NASA Earth Science Technology Office Technical Interchange Meeting

Theme: *Toward Quantum Enhanced Sensing and Measurements for Earth Observation in 2040*

Graphic by: NASA Ames/Allison Li

Report by

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Prepared under the guidance of the NASA's Earth Science Technology Office (ESTO) and NASA's Ames Research Center (ARC). We would like to thank the following individuals who contributed to this report: Xubin Zeng (University of Arizona), Jason Hyon, Graeme Stephens, & Darmindra Arumugam (Jet Propulsion Laboratory), Marlan Scully & Alexei Sokolov (Texas A&M), Yuping Huang (Stephens Institute of Technology), Peter Brereton & Bryant Loomis (GSFC), Shane Verploegh (Infleqtion), Alexander Gaeta (Columbia University), Milan Begliarbekov & Yong Meng Sua (QCi), Carl Weimer (BAE Systems), Jason Saied, Shon Grabbe & Lucas Brady & Eleanor Rieffel (QUAiL Group)

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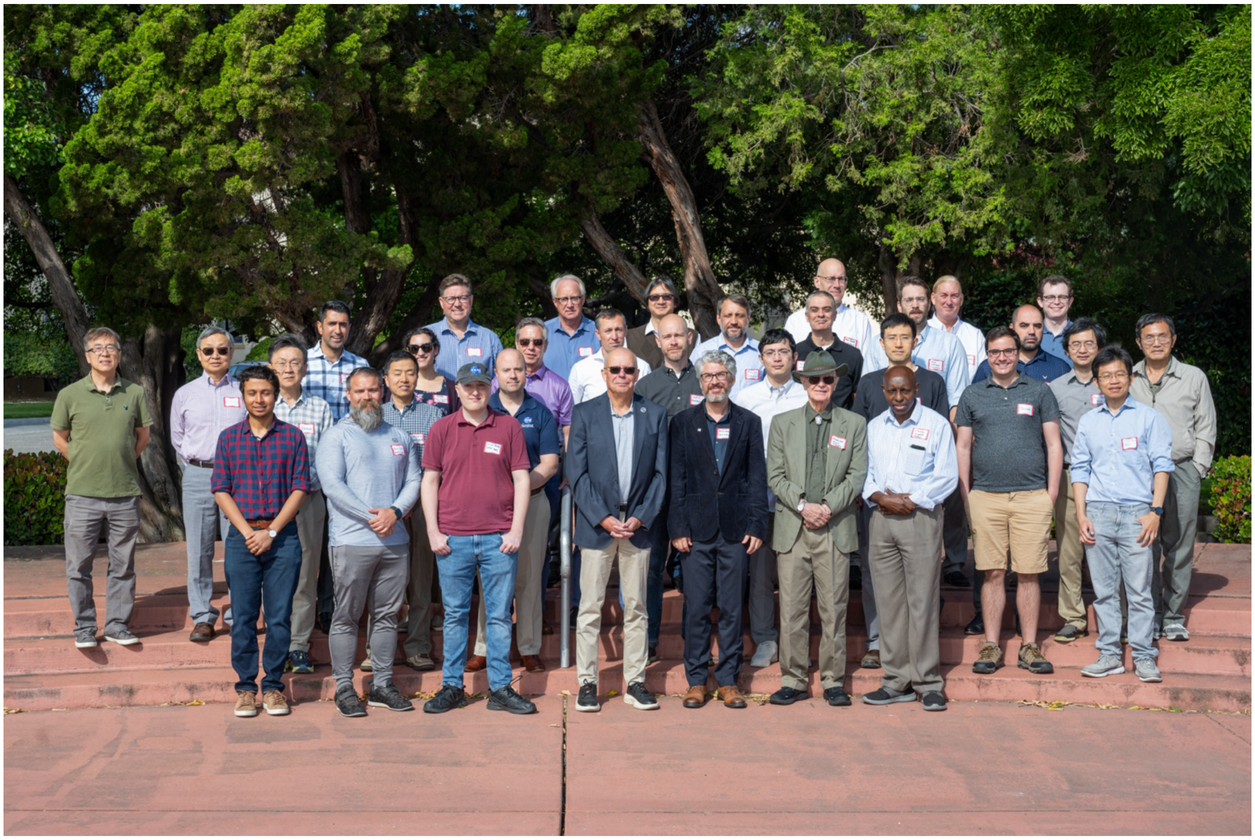

Group Photo, NASA Ames Research Center, June 26, 2024. The meeting was attended by over 35 invited participants from three NASA Centers (ARC, GSFC & LaRC), NASA HQ & JPL, Govt. Lab/Dept. (Brookhaven National Lab, USGS) Academic Institutions (U. Arizona, Columbia Univ. Texas A&M, Stevens Inst. Tech.) and Companies (BAE systems, QCi, HP, Infleqtion). Dave Korsemeyer (Depty Center Director), Michael Hesse (Dir. of Science) & Florian Schwandner (Earth Science Div Chief) gave opening remarks. See Appendix A: List of Participants.

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Executive Summary

Quantum technologies hold the potential to bridge observational gaps in Earth-related studies and offer significant advantages over traditional sensing methods. A group of engineers, Earth scientists, and quantum experts recently gathered at NASA's Ames Research Center (ARC) to share ideas on quantum technologies. The goal was to identify important Earth science remote sensing requirements that are difficult to accomplish using the current remote sensing concepts, and recommend various potential pathfinder applications of quantum sensing to Earth science remote sensing.

The two-day technical meeting brought together researchers and quantum practitioners from across several disciplines and specialties in Earth science and quantum scientists, all bound by a common desire to harness quantum phenomena for remote sensing. Some participants noted that Earth scientists can provide insights into important observables that will be most relevant to scientific questions, while quantum scientists can pinpoint the physical processes and measurements that can extract maximum information, which is bound by quantum theory. Presenters shared the latest developments in technologies like quantum computing and atom interferometry, detailing how those technologies could enable novel Earth observation missions.

NASA urgently needs a clear strategy for fully leveraging the breakthroughs presented by governments, industry, and academia. Rather than focusing solely on new measurements enabled by quantum technology—which may not yet be well-defined—the emphasis should be on enhancing the affordability and efficiency of concurrent measurements of multiple variables. The primary recommendations are structured around three key NASA science objectives: **measurement, Earth system model, and application.**

The technical meeting was sponsored by NASA's Earth Science Technology Office (ESTO).

NASA Earth Science Decadal Survey-Identified Gaps

By Xubin Zeng (University of Arizona) & Graeme Stephens (NASA/Caltech Jet Propulsion Laboratory)

Introduction

Quantum Sensing for Earth Science is needed for monitoring, understanding, prediction/projection of the Earth system, particularly of high-impact natural hazards and extreme events with time scales from minutes to centennial. For instance, the number of billion-dollar weather and climate disasters in the U.S. has kept increasing in recent decades and reached 28 last year (in 2023). It is also needed for NASA leadership, as quantum sensing, computing, and science have received increased attention and investment from foreign countries and institutions. Other U.S. agencies (e.g., National Science Foundation (NSF), U.S. Department of Energy (DOE)) are also heavily invested in this area.

Highlights:

NASA Earth Science Flight Program includes five elements:

- Program of Record - existing or previously planned observations
- Designated (including 5 targeted observables)
- Earth System Explorer (including 7 observables)
- Earth Venture (addressing Decadal Survey-recommended observables)
- Incubation (including 2 observables)

Decadal Survey-identified major gaps include these targeted observables or most important objectives/questions in five areas and three integrating themes. These gaps are also consistent with the research directions of major international research programs such as the World Climate Research Programme (WCRP).

Recommendation /Overarching questions:

Quantum Sensing for Earth Science needs to address five questions/issues:

- Can quantum sensors provide an advantage over traditional sensors (e.g., capability, SWaP (Size, Weight, and Power), cost) for any of the targeted observables or most important objectives presented here?
- Can quantum sensors reduce measurement uncertainties by increasing signal (more traditional approach) or reducing noise (e.g., using onboard quantum computing)?
- For quantum or traditional sensors, how can we reduce representativeness uncertainties (e.g., enabling a narrow-swath scanning lidar measurements to represent a grid box or the footprint of a microwave radiometer)?
- Using quantum or traditional sensors, how can we reduce uncertainties in using lidar or radar measurements (with a narrow swath) to calibrate passive (visible, IR, MW) sensors with a wide swath?
- How can all these quantum sensing efforts better entrain and involve Earth system scientists upfront, as they are crucial for accelerating the use of new measurements, finding new applications, and providing critical feedbacks?

- Regarding the question from the NASA's Earth Science Technology Office (ESTO) Director: what would be the next quantum sensing pathfinder mission after the first one (on atom-based quantum gravity gradiometry)? The suggestion is to focus on:
    - Targeted observables for designated or explorer missions (due to higher cost caps). For instance, with the recent selection of Earth System Explorer mission concepts, only two remaining targeted observables are not covered: snow depth/snow water equivalent and atmospheric winds.
    - Technology readiness level at 4-5 - otherwise the quantum sensor is not ready for a technology demo.
    - Cost – a big factor at present; the quantum sensor should have a lower cost than classical instrument for the same capability or have a similar cost for better capability.

