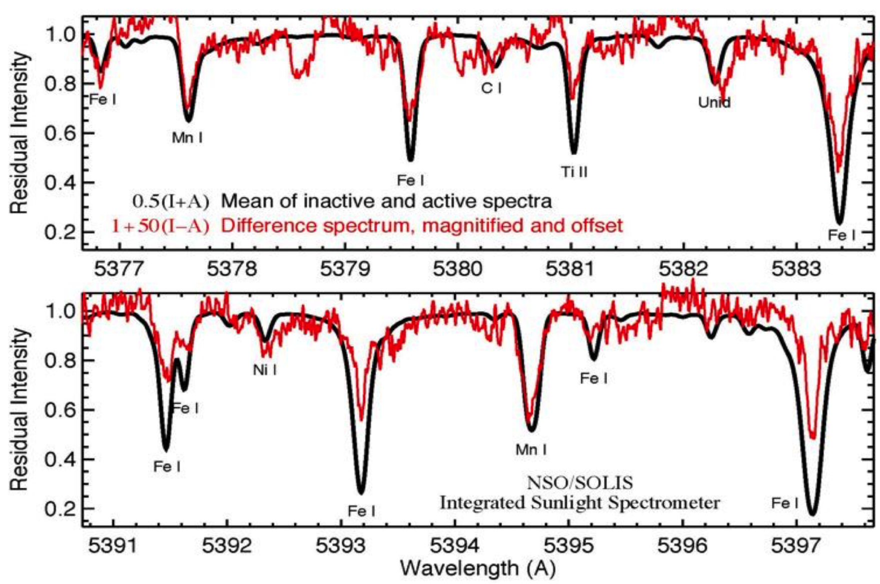

Figure 5.3: Full disk solar spectrum and the magnified difference between active and inactive states. Individual lines respond differently to activity changes, providing a way to help distinguish surface phenomena from Keplerian velocity shifts (Courtesy of Jeff Valenti).

- The correction of telluric absorption is based on the unrealistic assumption of a relatively stable atmosphere.
- There are inaccuracies in the radiative transfer code.
- The fractional sky background contamination is variable.
- These effects all worsen as one moves out into the near-IR, where atmospheric absorption (Figure 5.5) and night sky emission are considerably worse than at shorter wavelengths.

It is obvious that observing from above the Earth's atmosphere would eliminate these telluric effects at all wavelengths and would bring the power of a broad suite of wavelengths from 0.4 to 2 microns to bear on the problem of removing stellar noise. The next year or so will test the ability of ground-based instruments to operate through the atmospheric veil. Given the importance of EPRV measurements to NASA's goals of imaging other earths and searching for signs of life, it is prudent to consider a robust backup plan in case the ground-based efforts fall short.

5.4 Precursor Science and Technology: The Alpha Centauri Reconnaissance Mission

We present here a technology roadmap for EPRV from space (Figure 5.7). This includes a pathfinder mission on a small platform satellite with the primary goal of obtaining extreme precision radial velocity measurements for our nearest stellar neighbors, Alpha Cen A and B. These stars are ideal targets for a search for low mass planets: they are extremely bright (with magnitudes of V = 0 and V = 1 respectively), they have low chromospheric activity, high metallicity (abundant material for rocky planet formation), and have a nearly edge-on orbital inclination angle (*Pourbaix et al.*, 2002). Although the two stars have a semi-major axis of 25 AU, planets that orbit within 2 AU of either star are dynamically stable. The Alpha Cen binary

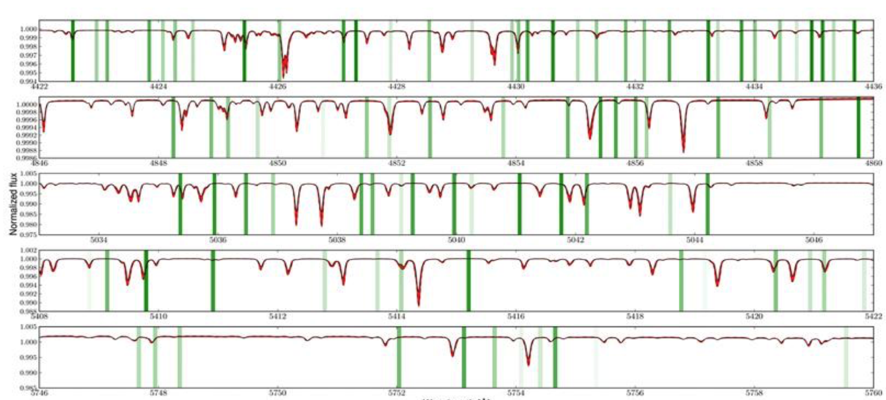

Figure 5.4: Telluric spectrum from 442–580 nm (Courtesy of *Cunha et al.*, 2014)

stars have already been the target of intense RV searches (*Dumusque et al.*, 2012, *Rajpaul et al.*, 2015) with controversial results to date. There are three significant handicaps that prevent EPRV for these stars with ground-based spectrometers:

- Photospheric velocity jitter;
- Telluric contamination;
- Blurring of light by the Earth's atmosphere, which results in contamination by the other star.

The high spectral resolution and broad bandpass of a space-based spectrometer would allow us to distinguish photospheric jitter from Keplerian motion with high fidelity (i.e., high SNR and stable instrumental line spread function) spectra. By virtue of working above the Earth's atmosphere, we eliminate the second two impediments for ground-based observations.

The mission concept employs a small, 25-cm telescope that couples light into a series of single-mode fibers (SMF). The SMFs illuminate high-resolution, diffraction-limited spectrographs (c.f., *Ghasempour et al.*, 2012; *Schwab et al*,. 2014; *Feger et al.*, 2014) that are wavelength calibrated with a frequency comb calibrated to reach 10 cm/s target RV measurement precision in a 900 sec exposure. With a diffraction-limited resolution of 2" at 2 μm coupled into an SMF, even a small telescope would be able to cleanly separate the light between the two stars whose separation is 5"–10" through 2030 (Figure 5.6).

The return from this experiment is two-fold: a long baseline and pristine data set would be made available for the closest star to us so that the noise floor of the RV technique can be explored in the absence of telluric contamination. Throughput estimates show that we could obtain sufficient SNR (500 from 0.5–2 μm in a R=150,000 resolution elements) on αCen A in

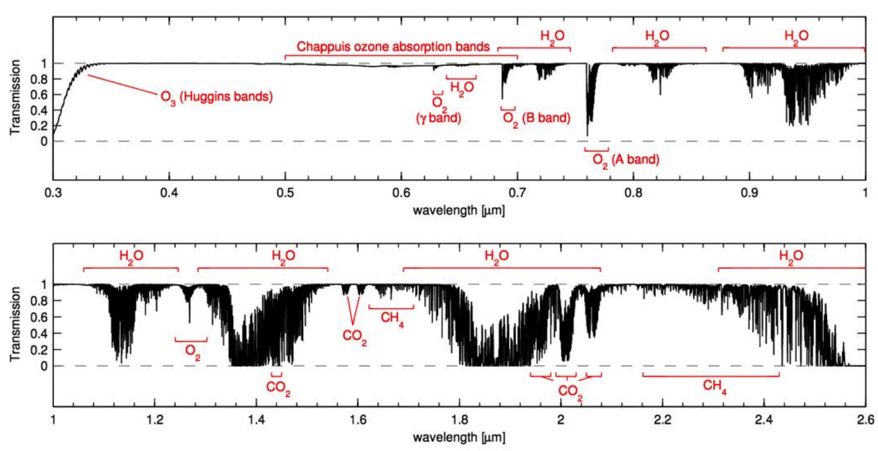

Figure 5.5: Telluric transmission spectrum from 0.3 to 2.6 microns (*Smette et al.*, 2015).

900 sec with efficient fiber coupling (>75%) and a high-throughput (>30%) optical design (Table 5.1). By averaging over 1,000 individual spectral lines in this wavelength range, this performance is adequate to achieve an instrumental EPRV measurement <5 cm/s. The ability to achieve this accuracy on αCen itself would, of course, depend on being able to remove the effects of stellar activity. That challenge is the fundamental goal of this experiment. Technology drivers for this experiment include:

- Radiation hardened single-mode fiber
- Broadband, flattened frequency comb with 10–30 GHz mode spacing over the 0.4–2 micron range
- Efficient and broadband multi-single-mode fiber coupling

Such an instrument could be proposed for a Mid- or Small-Explorer mission solicitation. The bandpass of this instrument will be determined by the available comb technology and it will demonstrate the benefits of removing the atmospheric veil from EPRV measurements. Astronomers have never been able to obtain extremely high-resolution broad bandpass spectra of stars that are free from telluric contamination. A mission that could obtain high-cadence time series with high SNR, high resolution spectra spanning from 0.4 to 2 microns toward a large number of bright stars would have a significant impact on fundamental stellar astrophysics. Such spectra would provide the needed breakthrough to reach the highest possible Doppler precision and would provide a

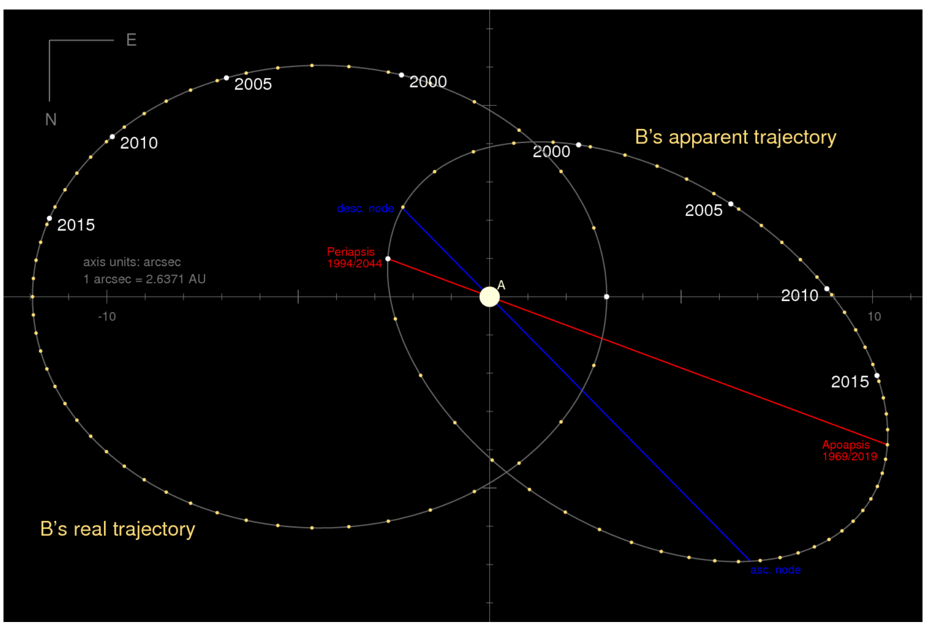

Figure 5.6: The true and apparent orbit of Alpha Cen A & B in arcsec. `https://commons.wikimedia.org/wiki/File:Orbit_Sirius_B_arcsec.png`

better understanding of the wavelength dependence of phenomena in stellar photospheres—spots, faculae, and granulation—across many spectral types and evolutionary stages. This information will be a critical pathfinder for the coming LUVOIR/HabEX observatory.

