Rydberg Radar

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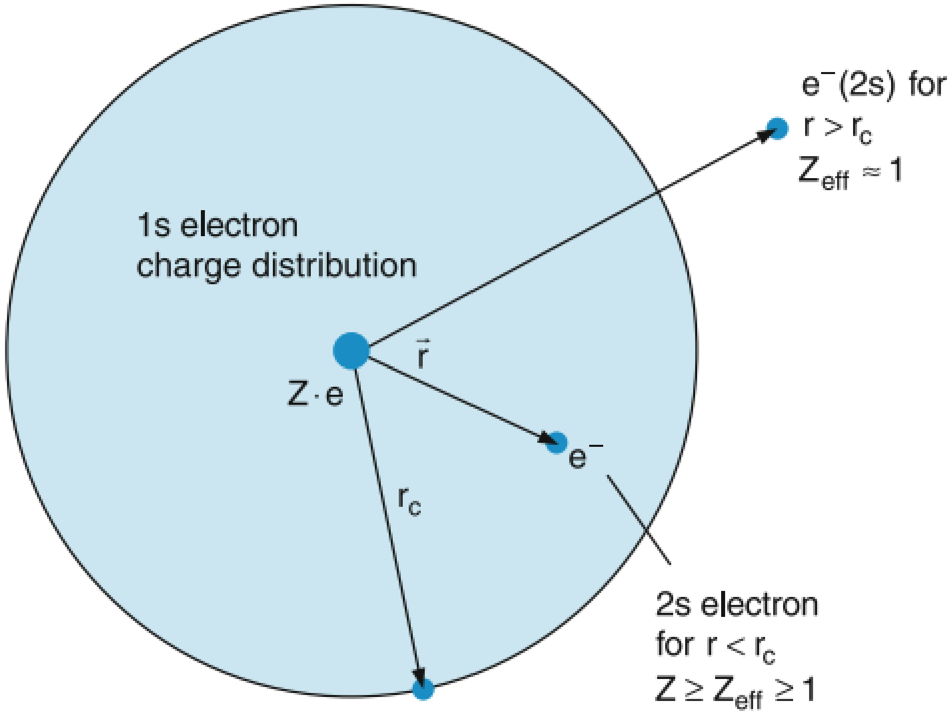
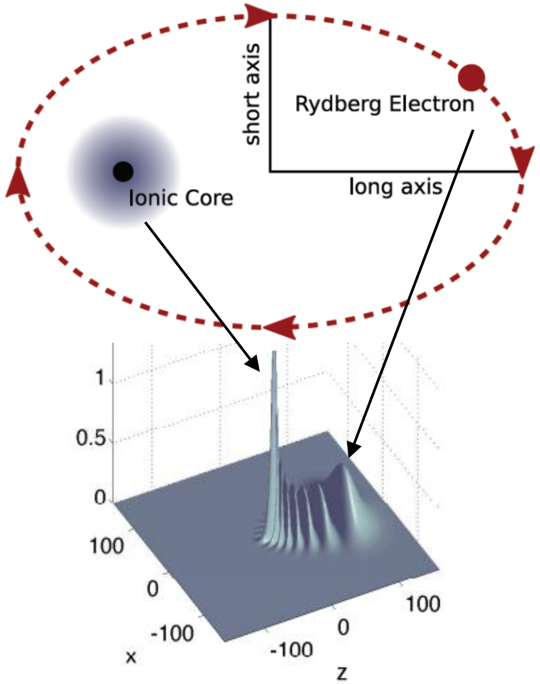
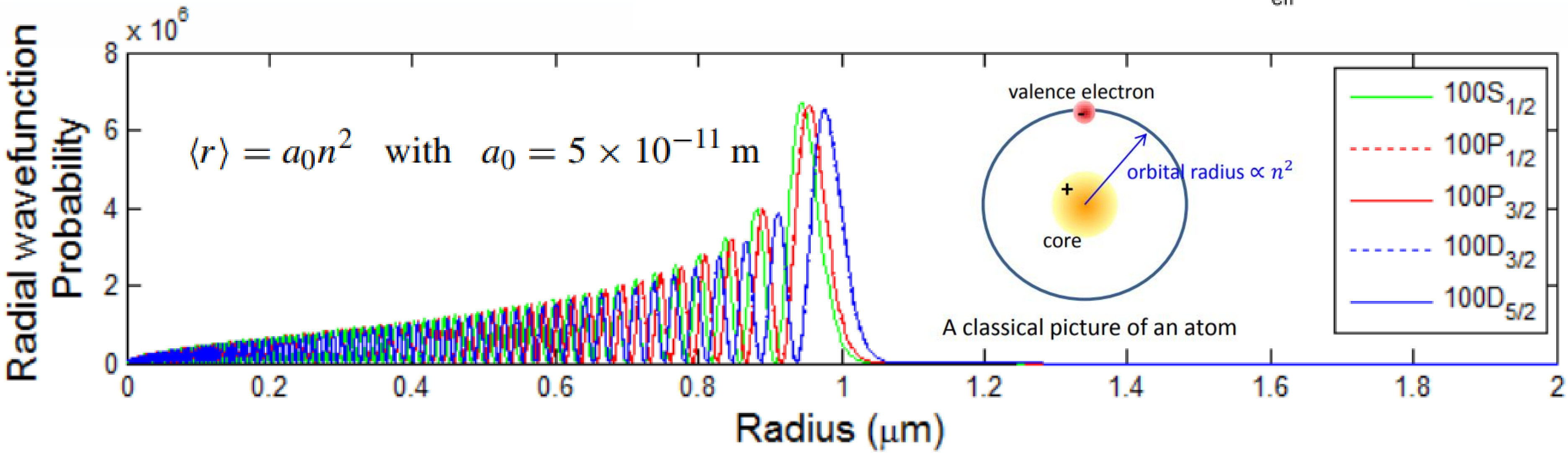
NASA ESTF, Earth Science Technology Office (ESTO)

The Rydberg atom

- Rydberg states are highly excited states of the outer valence electron where properties scale in terms of the principal quantum number, n
- For large n, the quantum mechanical description converges towards a classical one with the electron orbit approaching a circular path
  - Potential approaches a Coulomb potential of the H-atom (point-like nucleus with a positive charge) – large dipole moment
  - Atoms are large ($\sim um$) - easily perturbed by external fields



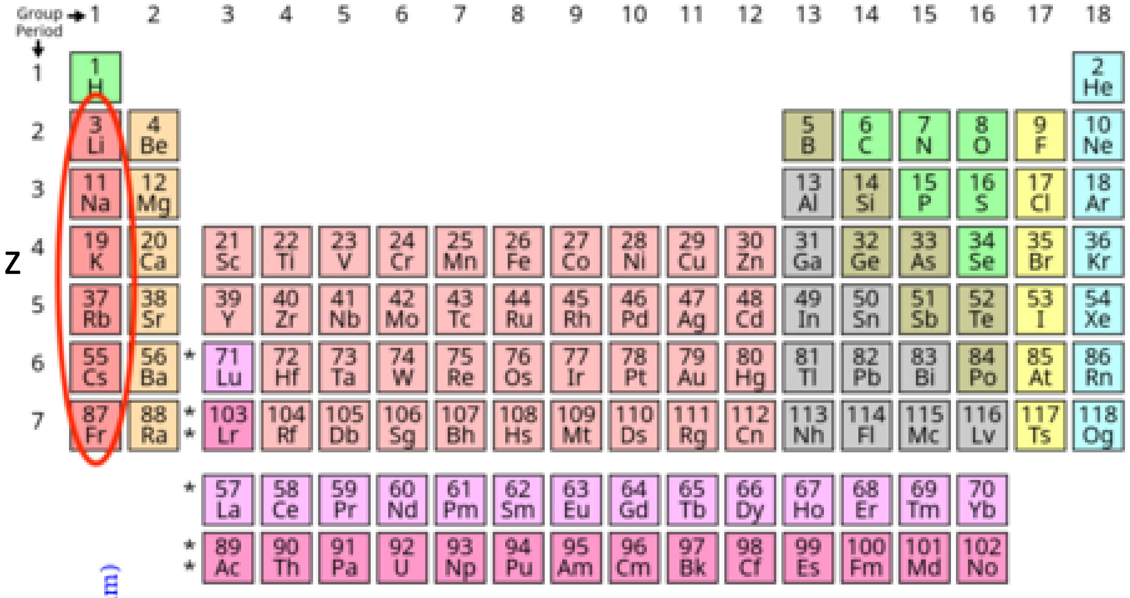




Atoms, Molecules and Photons, Springer 2010
Visualization and interpretation of Rydberg states, arXiv:1203.4768 [physics.atom-ph]
Rydberg Atoms, Springer, 2012

Alkali atoms & Cs vs Rb

- Group 1A element and have a single valence electron
- Rydberg field sensors typically use alkali metal vapors (Li, Na, K, Rb, Cs, Fr) at high principle quantum numbers to detect kHz to THz waves/fields
- These are the main elements used in atomic physics experiments (clocks, BEC, atom interferometry, etc.)