Science and Application Traceability Matrix (as used in the Decadal Survey) along with trade analysis (e.g., between costs and instrument capabilities) should be used to connect science gaps with specific questions to be addressed, measurement requirements, and quantum sensing and computing capabilities.

Quantum inspired, enhanced, and enabled technologies with impact to Remote Sensing Earth Science applications

by Marlan Scully & Alexei Sokolov (Texas A&M)

Introduction

We leverage our team's expertise and utilize recent advances in quantum optics and quantum informatics to develop quantum-enhanced remote sensing techniques, improving on existing technologies and pushing scientific frontiers beyond the current scope via stimulating interdisciplinary collaborations. Our focus areas are:

- Single-photon remote sensing techniques that will enable high-resolution optical imaging from space,
- Satellite-to-satellite quantum sensing systems utilizing squeezed light and entangled photon sources,
- Atmospheric lasing, providing coherent backward-propagating probe beam which enables efficient remote sensing with improved signal/background ratio, and
- Molecular coherence-based detection and identification for efficient remote sensing.

Our research requires full collaboration from Earth scientists, space hardware engineers, quantum physics/optics scientists to create the best of its kind technology for space-based remote sensing applications using quantum enabled techniques. Earth scientists will provide insights into important observables that will be most relevant to scientific questions, while quantum scientists can pinpoint the physical processes and measurements that can extract maximum information, which is bound by quantum theory. While guided by scientific insights, engineering part of the proposal will need to reach classical limits to take full advantage of quantum technologies, all of which will heavily rely on both space engineering and scientific (light sources, optics and detector) engineering. The major product will be a suite of quantum-enabled technologies, such as ultra-stable, high precision measurement systems with single photon sensitivity that can be incorporated into a broad range of future NASA missions.

Highlights

As an example, we consider bright twin-beam squeezed light for weak absorption measurements – an approach pioneered by Girish Agarwal et al (2021). We explore approaches for implementing satellite-to-satellite laser links that can benefit from entanglement and measurement sensitivities below the standard quantum limit. This can be done by sending squeezed light from one satellite to another in the same orbit, to scan a layer of atmosphere. Twin beams, produced by using either a strongly pumped optical parametric amplifier or a four-wave-mixer (FWM), have strong quantum correlations between the generated probe and conjugate beams. The probe field, in addition, can have an input seed so that we get bright twin beams. In such a case the twin photons have their number difference that possesses strong squeezing characteristics as shown by the Fig. 1(a). These squeezing characteristics can be used to monitor weak absorption with a definite quantum advantage (Ribeiro et al., 1997; Hayat, Joobeur and Saleh, 1999; Whittaker et al., 2017; Moreau et al., 2017; Garces et al., 2020). The quantum advantage is defined by quantum advantage(dB)=10×log_10 (Δα_sqz)/(Δα_snl), where Δα_sqz is the sensitivity measured by squeezed light and Δα_snl is that measured by coherent light. One can for example pass the probe beam through the absorber and then study the intensity difference fluctuations to obtain Δα_sqz. The Fig. 1(b) shows theoretical estimates of the quantum advantage as a function of the losses suffered by probe and conjugate beams. Using FWM in atomic vapor, which produced twin beams with about 6.5dB intensity difference squeezing, a quantum advantage of about 1.3 dB was demonstrated (Li et al., 2021) under the condition of realistic optical losses for the twin beams.

Recommendations

There is room for improvement in such tabletop experiments by having better sources of twin beam photons such as those produced by optical parametric oscillators. It is anticipated that such tabletop measurement of absorption in satellite-to-satellite sensing can possibly be implemented by having the probe beam sent to other satellite and holding the conjugate beam in a fiber. The return probe beam and the conjugate beam from the fiber can be used to do intensity difference fluctuation measurement resulting in better estimate of the absorption parameter.

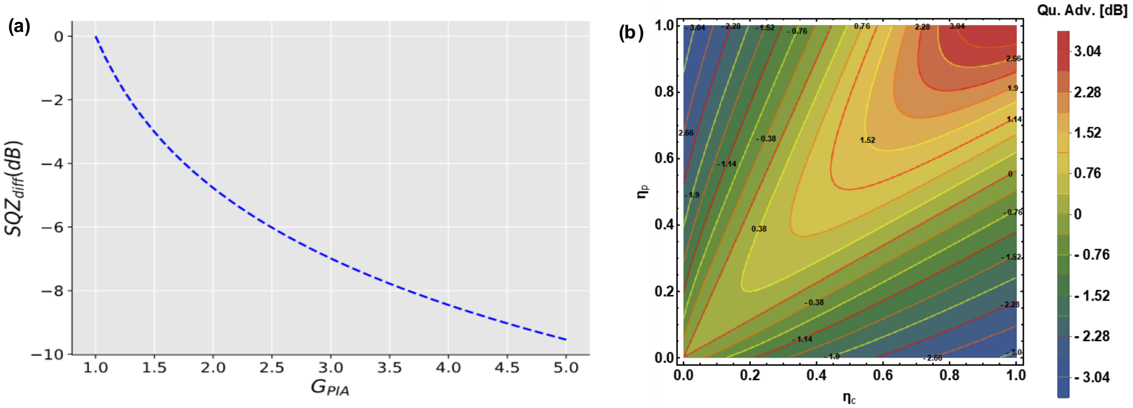


Figure 1. (a) the intensity difference squeezing in twin bright beam as a function of the gain of the amplifier; (b) theoretical squeezed-light quantum advantage versus optical loss of probe and conjugate beams.

Quantum enhanced and directional Raman backscattering for airborne and spaceborne applications

By Alexei Sokolov (Texas A&M) and Yuping Huang (Stevens Institute of Technology).

Introduction

Remote generation of a backward-propagating probe beam via optically pumped lasing of air

A remote-sensing method has been developed based on backward-directed lasing in optically excited dominant constituents of plain air, N2 and O2. This technique relies on the remote generation of transient population inversion, thus enabling a transient gain for an optical field propagating toward the observer. This technique results in the generation of a strong, coherent, counterpropagating optical probe pulse. Such a probe, combined with a wavelength-tunable laser signal(s) propagating in the forward direction, provides a tool for various remote-sensing applications. The proposed technique can be enhanced by combining it with the gain-swept excitation approach as well as with beam shaping and adaptive optics techniques.

Highlights

The continuous monitoring of the atmosphere for traces of gases and pathogens at kilometer-scale distances is an important and challenging problem, with applications in environmental science and national security. Measurements using light detection and ranging (LIDAR) techniques coupled with differential absorption LIDAR (DIAL) provide valuable tools for the measurement of trace impurities in the atmosphere. The utilization of the strong backward-propagating optical probe in remote spectroscopy applications will result in a dramatic improvement of the detection sensitivity compared to the standard LIDAR techniques. LIDAR is based on the detection of the nearly isotropic scattering of a forward-propagating probe beam. The component of this scattering that propagates toward the observer is a priori weak. On the other hand, the sensing approach proposed here employs a bright and highly directional backward-propagating probe, thus increasing the signal-to-noise ratio of the detected signal dramatically.

There were a good number of questions raised by the audience during the discussion session; here are some:

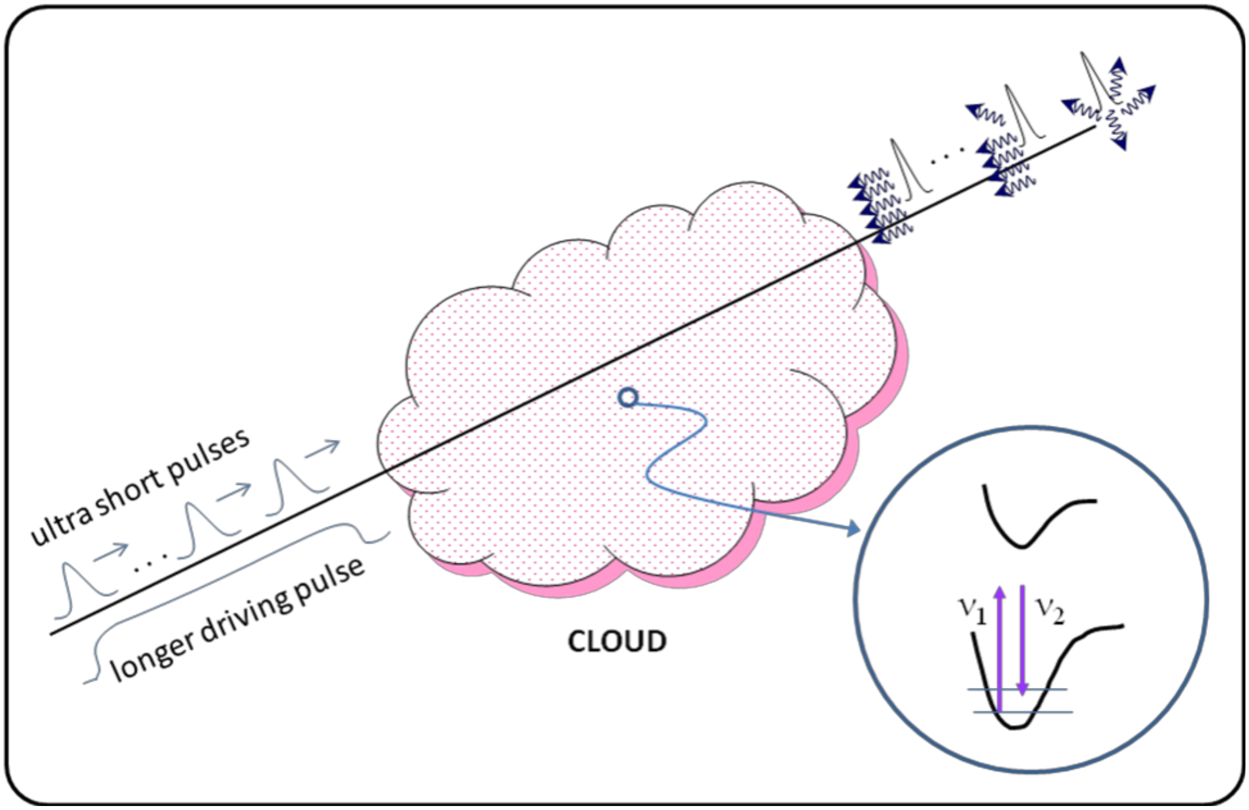
- How can we improve signal strength detected from a lidar in space?
  - Backward-directed lasing is a promising approach to check out.
- The next question was: can this be done at distances of 100 km or longer?
  - In principle, yes – if large enough laser focusing optics are used.
  - Air turbulence will be an issue; the problem can, however, be less severe for a downward-looking, satellite-based system.
- Will we be able to produce enough power density to produce the non-linear interactions?

    - In principle, yes – it's a matter of numbers: how much laser power can one afford to produce on a satellite.
- What molecular species can be detected? For clouds, can you be sensitive to species dissolved in the water? Can trace species be detected, and the full composition measured?
    - This is a general use technique. In principle, coherent Raman spectroscopy can be used for detection and identification of trace species.
    - You can collect a fingerprint from a species, you match it against a database and you determine what the species is.

Recommendations

The recommendation from this meeting is perform a feasibility analysis for remote generation of a backward-propagating beam via optically-pumped lasing of air, in NASA-relevant satellite-based scenarios, and further test this approach to detection and identification of molecular species.

The figure below depicts the concept of this approach:



Gravity Gradiometer Application

By Jason Hyon, Sheng-wey Chiow, Nan Yu, David Aveline, Javier Bosch-Lluis, Robert Thompson, Siamak Forouhar, Clayton Okino, Norman Lay, Peter Brereton, Holly Leopardi, Anand Mylapore, Scott Luthcke, Bryant Loomis, Parminder Ghuman, Srinivas Bettadpur

Introduction

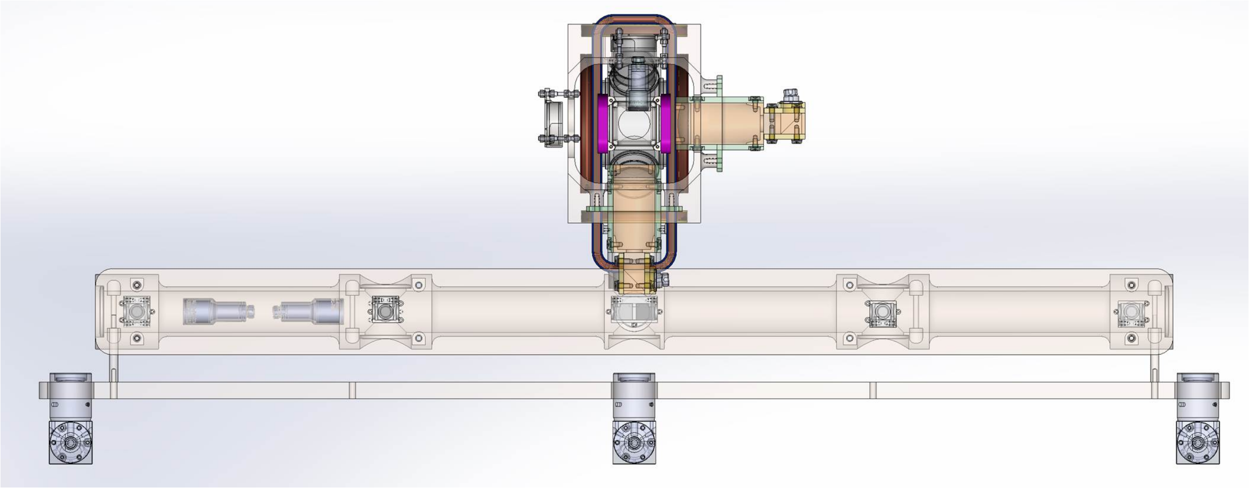
Atom-based quantum gravity gradiometry (QGG) is a promising technology to achieve the time-variable gravity and mass change observable goals called out in the 2017 Earth Science Decadal Survey. In this technique, laser cooled atoms in an ultra-high-vacuum enclosure are placed into a superposition state via optical manipulation and subject to free fall in the Earth's gravity field. The resulting cold atom interference phase is a function of the local gravitational- and non-inertial accelerations and the interaction time of the atoms in these fields, in addition to the phases of the manipulating optical fields. Using two atom-interferometric sensor heads separated by a baseline and utilizing a common interferometry laser eliminates most common-mode noise and is highly sensitive to relative differences in the gravitational acceleration between the two sensor heads. The exquisite sensitivity and long-term stability of laser cooled atoms to Doppler shifts from inertial and rotational accelerations could enable single-satellite orbital sensors to achieve an order of magnitude improvement over that achieved by the Gravity Recovery and Climate Experiment (GRACE) and GRACE follow-on missions. NASA's Earth Science Technology Office has funded several terrestrial prototype instruments and studies to better understand the fundamental physics and mature the supporting sub-systems required to develop a QGG for Earth observation missions.

NASA ESD/ESTO has funded the QGG pathfinder mission in FY25. The QGG pathfinder mission is a technology demonstration of using QGG for Earth gravity mapping, as a stepping stone for a science grade instrument that will provide data of sufficient precision to benefit Earth science. Targeting a host platform operating in the low Earth orbit (LEO), the payload is designed to measure the gravity gradient in the cross-track direction, with a sensitivity target of 100 mE/sqrt(Hz), a cycle time of 14 seconds per measurement, and a stability up to about 90 minutes.

Highlights

There are two primary objectives of the QGG pathfinder mission. The first objective is an end-to-end system demonstration and validation of atom-interferometric gravity remote sensing. A successful demonstration of QGG performance on a free-flyer platform in LEO for an extended duration will be crucial for the science community to embrace and exploit the technology for future missions.

The second objective is advancement of ultracold atom interferometry technology and methods. Exploration on long-interrogation time atom interferometry is limited in terrestrial facilities. The figure below illustrates the overall architecture of the baseline design concept and the physics protocol, and we will continue trades between different configurations. We presented envisioned technology-driven campaigns in the pathfinder mission, and how these will advance the technology towards the QGG science grade instrument for other planetary applications.



Single source design of the pathfinder payload based on Rb source

There were many science questions raised during the session; here were some of questions raised by the audience during the workshop:

- What is your risk perception to take this technology from the surface to space?
  - The key technique needs to be demonstrated in microgravity, which is a risk because we can't do it on the ground, need to put it on a rocket
- Current pathfinder is used for an instrument concept and then have a science instrument
  - Risks are: can we actually transport, can we get the number of atoms?
- Is the measurement that GRACE or QGG, is that going to turn new science over or is it going to be an incremental improvement over what grace follow-on will do or GRACE-FO or GRACE-C will do?
  - There are 12 science questions related to SST measurement by adding a QGG as a cross check measurement, it can answer up to six additional science questions.
  - You can get to more science questions, adding more science value by adding the two techniques.
  - In simple terms, if we can achieve a radial oriented QGG around 10 microE, the performance is comparable to a 4-platform Bender.
  - The benefit comes in, improving the accuracy at higher spatial resolutions
- Cost is the big factor, GRACE-C is near the upper limit cost. Would this one be cheaper
  - Depends who make the breakthrough, etc. The team is pretty confident that this will be cheaper.

Recommendations

The recommendation from this technical meeting was to engage science community to ensure that the QGG payload will provide science results beyond what the current GRACE-C mission will provide. Further, the team needs to develop a white paper response to the upcoming NASA Earth science decadal survey in order to make sure that the future mass change mission should consider the science grade QGG as a replacement to spacecraft to spacecraft ranging technique. The team should also infuse new breakthrough technologies to further reduce the size and cost of the science grade instrument.