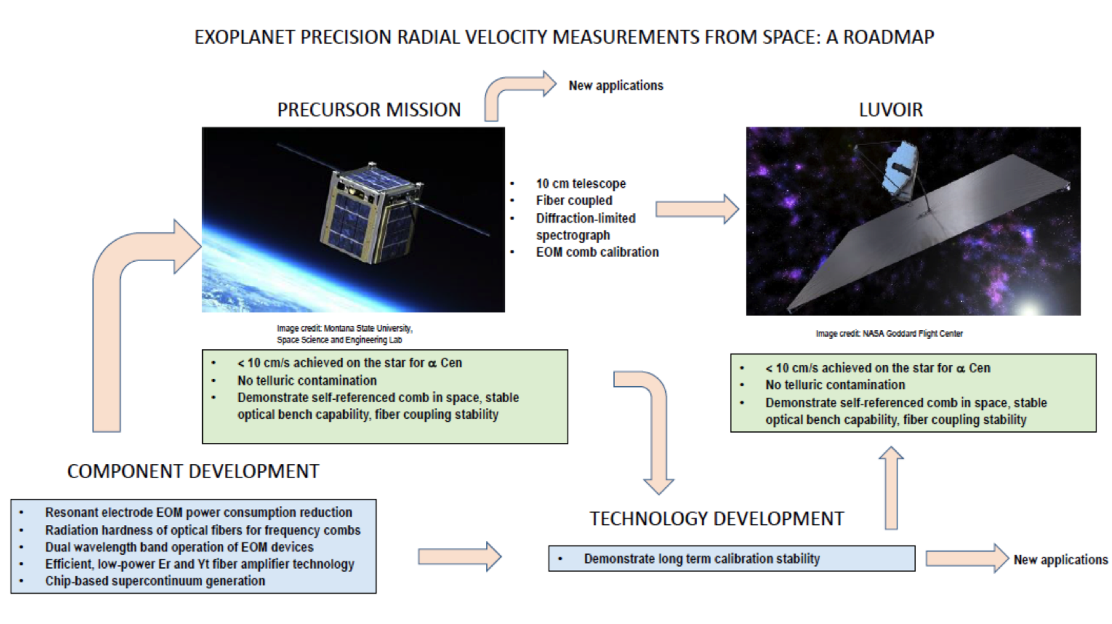

Figure 5.7: Technology Development Roadmap. Component development supports a precursor mission with a science goal of <10 cm/s with no telluric contamination achieved on the star for Alpha Centauri using a self-referenced comb, single mode fiber-coupled, diffraction-limited 10 cm telescope, and a high-resolution spectrograph over a broad wavelength range, from 0.4–2.4 microns, to understand the stellar atmosphere. Component development and the precursor mission validate the capabilities in preparation for an EPRV instrument for LUVOIR or HabEx.

5.5 An EPRV Instrument for LUVOIR or HabEx Concepts

Upon successful completion of the pathfinder mission, the benefit of measurements without telluric contamination will be demonstrated, as will many of the comb technologies. Additional development may be needed at the component level to assess the degradation in the comb performance, if any, over the >10-year duration of a flagship mission (for example, radiation damage to the fiber and long-term calibration stability). But the successful execution of the Alpha Centauri mission would put the development of a EPRV instrument for LUVOIR or HabEx for a launch in the 2030s on a sound scientific and technological footing. The driving requirements for spectrograph and comb for LUVOIR would be very similar to the pathfinder mission described, the main difference would be the greatly increased 1600× increase in photon collecting area of a 10 m vs. a 0.25 m telescope which would enable the study of stars 5–8 magnitudes fainter than Alpha Cen A.

5.6 Technology Roadmap for Laser Frequency Combs for EPRV

5.6.1 EPRV Frequency Comb

Wavelength calibration of the radial velocity spectrograph directly traceable to SI definitions of time and frequency will be provided by an optical frequency comb. The perfectly spaced modes of the comb are the backbone ruler for the spectrograph that enables comparisons to ground-based observatories and future space-based spectrographs apart from legacy artifacts. To match the wavelength resolution of an Alpha Centauri Reconnaissance Observatory, a relatively large comb mode spacing in the 10–30 GHz range is required. Moreover, to support the kind of ultra-wideband spectrographic observations uniquely possible outside the Earth's atmosphere, the calibration comb is desired to support the wavelength range 400–2400 nm. Finally, operating lifetime of at least 2 years would be necessary for a pathfinder mission, and much longer times (e.g., 10 years) for a flagship mission.

To meet these challenging goals, we propose a frequency comb based on either a microwave-rate electro-optic modulation (EOM), or a soliton microresonator frequency comb (microcomb) with subsequent spectral broadening in nonlinear media. Comb generation in each of these devices is described in Chapter 2. A 12 GHz EOM OFC has been demonstrated at ground-based observatories (*Yi et al.*, 2016), and self-referencing of an EOM comb has also been shown (*Beha et al.*, 2015; *Carlson et al.*, 2017). Further, many of the components used in an EOM comb have already been characterized for space applications (*Thomes et al.*, 2007). Microcombs offer the most promising technology path for spaced-based observations of earth-scale exoplanets. This class of frequency combs offers a number of advantages, including low size, weight, power consumption, and insensitivity to environmental fluctuations. Two groups (*Herr*, 2017; *Suh*, 2017) have now demonstrated microresonator frequency combs for astronomical spectrograph calibration. The pump laser for one of these demonstrations was locked to a 100 MHz fiber laser comb, and the other was a HCN-line referenced laser. Soliton microcombs can also offer the benefit of intrinsic comb line spacing desired for astronomical spectrographs.

Recommendations for moving forward on technological questions for EOM combs:

- Microwave electrical engineering study of resonant-electrode EOM devices to reduce the electrical power required in forming the EOM comb. There is already significant research literature in this area and the method relies on appropriate impedance matching and transformer engineering. A commercialization route should be sought.
- Explore dual wavelength band operation of EOM devices with the goal of generating both 1.5 μm and 1 μm EOM comb from a common set of EOMs. Wavelength filtering could separate the comb for subsequent spectral broadening.

- Explore efficient erbium and ytterbium fiber amplifier technology that can handle ~25 nm bandwidth. Need low-power consumption and ability to amplify <picosecond pulses.

- Develop chip-based supercontinuum generation media and their efficient interface with free space and fiber optics.

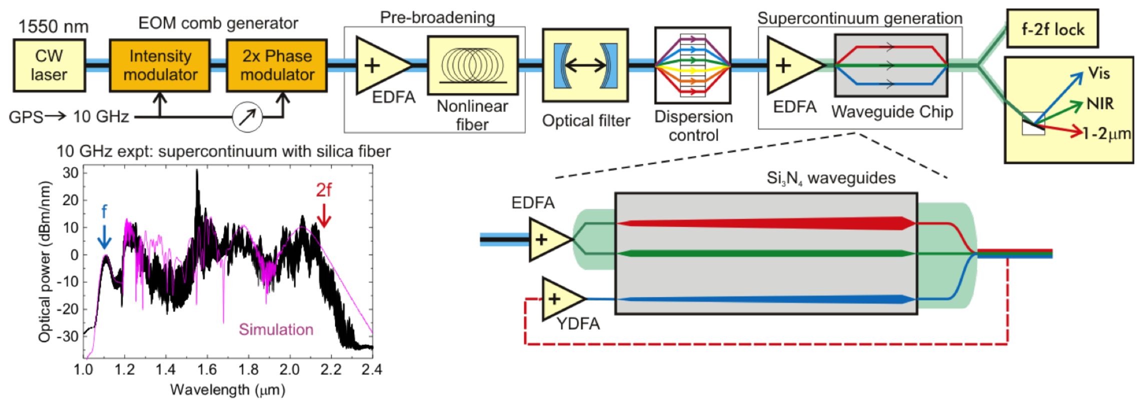

Figure 5.8: Layout of a self-referenced EOM frequency comb broadened with HNLF and SiN waveguide stages

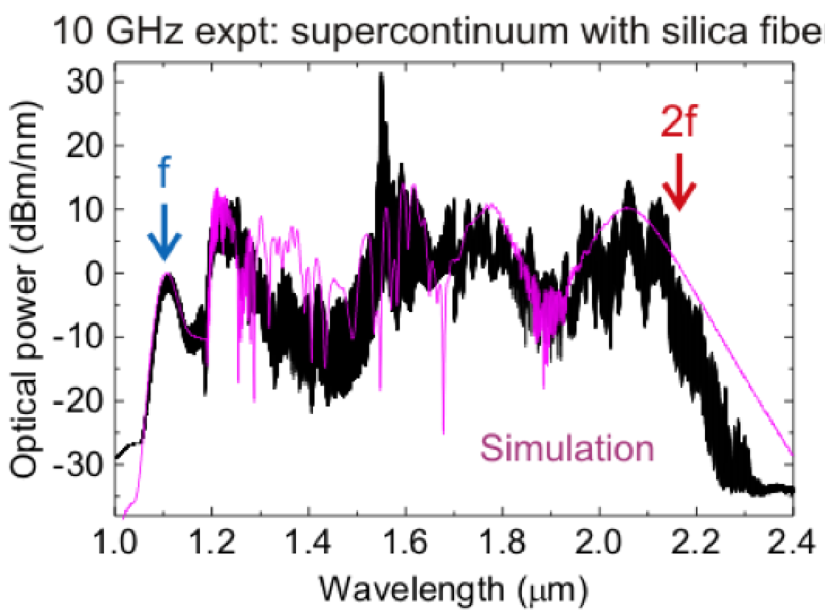

Figure 5.9: Octave-spanning supercontinuum spectrum of a 10 GHz HNLF-broadened EOM comb

5.6.2 Additional Technology Needs for an EPRV mission

In addition to the frequency comb itself, other technology work necessary for a space-based PRV mission include characterization of optical components, including optical fiber and detectors, for space environmental effects. Such work has been ongoing,[1] determining, for example, radiation effects on a wide variety of silica, fluoride, and photonic crystal fibers. Another requirement—the efficient coupling of diffraction limited starlight into single mode fibers—has been noted and investigated (*Jovanovic et al.*, 2017).

