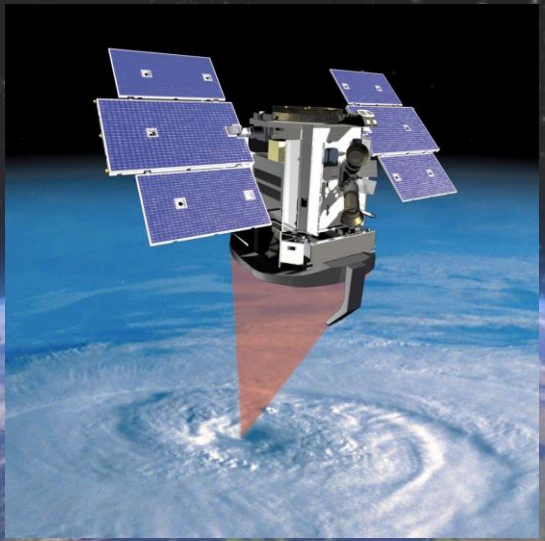
Remote Sensing with Rydberg Atoms

Darmindra Arumugam
Jet Propulsion Laboratory,
California Institute of Technology

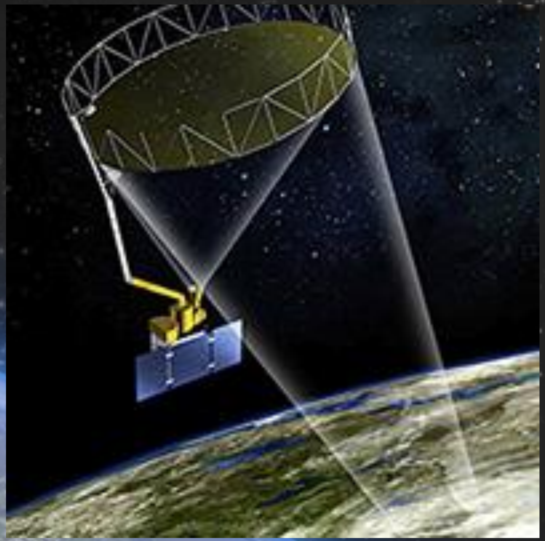
Different wavelengths and antenna/instrument size

Each of these satellites measures a different wavelength of light to study a unique aspect of Earth.

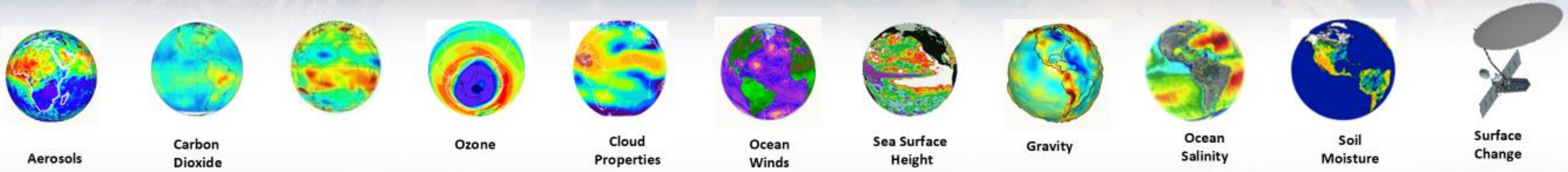
OCO-2/3 use a very short wavelengths to measure **carbon dioxide** in the atmosphere.



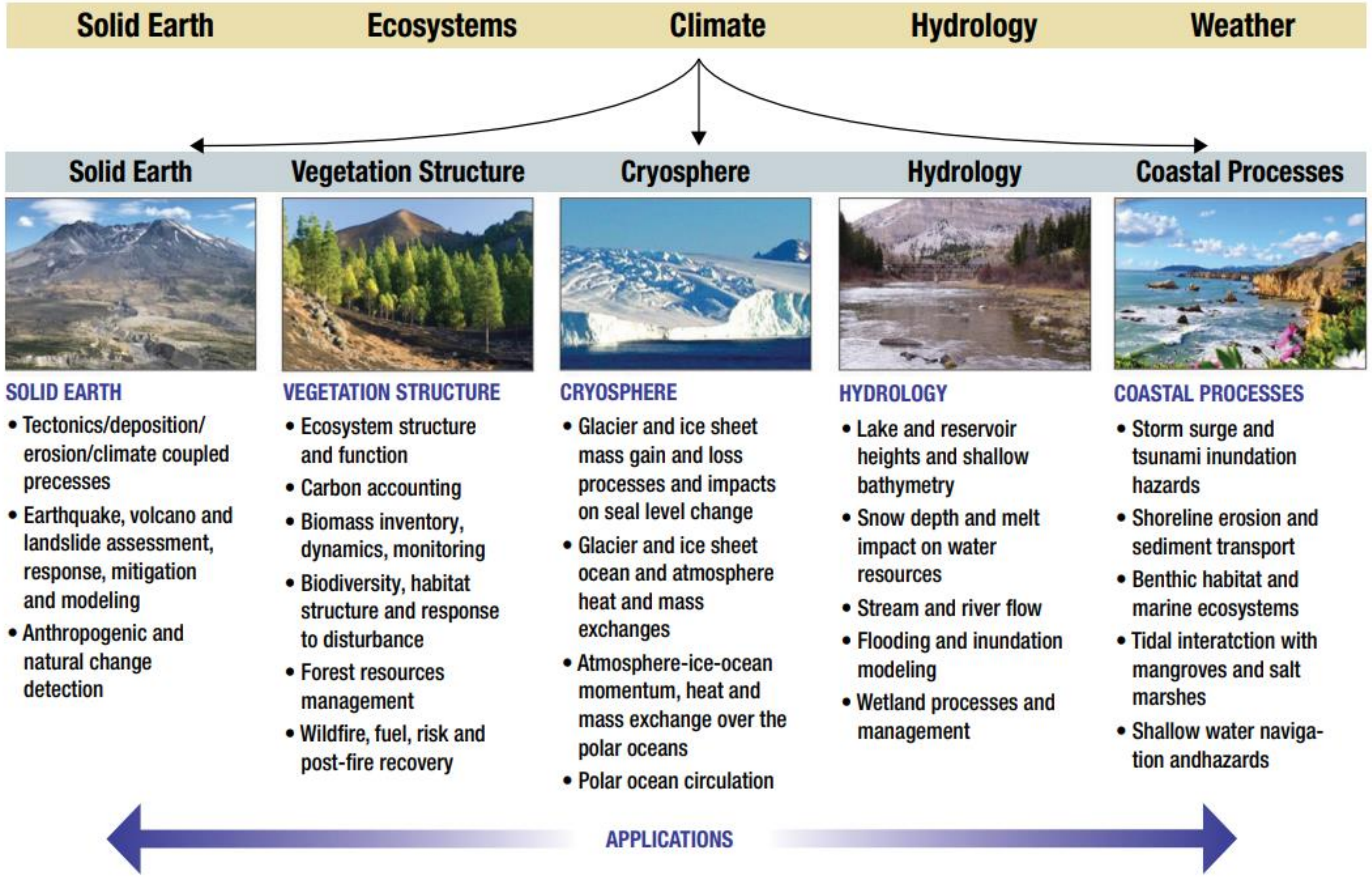
CloudSat uses mid-range wavelengths to study **cloud properties.**



SMAP uses longer wavelengths to detect **soil moisture.**

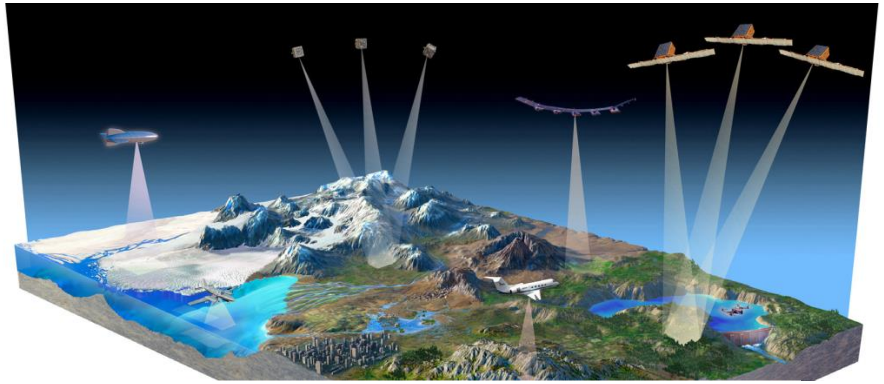


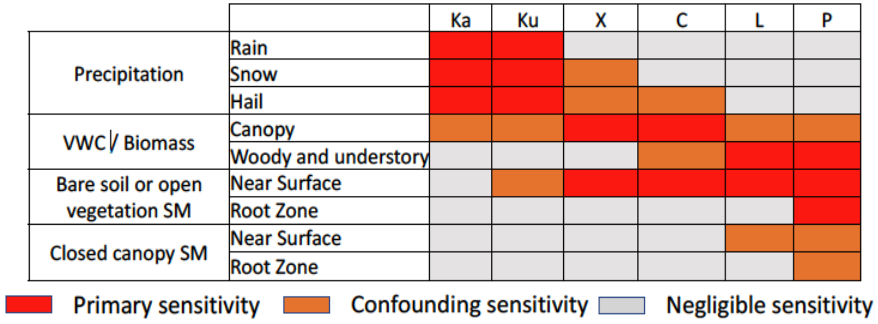
NASA Surface, Topography and Vegetation



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





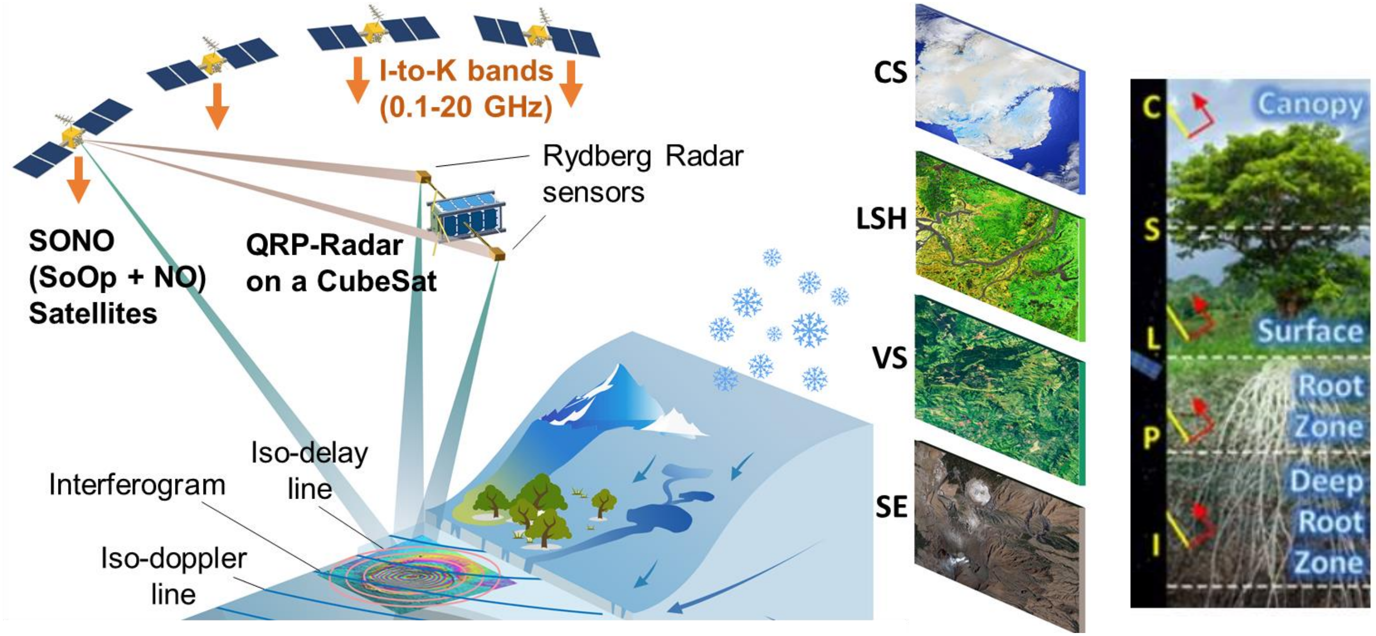
Sensitivity of bands Ka through P bands to water state variables. VWC: Vegetation Water Content, SM: Soil Moisture

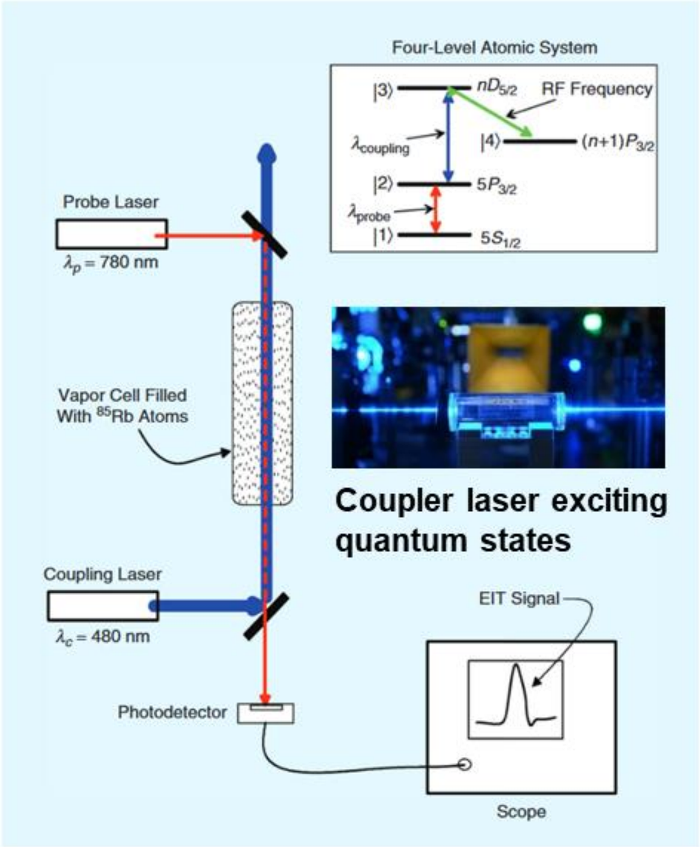
STV objectives would be best met by new observing strategies that employ flexible multi-source and sensor measurements from a variety of orbital and suborbital assets.