Why Rb or Cs?

- Availability of lasers and energies required typical requires Rb or Cs, both of which have been used for wave/field sensing

Benefits of Cs

- For equivalent low-frequency radio fields (<5 GHz), Cs provides:
  - Lower principle quantum number and smaller radius wavefunction – reduces atom-atom interactions
- Lab systems can implement both Cs and Rb
- Our current systems in B251 will initially use Cs

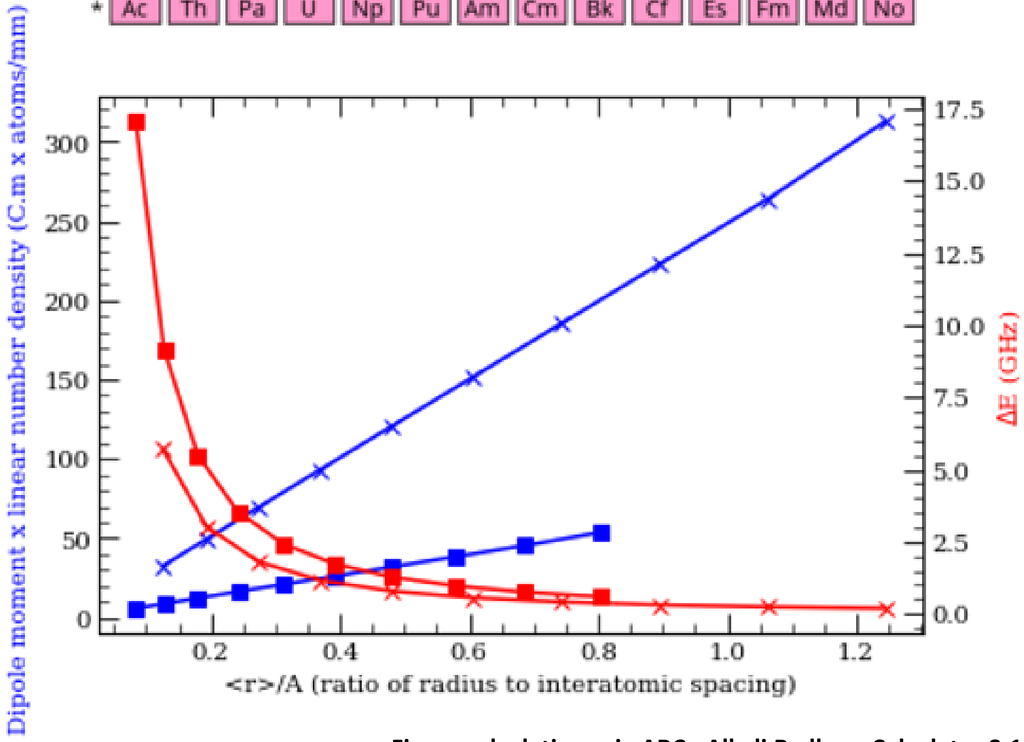


Figure calculations via ARC - Alkali Rydberg Calculator 3.1.0
https://en.wikipedia.org/wiki/Periodic_table

Basis of wave/field sensing & energy levels

- Energy levels scale as n^{-2}

Rydberg constant

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

- 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)

Energy levels of a cesium atom

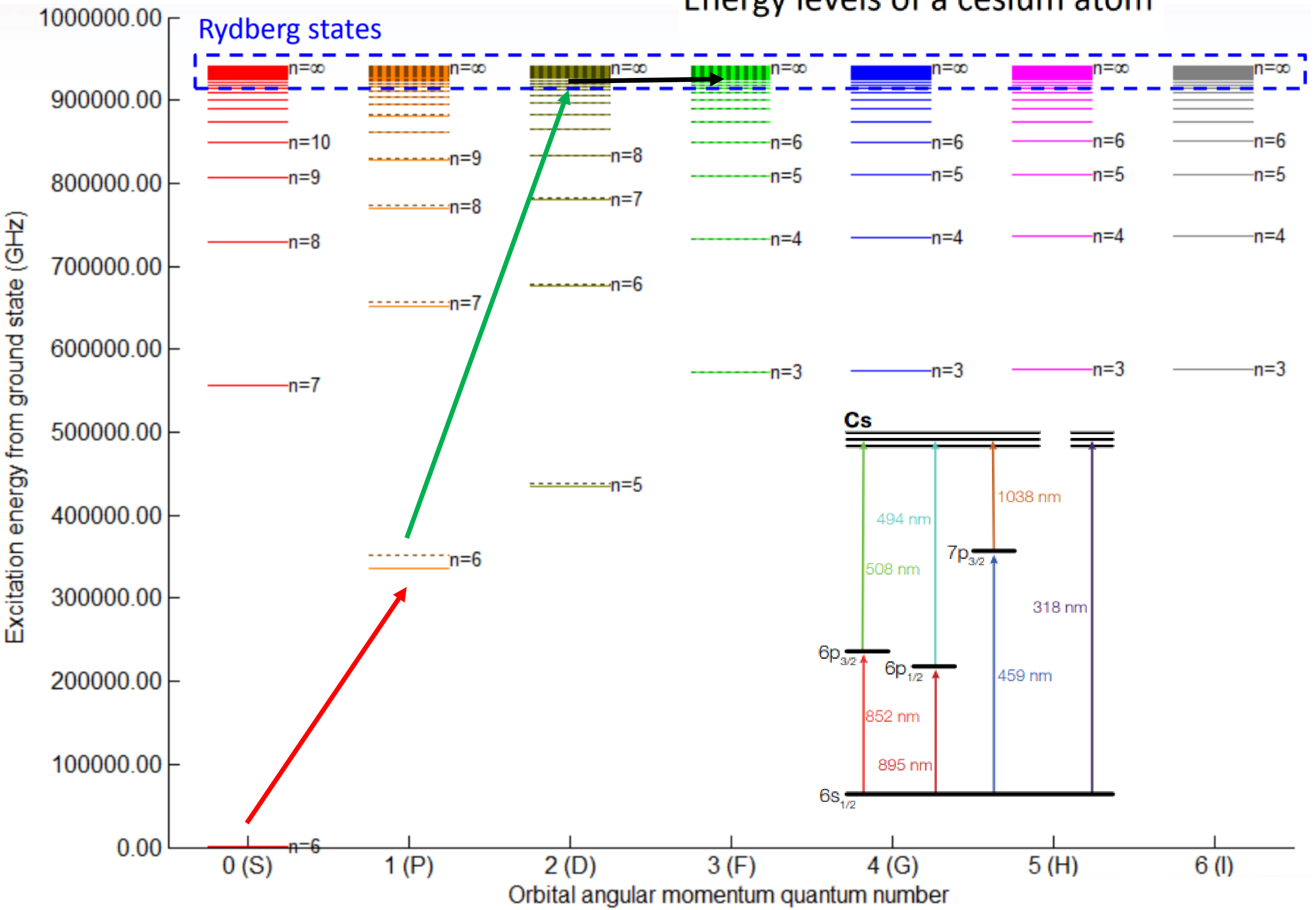


Figure calculations via ARC - Alkali Rydberg Calculator 3.1.0
https://www.toptica.com/fileadmin/Editors_English/11_brochures_datasheets/01_brochures/toptica_BR_Scientific_Lasers.pdf

