National Aeronautics and Space Administration

FY24 Strategic Initiatives Research and Technology Development (SRTD)

STV Multi-frequency Implementation using Quantum Rydberg Radar

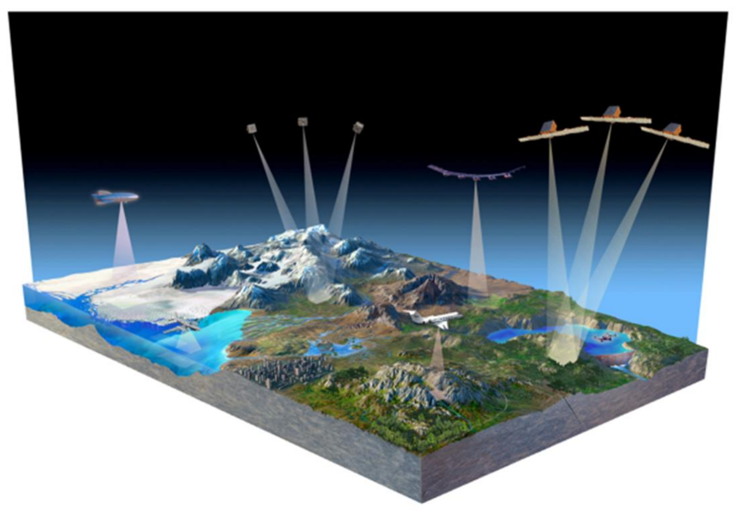
Principal Investigator: Darmindra Arumugam (334);

Strategic Focus Area: Next Earth Science Decadal Survey: Technology & Architecture for Planetary Boundary Layer (PBL)/ Surface Topography & Vegetation | **Strategic Initiative Leader:** Rashmi Shah

Quantum receiver based on Rydberg atoms to enable broad-spectrum radio remote sensing of the earth system, applied initially to surface, topography, and vegetation.

Motivation: Surface, Topography, and Vegetation (STV)

- Surface, Topography, and Vegetation or STV touches multiple science goals from solid earth, ecosystems, climate, hydrology, and weather as justified by the DS
- Targeted observable, potential candidate mission in the 2030's



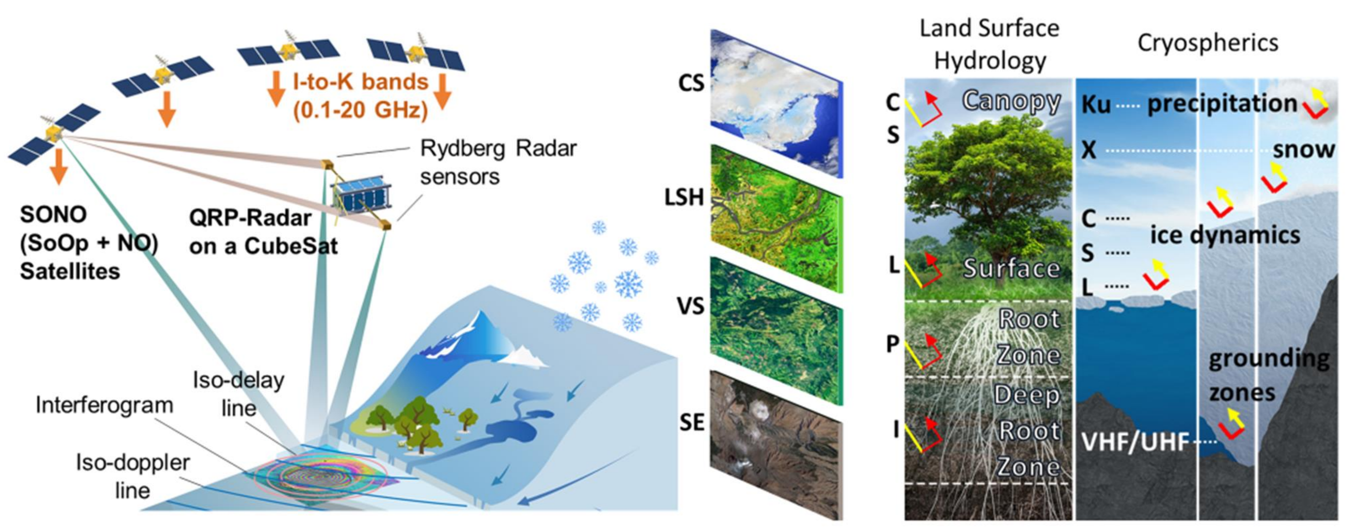
Multi-frequency and multi-platform needs in STV