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

Rydberg remote sensing high-level concept





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

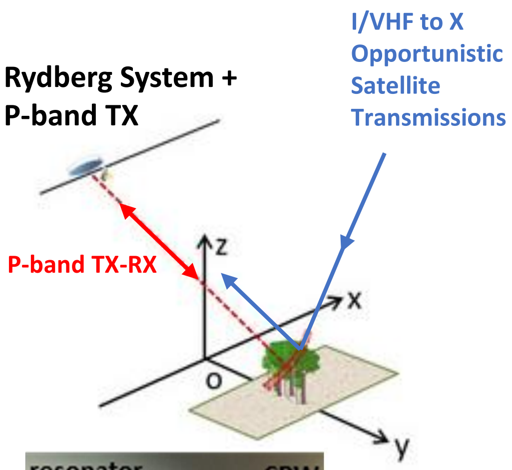
- Disruptive Quantum Rydberg architecture enabling high sensitivity, dynamic and rapidly tunable radar remote sensing throughout the entire radio window, with no science antennas or RF front-end electronics – providing significant improvements over state-of-art radars
- Enables measurement of key Earth 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)

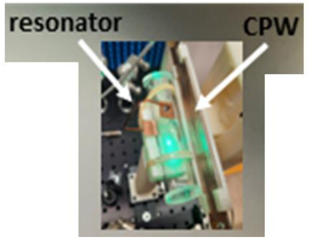
Graphic developed in coordination with JPL graphic team
Surface Topography and Vegetation (STV) Study Team Report

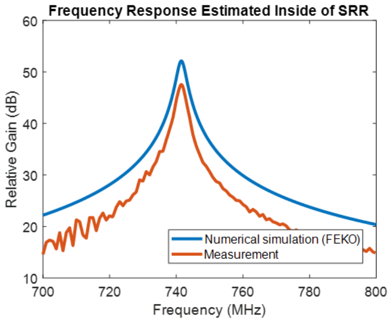
Other applications as examples of space applications

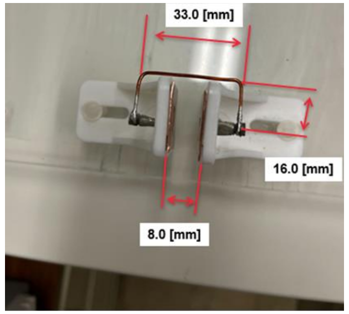
P-band SAR with multi-frequency DDM

- Integrate compact P-band TX and antenna
- Use SRR (resonator) to get high sensitivity with Rydberg detector
- Develop SAR at P-band and apply DDM based on SoOP signals
- Anchors broadband SoOP based DDM with a SAR P-band
- Applications:
    - **Foliage/Ground Penetrating:** Penetrates foliage, soil, and dry sand to detect **concealed targets**
    - **Forest Structure Mapping:** Deep canopy penetration for **tree trunk biomass estimation** and forest management.





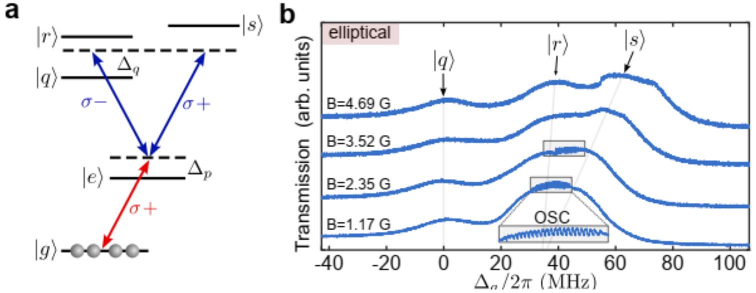


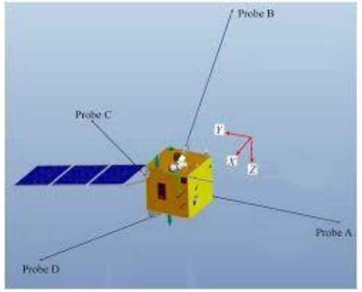


Fabricated design

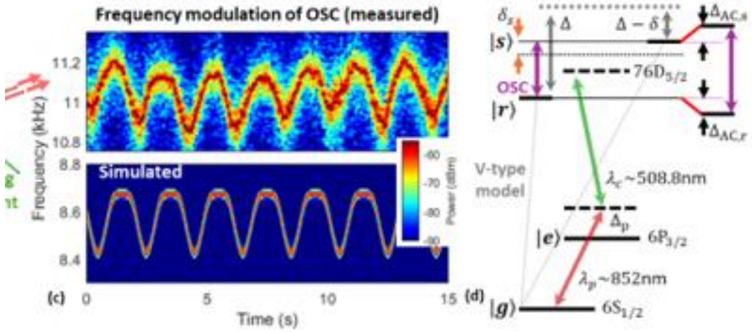
Rydberg limit cycle based LF sensing

- Use newly discovered time-crystal phase in Rydberg atoms
- Underwater communications intercept (ELF/VLF, typical 76 Hz to 30 kHz)
- Ionospheric disturbance monitoring (<100kHz)
- Low-Frequency ISR
- Earthquake Precursor Signals (ULF EM – down to ~100 Hz)
- Space Weather Monitoring
- Power Grid Disturbance Detection

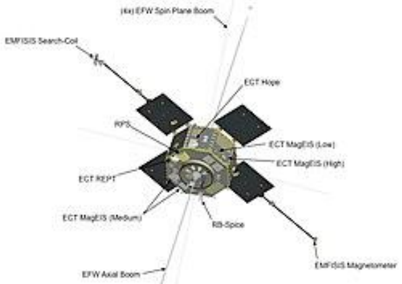




EFD onboard CSES-01 (>4.5m each axis)



Time-domain simulations of mode-competition between two excited and results in a modulation of the OSC frequency in the form of a frequency modulation.



Van Allen Probes (tip-to-tip is 100m)

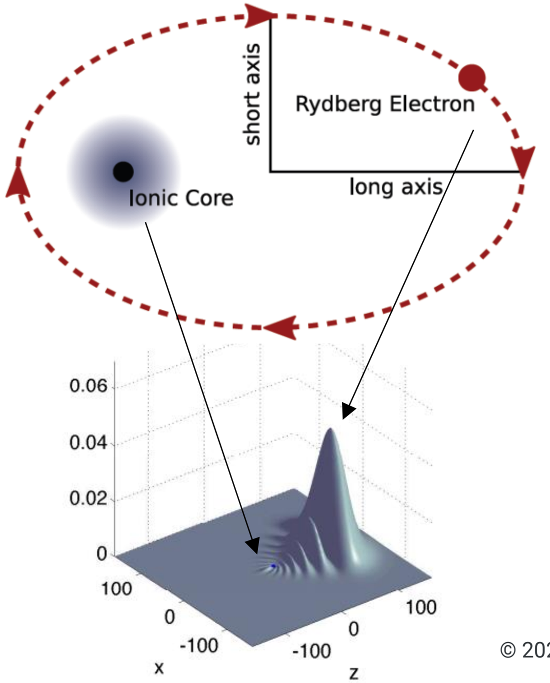
Classical systems

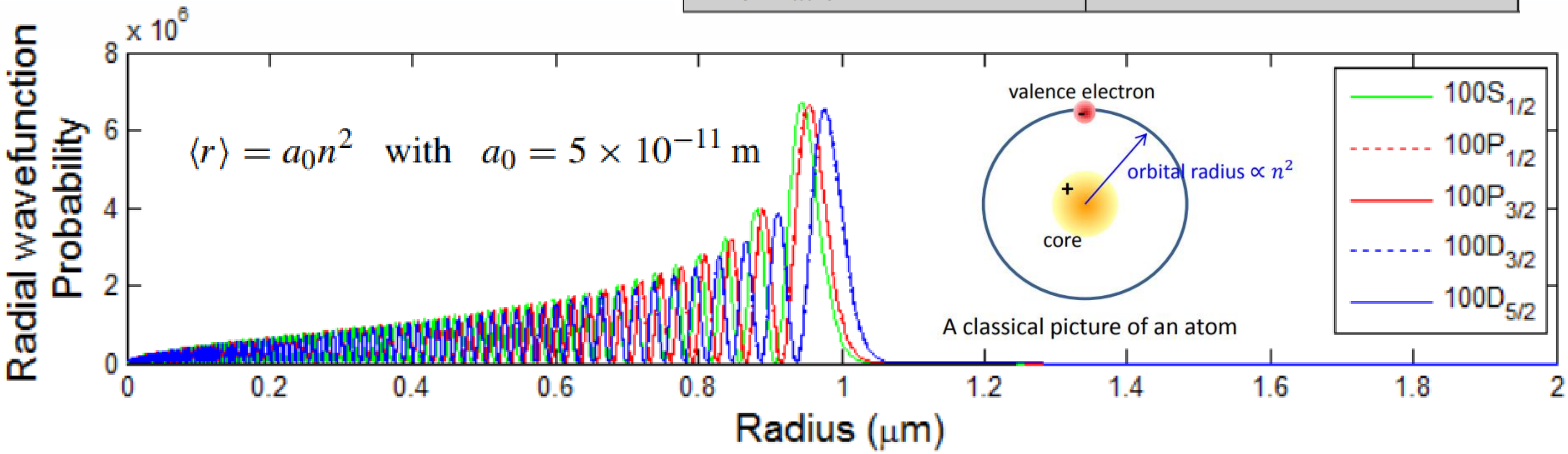
The Rydberg atom

- 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
  - Atoms are large ($\sim um$) - easily perturbed by external fields

Scaling characteristics of atomic Rydberg states

Physical quantity	n-dependence
Binding energy	$-Ry^{*}n^{-2}$
Energy $E(n+1) - E(n)$ difference	$\Delta E_n = Ry\left(\frac{1}{n^2} - \frac{1}{(n+1)^2}\right)$
Mean Bohr radius	$a_0 n^2$
Geometric cross section	$\pi a_0^2 n^4$
Revolution period	$T_n \propto n^3$
Radiative lifetime	$\propto n^3$
Critical electric field for ionization	$E_c = \pi \varepsilon_0 R y^{*2} e^{-3} n^{-4}$





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

Principle 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)