Spectral coverage, dipole moments & sensitivity

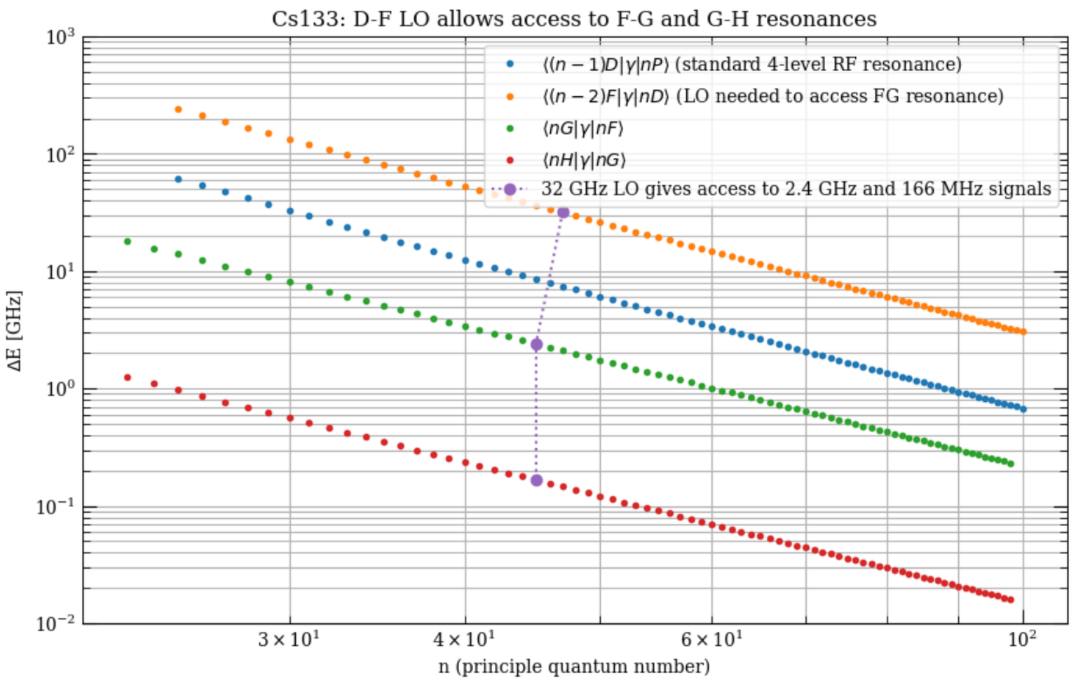
- Challenge with P-D transitions (based on laser only) is that it is difficult to get to low-RF (<GHz).
- This can be addressed by doing a F-G and G-H transition to get down to low MHz. A intermediate D-F transition is needed.
- To do this, you will need 2 controlled microwave excitations of the atoms (GHz signals)
  - Can be implemented via free-space radiation (e.g. horn) or field coupling (e.g. TEM cell)
- For nearest states, the dipole moment is $\vec{u} = e\vec{r}$, and $\langle r \rangle \propto n^2$, so it scales as $u \propto n^2$
- Sensitivity to external fields are directly related to principle quantum numbers and number of participating atoms

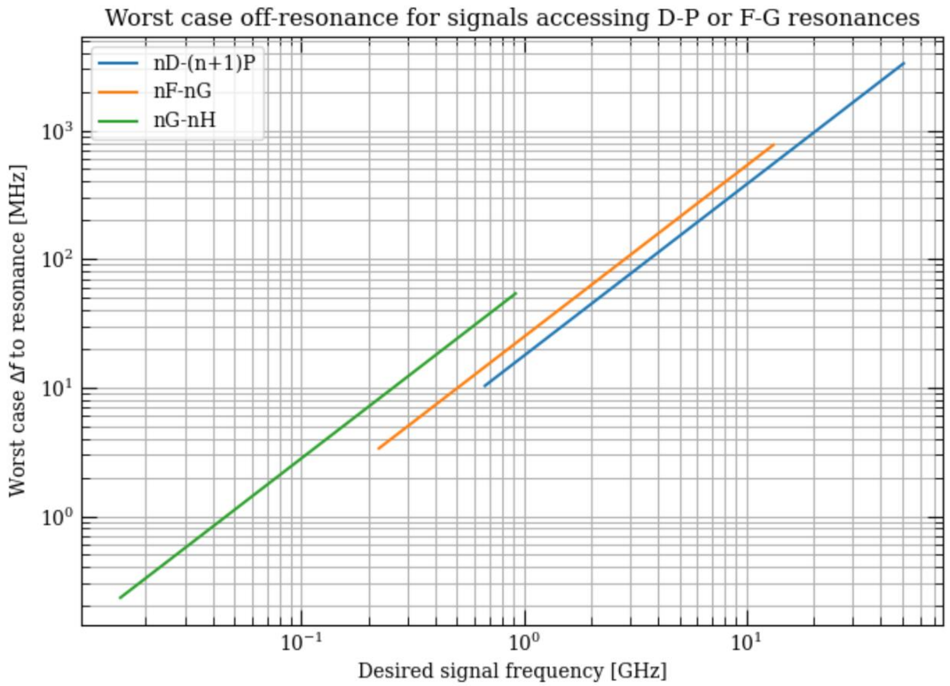
$$s = \frac{h}{u\sqrt{T_d N}}$$

Plank's constant

Number of participating atoms ($\sim 10^{14} s^{-1}$)

Coherence time



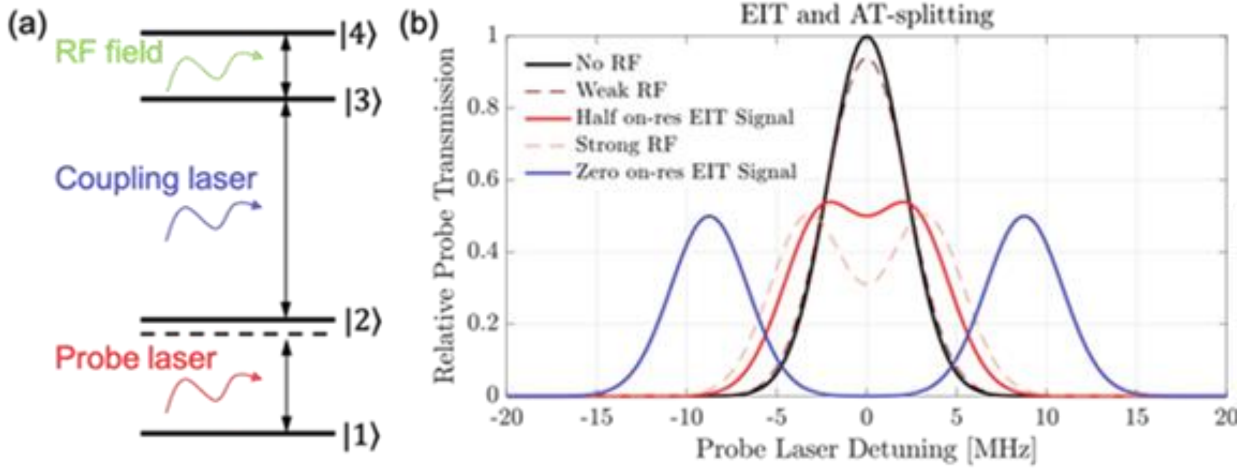


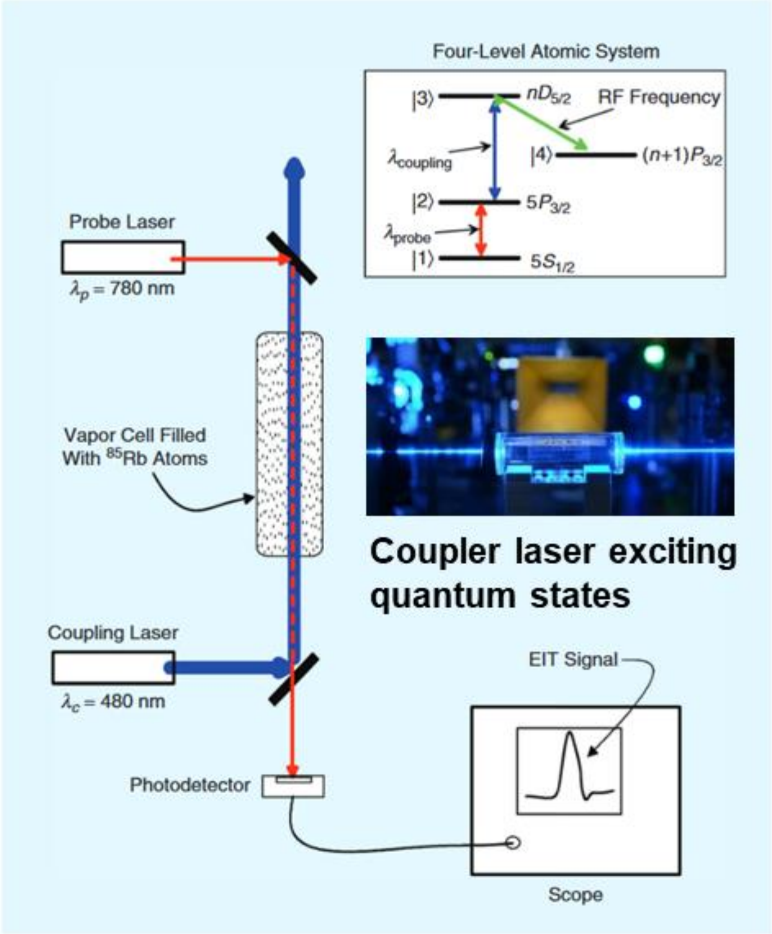
Year	Sensitivity (s)
2018	$\sim 0.5\, mVm^{-1}Hz^{-1/2}$
2020	$\sim 5\, uVm^{-1}Hz^{-1/2}$
2022	$\sim 50\, nVm^{-1}Hz^{-1/2}$