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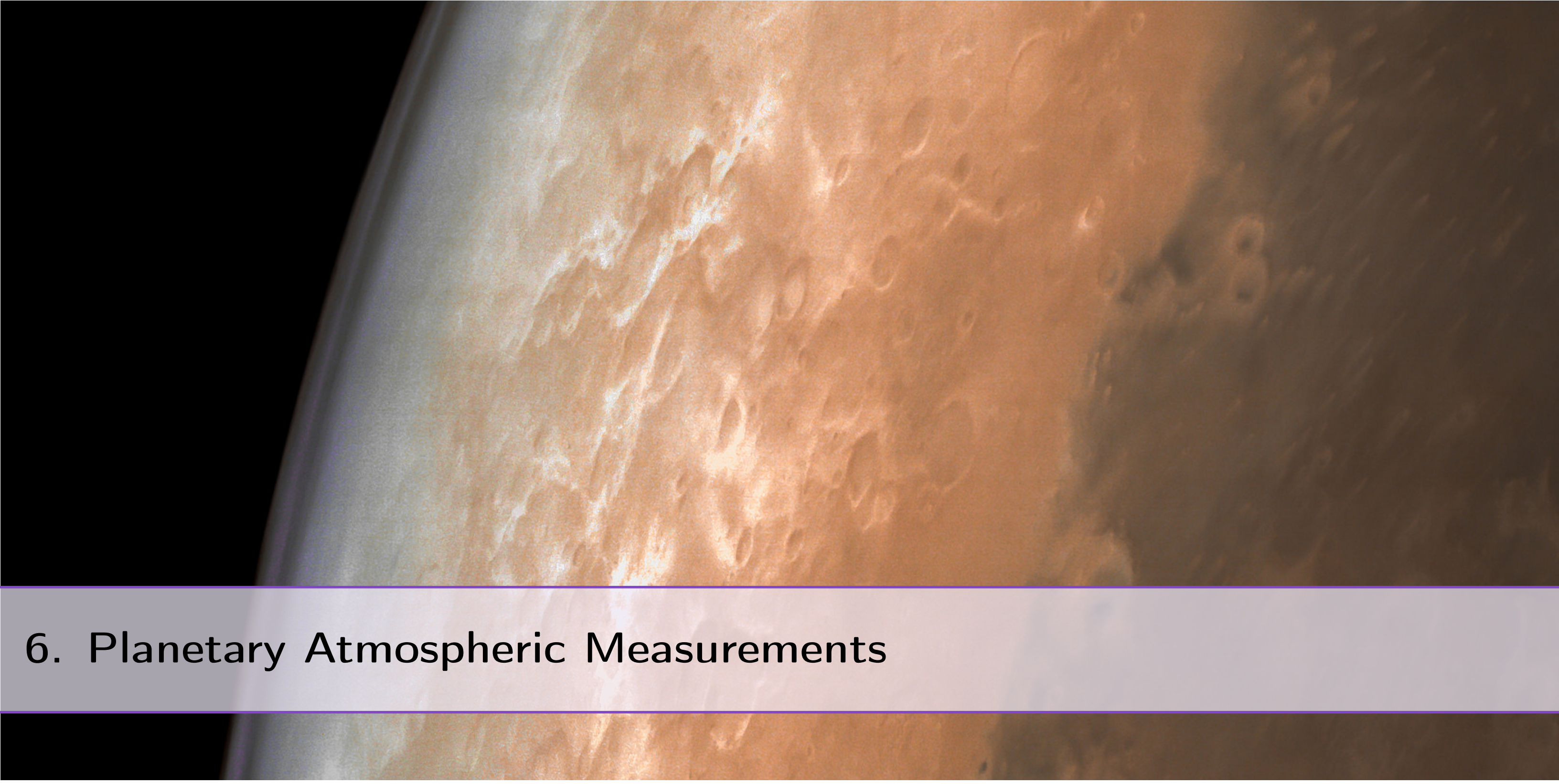

6. Planetary Atmospheric Measurements

One area where frequency combs have already found significant application is in ground-based spectroscopy. As described in Section 3.1.1, OFCs offer the potential for broadband, simultaneous, high-resolution, high-sensitivity spectroscopy with a small instrument package. In this chapter, we explore the potential advantages of a CubeSat-scale, space-based OFC spectroscopy instrument for performing atmospheric analysis either in situ or through active atmospheric occultation experiments to help elucidate atmospheric composition, properties, and changes at multiple targets throughout the solar system. The concept, the Comb Occultation Cubesat Observatory (COCO), removes the dependence on the sun as the light source, thereby enabling new spectral and temporal coverage.

In an occultation experiment, electromagnetic radiation passes through the atmosphere of a planetary body and is refracted as depicted in Figure 6.2; a detector measures the degree of refraction to discern information about the atmospheric temperature, pressure and density.

Atmospheric occultation experiments are well known in planetary science and have been used to study all planets and some moons in our solar system; missions including Pioneer Venus, Mariner, Magellan, Pioneer, Voyager, Cassini, Galileo, and New Horizons have used RF, stellar, or both types of occultation. RF occultation has also been performed at Earth by using GNSS satellites (GPS Radio Occultation, or GRO) since 1995. However, using infrared wavelengths as well as RF for occultation experiments can also provide compositional data. IR-laser occultation experiments were performed in 2011 between two telescopes on the Canary Islands in the first demonstration of laser occultation at Earth. This was a first step toward suggested LEO-to-LEO infrared laser occultation measurements in combination with GRO to monitor a complete suite of essential climate variables (*Kirchengast and Schweitzer*, 2011). The concept was part of the

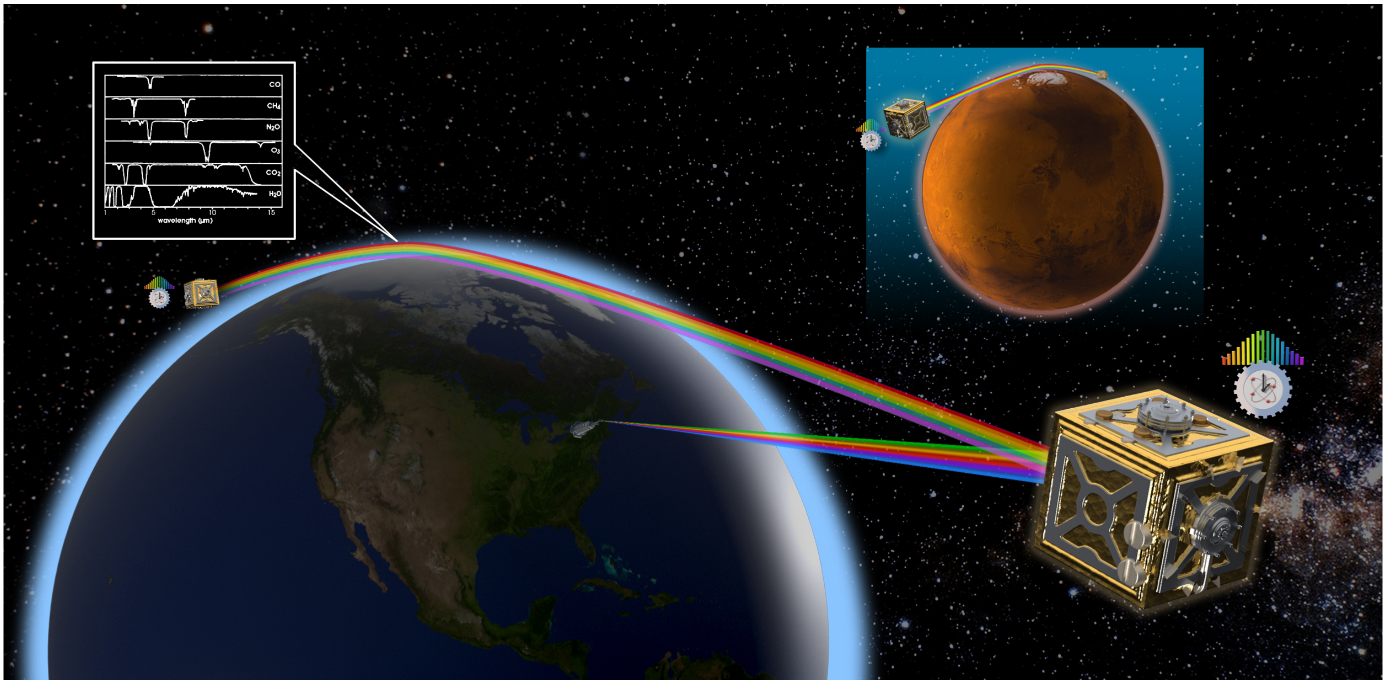

Figure 6.1: Atmospheric spectroscopy applications.

ACCURATE mission concept proposal to ESA. In the experiments, IR laser light was transmitted over approximately 144 km between two high-altitude (2.4 km) observatories. The main part of the transmitter breadboard consisted of four tunable single-mode distributed feedback lasers emitting in the near infrared spectral range—two lasers near 2.1 microns, and the other two lasers near 2.3 microns. One of the latter two lasers was used for measuring at a reference wavelength displaced from the absorption feature to cancel out effects such as aerosol, Rayleigh scattering, atmospheric scintillation, and cloud absorption. Laser power was between 4 and 10 mW (*Brook et al.*, 2012).

In another ground-based atmospheric spectroscopy experiment, an infrared dual comb spectrometer (using 2-mW combs with approximately 10% return of the launched power) has been used to demonstrate spectroscopy over a 2-km open air path (*Rieker et al.*, 2014) to measure the gas concentration of CO_2, methane, and H_2O; the time-dependent concentration of these gases was monitored over a three-day period.

At the very least, OFCs may replace the ultra-stable oscillators (USO), that are referenced by RF systems for radio occultation. However, a reasonable extrapolation of the ground-based laser and DSC spectroscopy work performed thus far is the Comb Occultation Cubesat Observatory concept, where various configurations for space-based dual comb spectroscopy can be envisioned, including two LEO spacecraft—a transmitter and a receiver, or an LEO spacecraft receiving comb light from a GNSS-like satellite. Conceptually, OFCs used for future space optical communications might perform both functions.

The Mars Cube One (MarCO) twin communications relay spacecraft to be launched along with the InSight mission to Mars in 2018 provide a demonstration of CubeSat architecture for deep space flight. As such, they are a pathfinder for future missions like COCO.

6.1 Science Cases for Laser Comb Occultation

Compared to solar occultation, active occultation removes the dependence on the sun as the light source, thereby enabling new spectral and temporal coverage. Moreover, comb laser sources provide wide instantaneous spectral coverage with high spectral resolution, offering simultaneous, sensitive measurements of multiple species. Dual comb laser spectroscopy offers not only an opportunity to measure atmospheric gas species throughout the solar system (see Table 6.1), but may also enable fast "on the fly" analysis of targets such as comet tails or geyser plumes at Enceladus. Workshop participants also suggested OFC-based spectroscopy for Zodiacal dust measurements.

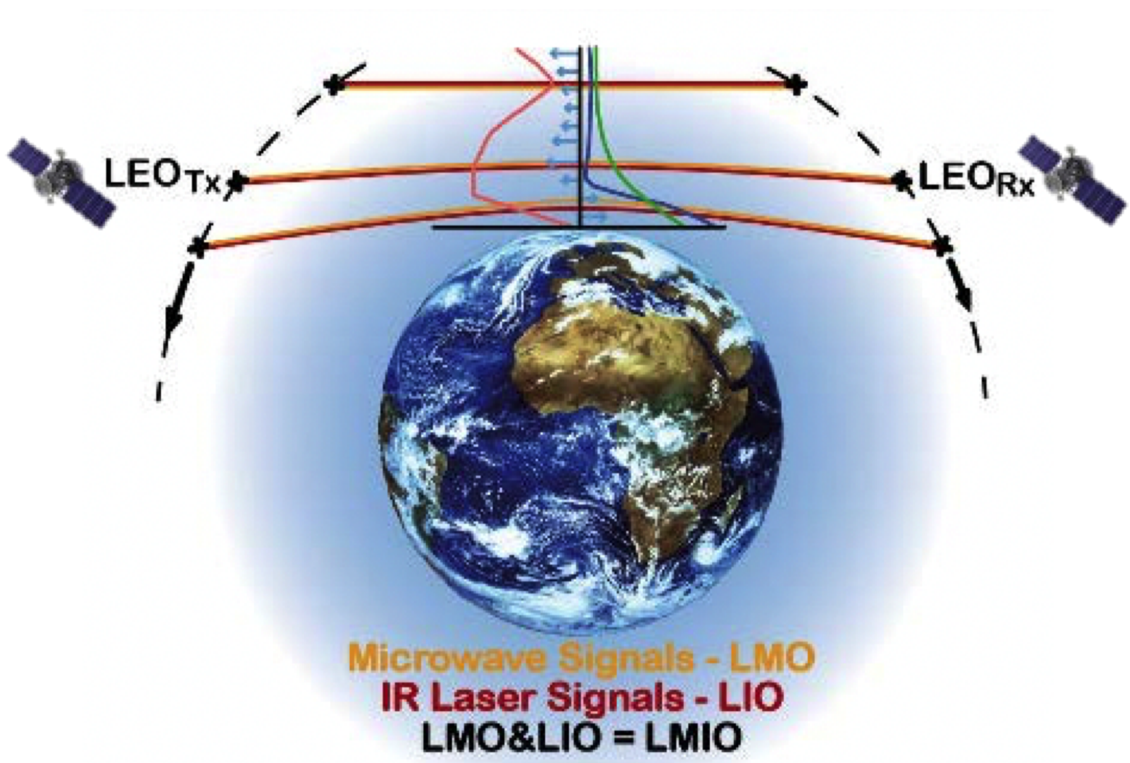

Figure 6.2: Active occultation at Earth concept adapted from *Kirchengast and Schweitzer* (2011).