The QGG pathfinder mission project is carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

Rydberg Sensors for Microwave Imaging and Radars

By Shane Verploegh (Infleqtion) and Darmindra Arumugam (JPL)

Introduction

Radio frequency sensing through Rydberg atoms holds promise as a new technique for sensitive and electronically-reconfigurable receivers. In this technology, alkali atoms in a ground state are typically held at room temperature or slightly above in vapor form in optically and radio frequency (RF) transparent enclosures. These atoms are then interrogated using multiple lasers with varying energy level schemes. Adding laser energies pushes the atom into the Rydberg state where the valence electron is held far away from the neutron core. The next photon energies capable of being accepted into this system are then in the microwave domain. Different implementations of sensor packages have potential benefits for usage - classified into ‘free-space’ or ‘hybrid’ systems.

In a free-space sensor, the atom-photon interaction region directly sees the environmental electric field and in a hybrid system, the electric field is fed to the atom-photon region through additional microwave structures or elements. In a free-space platform, benefits can arise from having a wavelength-independent, electrically-reconfigurable aperture as well as in sub-wavelength arrays of these apertures. In the hybrid platform, benefits can arise through well-characterized and confined interaction regions to enable self- and absolute calibration.

NASA ESTO has funded Quantum Rydberg Radar (QRR): A Quantum Architecture Covering the Radio Window for Multi-Science Signal of Opportunity Remote Sensing with Focus on Land Surface Hydrology, in the Instrument Incubator Program (IIP)-21 program. This effort is a technology and system demonstration of using Rydberg sensors for multi-frequency radar reflectometry to enable earth science retrievals covering 0.1-22 GHz.

Highlights

The objective of this effort is to develop the Rydberg Radar instrument concept for a CubeSat platform as part of a coordinated multi-satellite signal of opportunity (SoOp) concept to address dynamics and transients in land surface hydrology (LSH) science. The benefit of this concept is that it dynamically retrieves variables such as soil moisture content (SMC) (or vegetative water content, vegetation structure, etc.) from canopy to deep-root-zone using collocated detection from VHF-K bands, which are sensitive to variables including canopy water content, vegetation water content, as well as near-surface and deeper root-zone soil moisture. Collectively, the techniques developed address a NASA Decadal Survey need for multi-frequency measurements in Surface, Topography, and Vegetation (STV) focus areas, which is a targeted observable for the 2030’s.

NASA ESTO has funded the Quantum Atomic Rydberg Radiometer for Earth Measurements (QuARREM) in the Advanced Component Technology-22 program. This effort is a technology development of using Rydberg sensors for atomically referenced hyperspectral measurements, as a first step for a science grade instrument that will provide data of sufficient precision to benefit planetary boundary layer (PBL) Earth science. This effort targets noise equivalent delta temperatures in the 50 to 60 GHz band below 80 mK for 18 ms of integration.

There are two primary objectives of the QuARREM program. The first objective is the development and demonstration of sensitive hybrid atomic receiver to meet and exceed ATMS noise equivalent delta temperatures (NEDT) for temperature retrievals. A successful demonstration of atomic-based sensing retrievals from 50 to 60 GHz is crucial for the science and technologist communities to embrace and exploit the technology for future development programs. The second objective in QuARREM is the advancement of an in-measurement SI traceability via an atomic reference. Early demonstrations of this absolute calibration would show a clear quantum advantage through Rydberg sensors.

Many questions were raised during the session; most questions were about Rydberg fundamental science and comparison to existing microwave platforms:

- Is it continuously tunable or is it solely discrete frequencies at different Rydberg levels?
    - Rydberg systems are continuously tunable given a local oscillator RF field that biases the atom-energy level scheme – called colloquially as the “atomic heterodyne” technique. Without some extra field reference, typically sensitive regions are only around Rydberg transitions.
- How do you compare the current Rydberg sensors to current microwave technologies?
    - Currently, Rydberg sensors are compared via main receiver performance metrics – minimum sensitivity, instantaneous bandwidth, frequency coverage, and effective aperture. Most published work in literature focuses on minimum sensitivity and increasing bandwidth across significant swathes of frequency ranges. More effort is needed to determine antenna-like metrics for the free-space systems.
- What are the next key items for Rydberg systems?
    - The goal over the next 2-3 years is to complete some key ground demonstrations and prove specific quantum advantages before fully considering space-borne applications
- How does entanglement and other quantum techniques play into these technologies?
    - There is no entanglement in current configurations of Rydberg sensing. Quantum 2.0 ideas like squeezed light may play a benefit in reducing system noise contributions in the laser fields. However, further analysis is needed on the base configurations before increasing architectural complexity.

Recommendations

The recommendation from this technical meeting is to continue science and technologist community engagement to ensure that the implementations of Rydberg sensors in development will provide needed science results. Further it is recommended that development teams begin to show clear demonstrations as well as theoretical system analyses of quantum advantage over conventional sensing techniques.

The QRR project is led by Jet Propulsion Laboratory (JPL), California Institute of Technology, with co-investigators with NIST (National Institute of Science and Technology) and ARL (DEVCOM Army Research Lab) under a contract with the National Aeronautics and Space Administration (80NM0018D0004).

The QuARREM project is carried out in part at ColdQuanta doing business as (dba) Infleqtion, with co-investigators at Ball Aerospace (now BAE Systems), under contract with the National Aeronautics and Space Administration (80NSSC23K0517).

Enabling Technologies (e.g. Photonic integrated circuits) for remote sensing (filters, beam steering, detection)

By Alexander Gaeta (Columbia University) and Milan Begliarbekov (QCi)

Introduction

Integrated photonics offers a compelling platform for optical instrumentation based on quantum sensing in future NASA missions involving Earth observations. Its advantages include robustness, cost, scalability, ability for operation in extreme environments, and significant SWaP (Size, Weight, and Power) improvement over fiber and bulk counterparts. Over the past decade rapid advances have occurred in transferring and optimizing techniques and capabilities from electronics to photonics, and today numerous foundries in the US, Europe and Asia now offer a wide assortment of devices and components (e.g., splitters, filters, modulators, lasers) that can be readily incorporated into fully functional photonic chips that are fully integrated with electronic control. Such chips are now being fabricated for data communications and comprise thousands of components working together within an area of a few cm^2.

While there are currently significant efforts both in academia and in industry to develop quantum computing and communication technologies using integrated photonics, our belief is that quantum sensing offers the highest impact on NASA missions for Earth observations. These instruments include: 1) Rydberg sensors for detecting and performing imaging weak microwave and terahertz fields and optical clocks for precision timekeeping. Currently, these instruments take up a significant portion of an optical table. Integrated photonics would enable deployment in drones, aircraft, and satellites.

Highlights

Rydberg Sensors: These sensors use an atomic vapor (e.g., Rubidium (Rb) or Cesium (Cs)) to detect electromagnetic waves, which can span from the RF to the THz frequency regimes. Such sensors could offer a wide range of capabilities for Earth observations in these frequency spectral regimes. Technologies based on such Rydberg sensors promise offer dramatically improved capabilities in RF/microwave/THz electrometry, imaging, and communications. In this sensor, the atoms are excited into the Rydberg energy regime via 2- or 3-photon excitation with visible and near-infrared lasers. Rydberg transitions due to RF, microwave, or THz fields are sensed by a change in transmission by one of the visible/near-IR optical probe lasers. Such a system can offer large frequency detection bandwidths with relatively high sensitivity through use of detectors that operate in the visible or near-IR.

Current experimental setups for atom-based devices and sensors (e.g., Rydberg sensors, clocks, quantum simulators) largely rely upon bulk and fiber-optic components that span several square feet, which makes them prone to environmental (i.e., temperature, vibrations, etc.) perturbations. Integrating all the optical components onto a single platform, including the atomic vapor cell would represent a significant improvement robustness and stability for state preparation and readout, while also making the platform field deployable in aircraft and satellites. While most of the recent advances on high-performance, narrow linewidth (< 1 MHz) lasers have focused on the telecom bands, there has been recent work showing narrow linewidth devices in the visible regime at the ~ 10 mW powers. While this power level is suitable for some of the required lasers, other lasers will require power levels up to 200 mW.

Optical Clocks: Since the first realization of an optical frequency comb (e.g., electromagnetic source consisting of many frequencies that are precisely separated by a frequency, typically in the microwave regime), there has been a revolution in precision time keeping via the development of optical clocks. Their performance has greatly surpassed that of the microwave clock standard of Cs and is expected in the near future to be used for the new definition of the second. Optical clocks use extremely stable lasers tuned to ultranarrow atomic transitions combined with an optical frequency comb to achieve frequency precision that today is now better than 1 part in 10^{18}. These systems require extremely high-performance lasers and broadband optical frequency combs and typically take up an entire 4'x 8' optical table.