- **STV objectives are presently best met by observing strategies that employ flexible multi-source and multi-sensor measurements from a variety of orbital and suborbital assets.**

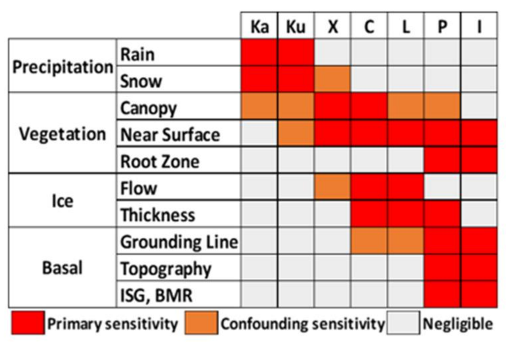
Radar Gaps	
Optimal frequency for observing (1) forest structure, (2) varying snow conditions,(3) terrain types, not known	→ Multi-frequencies
Formation flying (FF) configuration not known for imaging (e.g.: TomoSAR)	→ Spatial-diversity
Miniaturized radar antennas and electronics needed at various bands	→ Compact systems
Reduce cost with access to various bands for different applications	→ Cost reductions
Different system architectures required with multiple accuracy/coverage needs	

This is challenging to fit within the NASA cost cap, and motivates us to look at disruptive options

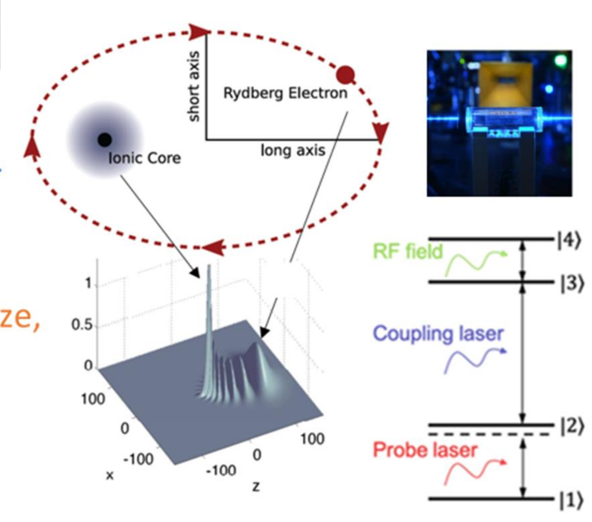
Quantum Rydberg Receivers (QRR)



Mission concept for radar remote sensing of surface, topography, and vegetation



- Disruptive architecture enabling high sensitivity, dynamic and rapidly tunable radar remote sensing through the entire radio window
- Enables measurement of key Earth Science variables spanning numerous science applications in a (1) post-launch dynamic/rapid on-the-fly tunable, (2) low SWaP (size, weight, power) system covering all bands
- Broad-band (10kHz-1THz, but when limited to SoOp's I-to-K bands) capability in an small detector (independent of wavelength)