Solar System Body	Atmosphere and Ionosphere	Radio Occultation Mission Heritage
Mercury	—	Mariner 10 (1973)
Venus	CO_2, N_2	Mariner 5 (1967), 10; Venera 9, 10, 15, 16; Pioneer Venus Orbiter (1978); Magellan (1989); Venus Express (2005)
Earth • Greenhouse Gases	N_2, O_2	GNSS Radio Occultation (GRO) (since 1995)
Mars	CO_2, Ar	Mariner 4, 6, 7, 9 (1964, 1969, 1971; Mars 2, 4, 5, 6; Viking 1, 2 (1975); Mars Global Surveyor (1996); Mars Express (2003); Mars Reconnaissance Orbiter (current)
Jupiter • Io • Callisto • Europa • Ganymede	H_2, He, CH_4, NH_3	Pioneer 10, 11, Voyager 1, 2 (1977); Galileo (1989)
Saturn • Titan • Enceladus	H_2, He, CH_4, NH_3; N_2, CH_4, H_2O geysers	Pioneer 11; Voyager 1, 2 (1977); Cassini (1997)
Uranus • Titania	H_2, He, H_2O, CH_4, NH_3, CO_2?	Voyager 2 (1977)
Neptune • Triton	H_2, He, CH_4, N_2, CO	Voyager 2 (1977)
Pluto • Charon	N_2	New Horizons (2015 uplink)
Comet Halley	—	Giotto, Vega 1,2

Table 6.1: Solar system atmospheres and ionospheres

An OFC-based active occultation instrument on COCO could potentially provide global, day-night, broad spectral coverage in a low SWaP package to substantially enhance understanding of atmospheric gases.

6.1.1 Earth Atmospheric Science

Earth climate researchers rely heavily on atmospheric composition data obtained in-situ at ground stations and aerial platforms, and from orbital observations. The latter has been provided by missions like NASA's Orbiting Climate Observatory (OCO-2) that launched in 2014 and collects column CO_2 measurements, the Atmospheric Infrared Sounder (AIRS) instrument on the Aqua satellite launched in 2002 that also collects column data of clouds, O_3, CO, CO_2, CH_4, SO_2 and suspended dust particles in an 800-km wide swath, and the Tropospheric Emission Spectrometer (TES) that was flown for 14 years on the Aura satellite and only recently decommissioned.

The OCO-2 instrument is a set of three high resolution grating spectrometers, each one specific to one of three narrow bands corresponding the O_2 A-band near 0.76 microns, the "Weak" CO_2 band near 1.6 microns and the "Strong" CO_2 band near 2.06 microns (*Pollock*, 2010). However, OCO-2 relies on passive illumination from sunlight and therefore cannot make measurements during the polar winters. Yet monitoring of multiple greenhouse gases (e.g. CO_2, CH_4, N_2O) over these dark regions are important pieces of the climate puzzle. For example, there is a disconnect between the measurement scales for fluxes of methane in the arctic tundra, which can be measured at the 100 m–1000 m scale, whereas model estimates are typically made at the ~100 km scale. Therefore, it is critical to upscale site level measurements to the larger scale for model comparison (*Davidson et al.*, 2017). More data is also needed in understanding CO_2 seasonal variations over Antarctica (*Murayama*, 2002).

The TES instrument was a Fourier Transform spectrometer covering infrared wavelengths from 3.2 to 15.4 µm. While TES was not limited to daytime observations and was able to distinguish altitude of the absorbing species (thus performing both tropospheric and stratospheric measurements), the instrument mass and average power allocations were 385 kg and 334 W[1], respectively. Developing instruments of this capability with much lower SWaP for deployment on lower cost space platforms would be very desirable.

As the dominant greenhouse gas, stratospheric H_2O also has a significant impact on Earth's climate (*Forster and Shine*, 2002; *Solomon et al.*, 2010). The record of stratospheric water vapor since 2000 has shown periods of both increasing and decreasing concentrations (*Randel et al.*, 2004, 2006; *Scherer et al.*, 2008; *Fueglistaler*, 2012; *Nedoluha et al.*, 2013), but the mechanisms driving changes in stratospheric water vapor concentrations are currently unresolved (*Kindel et al.*, 2015). The tropopause is a strong cryotrap, limiting stratospheric H_2O mixing ratios to a few ppm. Consequently, measurements of H_2O and its isotopologues are challenging. The dominant in-situ/chemical source of stratospheric H_2O is methane through reaction with hydroxyl radicals formed from singlet oxygen and H_2O. Simultaneous measurements of H_2O mixing ratios, isotope ratios (e.g., HDO/ H_2O, $H_2(18)O/H_2O$), and methane mixing ratios would be a powerful toolset for disentangling different mechanisms driving changes in stratospheric water

[1] TES Instrument: `https://tes.jpl.nasa.gov/instrument/instrumentspecs/`

vapor abundance, yet measurements thus far comprise mainly airborne, in-situ measurements, i.e., only spot coverage.

Also needed is an improved understanding of tropospheric OH chemistry. OH is the key species in tropospheric chemistry. It is a radical that does not react significantly with O_2; thus, it exists in sufficient abundance to be the main oxidant of other species in the atmosphere. Global mapping of tropospheric OH is not possible thus far, due to its exceeding low abundance (~10^6 molecules/cm^3). However, global mapping of multiple species that are chemically closely connected to OH (e.g. CO, CH_4, H_2O_2, etc.) will greatly enhance our understanding. Different proxy molecules, due to their different atmospheric lifetimes and spatial distributions, will provide complementary information regarding spatial and temporal characteristics of OH chemistry.

6.1.2 Mars Atmospheric Science

The Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) is an instrument on the Mars Reconnaissance Orbiter (MRO) for performing atmospheric science. The first demonstration of cross-linked occultation measurements at Mars were performed between MRO and Mars Odyssey in 2007 (*Ao et al.*, 2015). The mass and power of CRISM (*Murchie et al.*, 2007) is approximately 33 kg and 47 W, respectively.

COCO could be deployed in Martian orbit as well to provide a lower SWaP solution with more continuous coverage; a "Breathing Mars" mission to study seasonal processes could be undertaken with this technology. Currently, methane and CO_2 isotope detection requires multiple instruments to do correlated measurements (water, water isotopes, CO_2, CO_2 isotopes, and methane). With dual comb spectroscopy, this can be accomplished in one instrument while potentially also obtaining simultaneous ranging measurement of the surface. This science is complementary to the findings of the Mars Atmosphere and Volatile Evolution Mission (MAVEN) mission, the goals of which were to determine how the planet's atmosphere and water, presumed to have once been substantial, were lost over time. Data show seasonal variations in the rate of loss of Mars' CO_2-dominated atmosphere, as well as significantly increased deterioration during solar storms.[2]

The European ExoMars mission's Trace Gas Orbiter instrument suite (launched in March of 2016) will measure a large array of atmospheric molecules with unprecedented sensitivity, and as such, it will be a huge step in our understanding of Martian climate and habitability. It is currently in orbit around Mars with mapping activities planned in 2018. ExoMars will rely on solar occultation and its NOMAD and ACS instruments to provide atmospheric composition observations at the parts-per-billion (ppb) level twice per orbit with the local sunrise and sunset. COCO is a concept for performing such observations continuously through active occultation.

[2] https://www.nasa.gov/press-release/nasa-mission-reveals-speed-of-solar-wind-stripping-martian-atmosphere

6.2 Comb Technology Development for Atmospheric Spectroscopy

One of the earliest proposed, and most widely pursued, applications for frequency combs has been broadband molecular spectroscopy. As such, it is perhaps unsurprising that frequency comb-based spectroscopy offers a range of new opportunities for active satellite remote sensing. Particular strengths of a comb-based spectrometer include broad spectral bandwidths, long optical paths, and low systematics.

Fiber based frequency combs can reasonably access broad spectral bandwidths including the entire near-IR spectral region (1–2.2 microns). While this can be done simultaneously, the combs are also "reconfigurable" and could be designed to concentrate power in 10 nm to 100 nm bands to allow for more sensitive detection of specific molecules depending on system requirements. Here, we focus on systems to retrieve CO_2 and methane signatures in the 1.6 to 1.7 μm spectral region. Spectral coverage around 2 microns is accessible through a range of options and is attractive for monitoring other species such as N_2O or $^{13}CO_2$. In sparser planetary atmospheres such as Mars, operating deeper in the infrared is attractive. Optical frequency comb technology is becoming well established in the 3 micron region and with new quantum cascade laser (QCL), difference frequency generation (DFG) and optical parametric oscillator (OPO) techniques, combs are also becoming viable at longer wavelengths.

For satellite-based planetary monitoring, long optical paths of 100–1000 km scale are imposed by many operational geometries. Frequency combs sources emit a high brightness single spatial mode that can be propagated long distances. In many cases, the comb light transmitter and receiver systems would have very similar requirements to optical communications systems allowing the possibility of sharing apertures and possibly even detectors and electronics.

Frequency comb spectroscopy can, unsurprisingly, record spectra with a near-perfect frequency axis, but it also offers additional means to control systematics. For certain comb spectroscopy techniques, the spectral resolution of the system can be several orders of magnitude less than the already fine spectral point spacing. This means the system has a negligible "delta-function" instrument line shape that is not prone to drift and does not lead to spectral smearing. Finally, the combination of broad bandwidth and high spectral resolution potentially allows for the detection and removal of interfering species or parasitic etalons that can also impact concentration retrievals.

6.2.1 Earth Atmospheric Comb Spectroscopy System

One strong candidate approach for this measurement would be dual-comb spectroscopy. The dual-comb technique is based on the interference of two frequency combs, which can be recorded on a single moderately fast detector (see section 3.1.1). This technique can be used to record broad spectra with extremely high resolution and no instrument line shape and relaxes optical power requirements of the system by allowing one to concentrate all light on a single detector.

Given the length of the proposed measurement paths, significant beam attenuation and beam scintillation in the lower regions of the Earth's atmosphere is likely. This power loss would strain the sensitivity of any non-Fourier transform based spectrometer. At the same time, the scintillation would potentially modulate the resolution and instrument line shape of any conventional spectrometer, making it difficult to achieve the desired measurement precision.