Technological applications for optical clocks include improved timing and navigation systems and measuring Earth's gravitational shape (geodesy). For example, a 10^{-18} variation in optical frequency is equivalent to a 1-cm variation in the altitude on Earth. Such a capability could simplify the mapping of height variations across large distances and enable environmental monitoring via the changes in height of ice sheets or ocean surfaces. In addition, optical frequency combs themselves could be used for other forms of observations via spectroscopy and distance ranging.

Over the past decade, there has been tremendous developments in narrow linewidth lasers on chip that could eventually be part of the cooling and probing lasers required for a portable, low-SWaP optical clock. Similarly, optical frequency combs can also be generated via nonlinear optical interactions in chip-based microresonators, and recent demonstrations have been able to realize comb devices that can fit on the tip of a finger.

Integrated Photonic Platforms: The view is that future photonic chips will be a heterogenous mixture of different material systems. While silicon photonics is the most mature, lithium niobate (LiN) and InP offer key advantages. Silicon-nitride-based devices have been at the heart of a new generation of high-performance lasers and chip-based optical frequency combs that can be operated with very low electrical powers. Photonic devices based on thin-film LiN have made tremendous advancements in the past 5 years with large reductions in losses. This has led to the record high-speed modulators, narrow frequency filters, and electro-optics frequency combs. In addition, nonlinear frequency conversion and generation can be realized with mW power levels in LiN micro-resonators. In parallel with development of these different platforms has been heterogenous integration of devices made from these distinct materials. It is likely that within the next decade Silicon photonics chips will be produced in massive quantities in semiconductor foundries and will be able to be heterogeneously integrated with III-V amplifiers/lasers and LiN devices to realize enormously capable highly compact optical instruments that are fully packaged with the control electronics and can generate, process, and detect all the optical signals required for a specific quantum sensing application.

Quantum enhancement in remote sensing (squeezed light, entangled comb lines, multimode entanglement)

By Yuping Huang (Stevens Institute of Technology) and Alex Sokolov (Texas A&M)

Introduction

This session focuses on how quantum effects can enhance the performance of sensors, particularly those of active sensors such as Lidar and Radar. One direction that the community has frequently pursued is to use nonclassical light, such as quadrature squeezed light, quantum entangled light, and frequency comb lines, on the transmitter side, or the receiver side, or both. However, as pointed out in the "Independent Panel Report for Technical Assessment of NASA and External Quantum Sensing Capabilities," (NASA/TM−20230018123), those sensors using squeezed or entangled light are very susceptible to losses. Basically, when there is a 3-dB loss, any quantum advantage would quickly vanish. It remains to realize quantum enhancement in practical operations, where the losses can be easily 10 to 150 dB.

Highlights

There was a consensus that quantum sensing techniques based on squeezed or entangled light are not suitable for most remote sensing tasks. However, there could be some applications where the loss is less than 3 dB, or the illumination intensity needs to be very low, so that such techniques may still find usefulness. Examples include LIGO and some biomedical imaging.

Most quantum enhancement claims were made on the merit of information per photon. That gives the same number of illuminating photons, how much signal to noise can be obtained. However, in most cases this is not a relevant merit, because the photon number is usually not a limiting factor. For example, even in an optical pulse of just 1 microjoule, the photon number is on the order of 1013. Hence, it does not make sense to push the information per photon, but rather to maximize the signal to noise given a certain realistic optical power.

Quantum illumination is a quantum sensing technique that uses entangled photons in multiple optical modes to improve the signal to noise ratio by M, where M is the number of optical modes. While this is appealing, only one photon is used at a time to probe the target, so that the returning signal is extremely rare. For a given duration of measurement, the achievable signal to noise is actually orders of magnitude lower than the classical sensing techniques using bright optical pulses.

For quantum enhanced sensing techniques to be accepted and adopted, one must establish some clear practical advantages under similar or comparable device parameters, such as size, weight, power, and cost, or SWAP-C. Even if a quantum technique can have superior performance but with unreasonable SWAP-C parameters, it is unlikely to be deployable. Thus, it is important to benchmark quantum sensing techniques against the classical state of art in practical settings.

One promising technique that can establish a clear practical advantage mode matched photon conversion, based on a quantum enhancement effect similar to quantum super radiant emission. It utilizes parametric nonlinear processes where information-carrying electromagnetic signals (e.g., optical photons, microwave photons, radio photons) in a large number of electromagnetic modes are converted phase coherently to signature signals in a single mode or a few modes. The phase coherence means that while the signals before conversion may have unequal or uncertain phase values across the modes, the signature signal converted from those different modes to the same mode have a uniform phase. This phase coherence can lead to significant increase in the signal to noise ratio in detecting weak signals buried in strong background noise. The disclosed techniques can substantially improve the per-photon SNR similarly to how quantum illumination can outperform their classical counterparts. Yet, it can use bright twin beams at a similar intensity level as classical optical pulses, so that the end system performance is substantially improved from that of the classical systems

Over the next decade, we project that the most impactful applications of quantum technology for NASA Missions and Earth observation will utilize quantum sensing. We identify Rydberg sensors and optical clocks as the most promising instruments that could be deployed for various forms of remote sensing. Such sensing could include microwave imaging and geodesy across large distances. Integrated photonics will be a requisite technology in these devices in order to meet the sensitivity, SWaP, and environmental robustness needed for deployment in aircraft and satellites.

Recommendation

- Establish a new figure-of-merit to evaluate various quantum sensing proposals, based on: (1) its relevance to NASA missions; (2) its performance in practical settings; (3) if there is true advantage in signal to noise, resolution, sensitivity, etc., under the same device SWaP-C parameters.
- Explore mode matched photon conversion as a potential quantum remote sensing technique for NASA missions, including (1) performing proof-of-concept experimental validation; (2) identifying applications that can benefit from it; (3) develop an engineering roadmap for the applications.

Single photon detection and quantum parametric mode sorting for cloud penetration and daytime noise reduction

By Yong Meng Sua (Quantum computing Inc.) & Carl Weimer (BAE Systems Inc.)

Introduction

The Independent Panel Report for Quantum Sensing (Kitching et al., 2023) recently completed a review of the state-of-the-art superconducting photon counting detectors in the larger context of NASA science needs. The needs of photon counting for Earth Science needs a broader perspective. Mission cost and SWaP constraints and different science objectives force a system approach to be utilized. Fortunately, there is a broader set of detector choices that can be matched to the different needs of different systems for Earth Science (Eisaman et al. 2011).

Photon counting detectors have been flown on Earth Science missions for Aurora studies (PMT) Monfardini, 2001); atmospheric lidar for aerosols and clouds (Silicon APDs (Krainak et al., 2010), PMTs (McGill et al., 2015)); and for laser altimetry of land, vegetation, snow depth, and ocean near-surface (PMT)Yang et al. (2019). Photon counting lidars techniques continue to expand in ground and airborne use so it can be anticipated that the future will include a variety of space-based lidars utilizing quantum enhanced techniques such as mode sorting, coherent nonlinear, and Time Correlated Single Photon Counting (TCSPC) as presented in other sections. In the broader sense photon counting detectors will also need to be advanced for applications in quantum communication (qubits) using quantum protocols. With the pending onset of optical communication crosslinks on constellations, distributed sensors are a possibility that could utilize effects like entanglement. Having a variety of detectors available for space allows for more flexibility in system design.

The superconducting photon counting detectors have the advantages of lower dark noise, lower jitter, high QE and many are photon number resolving. It’s important however to take a larger look at the system impacts. The need for low cryogenic temperatures (~4K or less) to achieve superconducting requires the use of liquid cryogens (mission life limiting) or cryocoolers. The current spaceflight qualified cryo-coolers have high cost and create a significant burden on spacecraft resources (mass, power, vibration-load) that in turn will drive up the cost of the overall mission (Chen et al., 2024). For flagship missions this may be acceptable, but it would make demonstration or even missions in the Earth Venture or Earth System Explorer unlikely. As a low TRL alternative path, ESTO invested early in all solid-state laser cooling for detectors (Good et al., 2004) which demonstrated cooling to the 100K range (Vicente et al., 2020). A recent paper proposed a path for this technique to go to much lower temperatures (Tude et al., 2024).

An attractive alternative detector that has been developed for Quantum Information Science is the next generation of silicon APD for photon counting (SPADs). Their performance isn’t as good as superconducting solutions, but they significantly outperform PMTs in dark noise, timing jitter, and QE. They offer significant advantage in meeting these requirements near or at room temperature and requiring only 10s of Volts of bias (as opposed to kV for the PMTs). One weakness is that silicon device dark noise does rise due to radiation induced displacement damage causing the dark noise to rise. This can be addressed with multiple system level approaches including custom shielding (Han et al., 2023). Plus, there are ongoing studies that are designing approaches and testing the ability to anneal out the damage. Preliminary results, including an ESTO funded project, are returning dark counts to < 10 Hz with different approaches for heating the die (Krynski et al., 2023; Harwit et al., 2025).

Question: Why do we need cryocoolers if we can just couple to deep space and achieve the temperatures needed?