Basis of wave/field sensing & energy levels

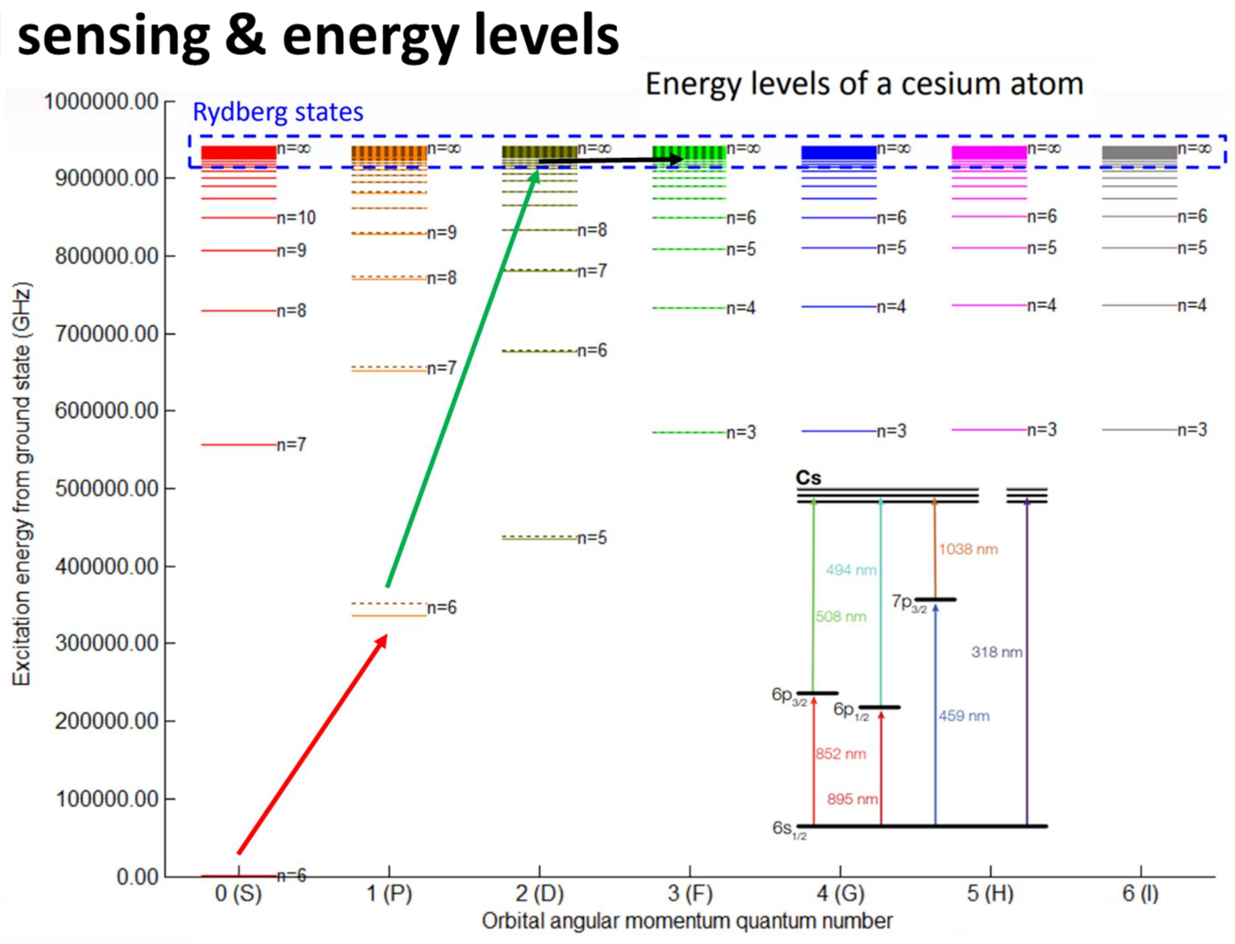
- Energy levels scale as n^{-2}

$$E_{n,l} = -\frac{Ry^*}{n_{\text{eff}}^2}$$ (Rydberg constant)