Assuming then a dual-comb approach, the ideal comb for this system would be two combs that deliver 10 nm to 100 nm of instantaneous bandwidth in the 1600 nm–1700 nm spectral region. Comb tooth spacing would ideally be in the 100 MHz–200 MHz range to adequately sample the ~1 GHz wide spectral features. The system would also need to deliver 10 μW–100 μW to the receiver detector. Current technology would suggest that this is an erbium fiber-based comb spectrally broadened to cover the 1.6–1.7 μm window. Solid state lasers, electro-optic modulator-based combs or ultra-low FSR micro-resonator based combs are also possible candidates, but typically have broader mode spacing.

6.2.2 Mars-Based System

For detection of methane in the Martian atmosphere, the problem is somewhat different. Here the atmosphere is rarefied, minimizing beam scintillation. Attenuation and interference from water vapor is also not a concern, nor is there a strong methane background. At the same time, the methane signal of interest is orders of magnitude weaker. In this case, maximizing measurement sensitivity is critical, while measurement precision considerations are relaxed. As such, a Mars atmospheric methane measurement would preferably be done in the mid-IR region (3 microns) where absorption cross-sections are two orders of magnitude stronger. Also, it may be advantageous to restrict the spectral bandwidth to a few nanometers and concentrate all optical power on a few lines of interest for maximal sensitivity. Martian gasses are cold and negligibly pressure broadened, so even finer comb tooth spacing (<50 MHz) would be required. Given the narrow bandwidths, spectral region of interest and low tooth spacing, a likely candidate might be QCL or ICL combs where 3 micron-centered combs could be directly generated. An electro-optic modulator-based comb at 1550 nm that is converted to 3 microns through nonlinear difference frequency generation using a high efficiency nonlinear waveguide device and a 1 micron pump source is another possibility. Solid-state lasers or optical parametric oscillators may also be possibilities assuming issues of complexity, size, and tooth spacing can be resolved.

6.3 Other Technology Requirements

As laser signals transmit through the atmosphere, turbulence, scintillation, and scattering will affect the intensity of the received signal. This signal attenuation could potentially be remedied with adaptive optics, enabling better measurements (*Marinan*, 2016).

Advanced pointing control technology will also be crucial for the implementation of active laser comb occultation experiments and would benefit from similar technology being developed for optical communications.

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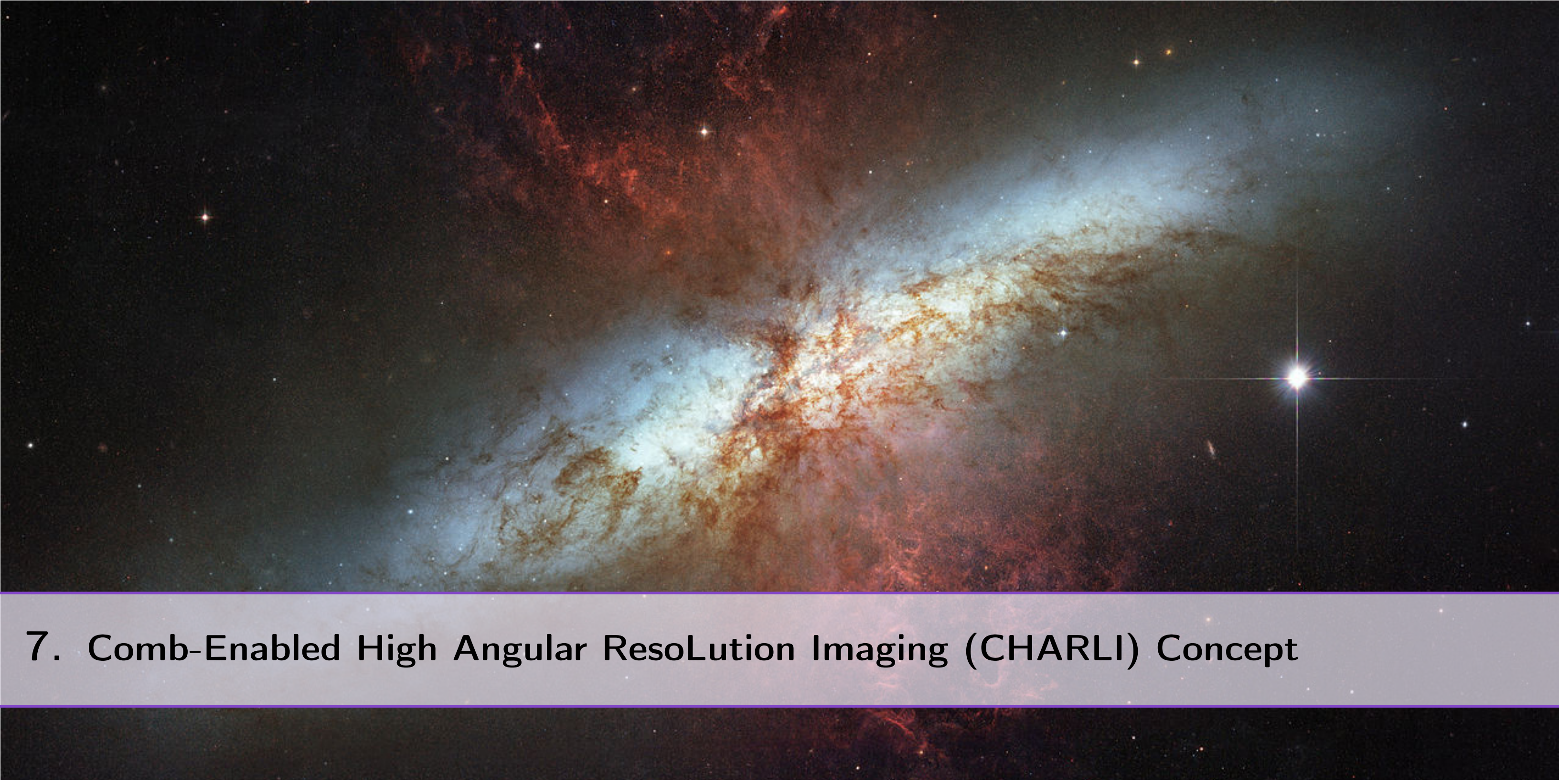

7. Comb-Enabled High Angular ResoLution Imaging (CHARLI) Concept

7.1 Introduction

In 1988, Charles H. Townes observed the first interferometric fringes from the Infrared Spatial Interferometer (ISI) he established at the Mount Wilson Observatory. ISI, operated by the University of California, Berkeley Space Sciences Laboratory, is a heterodyne interferometer operating in the mid infrared portion of the spectrum near 10.6 microns. It utilizes a single CO_2 laser as the local oscillator used to produce an Intermediate Frequency (IF) when combined with telescope light. Infrared heterodyne detection has long been known to provide a means of achieving high conversion gain between power at the input and at the difference frequency, and frequency selectivity to reduce noise bandwidth (*Teich*, 1968). By heterodyning astronomical signals with a local oscillator in the mid-infrared portion of the spectrum, ISI brings a special capability to observe stellar sizes, shapes and asymmetries, and the changes of these quantities over time with very high angular resolution. While stars are often surrounded by dust and may be obscured at visible wavelengths, mid-IR radiation from the star penetrates the dust better than shorter wavelengths and mid-IR radiation is also emitted by the warm dust. ISI observations in this band therefore give information about both the star and the surrounding dust.

However, ISI is limited by the signal-to-noise ratio that results in part from the single local oscillator channel offered by the CO_2 laser. Participants at the KISS workshops identified the Comb-enabled, High Angular ResoLution Imaging (CHARLI) Concept as an enabling application of optical frequency combs that could greatly mitigate this limitation; by substituting a mid-IR-centered frequency comb with hundreds or thousands of lines (n) for the CO_2 laser local oscillator, the SNR could improve by $\sqrt{n}$, thus making interferometry in the mid-IR competitive with single-channel direct observation in the visible or near-IR.

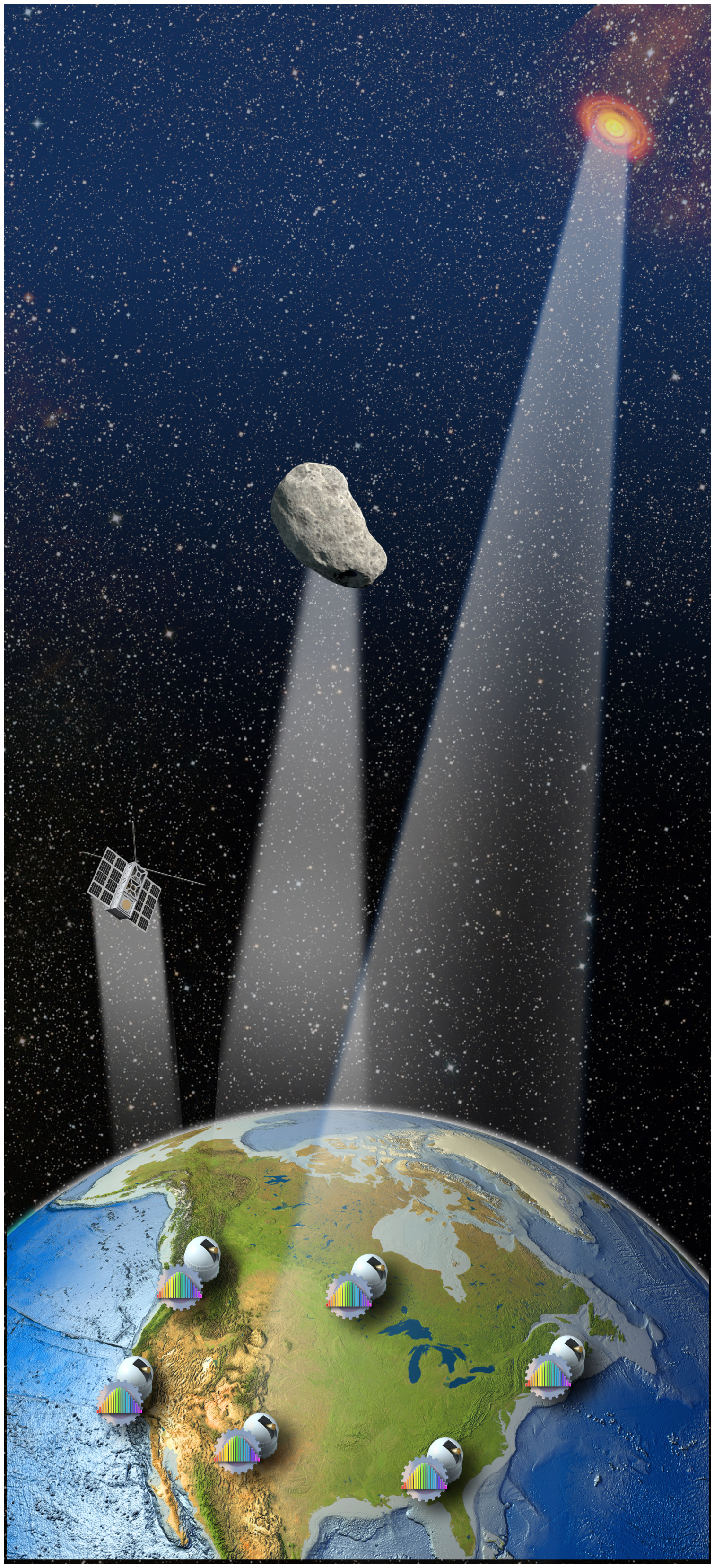

Figure 7.1: Comb-enabled High Angular Resolution Imaging (CHARLI) concept.

The advent of optical frequency combs, particularly combs centered around 10 microns, provides a critical, enabling component to interferometers such as ISI. It is only fitting that this implementation of optical frequency comb technology be named for the Nobel-prize-winning inventor of both the laser and the ISI—Charlie Townes.