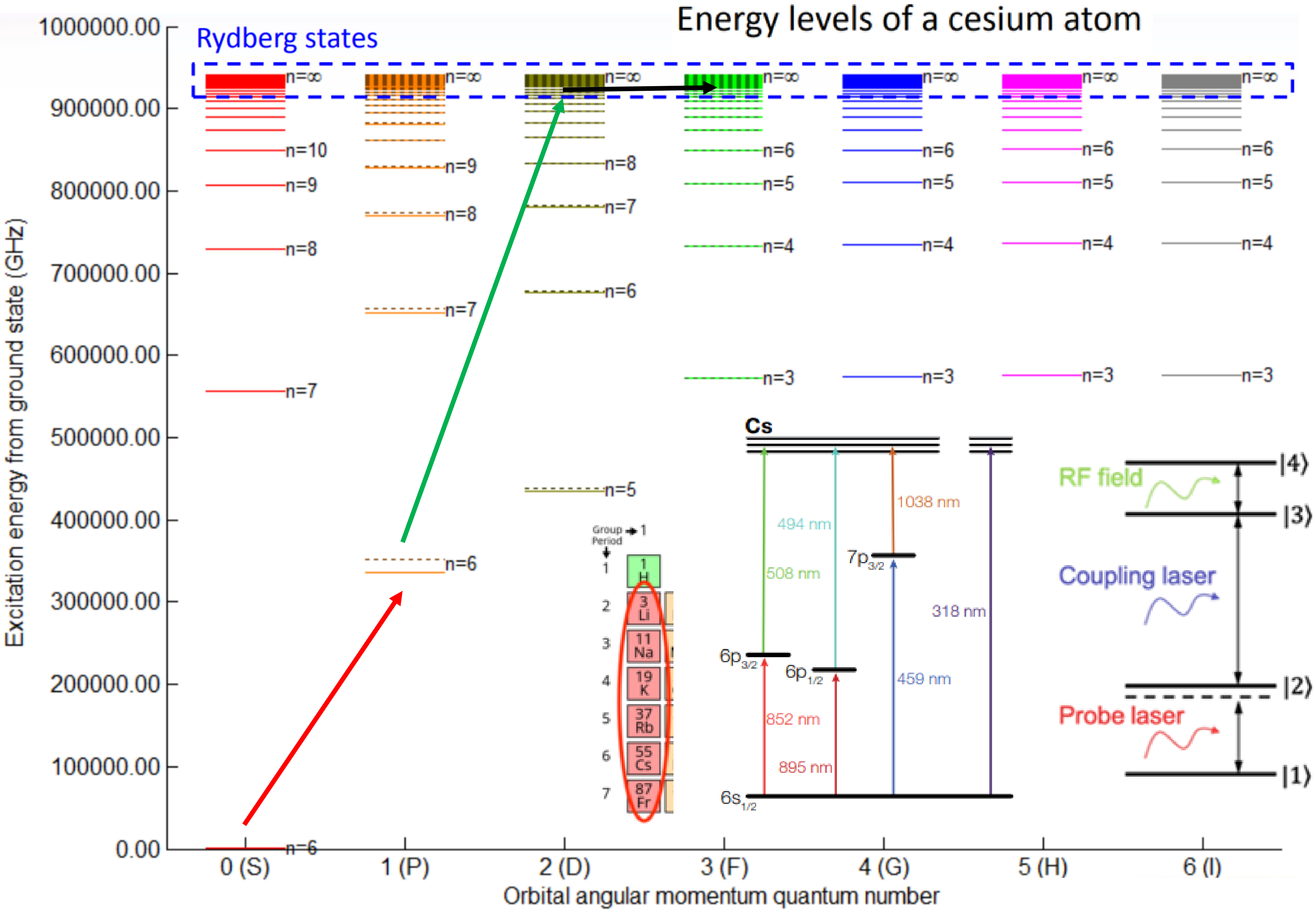


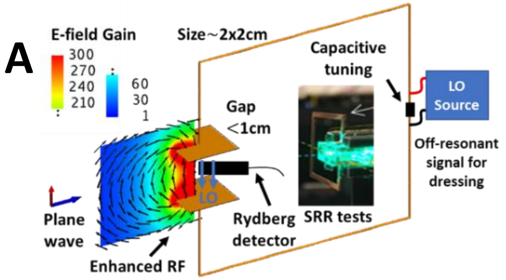
Figure calculations via ARC - Alkali Rydberg Calculator 3.1.0

https://www.toptica.com/fileadmin/Editors_English/11_brochures_datasheets/01_brochures/toptica_BR_Scientific_Lasers.pdf

Field Coupling to Rydberg detectors

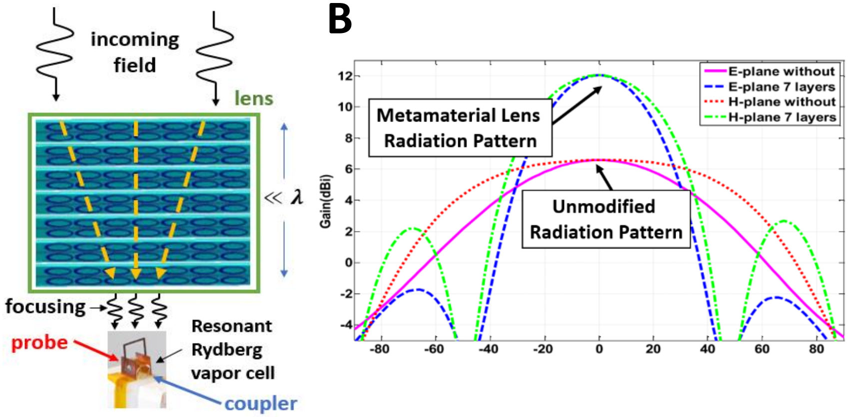
- Aside from direct coupling to vapor cells, multiple other approaches can be used to focus or enhance fields or provide beamforming capabilities:
  - Passive/active resonators (**A**)
  - Lenses to include meta-lenses (**B**)
  - Rydberg arraying (sub-cell and cell arraying) (**C**)
  - Reflector dishes to focus to a cell (**D**)

A



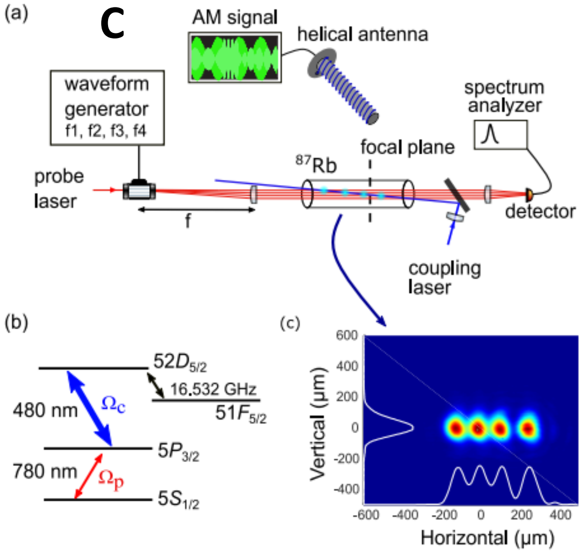
Ring resonator: Tunable SRR for resonant field enhancement with LO for super-heterodyning.

B



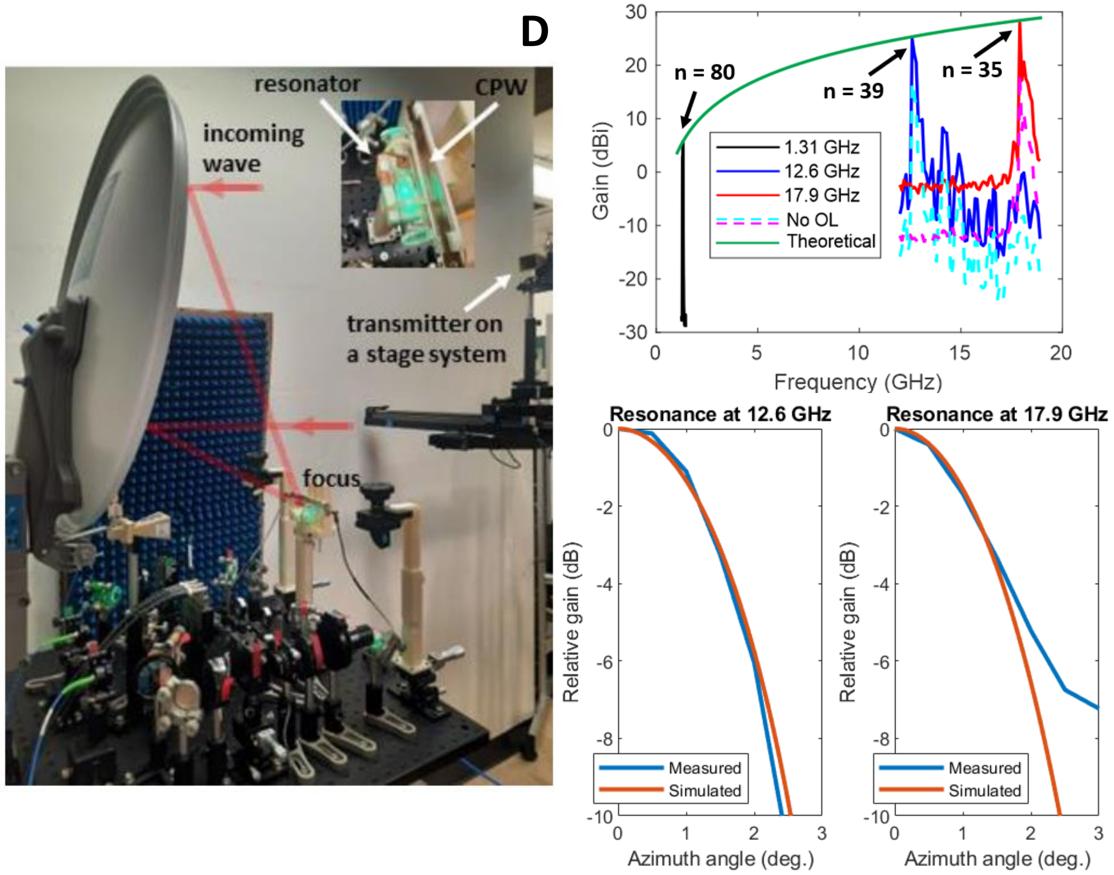
Sub-wavelength high-directivity lens: A high-directivity frequency-reconfigurable/tunable lens based on a ring-resonator array (RRA) that is sub-wavelength in scale is used based on an ISC supported effort

C



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

D



Compact Rydberg front-end system (30x30cm) with an integrated broadband reflector and optional coupled ring resonator undergoing broad-spectrum beamwidth measurements.

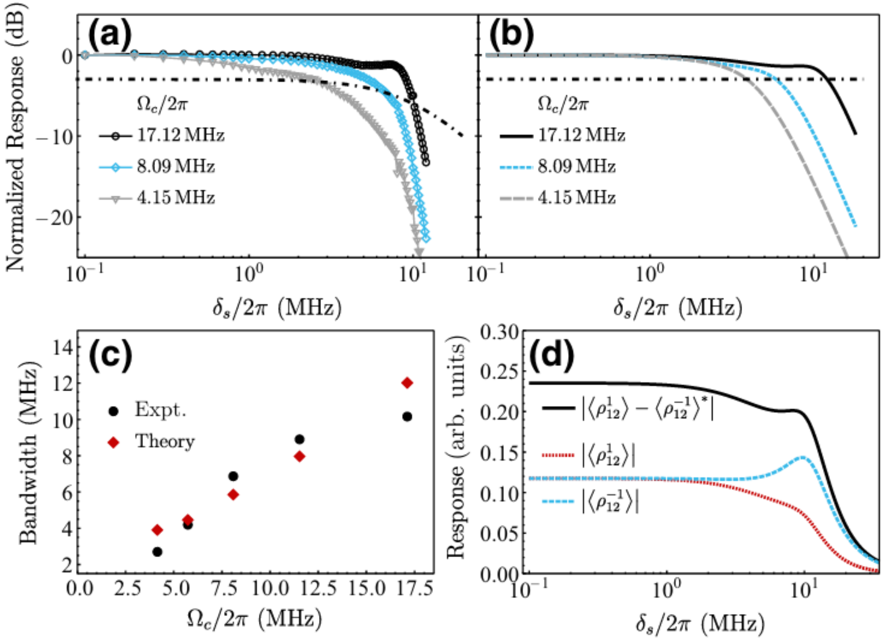
Instantaneous bandwidth – 2-photon vs 6-wave mixing

$$\gamma_{eff} \sim \frac{\Gamma}{2} + \gamma_{pb} + \frac{\Omega^2}{2\Gamma} + O(\Omega^4)$$