- Delta energy (energy difference between states) scale as n^{-3}

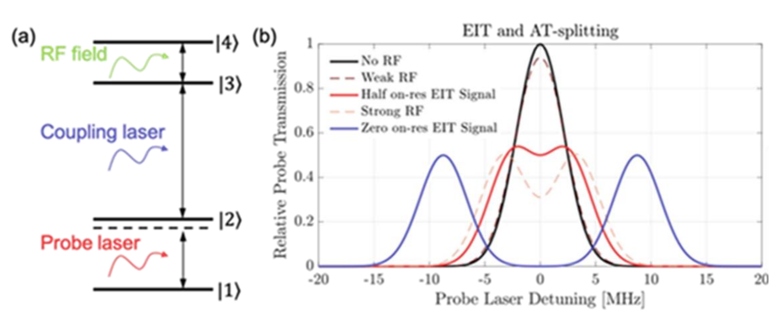
$$\Delta E \propto \frac{1}{n_{\text{eff}}^3}$$

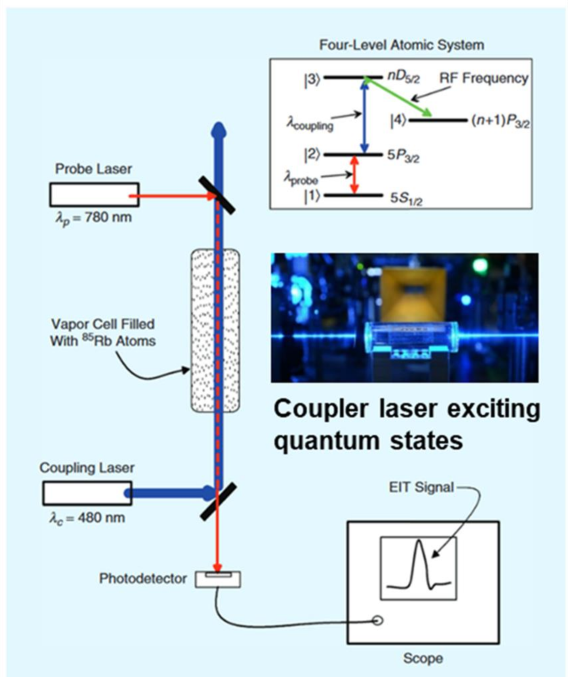
- At high n, $\Delta E \sim$ 0.1-1000 GHz ($E = h\nu$)
- Signals in these range can be absorbed by the atom to push the electron to nearby states
- Need lasers to get off ground-state (S-P) and to high n (P-D)



High-level concept for sensitive Rydberg wide-spectrum detector

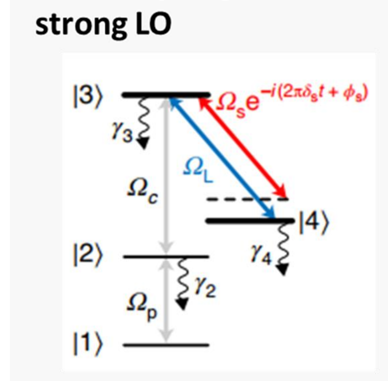
- Exploits the high sensitivity of gas-phase alkali atoms prepared in highly excited Rydberg states
- Broad-spectrum of 10 kHz - 1 THz
- Quantum direct demodulation of signals, not requiring any RF back-end sensors – permitting direct base-band sampling
- Detection volumes that is frequency agnostic and < 1cm3
- Most sub-systems and components at high TRL





Simple 4-level Rydberg EIT system. A probe laser excites room temperature alkali atoms (Rb or Cs, typically) from |1> to |2>, resulting in absorption of the probe laser. A coupling laser excites alkali vapor from |2> to |3>, resulting in EIT. A resonant RF field couples the |3> and |4> states, resulting in Autler-Townes (AT) splitting.