7.2 Heterodyne Interferometry in the Mid-IR with OFC Local Oscillators: The Basis of the CHARLI Concept

The realm in which heterodyne detection performance begins to equal that of direct (homodyne) detection interferometry is in the mid-infrared portion of the spectrum. An analysis of the relative performance of these two methods was recently performed by *Ashcom* (2015), who illustrates this point explicitly in Figure 7.2.

Aschom's analysis limits the number of channels to preserve a constant maximum bandwidth of 2% to avoid bandwidth smearing—where too wide a bandwidth would represent different effective baselines or different spatial frequencies, and therefore lead to blurring of the image in the interferometric reconstruction. This reduces the number of available channels for increasing wavelength in a calculation of the Cramer Rao lower bound for the required measurement time. However, the combined signal and comb light can be dispersed along an array of detectors so long as each narrow bandwidth is preserved around each comb line local oscillator. Bandwidth synthesis can then be performed as it is in radio astronomy so that the number of comb lines that can be used is then limited only by the visibility window, the comb generator technology, and the correlator for data processing.

The net benefit goes as a factor of $\sqrt{n}$, as if each comb line LO represented a separate telescope. Therefore, a substantially reduced observation time than that shown in Figure 7.2—assuming a case with ~1000 comb lines spaced 10 GHz apart between 8 μm and 11 μm for a single pair of 10 GHz heterodyned telescopes with all other assumptions made by Ashcom preserved—is enabled by frequency comb local oscillators and fast detector arrays. It should be noted that, similar to "bandwidth smearing," a related requirement is that the correlator must sample the signals fast enough that the change in beam direction is less than the beam width to avoid "time smearing" of the image.[1]

One might ask why not attempt heterodyne interferometry in the near-IR. At 1.5 microns the heterodyne receiver quantum noise is significant; the equivalent noise temperature of the receiver will be of order 6000–7000 K. This is a big disadvantage relative to direct detection interferometry. However, for bright objects, NIR heterodyne still may allow for high-resolution imaging.

[1]See Section 9.2.1 in Chapter 9 of "Interferometry and Aperture Synthesis," `ircamera.as.arizona.edu/Astr_518/interferometry1.pdf`

7.3 CHARLI Applications

7.3.1 Planet Formation Imager

Planet Formation Imager (PFI) is a concept put forward by Ireland and *Ireland & Monnier* (2014) for achieving the angular resolution and sensitivity sufficient to resolve structures within the Hill sphere—the region around a planet where it dominates gravitationally and attracts satellites—around newly formed giant planets orbiting solar-type stars in nearby star formation regions. In such regions, the thermal radiation from the newly-formed planet and its environment should overwhelm scattered light from surrounding dust; thus, observing in the mid-infrared portion of the spectrum offers an observational window not afforded by other methods. The PFI concept supposes a ground-based, multi-kilometer baseline heterodyne interferometer operating in the mid-IR where frequency combs are used as the local oscillators. In their notional design concept, Ireland and Monnier presuppose the use of HgCdTe detectors to heterodyne the telescope light and 3 GHz spaced comb modes produced in the mid-IR by difference frequency generation, and fringe tracking between telescopes with direct-detection interferometry in the H-band (~1.6 microns) using optical fiber. The objective is to achieve a 400 $\times$ 400 resolution element image for a 11.5 micron-centered band, 4 THz wide heterodyne detector. The authors explore the range of telescope collecting area, number of telescopes (baselines), and correlator requirements.

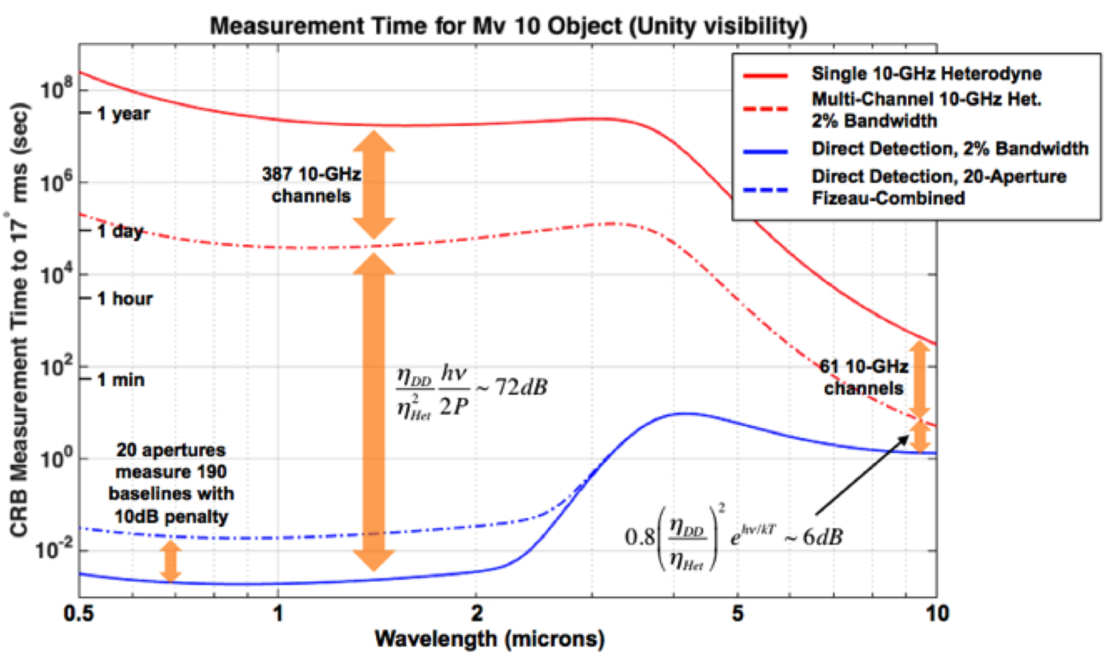

Figure 7.2: Cramer-Rao lower bound for the minimum measurement time required for the detection of an Mv = 10 object as a function of wavelength for heterodyne and homodyne interferometry (*Ashcom*, 2015).

The availability of faster combs offering 10 GHz (or higher) mode spacing and broad spectral coverage, along with commensurate advancing high-speed detector technology provide an optimistic picture for this concept. High quantum efficiency (QE) quantum well infrared photodetectors (QWIPs) (*Choi*, 2017)), or potentially hot electron bolometers (HEBs) operating in the mid-IR (*Cunnane*, 2015), are two detector technologies potentially capable of providing the higher speed detector technology needed for PFI. Furthermore, synchronization between telescope nodes could be provided by frequency comb-based optical clocks at each telescope location, obviating the need for optical fiber connections between sites for the NIR fringe tracking, thus further opening up the parameter space for a PFI infrastructure.

The discovery of Proxima b, an Earth-sized exoplanet orbiting Proxima Centauri, a red Dwarf star closest to the Sun, was reported in 2016 (*Anglada-Escudé et al.*, 2016). The planet was detected using the radial velocity method that is the subject of Chapter 5 of this report. It is notable that with a 50-km baseline, a PFI-inspired implementation of CHARLI would be able to image the surface of this exoplanet.

7.3.2 High Angular Resolution Imaging of Geostationary Satellites and NEOs

The approach outlined in the last section for high angular resolution imaging of planet formation regions or stellar surfaces may be applied to observations of objects much closer to Earth—for example, the ground-based imaging of objects in geostationary orbit. Information not otherwise easily obtained about variations in thermal emission across such a surface may be discernible with mid-IR heterodyne detection. Such observations are not achievable in the visible portions of the spectrum where passive illumination limits observations and active illumination is not feasible.

Another application suggested during the first workshop was high-resolution ground-based imaging of Near Earth Objects (NEOs)—primitive solar system formation remnants in orbital paths that can pass between 0.983 and 1.3 AU (*Morbidelli et al.*, 2002). CHARLI could provide a means of elucidating the surface morphology of these objects and a more direct determination of their diameters by observing them in the mid-infrared portion of the spectrum where they are brightest.

Spacecraft missions to asteroids benefit significantly from ground-based studies of their targets, yet mission planning can be hampered by the general lack of information on the physical properties of potential targets (*Mueller*, 2007). Physical studies of spacecraft target asteroids are of crucial importance in this respect, especially given the increasing number of missions to asteroids such as the Dawn[2] (Vesta and Ceres), Hayabusa (MUSES-C), Hayabusa 2, OSIRIS-Rex (asteroid Bennu), and the potential Psyche (main belt asteroid) missions.

[2]Note that thermal IR studies of Vesta have been reported from the DAWN mission by *Keihm et al.* (2012); *Tosi et al.* (2014); and *Capria et al.* (2014).

As of this writing, there are 17,935 near-Earth asteroids known[3]. The vast majority of these have been detected within the last decade due to a concerted effort to identify objects which may pose a potential threat of impact with the Earth. Most were identified by either the ground-based Panoramic Survey Telescope and Rapid Response System (Pan-STARRS) or Catalina Sky surveys.[4]

NEOs are composed of the most pristine material left over from the early days of the Solar System and have undergone much less processing than the planets or the Sun, thereby preserving crucial information on the formation and evolution of the Solar System. Near Earth Asteroids (NEAs), in particular, are believed to be remnant building material of the inner planets (*Muëller*, 2007). Historically, most information about NEA size was derived from the albedo measurements of solar-illuminated targets. But NEAs are very faint objects and for many of them, observation times have been very short, as they disappear from view quickly after discovery. Furthermore, the dependence on albedo, typically assumed to be 14% (ref CNEOS website: `https://cneos.jpl.nasa.gov/stats/`) for size determination, is unreliable given the variation in surface morphology and composition. Also, processes affecting near-Earth asteroid trajectories up to ~20 km in diameter are strongly dependent upon their thermal inertia. However, little is known so far about this topic. Thus, observations in the mid-infrared wavelength range are needed (*Muëller*, 2007).

Mainzer et al., (2015) provide a thorough history of IR telescope studies of asteroids. Efforts though the recent NEO-WISE mission has provided valuable space-based observations of asteroids at 3.4 and 4.6 μm. However, the short length of the observational arc means that ground-based follow-up is necessary to secure orbits for new discoveries (*Mainzer*, 2015).

Challenges to CHARLI-based NEO observations include the fast tracking that would be required for imaging. This technique might therefore have limited application for studying a subset of NEOs within a particular trajectory window.

7.4 Comb LO Heterodyne Receiver Technology Development

7.4.1 CHARLI System Concept

Several key technology developments are needed for an OFC-based MIR heterodyne receiver system. These include the mid-IR OFCs, high-speed MIR detectors, synchronization of the receivers in the telescope array, and data handling capability.

The CHARLI concept would entail dispersing comb and telescope light through a grating and mixing the signals on a detector array, with one single-pixel detector corresponding to each comb

[3] CNEOS website: `https://cneos.jpl.nasa.gov/stats/totals.html`

[4] `https://cneos.jpl.nasa.gov/stats/site_all.html`

line. The intermediate frequency (IF) for each pixel could then be amplified and sent to a correlator for combination with the same comb line IF signal from other nodes of the interferometer. The system concept has the following elements and properties for each ground-based antenna and is pictured in Figure 7.1:

- A 10 micron-centered, 10 GHz repetition rate comb source with ~1000 1-μW lines
- Detector array with commensurate (10 GHz) bandwidth and high coupling efficiency
- 2–4 m diameter telescopes
- Spectrometer with R~10,000
- Digitizer
- Correlator (with signals from other antennae)
- Array baseline could be 1–10 km, depending upon the application (imaging GEO objects on the 1 km scale to 10 km for a Planet Formation Imager)
- Could envision a system with polarization beam combining to measure both polarization states and optimize use of photons
    - This would require stacking multiple copies of the beam in the input aperture of the spectrometer and having 4 $\times$ (N channels)
    - Measuring both sine and cosine would require another 2 $\times$ (N channels)
- These choices will be engineering driven. If more LO (comb) power is available, the system could be simplified.