Figure calculations via ARC - Alkali Rydberg Calculator 3.1.0

High-level concept for Rydberg wide-spectrum detector

- Exploits the high sensitivity of gas-phase alkali atoms prepared in highly excited quantum states (principle quantum number: 30 < n < 100)
- Broad band of 10 kHz - 1 THz, without traditional RF front-end hardware
- 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 (no antenna)
- Most sub-systems and components at high TRL – mission injection ongoing now

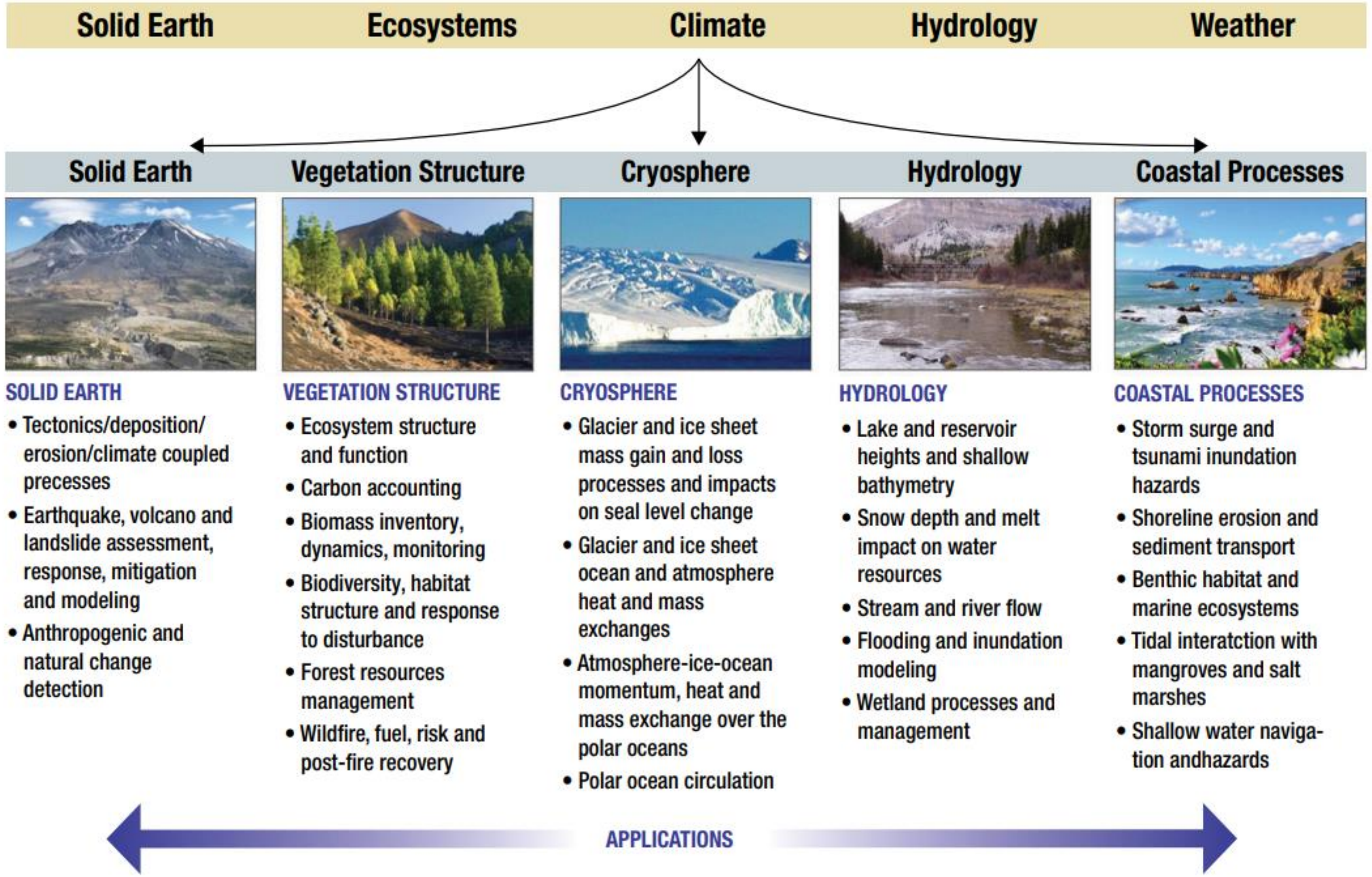


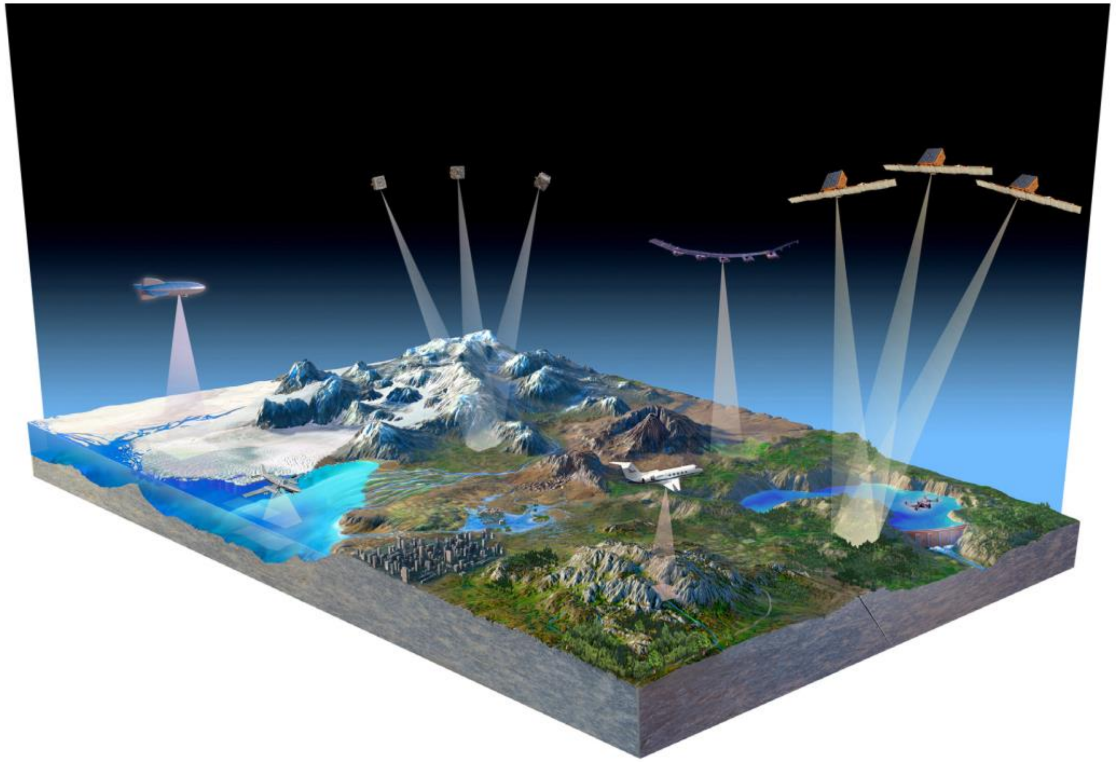


Simple 4-level Rydberg EIT system. A probe laser excites room temperature alkali atoms (Rb or Cs, typically) from |1> to |2>, resulting in absorption of the probe laser. A coupling laser excites alkali vapor from |2> to |3>, resulting in EIT. A resonant RF field couples the |3> and |4> states, resulting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

A Multiple-Band Rydberg Atom-Based Receiver, IEEE AP Mag (2020)
Graphic from citation above

NASA Surface, Topography and Vegetation





DS (Decadal Survey) science disciplines (top line) and STV Science disciplines (second line) with focus within each discipline.