Natural linewidth

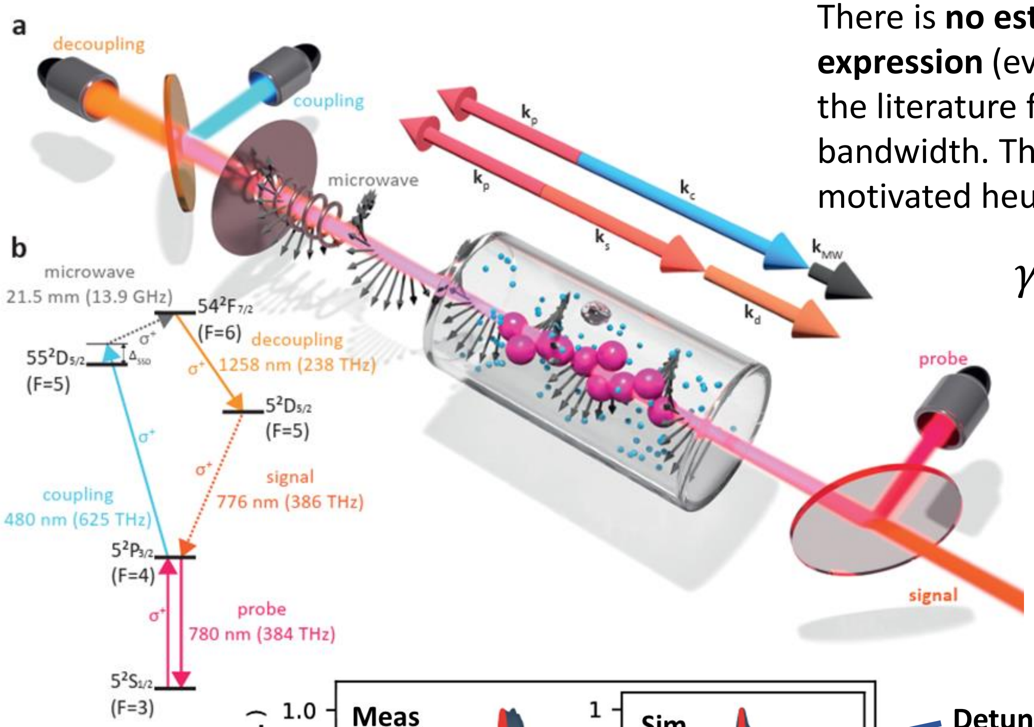
Pressure (collisional) broadening

Power broadening



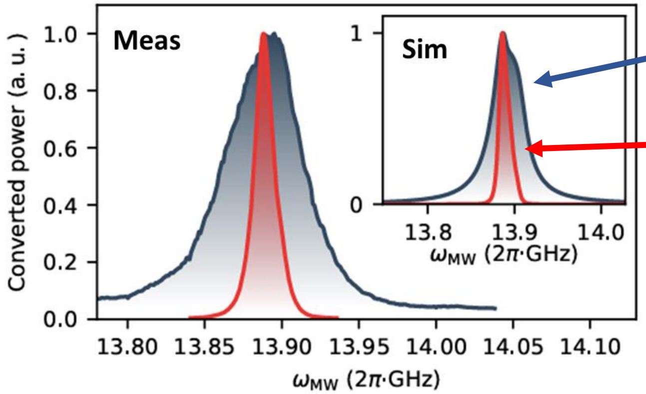
Instantaneous bandwidth of a Rydberg MW sensor (2-photon)

Bowen Yang *et al.*, "Highly sensitive microwave electrometry with enhanced instantaneous bandwidth," *Phys. Rev. Appl.* **21**, L031003 (2024), https://doi.org/10.1103/PhysRevApplied.21.L031003.



There is **no established analytic expression** (even approximate) in the literature for instantaneous bandwidth. This is physically motivated heuristic model:

$$\gamma_e \propto \sqrt{\Omega^2 + \Delta^2})$$



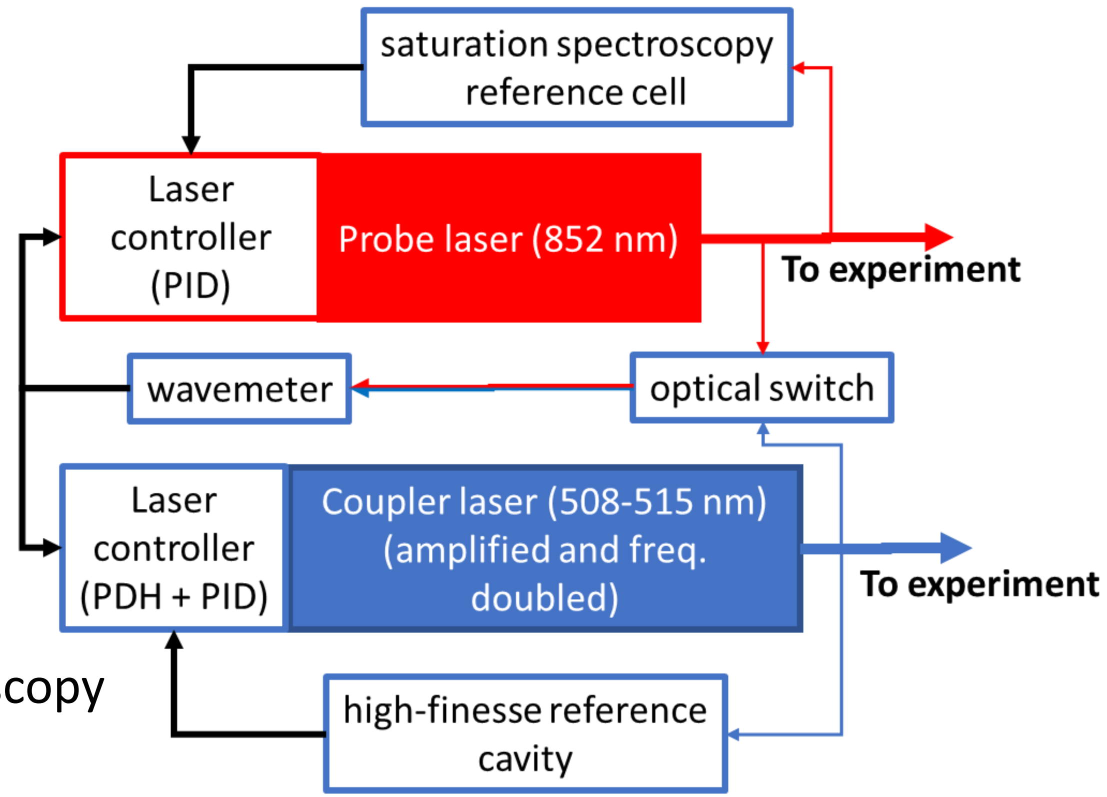
Detuned coupler and decoupler (60 MHz BW)

No detuning (16.2 MHz BW)

Borówka, S., Pylypenko, U., Mazelanik, M. *et al.* Continuous wideband microwave-to-optical converter based on room-temperature Rydberg atoms. *Nat. Photon.* **18**, 32–38 (2024). https://doi.org/10.1038/s41566-023-01295-w

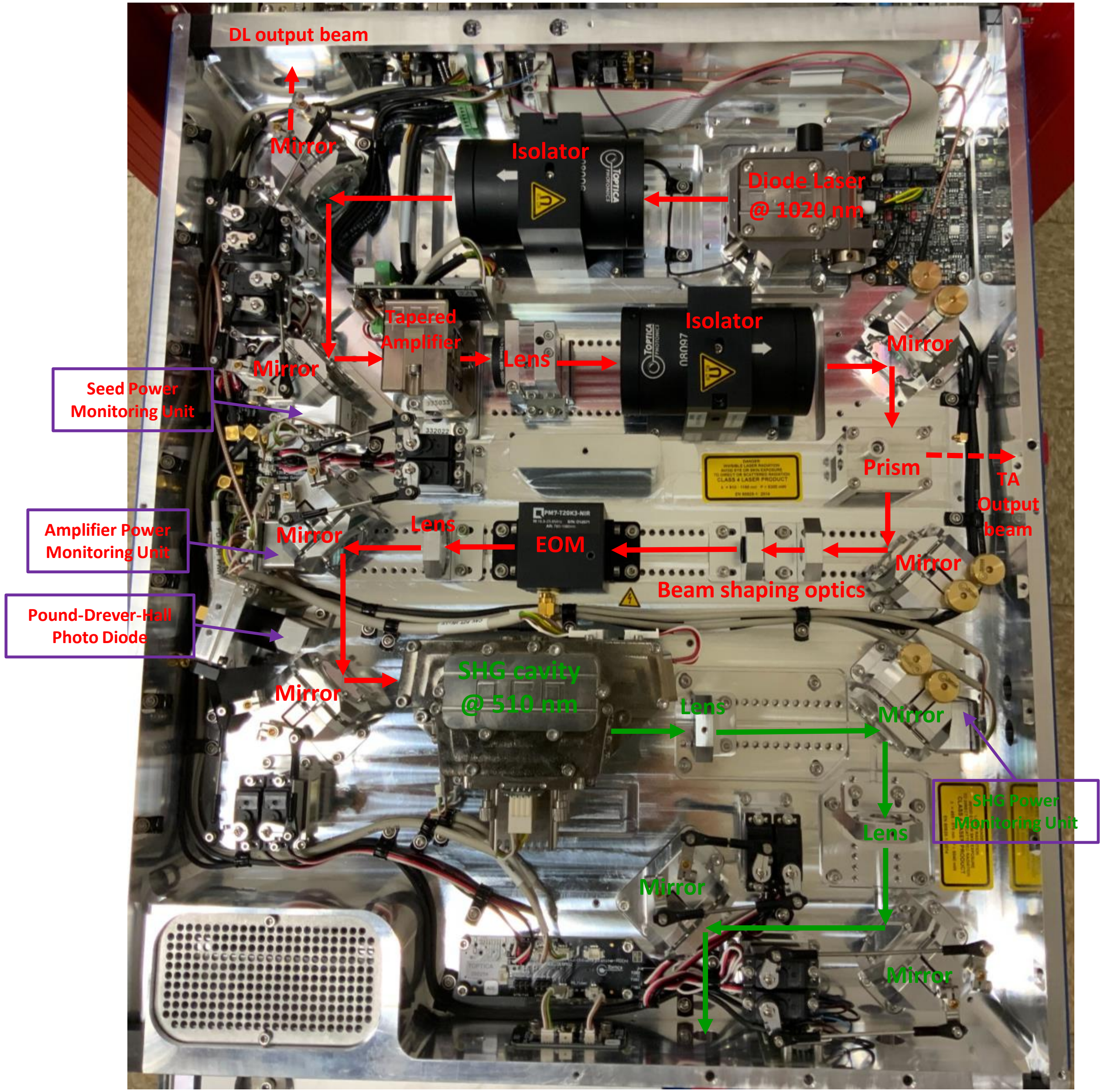
Typical experimental system (Cesium) – Laser and stabilization

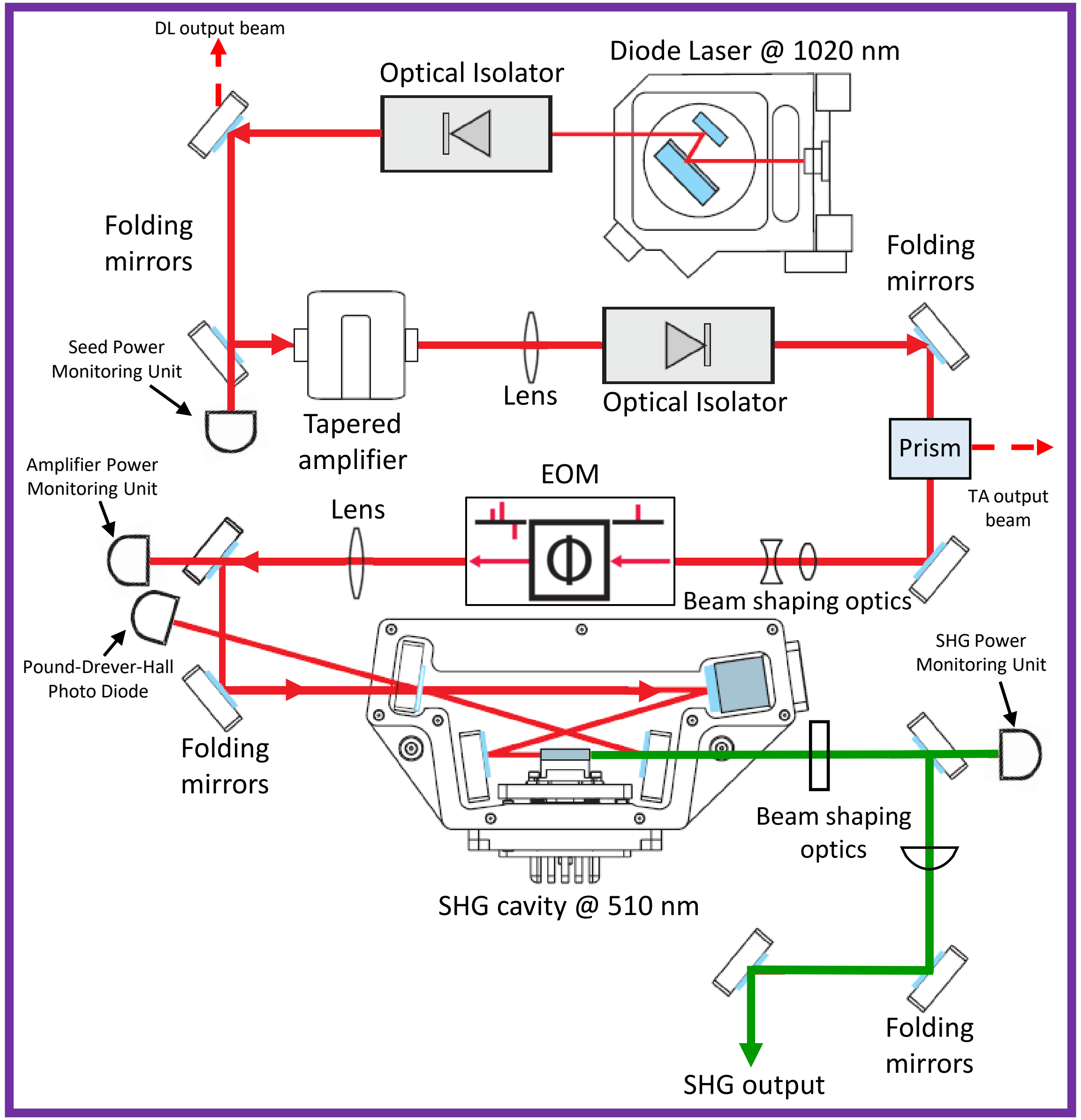
- **Laser systems**
  - Probe
    - Tuning range: 845 - 875 nm (design 852 nm)
    - Output Power: >35 mW in fiber
  - Coupler
    - Tuning range: 508 - 515 nm (design 510 nm)
    - Output Power: >750 mW in fiber



- **Laser stabilization systems**
  - Course tuning via wavemeter
    - Absolute accuracy: ~10 MHz
  - Probe stabilization via saturated absorption spectroscopy
    - 1 MHz bandwidth with field compensation <70uT
    - expect frequency stability ~200 kHz or better
  - Coupler stabilized via Pound-Drever-Hall method
    - Optical cavity with finesse 15k and 1.5 GHz free spectral range
    - offset lock up to 800 MHz
    - Expect frequency stability ~100Hz or better.