We discuss each of the system components in more detail in the following sections, and make recommendations for proof-of concepts steps along a technology development path.

7.4.2 CHARLI Subsystem Component Technologies

7.4.2.1 MIR OFCs

The requirements for a CHARLI Mid-IR OFC LO comb pertain to the mode spacing, power-per comb line, span, uniformity, and center wavelength. Mode spacing on the order of ~10 GHz is needed to address a daunting data rate. The comb power per mode will need to be in the μW regime, and the comb span would ideally match the Earth's atmospheric transmission window in the 8–14 micron band.

Several techniques for generating OFCs in the 10-micron region have been demonstrated, many of which rely on Difference Frequency Generation (DFG) of combs produced at shorter wavelengths (see for example, *Timmers et al.*, 2017). For mode spacing in the 10 GHz range, difference frequency generation combs using NIR electro-optic generated combs is promising and has been accomplished by multiple groups (*Yan*, 2016; *Jerez*, 2018). Direct generation of MIR OFCs has also been demonstrated in QCLs (see, e.g., Figure 2.6 of this report), which can also produce lines at the desired repetition rate with high power per mode. However, broad spectral coverage is an issue for QCLs.

7.4.2.2 Detectors

The problem of heterodyne detection in the mid-IR has been the subject of study for decades. One challenge is to identify fast enough detector technology to accommodate OFC mode spacing of ~10 GHz or higher; this is to provide coverage across the broad spectral region of interest without making the data handling problem completely intractable. Detector technology examined thus far for this application include three general categories—HgCdTe ("MCT"), quantum well infrared photodetectors (QWIPs), and superconducting hot electron bolometers (HEBs).

Specific detectivity (D*), which is the reciprocal of noise-equivalent power (NEP), normalized per square root of the sensor's area and frequency bandwidth is the figure of merit used to characterize the performance of various photodetectors (*Jones*, 1960). Figure 7.3 (from *Jones* [1960]), shows a comparison of the D* performance for some of these technologies.

Rogalski (2003) compared the then state-of-the-art in photon—QWIP and HgCdTe—infrared detector technologies and concluded that both technologies offer advantages, especially at low (<50 K) temperatures. However, QWIPs are characterized by high impedance, fast response time, long integration time, and low power consumption and have advantages over HgCdTe devices in terms of array size, uniformity, yield, and cost.

HgCdTe detectors operating with a limiting bandwidth of about 2 GHz became the detector of choice at the Infrared Spatial Interferometer. Oak Ridge National Lab (ORNL) conducted studies of QWIP-based heterodyne detectors (*Hutchinson et al.*, 1998) and found that although the QWIPs proved promising in terms of speed (they operated with a bandwidth of 7 GHz around 10.6 microns), their quantum efficiency (QE) was around 5%—too low to be practical. However, recent advances in producing higher QE QWIPs have been made by *Choi et al.* (2014, 2017), who have shown QWIP QE in the mid-IR in excess of 60% owing to resonant coupling structures designed into the devices to improve photon absorption. Further, *Palaferri et al.* (2018) has recently reported measuring the heterodyne signal of two QCLs in the 9 μm band using "photonic metamaterial" QWIPs at frequencies up to 4.2 GHz at room temperature.

Another detector technology of interest is hot electron bolometers (HEBs). A QCL LO and HEB-based heterodyne detector operating in the 2 TeraHertz band has been demonstrated (*Gao et al.*, 2005). The far-IR version of a HEB mixer has been developed and demonstrated with large bandwidth (*Cunnane*, 2015). Given the wavelength independent nature of the detection mechanism in bolometers, a similar performance may be possible at MIR wavelengths.

We considered the LO power required for shot noise-limited detection of the heterodyned signal. Using the D* of 3×10^{10} at 10 microns for HgCdTe detectors at 77K, and assuming a 10 GHz mode spacing and 100 micron detector size, a NEP of ~1 µW is derived, thus indicating the minimum required comb power per mode. Detectors would be built into linear arrays, where consideration must be given to the fill factor, necessary lenslets (e.g., ZnSe), and transimpedance amplifiers. A full quantum noise-limited mid-IR heterodyne receiver with all elements would handle mode matching, dual polarization—double side band, and the spectrometer (with R~10,000).

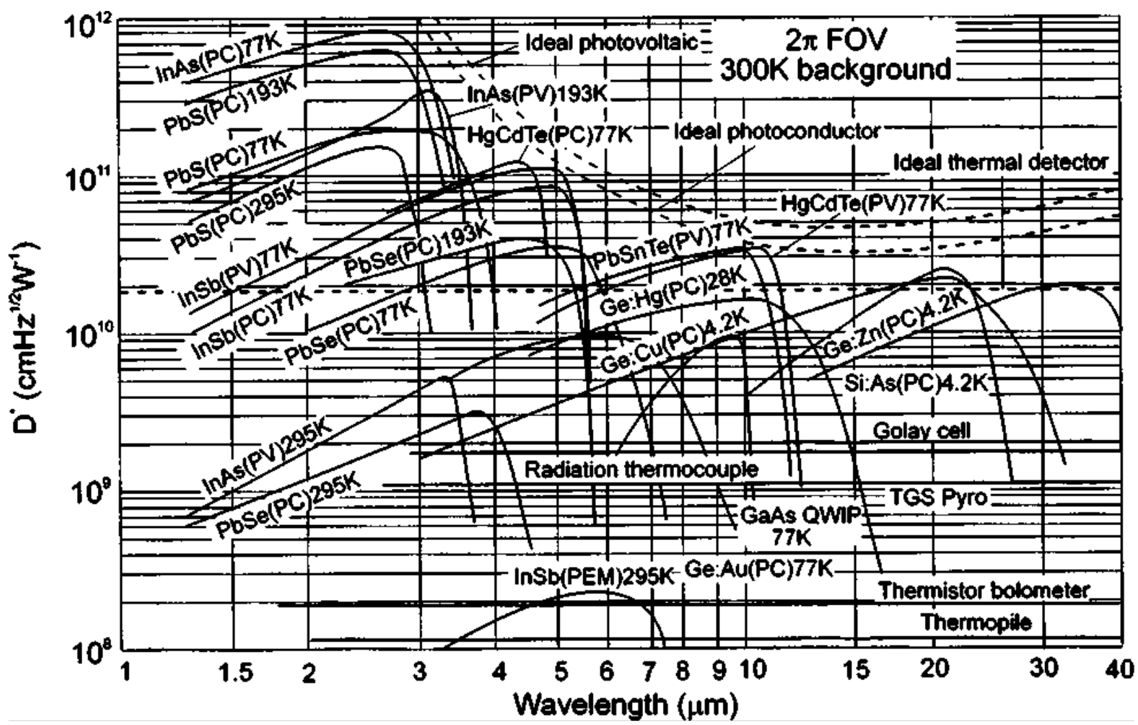

Figure 7.3: Specific detectivity (D*) of various IR detectors as a function of operating temperature, photoconductive (PC) or photovoltaic (PV) operation, and wavelength (*Rogalski*, 2003). Note that around 10 microns, the peak value is shown for HgCdTe detectors at 77K with D* ~ 3 × 10 cm $\sqrt{\mathrm{Hz/W}}$.

7.4.2.3 Synchronization

Three synchronization schemes were discussed at the workshop. Given a required comb stability level of 10^{-14} relative to a master clock, and assuming 1-minute long integration times and a 10 km long baseline, these options are: 1) have two combs distributed to each telescope and perform DFG independently at each. This option presents technical issues with dispersion of the comb light; 2) use a master clock and 1.5-micron CW laser light distributed to each node and generate combs locally at each telescope. This might represent the most cost-effective choice; and 3) have a stable clock at every antenna and combs local to each telescope node.

7.4.2.4 Data Handling

Data rates per telescope would be on the order of ~10 terabits (10^{13}) bits/sec. Data transfer rates per fiber to a central location are not impossible; see for example, the 55 terabit/s data rate demonstrated in a single fiber by *Marin-Palomo et al.* (2017) and mentioned in section 3.3.2.

7.4.2.5 Other Considerations

Direct interferometry in the NIR of, for example, objects in geosynchronous orbit, has not been deemed possible, primarily because of a lack of a way to deal with atmospheric turbulence. Therefore, a study of the dynamics of the sodium layer for atmospheric phase measurements (at 90–100 km) is also recommended. Aerial platform sensors might be used for interferometry experiments to determine micrometer level relative motion in a coherent light source. The objective of such a study would be to determine the phase change in light caused by turbulence in the air layer ~100 m above the ground. Another suggestion is to consider upconversion of the MIR signal, allowing for a regime with better detectors; CHARA does upconversion from the NIR to visible to enable use of silicon components.

7.4.3 Proof-of-concept tests

The ISI is a facility that lends itself as a testbed for various elements of a comb local oscillator heterodyne receiver; experimental detector arrays and comb sources could be explored as intermediate development steps. Lab-based experiments simply demonstrating the gains in SNR as a function of the number of comb lines could be demonstrated in the near-IR.

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8. Recommendations and Conclusions

Over the next several years, OFCs will continue to see development for the following applications, ideally, all in butterfly packaged sizes:

1. Synthesizers for frequencies from UV to THz. This will likely not be done in one device, but in bands—UV-visible, Near IR, Mid-IR, and THz.
2. Spectroscopy systems for remote and distributed chemical sensing
3. LIDAR systems with nm resolution and km range
4. Astrocombs
5. Clocks for time standards (secondary and perhaps primary)
6. Extremely stable RF and microwave sources

Given the breadth of OFC applications, many of which are critical in space operations, one can imagine frequency combs as the "heartbeat" of future spacecraft, providing concurrent capability in timekeeping, as the reference oscillator for other on-board instruments, and as the seed source for communications and science instruments like spectrographs and LIDAR.

8.1 Considerations for space flight

In addition to the technology developments needed specifically for frequency combs, consideration must also be given to launch survivability (vibration and mechanical shock) of comb optical assemblies, particularly use of appropriate epoxies due to potential shrinkage during curing and required strength, alignment tolerance and fixed positions of optics once in flight, and resilience against thermal shock which can be challenging for mounts, bonds, and materials with dissimilar CTEs. All of these considerations point toward alignment-insensitive designs, i.e., entirely fiber-coupled assemblies.

Lessons learned from prior flight project experience advises an investment in engineering models to identify potential failure mechanisms in thermal and vibration testing. Developing and practicing stringent contamination control procedures is also important, as the evolution of contaminants in an optical compartment is a one of the major long-term failure mechanisms in space-based lasers.

Lifetime of components, especially the comb pump lasers, are of prime importance. Needed are high reliability, long-life diode pump lasers with redundancy to meet mission lifetime requirements. Operating all optical components at appropriately derated levels increases the mean-time-before failure for any one of them.