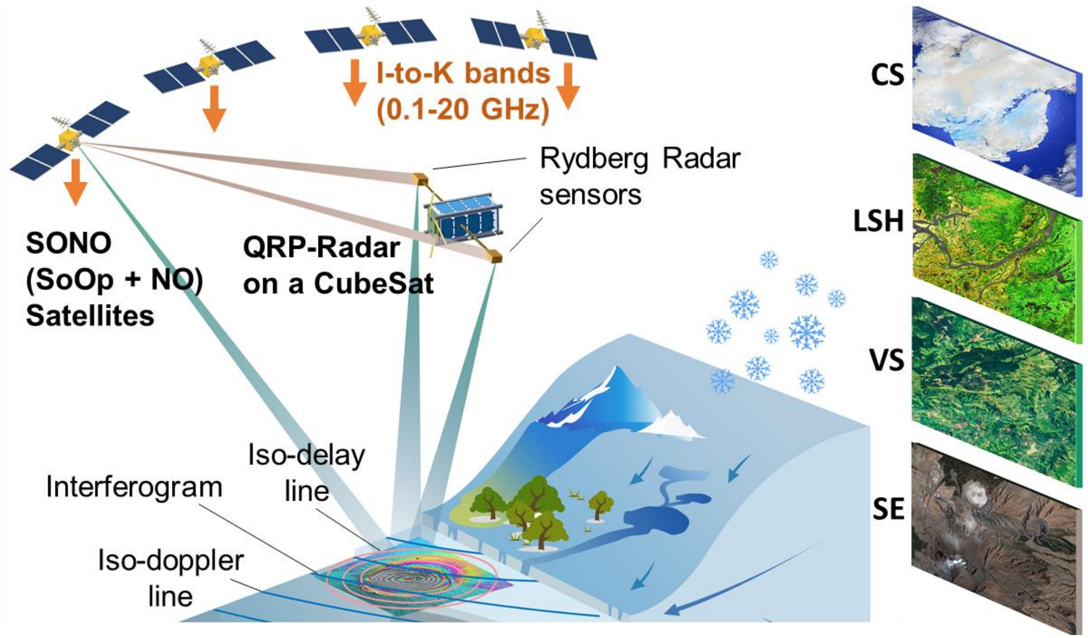
Applications are integrated throughout the science disciplines. The disciplines were derived from the DS highlighted in yellow at the top

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

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

2017-2027 Decadal Survey for Earth Science and Applications from Space (ESAS 2017)
Surface Topography and Vegetation (STV) Study Team Report
Graphics from DS and STV report cited above

Quantum Rydberg Radar (QRR)



Mission concept for STV (Surface, Topography, and Vegetation)

STV study gaps:

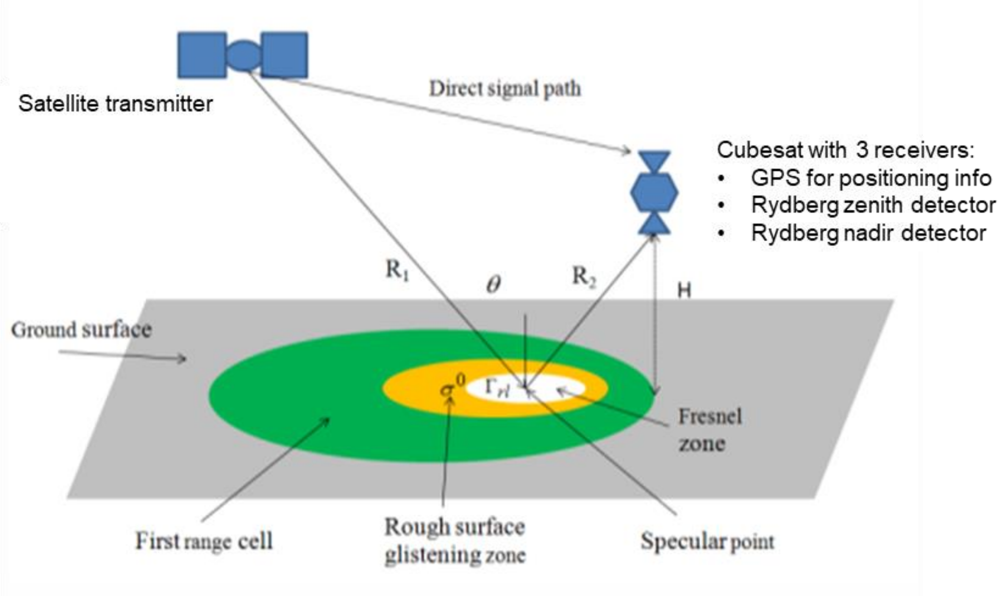
Radar Gaps	Proposed Solution
Optimal frequency for observing (1) forest structure, (2) varying snow conditions,(3) terrain types, not known	Ultra broadband radar covering I-to-K bands
Formation flying (FF) configuration not known for imaging (e.g.: TomoSAR)	No FF. Constellation for temporal resolution only.
Miniaturized radar antennas and electronics needed at various bands	cm-scale detector/antenna with no RF front-end
Reduce cost with access to various bands for different applications	No FF, broadband with no antenna, small form factor
Different system architectures required with multiple accuracy/coverage needs	Dynamically tunable bands post-launch on-the-fly

- Disruptive Quantum Rydberg architecture enabling high sensitivity, dynamic and rapidly tunable radar remote sensing throughout the entire radio window, with no science antennas or RF front-end electronics – providing significant improvements over state-of-art radars
- Enables measurement of key Earth Science variables spanning numerous science applications in a (1) post-launch dynamic/rapid on-the-fly tunable, (2) very low power, (3) small-sat instrument, (4) no science antennas required
- Super broad-band (10kHz-1THz, but when limited to SoOp's I-to-K bands) capability in an ultra-small detector (millimeter-to-centimeter-scale detector with no antenna, independent of wavelength)
- Addresses most radar applications (e.g.: SAR, inSAR, POLinSAR, Vertical Profiling, Tomography)

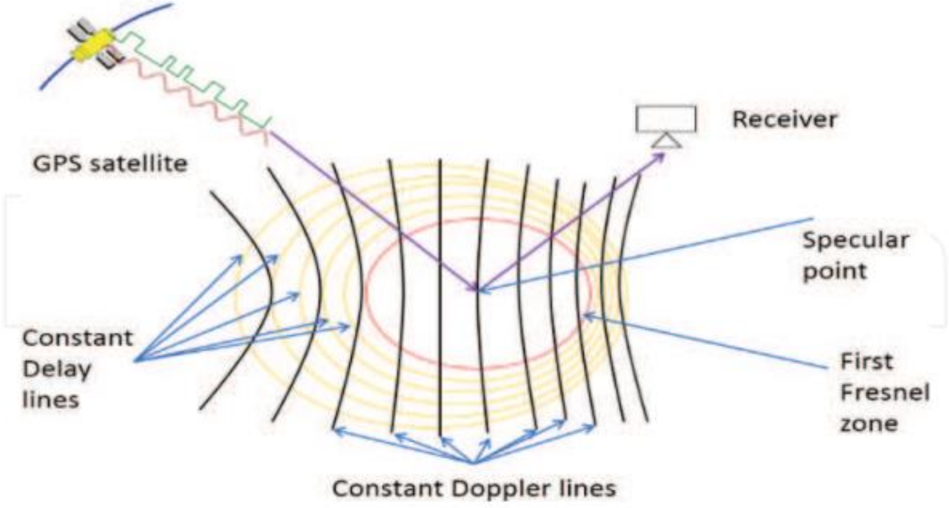
Graphic developed in coordination with JPL graphic team
Surface Topography and Vegetation (STV) Study Team Report

SoOP single cube-sat instrument-level approach

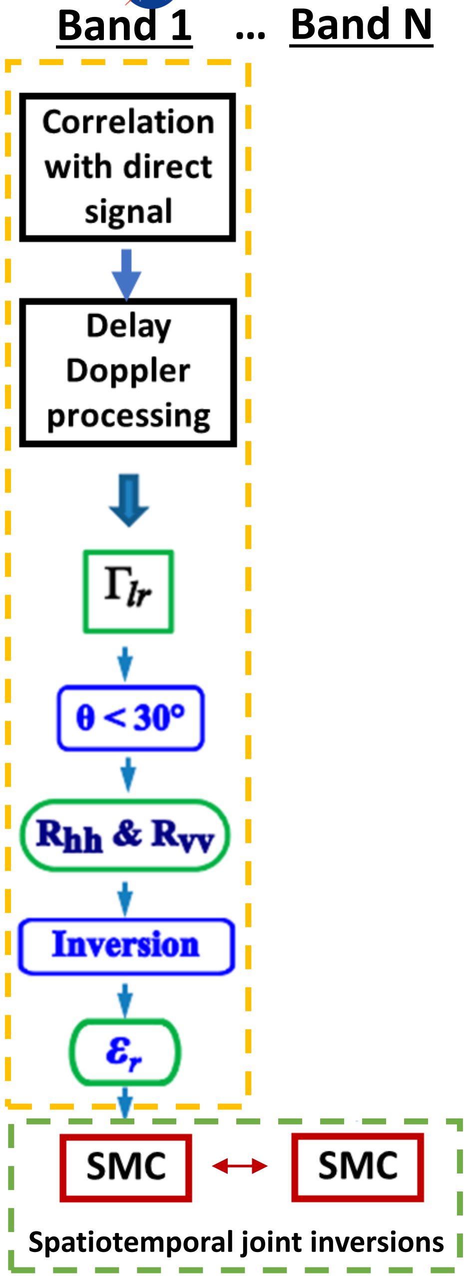
- Signal of opportunity in I-K bands detected at a cubesat in both zenith and nadir directions. Correlator used to obtain raw electromagnetic signal transients.
- Delay Doppler map processing used to focus response to the specular point and first Fresnel zone. Processing with GPS location of cubesat 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
- Joint processing from multiple cubesats to improve coverage and inversions