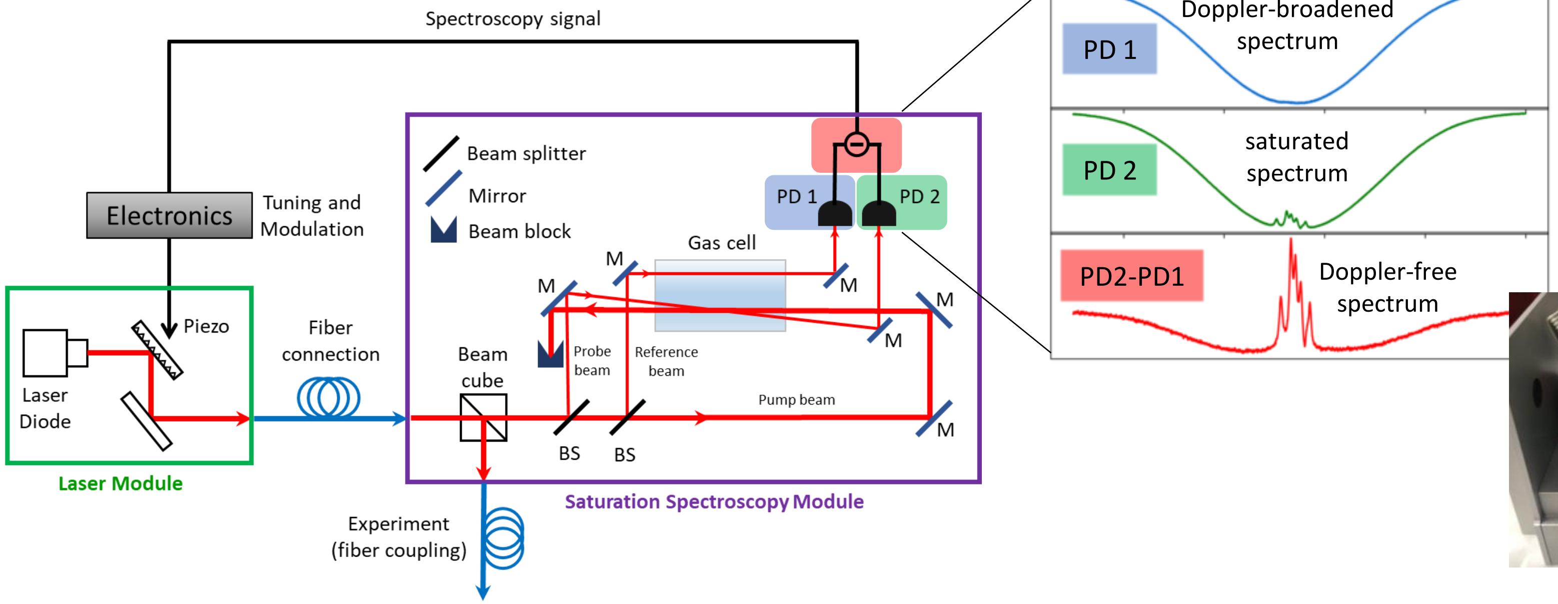
Frequency-Doubled Amplified Laser System (Coupler Laser)



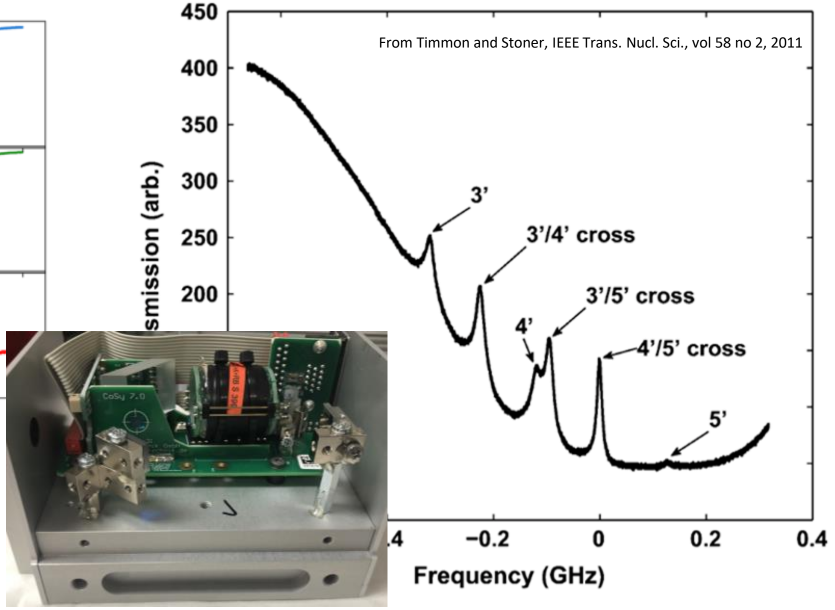


Probe and coupler laser locking

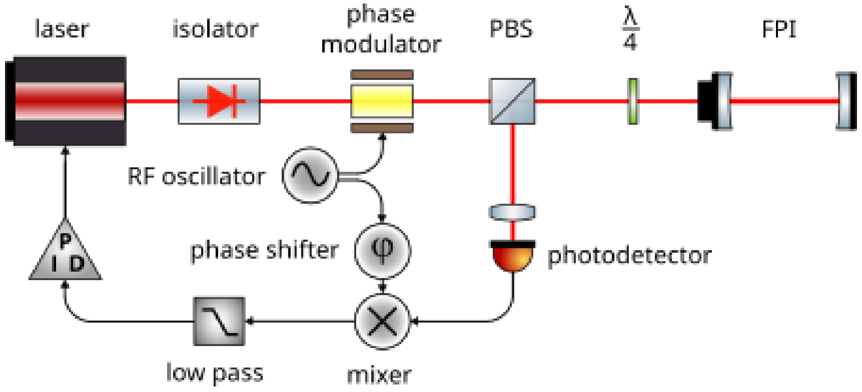
Probe – Saturation Absorption Spectroscopy System

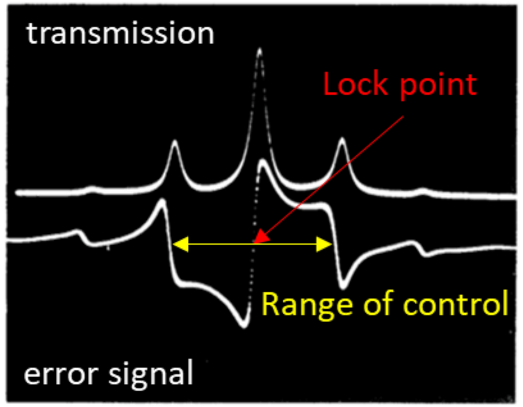


Cs D2 saturated spectrum

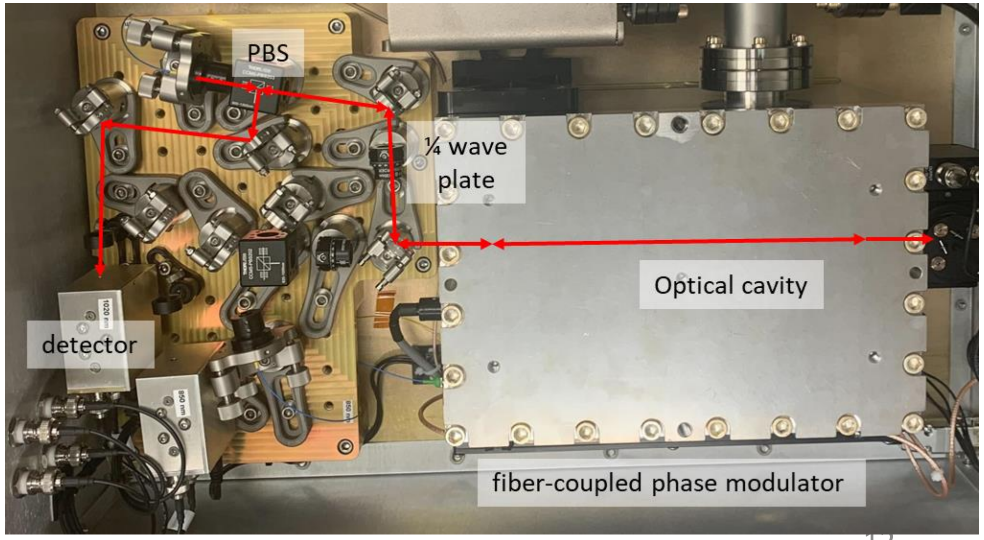


Coupler laser stabilization – PDH with electronic side bands





Drever et al., Appl. Phys. B, Vol 31 (1983)



Sampling of key satellite signals of interest

- 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, via a resonator or reflector or both. At XM and above, resonator is not needed (SNR > 20dB). At below GNSS, resonators are needed.

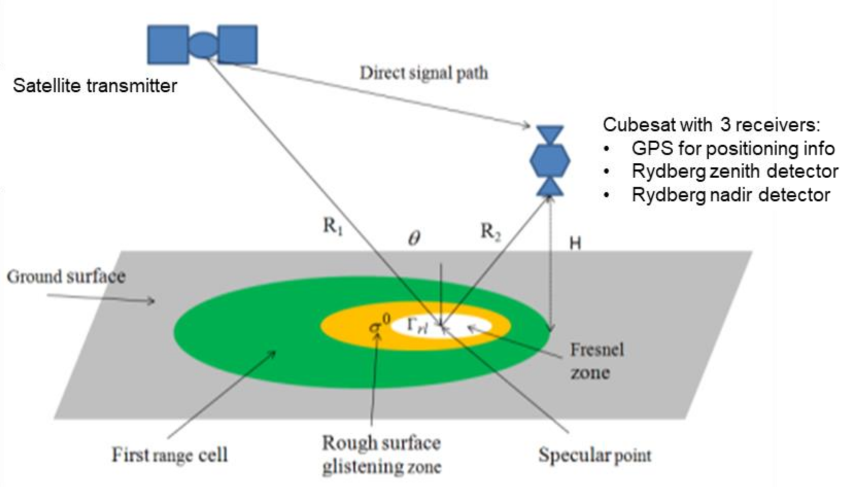
	Units	Orbcomm	MUOS VHF	MUOS UHF	GNSS	XM	DirecTV (Ku)	DirecTV (K)	AEHF (K)
Transmitter altitude	km	825.0	35786.0	35786.0	20200.0	35786.0	35888.0	35786.0	35786.0
Center Frequency	MHz	136.5	260.0	370.0	1575.4	2342.2	12450.0	18500.0	20700.0
Sub-channel Bandwidth	MHz	0.3	5.0	3.8	1.0	1.8	500.0	500.0	1000.0
Transmitting Power	dBW	12.0	27.0	43.0	26.0	68.5	50.0	53.0	50.0
Path loss	dB/m^2	132.0	162.5	162.5	157.7	162.5	162.1	162.5	162.5
Reflectivity (Γ)	dB	-15.0	-15.0	-15.0	-15.0	-15.0	-15.0	-15.0	-15.0
Reflector Gain	dBi	0.2	8.6	11.2	18.5	23.3	37.9	41.2	42.2
SRR Gain	dBi	60.0	55.0	55.0	25.0	0.0	0.0	0.0	0.0
Integration Time	s	0.0722	0.0432	0.0304	0.0071	0.0048	0.0009	0.0006	0.0005
Signal at Detector	V/m	3.52E-03	8.82E-04	4.22E-02	7.54E-04	5.67E-03	3.78E-03	7.53E-03	5.96E-03
SNR	**dB**	**47.49**	**33.22**	**65.30**	**24.01**	**39.85**	**29.04**	**33.28**	**30.45**