8.2 Recommendations

To achieve the goals of the four missions outlined in this report, as well as enable some of the other space applications identified, the recommendations for OFC technology development for space missions include the following:

1. Soliton microcombs, which offer low SWaP and geometry-tailored repetition rates, should be integrated with on-chip coupling waveguides, connectorized, and subjected to space environmental testing. For applications requiring broad comb spans, high repetition rates, and spectral flattening, broadening stages that require integrated non-linear waveguides, fiber amplifiers, and spectral wave shapers will be necessary. Long life, ultra-narrow line width pump lasers should be included in development activities.

2. Self-referenced EOM combs offer both high stability (*Carlson et al.*, 2017) and broad spectral coverage in the NIR. However, they require filtering of RF oscillator and amplifier phase noise in the wings of the comb, rendering them more complex than line-referenced EOM combs. Ultra-low phase noise oscillators and amplifiers in conjunction with Fabry-Perot cavities are desirable to mitigate this problem, and the availability of narrow line width, high-stability rubidium D2 line-referenced CW pump lasers at 1550 nm would provide line-referenced combs with stability adequate for many space science applications. As with soliton microcombs, nonlinear spectral broadening stages, narrow line-width pump lasers, and broad spectral flattening should be included in development activities.

3. Quantum Cascade Lasers and Interband Cascade Lasers (QCLs and ICLs) offer direct generation of frequency combs from the mid-IR (ICLs) through terahertz spectral regions

(QCLs). They are low power devices and dramatically more efficient than difference frequency generated (DFG) mid-IR combs, and thus are well suited for the development of compact spectrometers. QCL devices have been commercialized, but broad spectral coverage remains a challenge, and careful dispersion engineering to minimize group velocity dispersion would improve this performance parameter. Also, self-mode locking of ICLs has recently been reported (*Bagheri et al.*, 2018). DFG-generated combs offer broad spectral coverage and can be generated with fiber laser comb technology; increasing the power of the output combs of these systems remains a goal. Self-referenced fiber laser combs have been developed in small packages (volumes of <1 liter and power consumption of <50 W; *Sinclair et al.*, 2015), providing mode spacing in the ~100–200 MHz repetition rate regime. These devices are promising for numerous applications in the field.

4. Hybrid systems that combine multiple frequency comb generation stages can overcome some limitations of individual comb technologies. For example, soliton microcombs pumped with an electro-optically modulated pump source (*Obrzud et al.*, 2017) allow the microresonator to self-lock to the driving laser so that no active feedback-loop is required.

Further recommendation regarding the approach to incorporating comb technology into space science missions include:

6. Establish ground-based astronomy implementations of frequency combs as testbeds for OFC component technologies extensible to flight, starting predominantly with electro-optic modulation frequency combs due to the relatively low cost and availability of components, and fiber laser combs due to commercial availability and technical maturity, with near-IR comb implementation first, followed by extension into visible wavelengths;
7. Advance soliton microcomb Technology Readiness Level (TRL) through introduction at established ground-based frequency comb implementations;
8. Advance dual-comb spectroscopy TRL in ground-based applications, followed by airborne-to-ground, airborne-to-airborne, and space-to-ground demonstrations.
9. Demonstrate ground-based heterodyne detection with mid-IR frequency comb local oscillators with concurrent advancement of fast detector capability.

8.3 Conclusion

This study catalyzed the formation of four mission concepts that could significantly contribute to science goals in space and planetary science, Earth atmospheric science, basic physics, and defense applications. As there are multiple methods for generating OFCs, we considered the comb technologies that could best address each of these missions' requirements. Microcombs—chip-scale resonant cavity optical devices—were heavily favored for space-based applications due to their inherently small SWaP. Electro-Optic Modulation combs were also considered because they are robust and relatively simple to construct from commercially available telecommunications components. Quantum Cascade Laser, Interband Cascade Laser combs, and fiber laser combs, the latter of which have been deployed on sounding rocket flights, were also examined. To achieve spectral coverage in various bands of interest ranging from the visible through the mid-IR, each comb technology presents various benefits and challenges. While an investment is being made in comb technology by a several institutions internationally, notably including DARPA in the U.S., the targeted applications result in somewhat varying goals for comb performance and features.

Preparing this report has been like trying to hit a moving target; frequency comb technology has continued to advance rapidly in the two years since the end of the second KISS workshop. While we are not able to capture all of the developments in this burgeoning field, it is fair to say that this study marks only the beginning of space applications for optical frequency combs.

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Appendix A

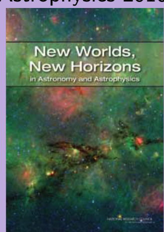
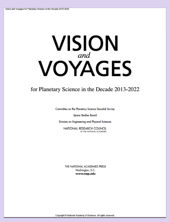
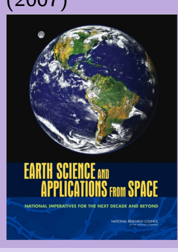
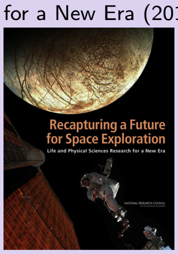
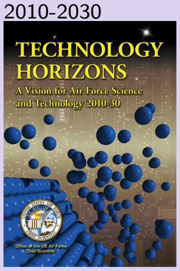
NRC Decadal Surveys			
Focus Area	Source	Program Goals	KISS OFC Focus Area
Astronomy and Astro-physics	New Worlds, New Horizons in Astronomy and Astrophysics 2010 	• What Are Planetary Systems Like? • How Do Stars and Planets Form? • How Can We Detect Gravitational Waves? What Can They Tell Us? • What Are Dark Matter and Dark Energy? • 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?	• PRV • High angular resolution imaging • precision timekeeping • formation flying
Planetary Science	Vision and Voyages for Planetary Science in the Decade 2013-2023 	Core Multi-Mission Technology needs: • Reduced mass and power requirements for spacecraft and their sub-systems • 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	• Spectroscopy, • autonomous navigation • timekeeping
Earth Science	2017-2027 NRC Decadal Survey for Earth Science and Applications from Space (2007) 	ASCENDS-like mission: Mission objectives: • Measure the number density of Carbon Dioxide (CO_2) 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	• PRV • High angular resolution imaging • precision timekeeping • formation flying
Biological and Physical Sciences in Space	Recapturing a Future for Space Exploration: Life and Physical Sciences Research for a New Era (2011) 	Recommended Program Element 2: Research That Tests and Expands Understanding of the Fundamental Forces and Symmetries of Nature 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.	• Optical clocks

Table A1: National Research Council Decadal Surveys: Excerpts related to OFC technology

<table>
<tr><th colspan="4">DoD</th></tr>
<tr><th>Agency</th><th>Source</th><th>Technology Area/Program</th><th>KISS OFC Focus Area</th></tr>
<tr><td>Air Force</td><td>"Technology Horizons" 2010-2030

</td><td>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
PCA 10: Next-Generation High Bandwidth Secure Communications
PCA12: Processing-Enabled Intelligent ISR Sensors
PCA27: Rapidly Composable Small Satellites</td><td>Chip-scale comb technology,
Combs and clocks for precision timing, navigation, and basic science</td></tr>
<tr><td>Office of Naval Research</td><td>Naval Science and Technology Strategy 2015

</td><td>Precision time and navigation</td><td>Combs and clocks for precision timing, navigation, and basic science</td></tr>
<tr><td>DARPA</td><td>DARPA DEFENSE ADVANCED RESEARCH PROJECTS AGENCY</td><td>GEO-sat imaging
Space Surveillance Telescope (SST):
Enable ground-based, broad-area search, detection, and tracking of faint objects in deep space for ... 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)
High stability timekeeping instruments with suitably low SWaP to enable widespread deployment in battery-powered portable applications."</td><td>Chip-scale comb technology,
Spectroscopy
Ground-based High Angular Resolution Imaging
Combs and clocks for precision timing, navigation, and basic science</td></tr>
</table>

Table A2: U.S. Department of Defense program goal benefiting from Optical Frequency Combs.

NASA 2015 Technology Roadmap	
Technology Area	**Desired Capability**
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.
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.
Position, Navigation, and Timing	
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, high stability, spectral resolution, 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.
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.

Table A3: NASA Technology Roadmap elements benefiting from OFC technology.

Appendix B

Award Year	Company	Award Type	Topic
2009	AdValue Photonics, Inc.	Phase I STTR DoD	An All-Fiber Mid-Infrared Frequency Combs[a]
2009	Calmar Optcom, Inc.	Phase I STTR DoD	Mid-Infrared Precision Frequency Combs
2009	Redwood Photonics, LLC	Phase I SBIR DoD	Self-Seeded Programmable Parametric Fiber Comb Source[b]
2009, 2010	AdValue Photonics, Inc.	Phase I SBIR Phase II SBIR DoC	Phase-stabilized 1-GHz Fiber-laser Frequency Combs at 2-5micron for Coherent Fourier Transform Spectroscopy[c]
2009, 2010	Q-Peak Inc.	Phase I STTR Phase II STTR DoD	Mid-Infrared Precision Frequency Combs[d]
2009, 2010	Q-Peak, Inc.	Phase I SBIR Phase II SBIR DoD	Mid-Infrared Precision Frequency Combs
2010	Advr, Inc.	Phase I SBIR NASA	A Compact, Waveguide Based Programmable Optical Comb Generator
2010	Polaronyx, Inc. (spin-off of Laser-Femto)	Phase II STTR DoD	All fiber-based high power Mid-IR precision frequency combs[e]
2010	Polaronyx, Inc. (spin off of Laser-Femto)	Phase I SBIR NASA	Compact Ultra-Wideband Optical Frequency Comb Fiber Laser[f]
2012	NP Photonics	Phase I SBIR DoD	Optical Frequency Comb-Based 10 GHz Microwave Oscillators[g]
2014	NP Photonics	Phase I SBIR DoD	Optical System for Precision Atomic Clocks and Stable Oscillators[h]
2014, 2015	Stable Laser Systems, Inc.	Phase I SBIR Phase II SBIR DoD	Optical System for Precision Atomic Clocks and Stable Oscillators[i]
2015, 2016	Vescent Photonics	Phase I SBIR Phase II SBIR NASA	Robust Frequency Combs and Lasers for Optical Clocks and Sensing
2016	Pranalytica, Inc.	Phase I SBIR DoD	Rugged, chip-scale, optical frequency combs for real-world applications
2016	OEWaves	Phase I SBIR DoD	Integrated and Packaged Mid-IR Kerr Frequency Comb Oscillator[j]

Table B1: SBIR and STTR frequency comb technology awards from Department of Defense (DoD), NASA, and Department of Commerce (DoC)

[a] https://sbirsource.com/sbir/awards/56870-an-all-fiber-mid-infrared-frequency-combs
[b] https://www.sbir.gov/sbirsearch/detail/290702
[c] https://www.sbir.gov/sbirsearch/detail/72586
[d] https://www.sbir.gov/sbirsearch/detail/363825
[e] https://www.sbir.gov/sbirsearch/detail/9093
[f] https://www.sbir.gov/sbirsearch/detail/9075
[g] https://sbirsource.com/sbir/awards/141732-optical-frequency-comb-based-10-ghz-microwave-oscillators
[h] https://sbirsource.com/sbir/awards/149195-optical-system-for-precision-atomic-clocks-and-stable-oscillators
[i] https://sbirsource.com/sbir/awards/149195-optical-system-for-precision-atomic-clocks-and-stable-oscillators
[j] https://www.sbir.gov/sbirsearch/detail/1250027