- The instrument electronics must be kept close to room temperature to survive so typically heat is applied. For LEO orbits there is typically also significant solar heating. We can use cryo-radiators e.g. one is used on Ralph on New Horizons now located in the Kuiper belt that achieves a detector temperature of 160 K. System constraints ultimately prevent our ability to cool a detector passively to 4K.
- There is a larger set of superconducting detectors used in astronomy and planetary science we might be able to leverage.

Quantum Parametric Mode Sorting and Time-gated Photon Detections for Earth Science

Detection signal-to-noise ratio (SNR) lies at the heart of any remote sensing task in Earth Science. Spectral filters and temporal shutters are widely used for background light noise rejection in the spectral and temporal domains, respectively. By carefully cascading the two domains, optimally matched filters can be constructed to achieve maximum noise rejection. In a project funded by Brookhaven National Lab, a prototype of a time-gated, time-correlated single-photon-counting (T2) lidar for atmospheric observations at range resolution down to 10 cm, or two orders of magnitude finer than that of traditional lidars (Yang et al., 2023). Time-gated mode allows the lidar to explore a small region of interest (e.g., cloud base) in detail and with lower uncertainty (i.e., higher signal-to-noise ratio), observe cloud base structures at decimeter scales. Results show that the air–cloud interface is not a perfect boundary but rather a transition zone where the transformation of aerosol particles into cloud droplets occurs. The highly resolved vertical profile of backscattered photons above the cloud base enables remote estimation of droplet concentration, an elusive but critical property to understanding aerosol–cloud interactions (Yang et al., 2024). The results show the feasibility of remotely monitoring cloud properties at submeter scales, thus providing much-needed insights into the impacts of atmospheric pollution on clouds and aerosol-cloud interactions that influence climate.

However, there is a fundamental trade-off between the signal detection efficiency and the extinction of noise rejection for linear filters (Eisaman et al., 2017). Quantum parametric mode sorting (QPMS) has been shown to enable photon counting with precise time gating and exceptional noise rejection that significantly exceeds what is possible with linear filters (Ansari et al., 2018; Brecht et al., 2018). While previous experimental demonstrations were in a collinear optical configuration, its response to off-axis scattering must be understood to apply it more broadly in remote sensing missions. To evaluate this prospect, a laboratory testbed funded by ESTO to evaluate its performance for detecting photons at small angles, along both forward and backward directions, after passing through strongly scattering media (Zhu et al., 2021). Our results find no measurable degradation in detecting noncollinear photons along both directions. This finding indicates that the key intra-pulse coherence essential to quantum parametric mode sorting is maintained at a small scattering angle, permitting its applications in Earth Science. Currently, a visible QPMS lidar funded by ESTO (ongoing) is being tested for photon counting lidar measurement of snow depth for Snow Water Equivalent and Depth retrieval.

Highlights

- Efficiency matter for remote sensing applications, the advantages of having additional 20% quantum efficiency from superconducting nanowire single-photon detector (SNSPD) vs Single-photon avalanche diode (SPAD) is highly dependent of the applications.
- “80% solution”, how imperfect technologies or solutions will contribute to the Earth Science community.
- The practicality (cost effectiveness, SWaP- Size, Weight, Power and Cost) and performance matters of the remote sensing.
- Annealing of SPAD can be repeatable, potentially with a reasonable pathway towards space mission.
- High performance time tagging instrument, a key instrument for photon counting lidar has been proven in space.
- Beyond detectors, system level radiation hardening is required for space applications
- SNSPD may not have more sensitivity against radiation damage.
- Optimal mode matched filtering approach-T2 lidar. Good for backscattering based remote sensing, needs refinement for Raman, fluorescence, and doppler measurement. Demonstrated for air–cloud interface observation, enable estimation of droplet concentration.
- QPMS- ultra-narrow gating comes at the price of a smaller observation window, conversion efficiency needs improvement, system throughput is critical for practicality. Viable path identified. Observation for snowpack being carried at BAE Systems.

Recommendations

- Quantum technologies can be very helpful to advance our understanding of cloud processes that are crucial to weather and climate. This aligns with two themes mentioned by Xubin Zeng (ASU), needs for Earth Observations: extreme precipitation events, water and energy cycle.

- Quantum technologies can fill observational gaps in Earth-related observations, e.g., in laboratory studies (e.g., cloud chamber), or in field observations. More importantly, these new observation opportunities can be helpful to solve key scientific questions, e.g., aerosol-cloud interactions, that cannot be addressed using existing techniques/instruments. Integrating quantum-based remote sensing techniques for laboratory, ground-based, airborne, drone, satellite observations. What we learn in the laboratory will help us to understand what we observe from space. But the laboratory work must be done with an understanding of what is needed and the limitations of operating in space.

- Shaking hands between "classical world" and "quantum world", needs good communication and close collaborations between quantum community and other communities, e.g., atmospheric science and cloud physics. Understand the pro and cons of quantum technologies. Explore research opportunities to apply quantum technologies to address key scientific questions that cannot be addressed using existing technologies. More workshops bringing together technologists and Earth Scientists are needed. We can’t rely on the expectation that the boundaries can be overcome naturally.

- Gaps exist between the needs for science vs technology offerings for the entire community, different branches of research- the differing needs of astrophysics, planetary science, heliophysics and Earth science. ESTO and NASA can help to consolidate the effort.
- The larger changes in the space community will likely enable the introduction of quantum technologies to enable Earth Science. This includes: the drastic drop in launch costs; the rise of commercial mega-constellations; the expected sharp rise in optical comm enabled cross and down links; the introduction of new computing capabilities (including quantum optimization engines); the rise of AI powered data collection and analysis (both onboard and ground based)[14]; the miniaturization enabled by photonics, etc.
- ESTO’s InVEST program is an excellent way to demonstrate technologies in space. Expanding the program would give emerging quantum technologies a faster path to space, especially where the airborne environment doesn’t make sense.

Applications of Quantum Annealing in Lidar Remote Sensing from Space

By Yongxiang Hu, Yuping Huang, Xubin Zeng, Charles Gatebe, Carl Weimer, Jennifer Lee, John Yorks

Introduction

The main objective is to reduce cost of future space lidar missions. Achieving the desired signal-to-noise ratios (SNRs) of ocean and atmospheric profiling lidar measurements from space is the key cost driver of space lidar missions. Brute force hardware approaches, such as an increase of telescope size and/or laser energy, have been traditionally considered to enhance SNRs and meet the scientific measurement requirements. These signal centric approaches often come with a high price-tag.

Highlights

An innovative noise centric approach, taking advantage of quantum annealing, is introduced. This approach leads to the reduction of noise without reducing resolution and information content of profiling lidar measurements. The quantum denoising technique is based on the fact that:

1. Signals is spatially correlated while noise is not;
2. Noise increases the diagonal components of the auto-covariance matrices, while not affecting the non-diagonal components;
3. reducing / removing the noise can be achieved if we can find the noise in each pixel of an image so that we can (a) minimize the trace of the covariance matrix of the residual image; (b) minimize the differences of non-diagonal components between the covariance matrices of the noisy and the residual images.

Computational burden of solving such an optimization problem is equivalent to decrypting a long password (a password as long as the total number of pixels), which is difficult for conventional computers. On the other hand, this optimization problem is one of the very few low hanging fruits of quantum computing through quantum annealing. Our new technique requires finding the noise at each pixel that will minimize a Hamiltonian-like polynomial of this noise, which is what quantum annealers are good at, while it is difficult (if not impossible) for conventional computers. This quantum denoising technique is demonstrated on the Dirac-3 quantum computer. Dirac-3 system is a photonic-chip-based quantum computer developed by Quantum Computing Inc (QCI) (Nguyen et al., 2024). Dirac-3 is quantum annealing system enabled by the “entropy quantum computing” concept developed by Dr. Yuping Huang of the Stevens Institute and QCI (Bu et al., 2022).

The quantum denoising concept can be applied to the existing space lidar measurements to improve their scientific applications. Limited by data downlink bandwidth, space lidar measurements can only send down a subset of the lidar measurements (e.g., spatially averaged onboard). Putting the quantum annealing device in orbit can help achieve the highest space lidar SNRs with best noise reduction before onboard averaging. The portable Dirac-3 quantum annealing system can be repackaged for onboard denoising with its limited size/power/weight (3U / 25W / 5kg). We recommend NASA investment in maturing the quantum annealer for onboard noise reduction and data analysis.

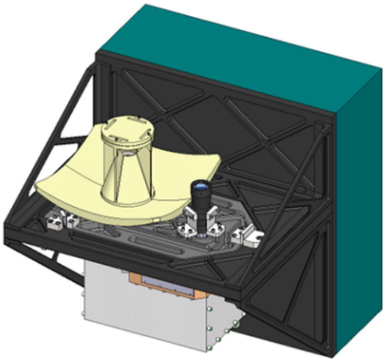


Figure 1. left: lidar; right: quantum annealer.