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

GNSS Reflectometry for Remote Sensing of Soil Moisture, IEEE-RTSI (2015)

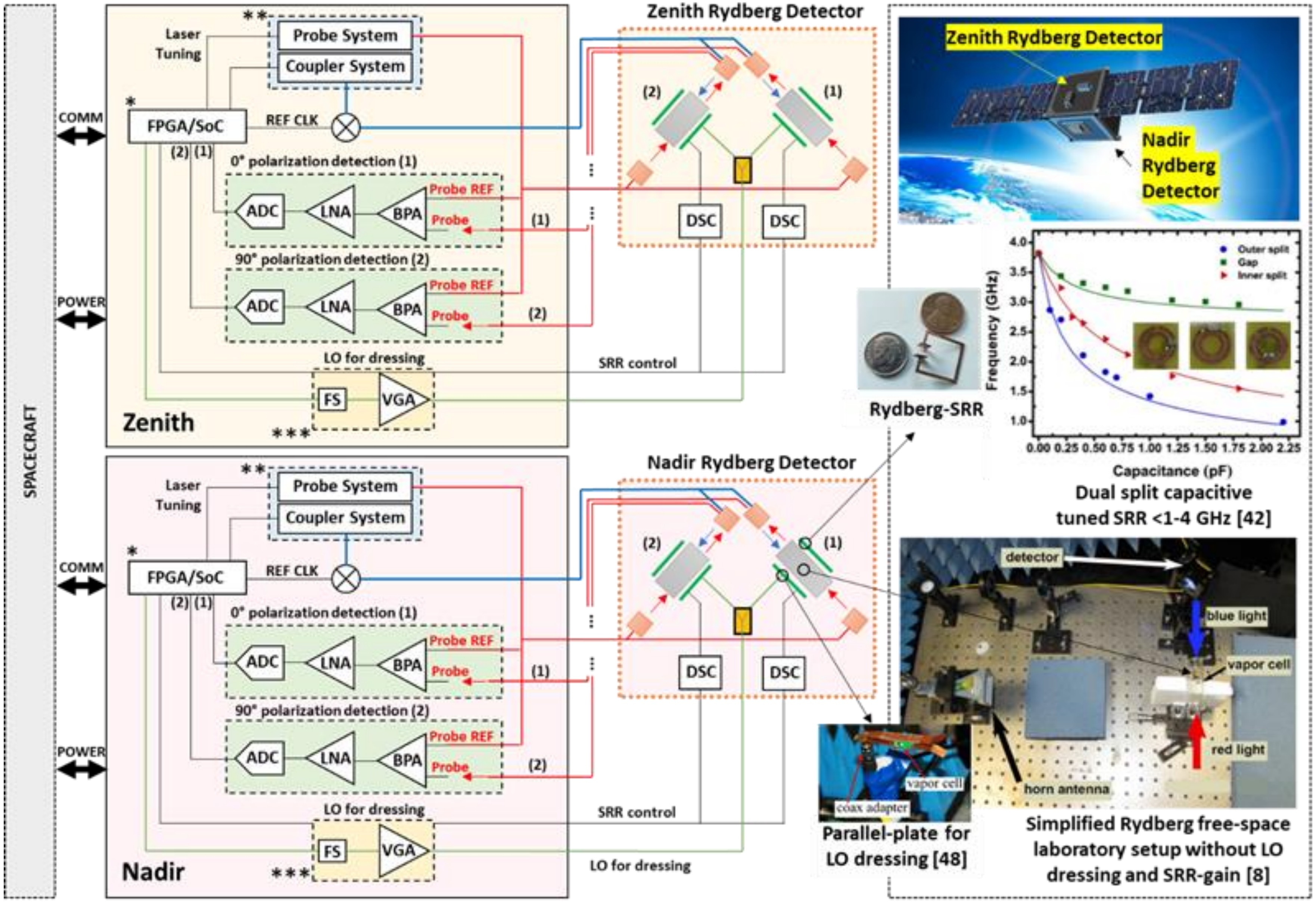
Satellite signals of interest in current investigations

- Early ground experiments will not need Doppler information (since we are not intending to do SAR), so we can use geostationary satellites without lose of information
  - Examples include MUOS, XM, IntelSat, DirectTV, AEHF
- Subsequent to these, experiments will use Doppler information from satellite systems in LEO, and after that TRL maturation will support airborne experiments where SAR, inSAR, POLinSAR can be enabled
- Front-end gain is required to enable sensing, this is currently proposed through a split-ring-resonator. Typically these can offer <200 in field enhancements. Ongoing efforts to validate this and to look at alternative approaches.

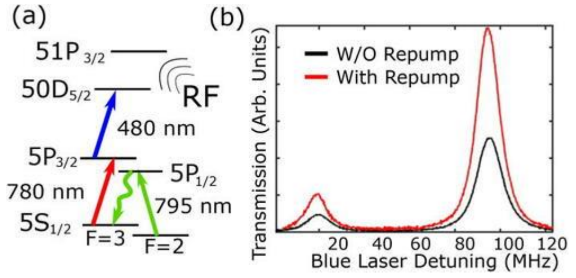
Value	Unit	Orbcomm	MUOS VHF	MUOS UHF	GNSS	XM	IntelSat	DTV (Ku)	DTV (K)	AEHF (K)
SoOp Transmitter Altitude	k-km	0.825	36	36	21	36	36	36	36	36
Center Frequency	MHz	136.5	260	370	1575.4	2342.2	3950	12450	18500	20700
Total/Min. Sub-Channel BW	MHz	1/<1	20/5	20/5	1/1	1.8/1.8	500/<1	500/<10	500/<10	1000/<10
EIRP or Transmitting Power	dBW	12	27	43	26	68.5	36	50	53	50
Total Path loss	dB/m^2	136	162.6	162.6	158	162.6	162.6	162.6	162.6	162.6
Field strength at detector	**μVm^{-1}**	0.69	0.18	1.14	0.27	21.54	0.51	2.56	3.62	2.56
Nominal integration time	s	0.067	0.039	0.032	0.016	0.013	0.010	0.006	0.005	0.004
Free-space sensitivity	**$\mu Vm^{-1}Hz^{-1/2}$**	**0.18**	**0.04**	**0.21**	**0.03**	**2.45**	**0.05**	**0.19**	**0.25**	**0.17**
Detector gain requirement	**linear**	**28.02**	**140.45**	**24.30**	**145.03**	**2.04**	**98.40**	**26.10**	**20.39**	**29.79**

SoOp constellation transmission sources, signal parameters, and Rydberg Radar detector requirements

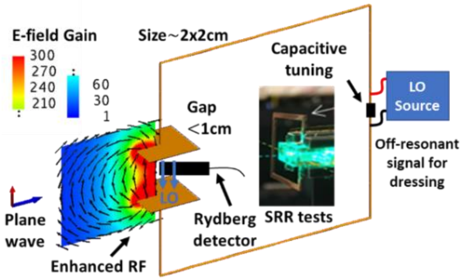
Quantum Rydberg Radar (high-level architecture)



