Rydberg Probes: Can We Transform RF Measurements and Communications?

Christopher L. Holloway
N. Prajapati, M.T. Simons, A. Artusio-Glimpse,
S. Berweger, A. Rottunno, K. Campbell, M. Jayaseelan

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E-field Probes and Power Meters

RF Camera

Receivers

64 QAM
(64 phase states)
6 bits/symbol

Quantum TV and Gaming
One needs motivation to set through a workshop!

Prajapati, et al., AVS Quantum Science, August 2022
WHO is National Institute of Standards and Technology (NIST)

**NIST is a Federal Research Laboratory**  
**NIST’s mission:** To promote U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology in ways that enhance economic security and improve our quality of life.

*NIST in Gaithersburg, MD: 2500 researchers*  
*NIST in Boulder, CO: 600 researchers*
Basically, we kept track of the weights and measures for the country and for the world. Also, we do fundamental research for technology that is 5 to 30 years down the road.
The International System of Units (SI, abbreviated from the French Système International d’unités: SI system) is the modern form of the metric systems and the World’s most widely used system of measurement.

International Bureau of Weights and Measures (Bureau International des Poids et Mesures, BIPM)

Why are pirates responsible for NO metric system in the US?
Artefact Standards for the World: No MORE

This sounds like a good idea.

But, Artefacts Change?
The world of measurement science is changing rapidly with the SI redefinition planned for 2018.

The key here is that the world moved from artefacts standards to fundamental physical constants.

As a result of the shift towards fundamental physical constants, we can rethink about how SI traceable measurements and calibrations are done.

We propose to transform calibration services and the traceability path for *E-field* and of *RF power* (defined as 100’s MHz to just below THz).
What are We Trying to Solve

Calibrating an E-Field Probe

To calibrate a probe, one must place the probe (sensor) in a “known” field.

However, to know the field we need a calibrated probe.

Somewhat of a “Chicken-or-Egg” dilemma
How will we do Better, by using atoms!

Atoms will respond to their environment.

So, the BIG question is:
How do we use the atom to measures E-fields?

by Generating Rydbergs Atoms and
Electromagnetically Induced Transparency (EIT)

0.5 dB (or 5%) accuracy
Rydberg states have very large dipole moments: Meaning they are very sensitive to RF E-fields (making for good RF E-field sensors).

So how do we read out the respond of the atom to an electric field? By electromagnetically induced transparency (EIT)

\[ |E| = \Delta f \frac{\hbar}{\phi} \]

\[ |E| = \sqrt{\frac{4 \Delta f}{\alpha}} \]
**Fundamental Change: Replace Classic Antenna with Rydberg Atoms**

**Classic Antenna or Probe**

Conduction electrons bound by antenna geometry.

**Rydberg Atom Probe**

Atom-bound electrons in a vapor cell have no geometry per se as long as they interact with controlling lasers.

Counter propagating Lasers
Historical Perspective - 8 Year History

Prior to 2010: Many groups investigated E-field interactions with Rydberg atoms

2010: NIST wrote paper discussing using Rydberg atoms for SI measurements of electric fields

2011: DARPA funded two groups on atom-based electric field sensors:

   one lead from the University of Oklahoma/Stuttgart: Sedlacek et al., 2012
   one lead from of NIST/U. of Michigan: Holloway et al., 2014

2014-Present: Great progress has been made in using Rydberg atoms of electrical field sensors by various groups around the world.

Because of the success of this program, several groups around the world (including National Metrology Institutes, private companies, universities, and other government laboratories) have started programs in the area of Rydberg atom-based sensors.

Including: USA, Germany, UK, Canada, China, Japan, South Korea, India, New Zealand, etc..

Gov. Labs: NIST, DOD, DOE, National Institute of Metrology (China), NPL (UK), etc..

Universities: U of Michigan, U of Oklahoma, U of Stuttgart, Durham Univ., U of Colorado, U of Maryland, Shanxi University, U College London, U of Ele. Science and Technology, U of Otago, U of Chinese Academy Sciences, Chongqing University, Institute of Laser Spectroscopy, Jiliang University, Jiliang University, Shandong University of Science and Technology, Pusan National University, Beijing Institute of Technology, etc.....

Several private companies: Rydberg Technologies, MITRE, SRI, Raytheon, Northrop Grumman, other that I cannot mention, etc.......
Electromagnetic Induced Transparency (EIT) for SI Traceable Measurements

480 nm

The blue laser gets us high enough that the next transition can be made with RF.