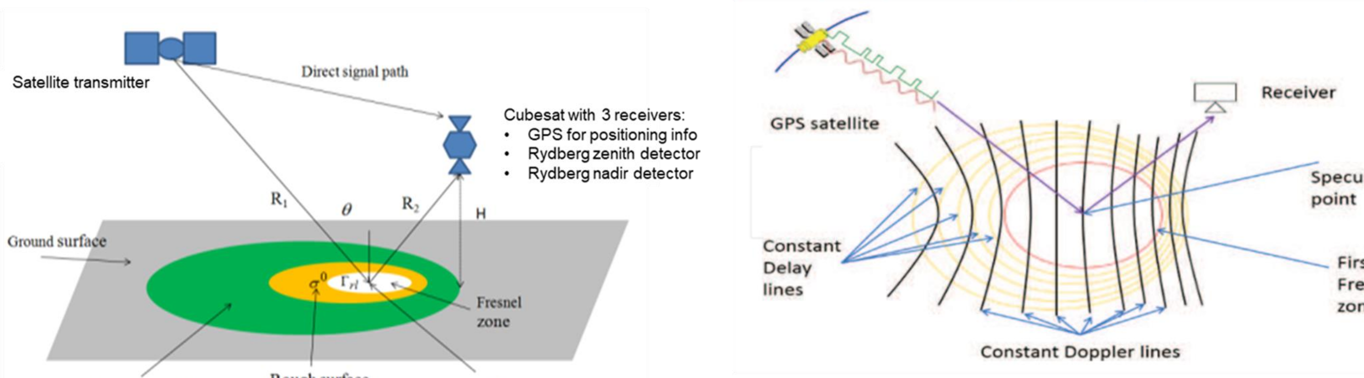
Heterodyning with strong LO



- Near resonance, shifts may be too small to resolve
- A strong local microwave signal on resonant to the transition can be used to increase sensitivity

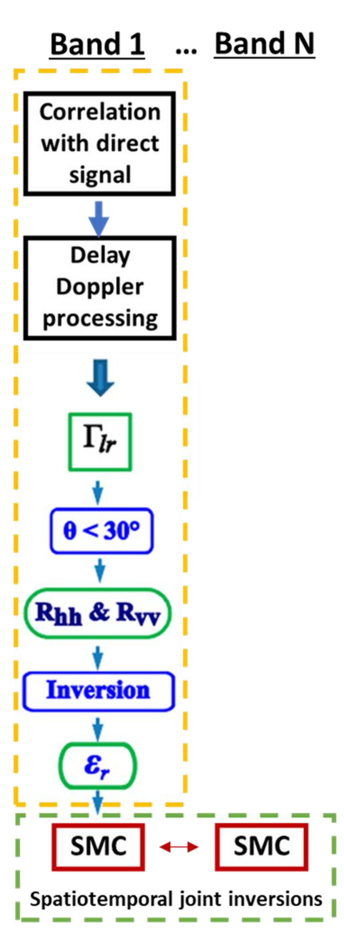
SoOP approach for remote sensing

- Signal of opportunity in I-K bands detected at a cubesat in both zenith and nadir directions. Correlator used to obtain raw electromagnetic signal transients.
- Delay Doppler map processing used to focus response to the specular point and first Fresnel zone. Processing with GPS location of cubesat done to retrieve dielectric properties as a function of frequency (band).
- Joint spatiotemporal inversions to enable multi-parameter retrievals for soil moisture content as a function of depth from surface to deep soil moistures
- Example SoOP's include: ORBCOMM, MUOS, GNSS, XM, IntelSat, DirectTV, AEHF