Recommendations

Demonstration in space: snow depth / snow density lidar measurements with quantum denoising in orbit (Hu et al., 2022). A smallsat snow lidar (backscatter channel with CALIPSO heritage, plus a vibrational Raman channel) (Fig. 1) provides accurate measurements of snow depth / density. The lidar measurements will be used for training AMSR-3 microwave radiometer measurements to provide daily / global measurements of snow depth, density and water equivalent – which is one of the targeted observables recommended by the decadal survey and provides critical information for NASA's Earth Science to Action.

Quantum Computing

By Jason Saied, Lucas Brady, P. Aaron Lott, Nishchay Suri, Shon Grabbe, & Eleanor Rieffel

Introduction:
Quantum computing is one of the most promising computational paradigms with the potential to revolutionize diverse areas of future-generation computational systems, including high-precision sensing and data analysis. While quantum computing hardware has advanced rapidly, from tiny laboratory experiments to quantum chips that can outperform even the largest supercomputers on specialized computational tasks, these noisy intermediate-scale quantum (NISQ) processors are still too small and non-robust to be directly useful for real-world applications. In a recent review article (Rieffel, et al., 2024), the NASA Quantum Artificial Intelligence Laboratory (QuAIL) team describes their work in assessing and advancing the potential of quantum computing. An overview of this work was provided by QuAIL team members during the Quantum Computing Session at the NASA ESTO Quantum Sensing Technical Interchange Meeting.

Highlights

The team discussed advances in algorithms, both near- and longer-term; physics-inspired classical algorithms that can be used at application scale today; and the results of our explorations using simulations and current hardware, which illustrate the benefits of algorithm-hardware co-design. The session also highlighted QuAIL's innovative tools supporting the assessment and advancement of quantum computing, such as improved methods for simulating quantum systems of various types under realistic error models on high-performance computing systems. Additionally, the team provided an overview of recent methods for benchmarking, evaluating, and characterizing quantum hardware, as well as insights into fundamental quantum physics that can be harnessed for computational purposes.

As a specific example of the team's ESTO-funded quantum computing aided work (Asanjan et al., 2023) discussed during the workshop, the team described a generative machine-learning model that performs stochastic wildfire detection, allowing fast and comprehensive uncertainty quantification for individual and collective events. This model integrates a U-Net architecture with a Variational Auto Encoder (VAE), comprised of four sub-models:

- A prior network
- A posterior network
- A U-Net network for feature extraction
- A combination network

The model is effective in generating stochastic wildfire segmentations and simulating unknown wildfire scenarios. The team described how incorporating quantum-sourced samples could further enhance the predictive accuracy and robustness of the model, particularly in analyzing high-dimensional satellite imagery. The model is an example of a "quantum-ready" machine learning model, one that already can be run on today's classical computers, advancing state of the art machine learning methods, but is also designed with an eye as to how quantum processing could be incorporated once the quantum hardware becomes sufficiently large and robust. In particular, the latent space is small and is likely the best place to plug in a small quantum computer. In particular, the team discussed it's work using a Quantum Ising Born Machine

(QIBM), which has the same connectivity as a Boltzmann machine but with quantum instead of thermal fluctuations. The training of the Born Machine is possible and relies only on easy-to-produce quantum measurements. Lastly, we discussed problems and hurdles associated with Quantum Machine Learning (QML), including the challenge of finding problems with useful advantage leveraging today's small and noisy NISQ hardware and the challenge associated with barren plateaus, which are regions of the control landscape where the gradients of variational parameters are too small to give guidance in the learning of the parameters.

Looking towards the future, many industry, government, and academic groups have ambitious programs to increase the size and improve the robustness of quantum processors. The NASA Quantum Artificial Intelligence Laboratory (QuAIL) team has built several partnerships and has the potential to build more partnerships in the coming years. For the next several years, however, a gap will remain between the capabilities of the hardware and the capabilities needed to run quantum and quantum-classical algorithms at application-scale. While performing spectacular one-off experiments are tempting, the field will advance by prioritizing experiments and theory that inform efforts to reach application scale in a robust, repeatable way. As hardware matures, the team will have increasing opportunities to explore algorithms, significantly beyond what has been possible up to now, and also opportunities to investigate application of quantum computing to quantum sensing. This work could take many paths, including but not limited to modeling and simulating quantum sensors, investigating quantum error correction (QEC) techniques for quantum sensing, studying the preparation of entangled states that could be useful in quantum sensors, processing quantum information from sensors including, but not limited to, very long baseline telescopes, and applying quantum computing to output from quantum sensors. This brief overview provides NASA Ames QuAIL team's current research and potential future directions, which demonstrates the need for NASA to continue to support efforts in the promising field of quantum computing.

Recommendations

Current quantum processors, referred to as noisy- intermediate scale quantum (NISQ), are still too small and non-robust to be directly useful for real-world problems. Thus, the recommendation from the Quantum Computing session is for NASA ESTO to continue to provide stable support for research in quantum computing, including quantum-ready classical machine learning, and to broaden its support to include applications of quantum computing to quantum sensing efforts. This investment will enable the technology to develop in directions that will impact NASA missions in the longer term. Ultimately, such efforts will lead to great advancements in our understanding of Earth's natural systems.

Recommendation for Advancing Quantum Technologies in Earth Science

Quantum technologies hold the potential to bridge observational gaps in Earth-related studies and offer significant advantages over traditional sensing methods. However, there is currently no clear strategy for their effective implementation. To fully leverage the breakthroughs presented by governments, industry, and academia, NASA must create strategic opportunities for integrating these technologies. Based on workshop discussions, it is recommended that this process be guided by the scientific community to ensure proper prioritization and relevance. Rather than focusing solely on new measurements enabled by quantum technology—which may not yet be well-defined—the emphasis should be on enhancing the affordability and efficiency of concurrent measurements of multiple variables. This approach mirrors the transformation seen in semiconductor technology, which evolved from large, unwieldy computers to compact, powerful laptops and cloud services.

Based on the workshop, the primary recommendations are structured around three key NASA science objectives: **measurement, Earth system model, and application**.

1. Innovative Measurement Approaches

Quantum sensing offers breakthroughs in key science measurements such as mass change, vegetation, topography, global hydrology including snow, fresh water, and soil moisture. Atom interferometer based Quantum Gravity Gradiometry (QGG) and Rydberg microwave sensors have made a significant progress. Advances in single-photon detectors and quantum properties have the potential to significantly enhance lidar measurements. It is crucial to involve the quantum scientific community early to validate these measurement concepts and assess their impact on addressing scientific questions. It's crucial to communicate the key problems and needs of the Earth Science community.

Recommendations:

1. **Community Engagement:** Vet instrument concepts like QGG and Rydberg microwave sensing through scientific communities such as the Earth Science Technology Forum (ESTF) or conferences like American Geophysical Union (AGU). Consider organizing a coordinated workshop between the NASA Earth Science Division (ESD)'s Earth Science Technology Office (ESTO), and Research and Analysis (R&A) programs.
2. **Workforce Development:** Establish testbeds and internship opportunities to train a diverse workforce.
3. **Technology Investment:** Enhance existing sensors through ESTO's Research Opportunities in Space and Earth Sciences (ROSES) programs. Key areas include:
    - **Quantum Annealing:** Leverage quantum effects to solve optimization problems, particularly in space lidar missions, to reduce costs and improve signal-to-noise ratios. Focus on maturing quantum annealers for onboard noise reduction and data analysis.

  - **LIDAR (DIAL):** Analyze the feasibility of generating a backward-propagating beam via optically-pumped lasing of air in satellite-based scenarios, making sure that laser eye safety is maintained and test this approach for molecular species detection.
  - **Rydberg Microwave Sensors:** Continue engagement with the science and technology community to ensure Rydberg sensors meet scientific needs. Development teams should demonstrate clear theoretical and practical advantages over conventional techniques.

Enabling component technology: Various photonic devices will play a significant role in reducing SWaP and increasing sensitivity for optical and microwave sensors.

2. Remote Sensing Architecture For Systematic Observation

Future Earth science applications will require higher temporal and spatial resolution measurements. Quantifying natural processes such as carbon and fresh water flux or energy cycle for weather require concurrent and coordinated measurements from space. Investing in spacecraft and communication technologies will enable such advancements. Space quantum communication and networks are critical for near-real-time, coordinated observations, while precision clocks (such as photonic integrated circuit (PIC)-based optical clocks) will enhance PNT (Precision Navigation and Timing) and multi-static active sensing with GPS.

Recommendations:

1. **Architecture design:** Integrate quantum communication as a protocol in AIST NOS architecture for future observational capabilities.
2. **Infusion and monitoring technology breakthroughs:** Monitor and potentially incorporate advanced clock technologies into ESTO’s distributed sensor investments.

3. Digital Twin Earth to Support ES2A

The ES2A initiative requires advanced models with functional "What-If" capabilities, supported by the Earth System Digital Twin (ESDT), and enhanced by quantum computing. Quantum computing will be pivotal in developing these models.