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

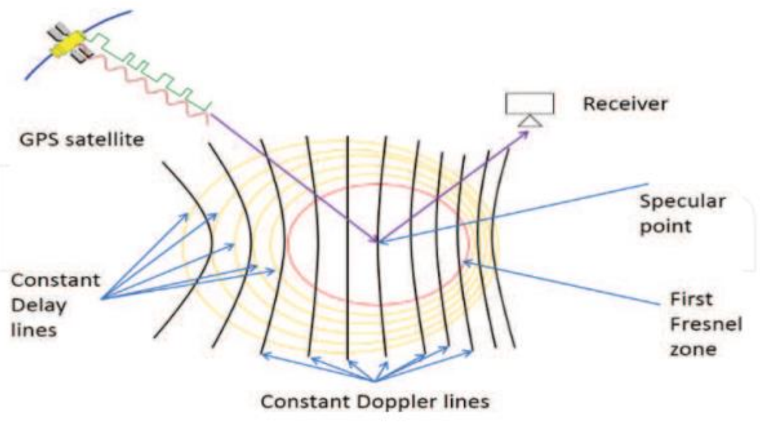
Receiver altitude of 500km, incidence angle of 45°, reflectivity of -15dB, atmospheric-loss of 1dB assumed, based on sensitivity of 0.4uVm^{-1}Hz$^{-1/2}$

SoOP single cube-sat instrument-level approach

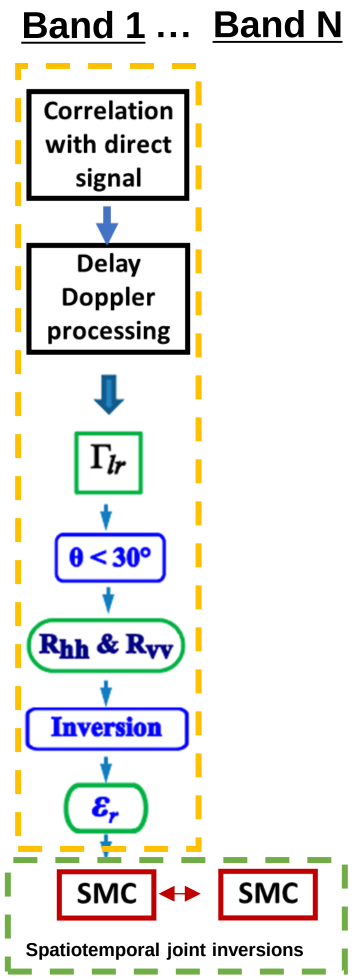
- Signal of opportunity in I-K bands detected at a cubesat in both zenith and nadir directions. Correlator used to obtain raw electromagnetic signal transients.
- Delay Doppler map processing used to focus response to the specular point and first Fresnel zone. Processing with GPS location of cubesat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

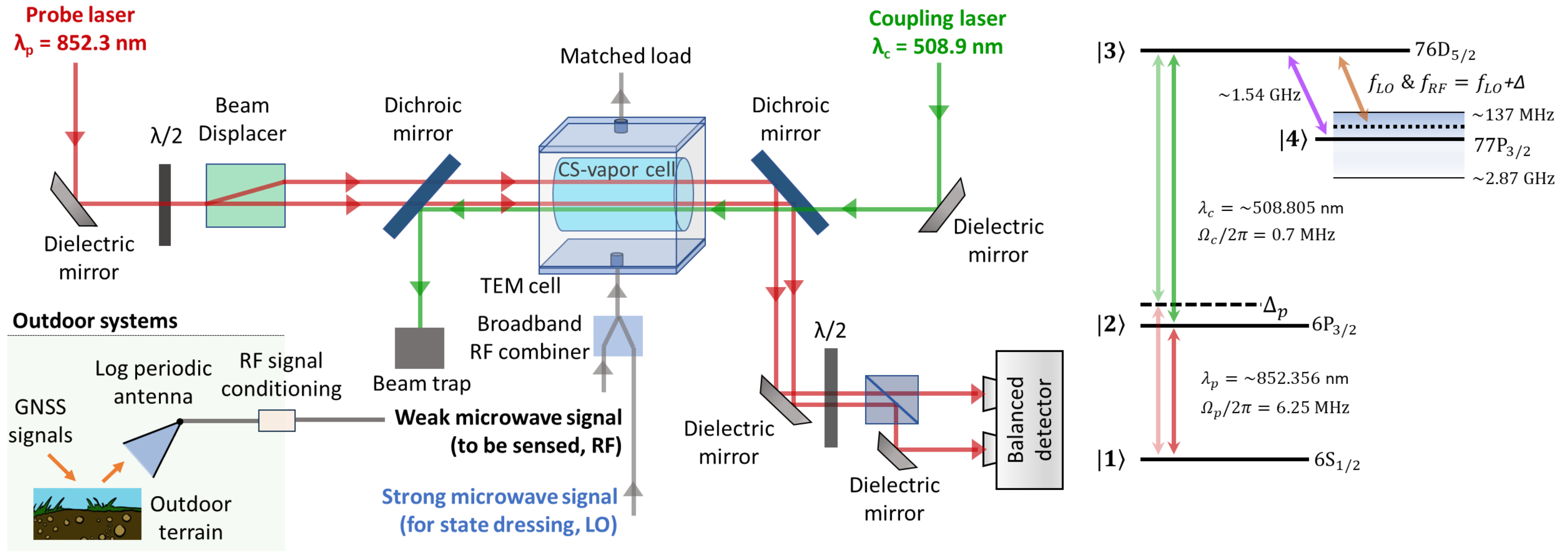


Iso-range and iso-Doppler around the specular reflection point used for delay Doppler map or SAR processing



Overview algorithm block diagram at the high level

Multi-band sensing through tunable strong LO field



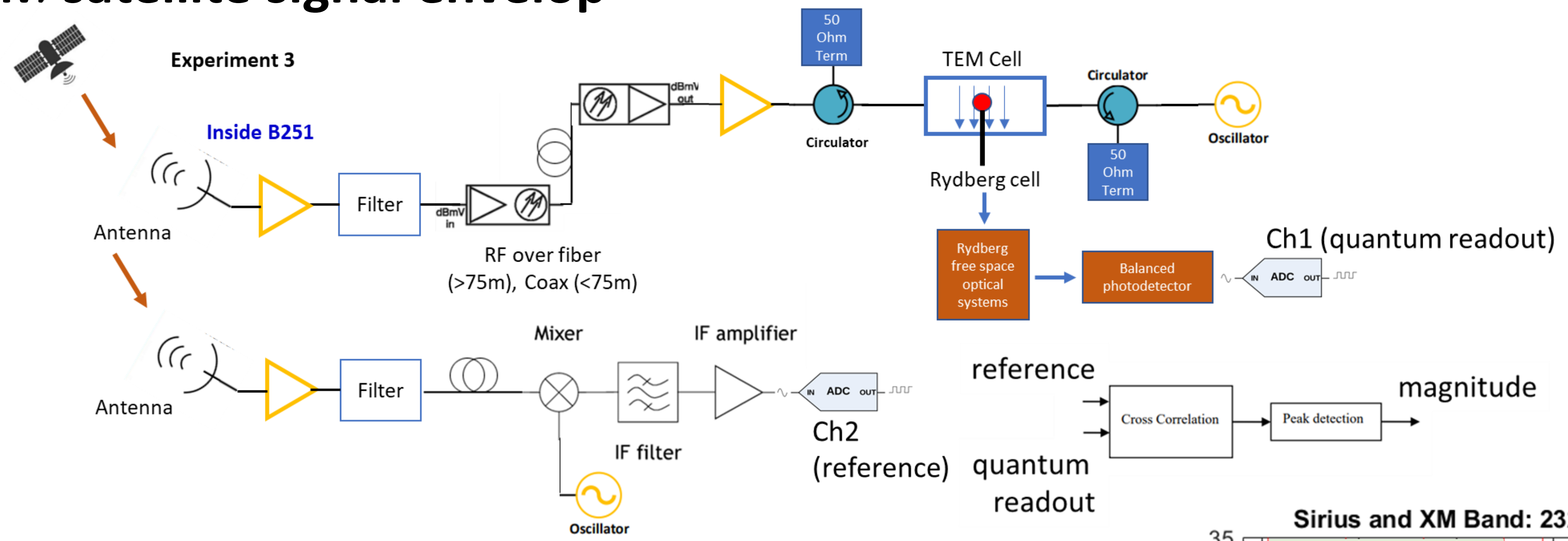
- In an off-resonance case, the Stark shift of the target Rydberg state (i.e., the optically probed Rydberg state) depends on the atomic polarizability
- A strong local microwave signal can be used to provide gain
- We switch the LO frequency and optimize power for each band we intend to sense (137 MHz to 2.38 GHz)

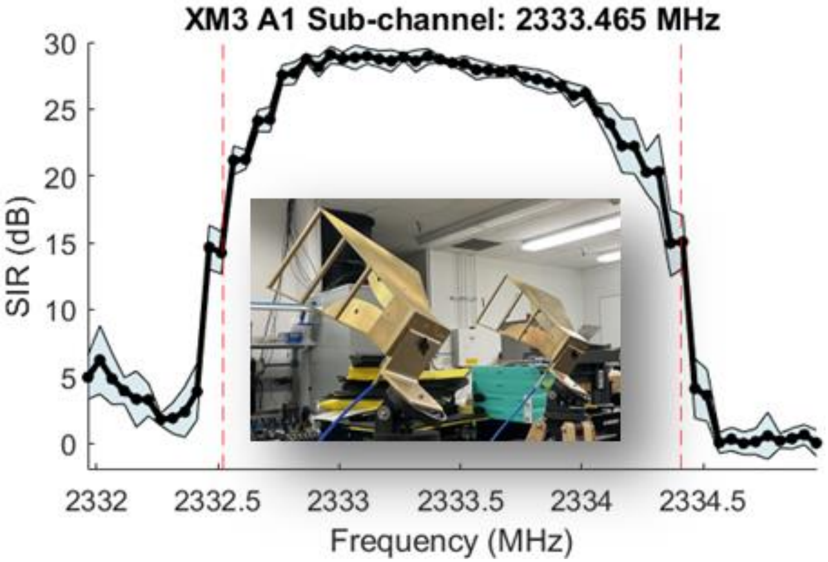
$$\hbar\Omega_{\text{off}} = -\frac{\hbar}{2}\alpha\langle E^2\rangle$$