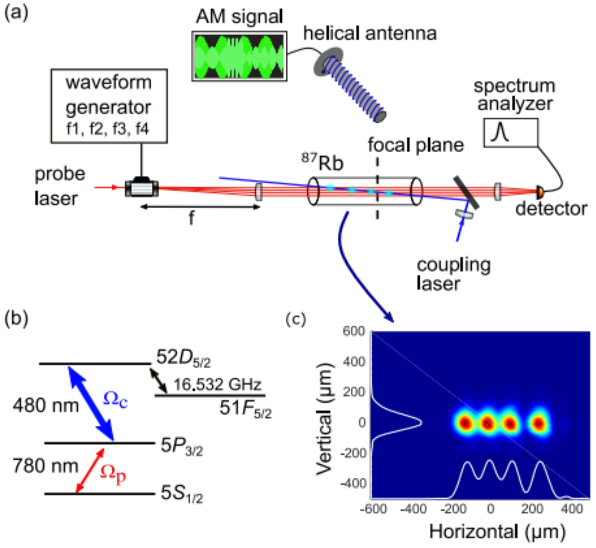
Detector research and improvements



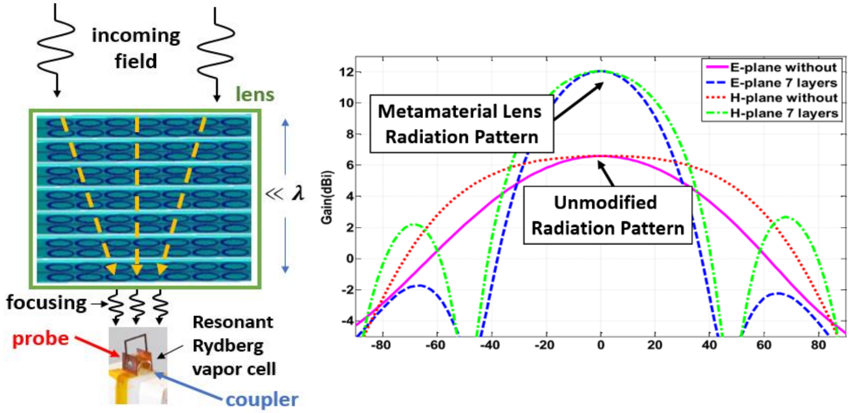
Probe repumping: Level diagram from EIT coupling 5S to 50D through the $5P_{3/2}$ with repumping from unused $5P_{1/2}$ (a). Laser transmission gain (b).



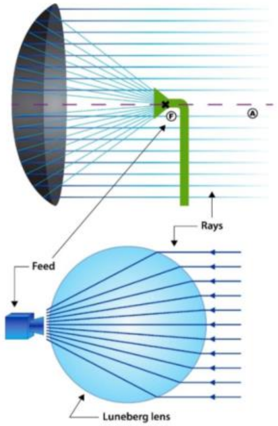
Ring resonator: Tunable SRR for resonant field enhancement with LO for super-heterodyning.



Sub-cell arraying: Arraying of Rydberg transitions in a cell to either increase sensitivity or increase instantaneous bandwidth



Sub-wavelength high-directivity lens: A high-directivity frequency-reconfigurable/tunable lens based on a ring-resonator array (RRA) that is sub-wavelength in scale is used based on an ISC supported effort

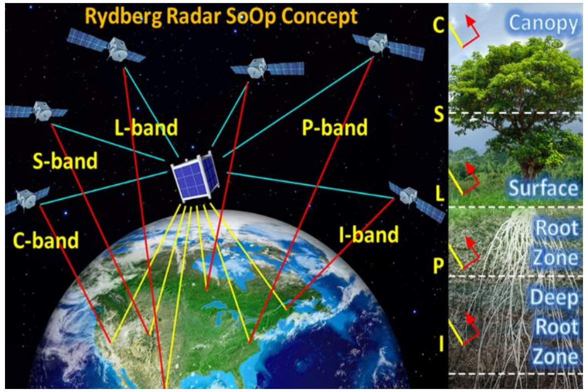


Dish to focus: Use of dish to focus to a Rydberg vapor cell receiver or feed

Enhancement of electromagnetically induced transparency based Rydberg-atom electrometry through population repumping, Applied Physics Letters, 2023
Ring resonator graphic – JPL ISC 2022
Sub-wavelength lens – JPL ISC 2023
"Negative Index Metamaterial Lens for Subwavelength Microwave Detection", Sensors 2021
"Lens antennas focus multiple wireless beams", 5G Technology World
"Data capacity scaling of a distributed Rydberg atomic receiver array", Journal of Applied Physics 129, 154503 (2021)

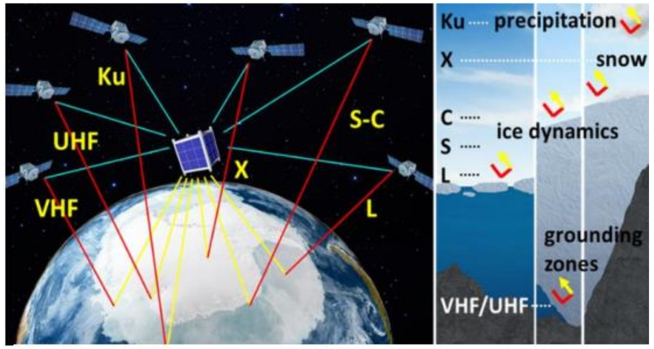
ES QRR efforts with ongoing concept studies

Jet Propulsion Laboratory
California Institute of Technology



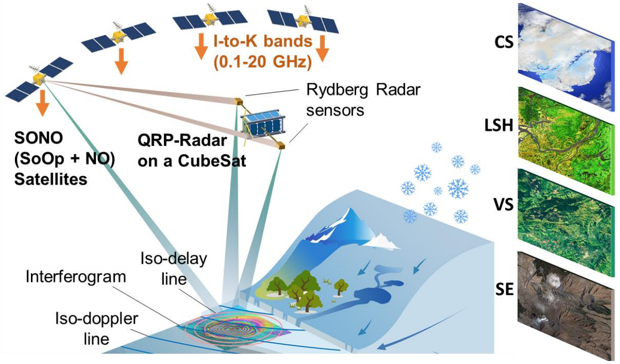
SAR and vertical profiling for canopy to deep root zone soil moisture (I-C band) using SoOp

- First profiling and imaging study (SAR) with SoOp for LSH
- I-C band with standard SRR
- Supports key POC for SoOp detection
- Develops and validates RF and Rydberg detection models
- Trade space analysis for Rydberg Radar applied to LSH



SAR in Cryospheric applications (I-Ku band) using SoOp in polar orbits

- SAR with polar orbit signaling (data-base development and POC)
- Modelling efforts for bedrock topography (137MHz), snow water equivalent (SWE) of snow accumulation (255 and 370MHz), ice sheet dynamics/flow (1.2-2.2GHz), snow accumulation rates (5.4-9.6GHz), and precipitation (13.5GHz) [I-Ku]



Broad-band (I-K band) POLinSAR for STV using SoOp and NO (non-opportunistic transmitted science signals)

- First inSAR & POLinSAR studies (QRP)
- Develops POLinSAR QRP simulator
- Multi-band EM STV modeling for QRP
- I-K bands and focused on multi-science applicability to all of STV (which require dynamic arraying of QRR)
- Studies NO (science transmission) signaling as complement to SoOp

	FY23	FY24	FY25	FY26	FY27	FY28
Technology Roadmap	System development for radar measurements	Field demo of radar reflectometry	Airborne demo (specific science goal)	Component tech. development	Optimization for Cube/SmallSat	Experiments in space
NASA Opportunities	ACT, AITT	IIP-IDD	ACT	DSI, AITT, AIST		
Decadal Survey Timeline				RFI Response		DS Release
Small Mission						InVEST

Graphics developed in coordination with JPL graphic team

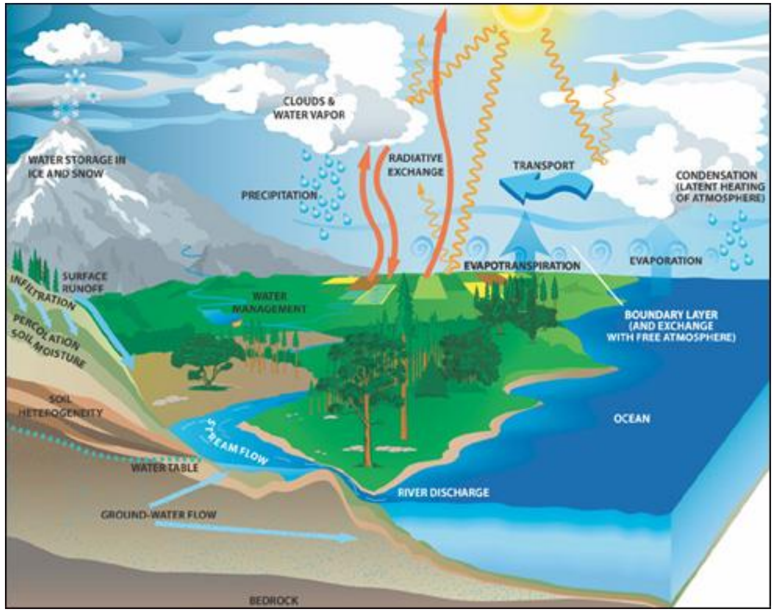
Vertical Soil Moisture Profiles

- Soil moisture is an Earth system variable that connects land surface processes to atmosphere (**water-energy cycle coupling**)
- Soil moisture has a complex connection to soil evaporation, plant transpiration, rain runoff, drainage and recharge of aquifers (etc.) -- all depend on its **vertical distribution** in the soil
- Key questions are:
  - H-1. How is the water cycle changing?
  - H-3. How do changes in the water cycle impact local and regional freshwater availability, alter the biotic life of streams, and affect ecosystems and the services these provide?
- To effectively study soil moisture from canopy to root-zone, spectral coverage from S-to-P/I bands are needed (~0.1-4 GHz)
  - Significant portions are limited from science transmissions, but heavily used for navigation, communications, military