Recommendations:

1. **Partnership in Quantum Computing:** NASA should co-invest in systems offering exponentially faster processing power with a partnership with industry. Current quantum processors (NISQ) are not yet fully robust for real-world problems, so ongoing support for research in quantum computing and its applications to sensing is crucial. This will advance technology in ways that will benefit NASA missions in the long term.

4. Programmatic Recommendations

ESTO’s In-Space Validation of Earth Science Technologies (InVEST) program is well-suited for demonstrating space technologies. Expanding this program to accelerate the deployment of emerging quantum technologies—particularly where airborne solutions are impractical—is recommended. Facilitate workshops to foster collaboration between quantum technologists and Earth scientists to understand the strengths and limitations of quantum technologies and explore their application to key scientific questions.

Summary

These recommendations aim to accelerate the adoption of quantum technologies in Earth science and other fields such as astrophysics. Early adoption could lead to reduced launch costs, the rise of commercial mega-constellations, increased optical communication capabilities, new computing advances including quantum optimization engines, and enhanced AI-powered data collection and analysis.

These primary recommendations will hasten the adoption of quantum technologies and enable the introduction of quantum technologies in Earth Science, but also in other areas such as astrophysics or the specific use case of coronagraphy for high-contrast imaging detection and characterization of exoplanets. Early adoption will potentially lead to drastic drop in launch costs; the rise of commercial mega-constellations; the expected sharp rise in optical comm enabled cross and down links; the introduction of new computing capabilities (including quantum optimization engines); the rise of AI powered data collection and analysis (both onboard and ground based); the miniaturization enabled by photonics, etc.

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Appendix A: List of Participants

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- **Eleanor Rieffel** - *NASA Ames Research Center*
- **Reem Hannun** - *NASA Ames Research Center*
- **Parminder Ghuman** - *NASA Earth Science Technology Office*
- **Michael Seablom** - *NASA Earth Science Technology Office*
- **Keith Murray** - *NASA Earth Science Technology Office*
- **Haris Riris** - *NASA Earth Science Technology Office*
- **Omid Noroozian** - *NASA Goddard Space Flight Center*
- **Lihua Li –** *NASA Goddard Space Flight Center*
- **Bryant Loomis –** *NASA Goddard Space Flight Center*
- **Graeme Stephens** - *NASA Jet Propulsion Lab*
- **Jason Hyon** - *NASA Jet Propulsion Lab*
- **Rob Thompson** - *NASA Jet Propulsion Lab*
- **Yongxiang Hu** - *NASA Langley Research Center*
- **Marlan Scully** - *Texas A&M University*
- **Jay Singh** - *NASA Ames Research Center*
- **Alexei Sokolov** - *Texas A&M University*
- **John Stock** - *NASA Ames Research Center*
- **Carl Weimer** - *Ball Aerospace*
- **Xubin Zeng -** University of Arizona
- **Jiuyi Zhang** - *Hewlett Packard Enterprise*
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Appendix B – Schedule

Wednesday, June 26th, 2024

Theme: **Toward Quantum Enhanced Sensing and Measurements for Earth Observation in 2040**

Time	Agenda	Location	Speaker/POC
8:00 am-8:45 am	Room available for those arriving early, set up, & **breakfast**	NASA Ames Conference Center	
8:45 am-9:00 am	Logistics of the workshop	NASA Ames Conference Center	Charles Gatebe (Organizing Committee)
9:00 am-9:30 am	**NASA Ames Welcome:** Remarks & NASA Vision 2040	NASA Ames Conference Center	David Korsmeyer (Deputy Center Director), Michael Hesse (Director of Science), Florian Schwandner (Earth Science Division Chief)
9:30 am – 9:45 am	**Group Photograph with the Center Director/Deputy Center Director/Break**	NASA Ames Conference Center (outside)	ALL
9:45 am-10:15 am	**Keynote:** Quantum resources for enabling NASA Earth Observation in 2040	NASA Ames Conference Center	NASA Earth Science Technology Office (ESTO)/ Michael Seablom (virtual).
10:15 am-10:45 am	**Keynote**: NASA Earth Science Decadal Survey - identified gaps …	NASA Ames Conference Center	**Xubin Zeng** (Univ of Arizona) & **Graeme Stephens** (JPL)
10:45 am-11:15 am	**Keynote**: Quantum inspired, enhanced, and enabled technologies with impact to Remote Sensing Earth Science applications	NASA Ames Conference Center	**Marlan Scully** & **Alexei Sokolov** (Texas A&M)
11:15 am-11:45 am	**Keynote**: Lessons from the past quantum sensing workshops/technical meetings	NASA Ames Conference Center	**Peter Brereton (GSFC) & Jason Hyson** (JPL)
11:45	**Lunch**		

1:00 pm- 1:45 pm	**Technical Session 1**: Quantum enhanced and directional Raman backscattering for airborne and spaceborne applications	NASA Ames Conference Center	Guided discussions led by **Alexei Sokolov** and co-led by **Yuping Huang**. Each participant will be given about 2 minutes each to contribute to the topic and provide potential science benefits. Those who have nothing to contribute will pass.
1:45 pm- 2:30 pm	**Technical Session 2**: Gravity gradiometer application	NASA Ames Conference Center	Guided discussions led by **Jason Hyon** and co-led by **Bryant Loomis**. Each participant will be given about 2 minutes each to contribute to the topic and provide potential science benefits. Those who have nothing to contribute will pass.
2:30 pm- 3:15 pm	**Technical Session 3**: Rydberg sensors for microwave imaging and radars	NASA Ames Conference Center	Guided discussions led by **Shane Verploegh** and co-led by **Darmindra Arumugam**. Each participant will be given about 2 minutes each to contribute to the topic and provide potential science benefits. Those who have nothing to contribute will pass.
3:15 pm- 3:30pm	Break		
3:30 pm- 4:15 pm	**Technical Session 4**: Enabling Technologies (e.g. Photonic integrated circuits) for remote sensing (filters, beam steering, detection)	NASA Ames Conference Center	Guided discussions led by **Alex Gaeta** and co-led by **Milan Begliarbekov**. Each participant will be given about 2 minutes each to contribute to the topic and provide potential science benefits. Those who have nothing to contribute will pass.
4:15 pm- 5:00 pm	**Technical Session 5**: Quantum enhancement in remote sensing (squeezed light, entangled comb lines, multimode entanglement)	NASA Ames Conference Center	Guided discussions led by **Yuping Huang** and co-led by **Alex Sokolov**. Each participant will be given about 2 minutes each to contribute to the topic and provide potential science benefits. Those who have nothing to contribute will pass.
5:00 pm – 7:00 pm	Happy Hour at SpaceBar	NASA Ames Conference Center	

Thursday, June 27th, 2024			
Time	Agenda	Location	Speaker/POC
8:15 am- 9:00 am	Room available for those arriving early, set up & **breakfast**	NASA Ames Conference Center	
9:00 am- 10:00 am	**Technical Session 6**: Single photon detection and quantum parametric mode sorting for cloud penetration and daytime noise reduction	NASA Ames Conference Center	Guided discussions led by **Yong Meng Sua** and co-led by **Carl Weimer**. Each participant will be given about 2 minutes each to contribute to the topic and provide potential science benefits. Those who have nothing to contribute will pass.
10:00 am- 11:00 am	**Technical Session 7/part 1**: Quantum computing for lidar remote sensing and applications to climate simulations, natural disasters and big data	NASA Ames Conference Center	Guided discussions led by **Yongxiang Hu** and co-led by **Jason Saied/ Shon Grabbe/Lucas Brady**. Each participant will be given about 2 minutes each to contribute to the topic and provide potential science benefits. Those who have nothing to contribute will pass.
11:00 am- 11:10 am	Break		
11:10 am- 12:00 pm	**Technical Session 7/part 2**: Quantum computing for lidar remote sensing and applications to climate simulations, natural disasters and big data	NASA Ames Conference Center	Guided discussions led by **Yongxiang Hu** and co-led by **Jason Saied / Shon Grabbe/Lucas Brady**. Each participant will be given about 2 minutes each to contribute to the topic and provide potential science benefits. Those who have nothing to contribute will pass.
12:00 pm- 1:00 pm	lunch		
1:00 pm- 2:45 pm	Recap sessions 1-7 & go backs	NASA Ames Conference Center	Session leads (**Xubin Zeng**, **Alexei Sokolov**, **Jason Hyon**, **Yuping Huang**, **Alex Gaeta**, **Yong Meng Sua**, **Yongxiang Hu**, **Jason Saied**)

2:45 pm-3:00 pm	**Writing Session** – Capture discussion that occurred during the workshop	NASA Ames Conference Center	TBD
3:15 pm – 4:15 pm	**Guided tour** of the National Full-Scale Aerodynamic Complex (NFAC) 80’x120” Test Section (US Citizens only)	Arnold Park.	All
4:45 pm	**Closing** remarks and Recap	NASA Ames Conference Center	ESTO Rep /ARC Rep