$$\langle E^2\rangle \sim E_S^2 + E_L^2 + 2E_S E_L \cos(\delta_s t + \phi_s)$$

Amplifies signal

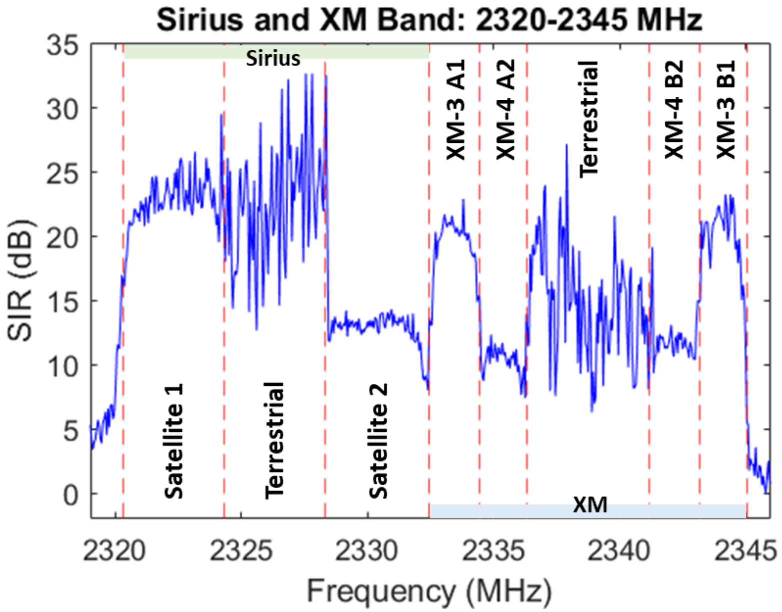
XM satellite signal envelop



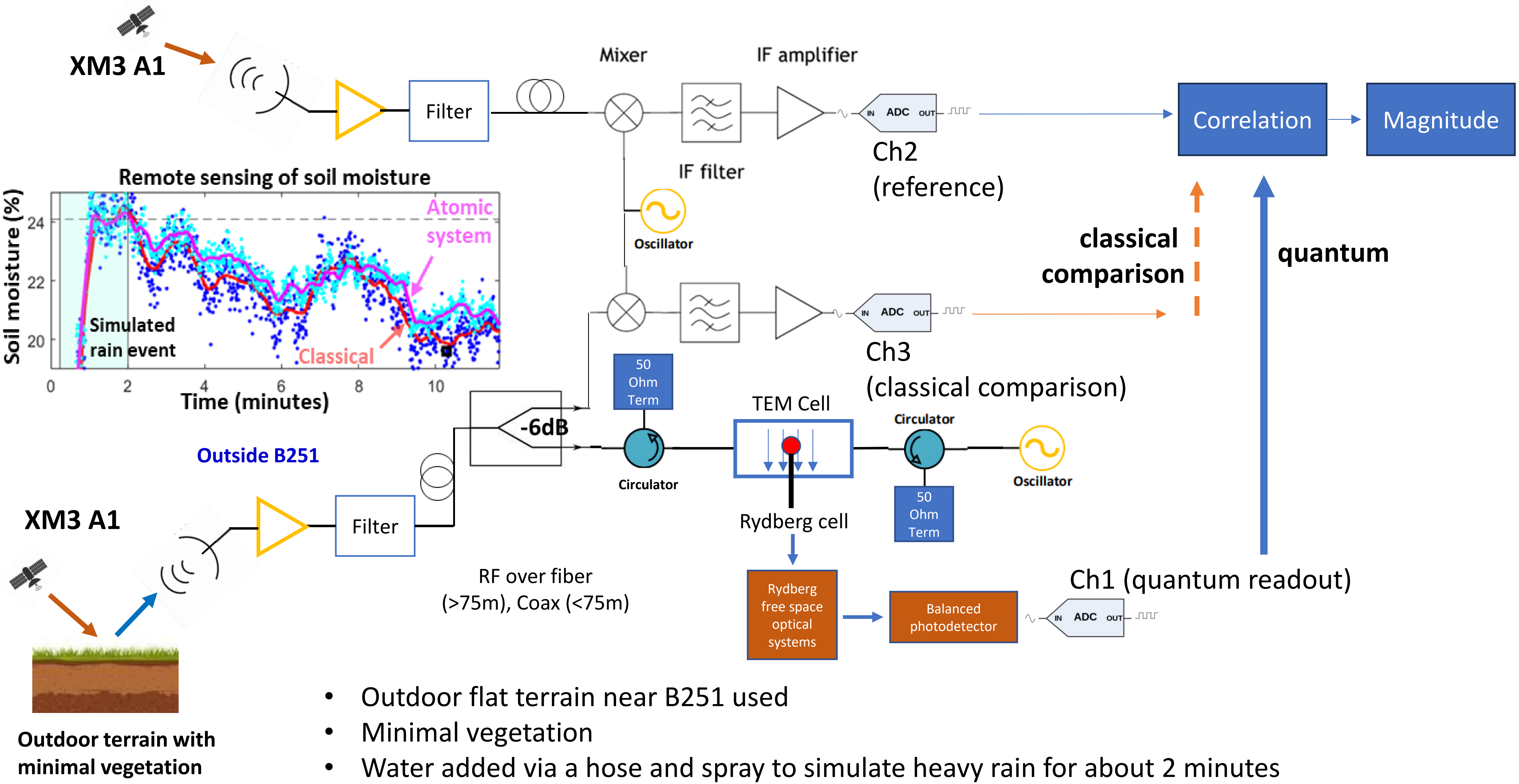


Findings:

- Entire XM and Sirius band is detected with up to 25dB of signal to interference, noise, distortions
- Given that reflection losses of soil are on order of 5-15dB typically, the setup should permit SM retrievals using the satellite signals



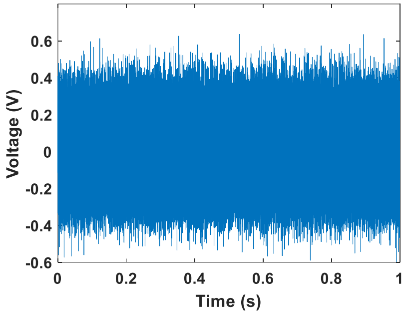
Simulated rain event outside B251 with classical reflectometry comparison

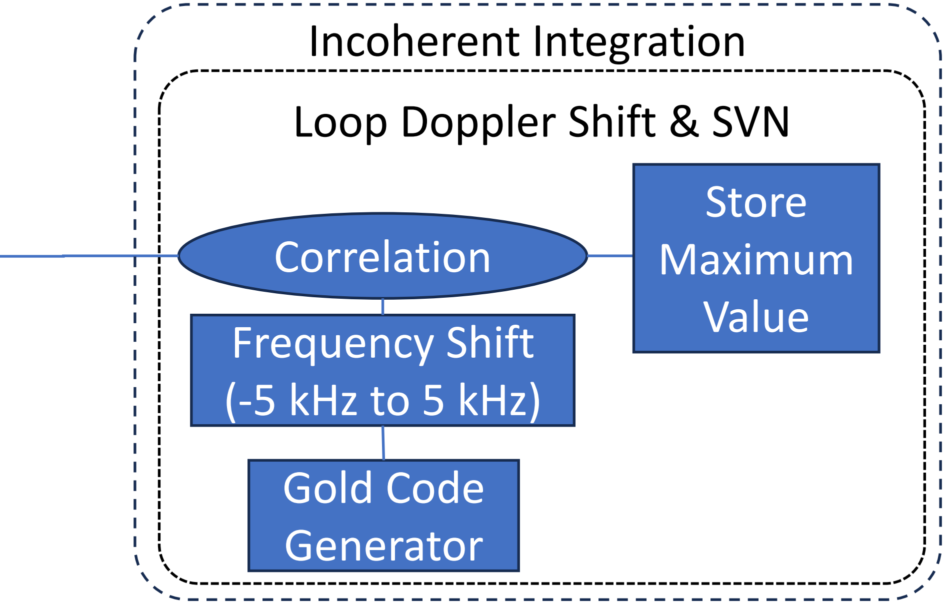


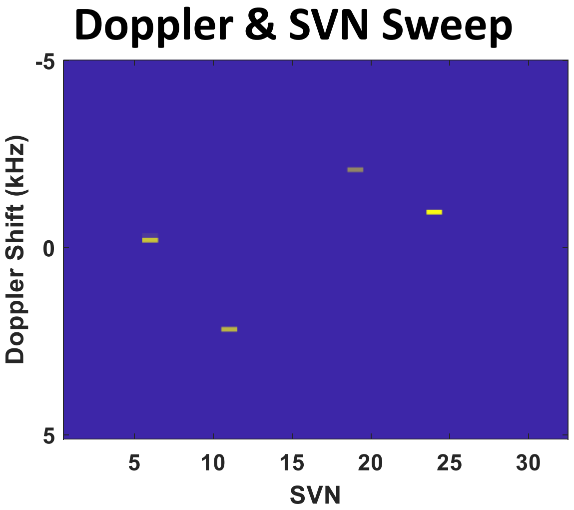
- Outdoor flat terrain near B251 used
- Minimal vegetation
- Water added via a hose and spray to simulate heavy rain for about 2 minutes

GNSS Detection

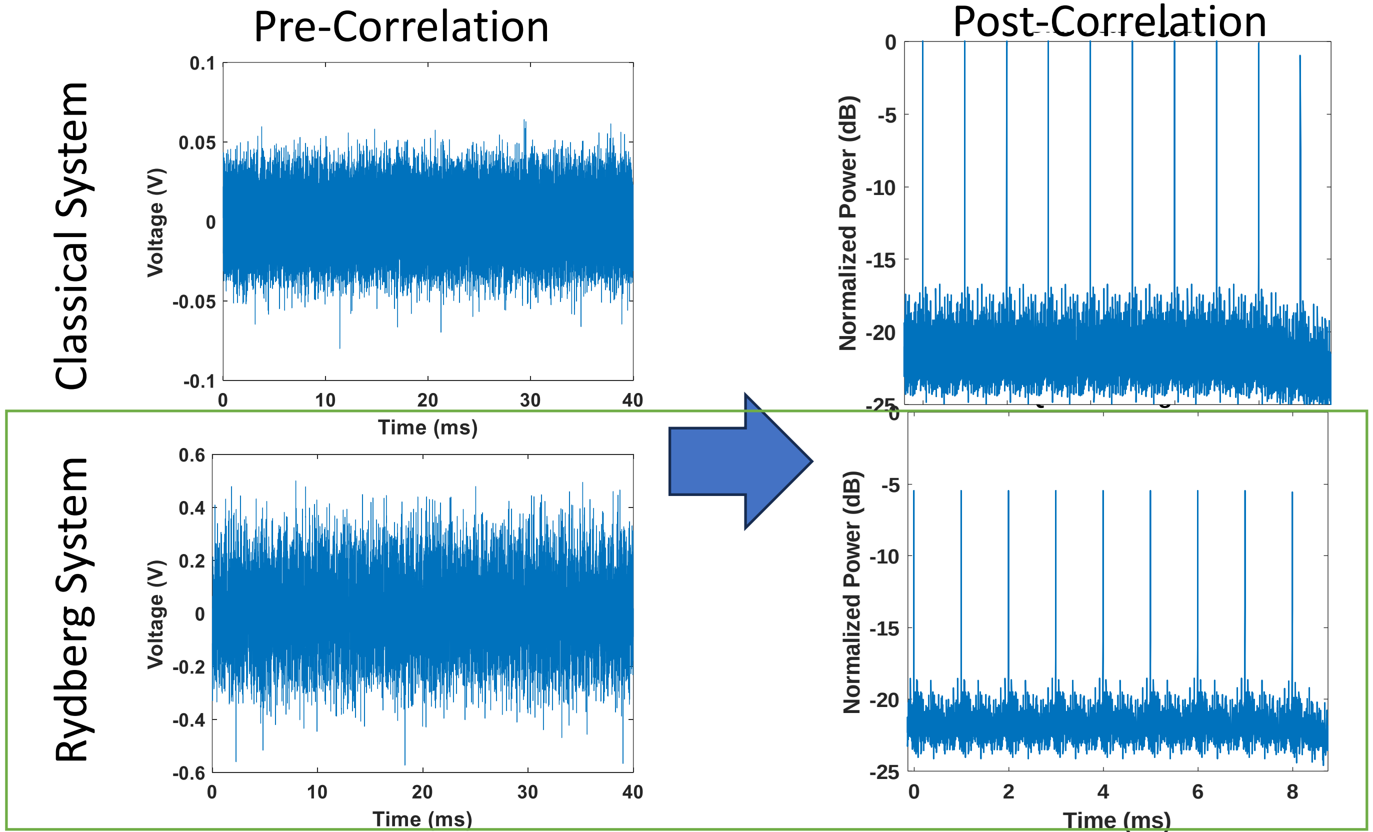
- The GPS detection algorithm conducts multiple correlations of the known ‘Gold Code’ of each GPS satellite, and a sweep of doppler







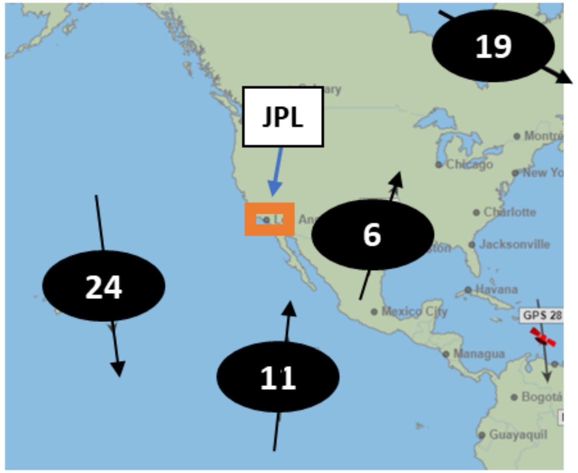
- Each of the 31 gold codes are orthogonal to one another, which allows for the differentiation between all GPS satellites
- Using this method, both the classical and Rydberg systems were used to detect multiple GPS satellites within the given observation window