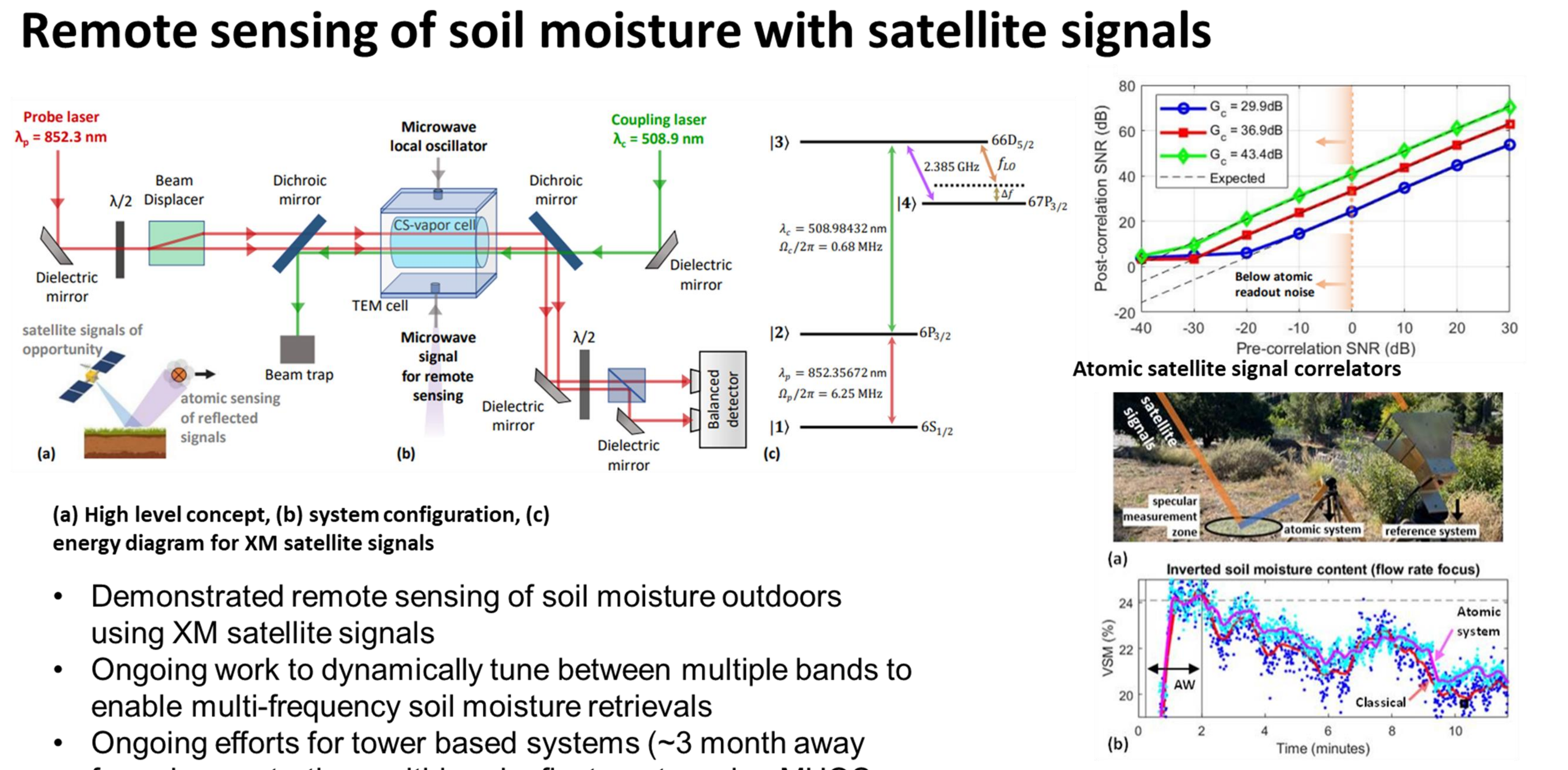
SoOP bi-static radar geometry

Iso-range and iso-Doppler around the specular reflection point used for delay Doppler map or SAR processing



Overview algorithm block diagram

Remote sensing of soil moisture with satellite signals



(a) High level concept, (b) system configuration, (c) energy diagram for XM satellite signals

Atomic satellite signal correlators

SMC retrieval from an atomic system compared to classical radar retrievals: Outdoor setup (a) and comparison between both datasets (b)

- Demonstrated remote sensing of soil moisture outdoors using XM satellite signals
- Ongoing work to dynamically tune between multiple bands to enable multi-frequency soil moisture retrievals
- Ongoing efforts for tower based systems (~3 month away from demonstrating multi-band reflectometry using MUOS, XM, GNSS, ORBCOMM)

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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Publications:

https://www.nature.com/articles/s41598-024-68914-6
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PI/Task Mgr. Contact Information:

Darmindra Arumugam (darmindra.d.arumugam@jpl.nasa.gov)