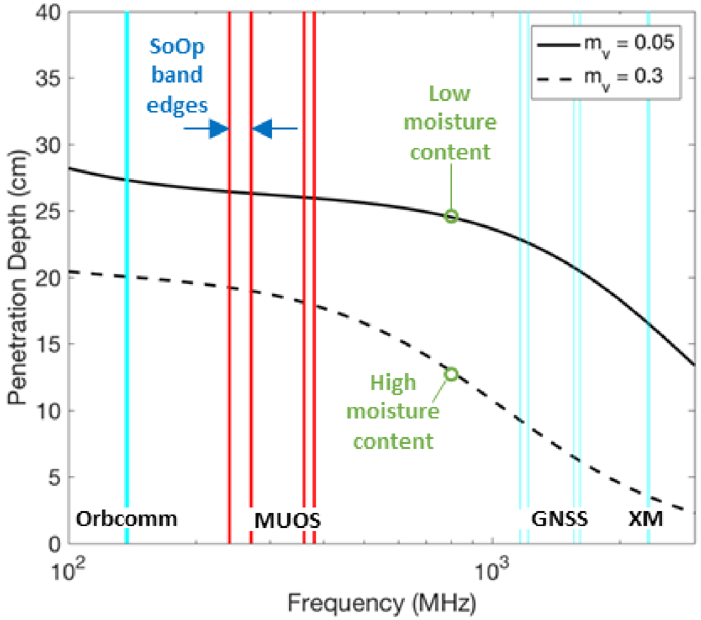
		Ka	Ku	X	C	L	P
Precipitation	Rain	Primary	Primary	Negligible	Negligible	Negligible	Negligible
	Snow	Primary	Primary	Confounding	Negligible	Negligible	Negligible
	Hail	Primary	Primary	Confounding	Confounding	Negligible	Negligible
VWC / Biomass	Canopy	Confounding	Confounding	Primary	Primary	Confounding	Confounding
	Woody and understory	Negligible	Negligible	Negligible	Confounding	Primary	Primary
Bare soil or open vegetation SM	Near Surface	Negligible	Confounding	Primary	Primary	Primary	Primary
	Root Zone	Negligible	Negligible	Negligible	Negligible	Negligible	Primary
Closed canopy SM	Near Surface	Negligible	Negligible	Negligible	Negligible	Confounding	Confounding
	Root Zone	Negligible	Negligible	Negligible	Negligible	Negligible	Confounding

Primary sensitivity Confounding sensitivity Negligible sensitivity

Sensitivity of bands Ka through P bands to water state variables. VWC: Vegetation Water Content, SM: Soil Moisture



Hydrological cycle Source: U.S. Global Change Research Program

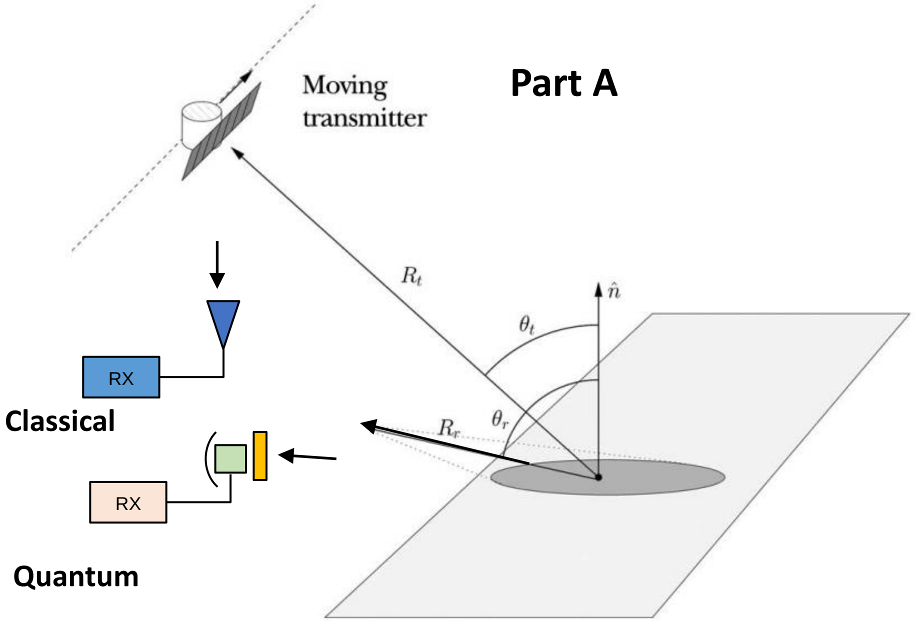


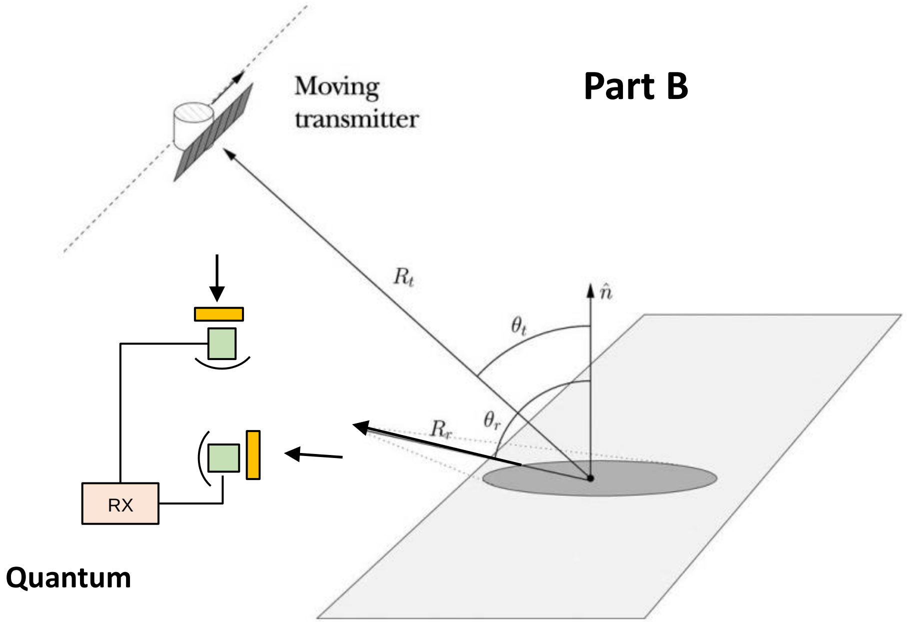
Soil penetration depth vs. frequency.

Status and Testbed for Ground-based Reflectometry

- High level status:
    - Developed Rydberg quantum optics architecture and systems for radar remote sensing
    - Developed high-level radar architecture
    - Advanced a few key sub-systems for Rydberg radar (example: ring resonators or SRR concept)
    - Completed some key link budget analysis and signal models

- Main objective in FY23/24 is to show that you can perform correlations as needed in radio reflectometry via direct and indirect signal detection by Rydberg detection





JPL SRTD: STV Multi-frequency Implementation using Quantum Rydberg Radar
Figures modified from "SABRINA: A SAR Bistatic Receiver for Interferometric Applications," in IEEE Geoscience and Remote Sensing Letters, vol. 4, no. 2, pp. 307-311, April 2007.

Summary

- Rydberg based remote sensing is an emerging field with many applications
  - Uses atom based broad spectrum sensing
  - Uses existing networks of transmitters in LEO, MEO, GEO

- Current effort focuses on soil moisture remote sensing and techniques for surface, topography, and vegetation remote sensing

- Some valuable improvements to the detector (sensitivity, bandwidth, directivity) is expected in the near term

- Testbed development in FY23/24 will substantially advance our understanding of Rydberg Radar