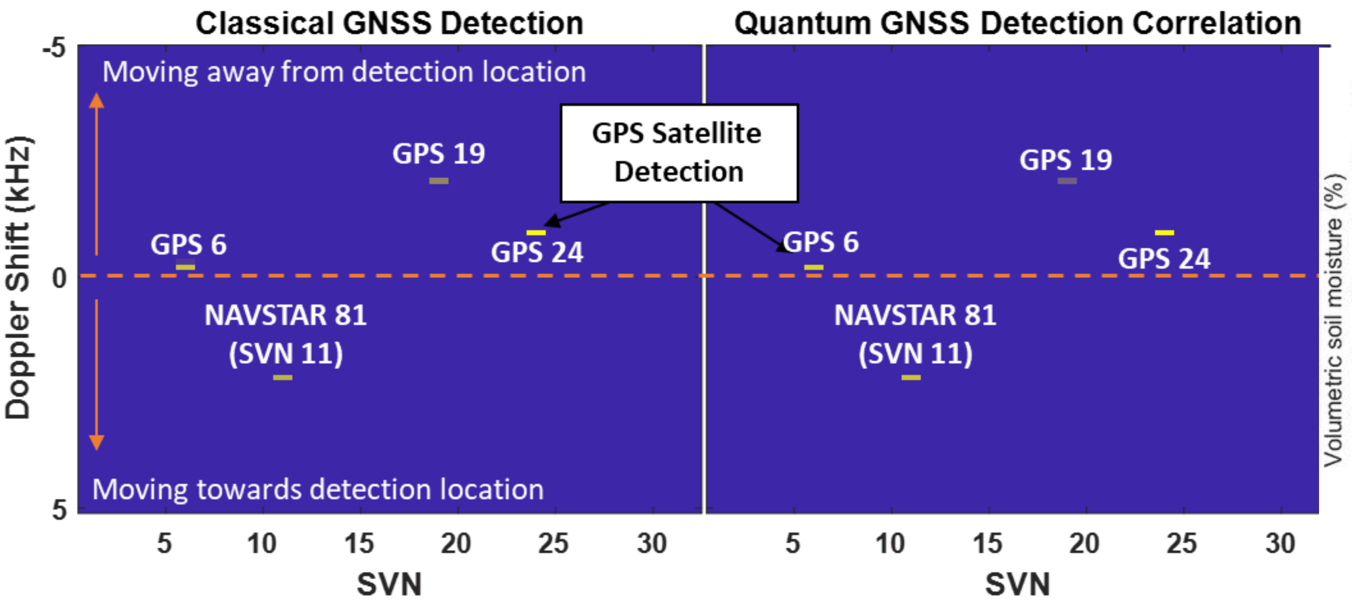


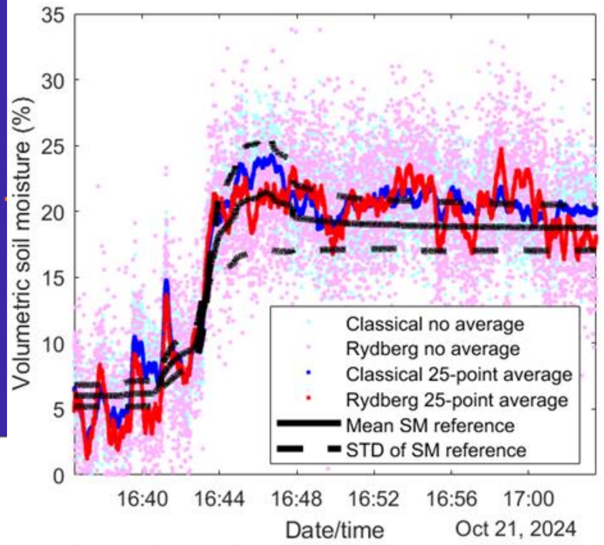
GNSS Detection and Soil Moisture Sensing Results

4:16 PM

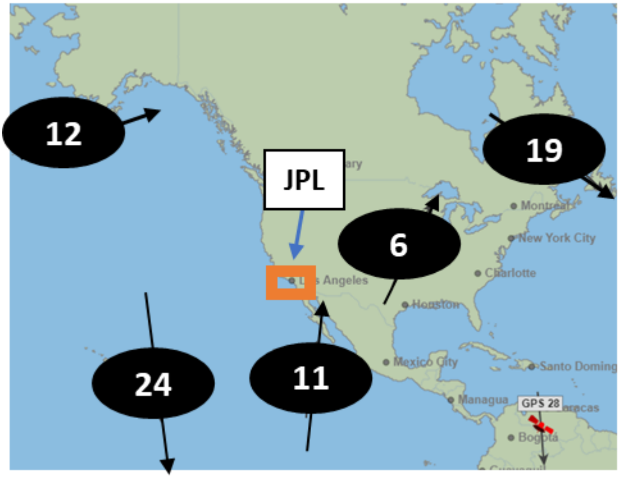
GPS Satellite Positions

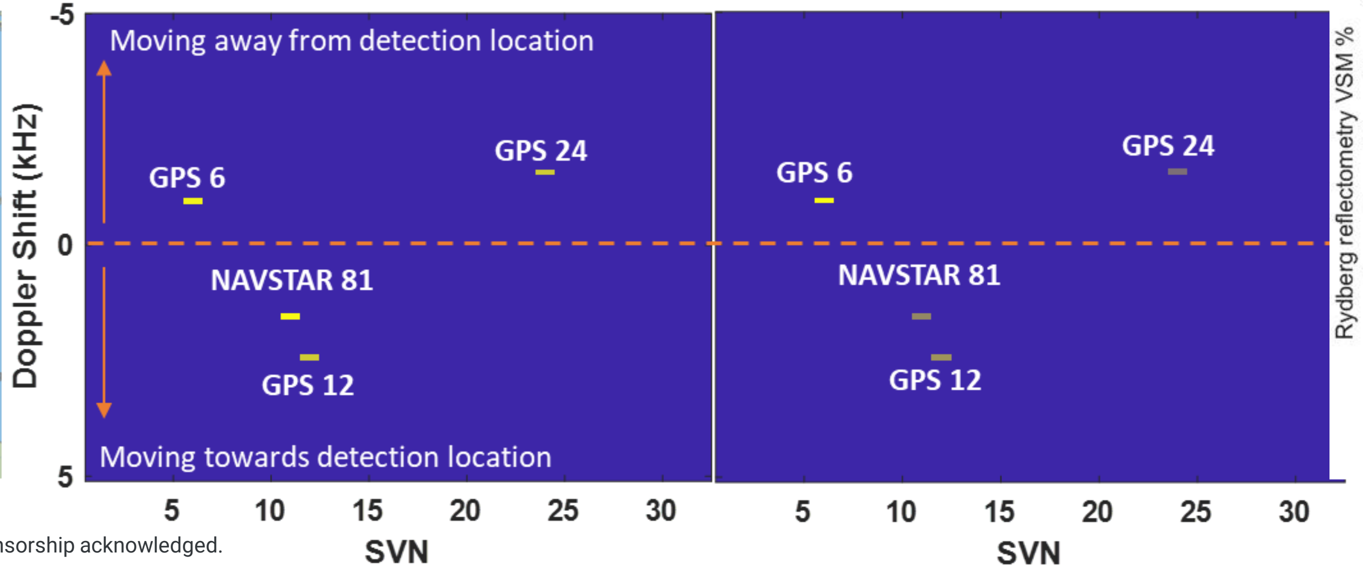


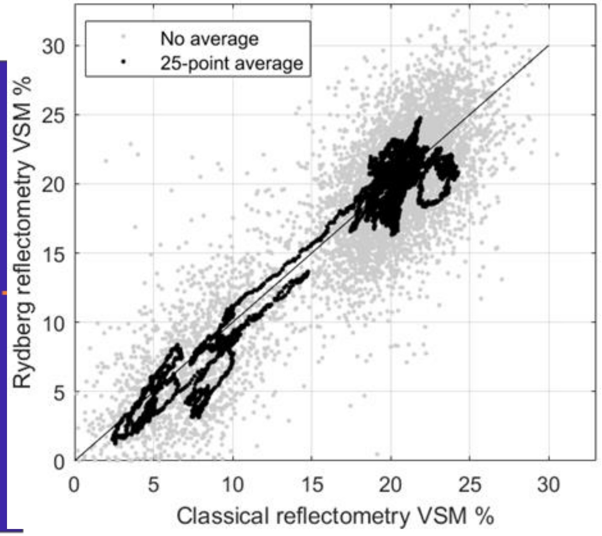




4:33 PM







Summary, Roadmap, Collaborations

Summary:

1. Rydberg atoms are a promising sensor technology for broadband space based remote sensing – although still at its infancy
2. Systems SWaP are high, but it is expected that these can be significantly reduced in the future

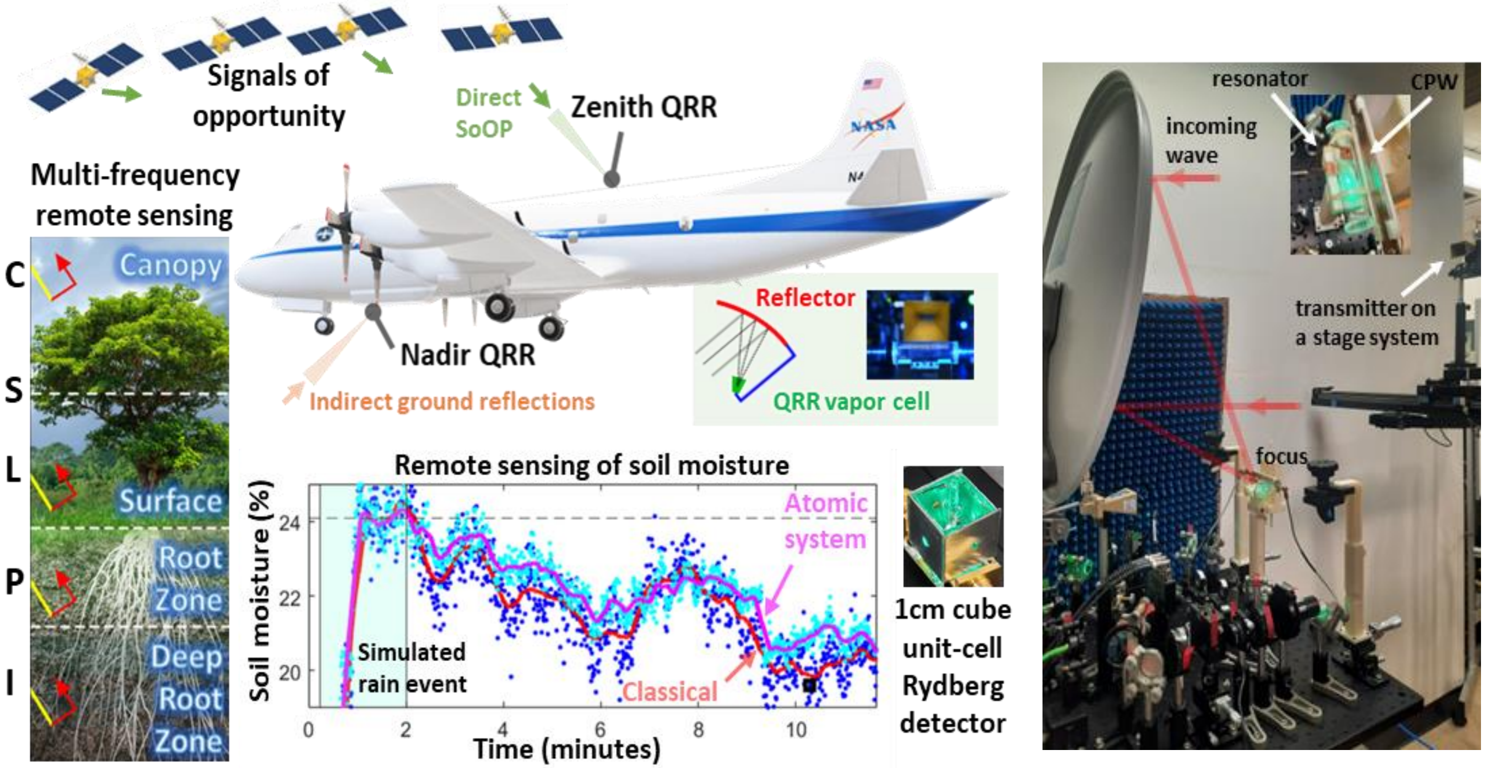
Ongoing development to TRL 5 airborne systems:

- Phase 1: Technology Development & Lab Testing
- Phase 2: Field Testing & Integrated Systems
- Phase 3: Science Flights & Data Collection

Collaborations:

Team is looking for international collaborations to support ongoing efforts towards an airborne technology demonstration by 2027.

Thank you!



RAID airborne instrument high-level concept, using QRR (quantum Rydberg receivers) on a P3 for multi-frequency remote sensing (left). Hybrid broadband and sensitive, tunable Rydberg system (right).

Technology Roadmap

FY23 – System development for laboratory radar measurements
FY24 – Outdoor field demonstrations
FY25/FY26/FY27 – Airborne instrument development and deployment
FY27-FY29 – Small Mission (InVEST)