Splitting in the EIT signal (Autler-Townes Splitting)

\[ \Delta f = \left| E \right| \left( \frac{P}{2 \pi \hbar} \right) \rightarrow \left| E \right| = 2 \pi \Delta f \frac{\hbar}{P} \]

SI traceable via Planck’s constant

We have reduced an amplitude measurement to a frequency measurement.
Room Temperature Measurement
Signal on the Detector: Typical Experimental Result for the Splitting
Typical EIT Signal

![Graph showing EIT signal with two curves: one with RF off and the other with RF on.](image)

- **EIT signal (arb. units)**
- **\( \Delta f_m \)**
- **\( \Delta p/2\pi \) (MHz)**

**Legend:**
- Black dashed line: Cs atoms with RF off
- Red line: Cs atoms with RF on
These results for >110 GHz are important from a calibration viewpoint.

\[ |E| = 2\pi \frac{\hbar}{\varphi} \Delta f \]

Broadband Sensor: One setup can measure a field from 10 MHz to THz (we recently figured out how to get down to 100 kHz).

Fiber-Coupled Probe: Moving Probe OFF Optical Table

Simons et al., Applied Optics, 2018
Fiber-Coupled Cubic Cell (10 mm cube)

Printed Circuit Board

Antenna Measurement

IoT-Test Chambers (current IMS)
Communication Receiver: Atom Receiver

AM/FM modulation is easy with the atoms!

Several groups have demonstrated AM/FM reception:

- Data transmission:
  - Simons *et al.*, 2018.


The atoms automatically do the demodulation.

It is quite amazing that over the past decade we have learned to control ensembles of atoms to such an extent that they can be used to record musical waveforms (and a wide array of other applications).

Toptica Photonics: call them and listen!!
Multi-Band/Channel Receiver: Dual Atomic Species for Stereo Reception

Instrumental on Rb atoms
Vocals on Cs atoms

Diagram:
- Computer with Audacity software
- Stereo microphone input and stereo headphone output
- AM mod. input, FM mod. input, 19.623 GHz SG, Horn for 19.623 GHz, Horn for 20.644 GHz
- Vapor cell (Cs and Rb atoms)
- Probe Rb 780 nm, Probe Cs 850 nm
- Detector Rb, Detector Cs
- Switches for left and right channel
- Left speaker, Right speaker
Dual Atomic Species Stereo Reception

Holloway et al., IEEE APS Mag., 2021.

Instrumental on Rb atoms
Vocals on Cs atoms

Original Waveform
- Left Channel: Instrumental Part
- Right Channel: Vocal Part
- Waveform (arb. units)
- Time record (total time period of 76.7 seconds)

Received Waveform
- Left Channel: Instrumental Part
- Right Channel: Vocal Part
- Waveform (arb. units)
- Time record (total time period of 76.7 seconds)

AM/FM Stereo Receiver
Video Streaming with Quantum Sensors

Prajapati, et al., AVS Quantum Science, August 2022
NSTC format video signals

High Score got to be FIRST author on Paper
(240 row/frames) x (640 pixel/row) x (60 frames/s) x
(24 color bits/pixel) = 221 Mbits/s
Amplitude: Most of this work was toward amplitude of the E-field by NIST and a few others.

Polarization: [Sedlacek et al., APL, 2013].

AM/FM Reception is possible.

The missing link was “phase”!

Phase: NIST-[Simons et al., APL, 2019].

We can now fully characterize a radio frequency field, in that the amplitude, phase, and polarization of the field can be determined in one compact quantum-based sensor.

We can now start looking at a wide array of applications.
Phase Measurements: Rydberg Atom-Based Mixer

Simons et al., APL, 2019

\[ f_{\text{SIG}} = f_{\text{LO}} + f_{\text{IF}} \]
Measuring the Phase of a Phase Shifter

Variable Phase Shifter

Vector Network Analyzer
Measuring the Phase of a Phase Shifter

Simons et al., APL, 2019

CW carrier: Phase Shift

About 1 degree resolution!
**Phase Modulation for Communications (Phase Modulated Carrier)**

Holloway et al., IEEE AWPL, 2019

- **BPSK (Binary Phase Shift Keying)**
  - LO → IF
  - SIG

- **QPSK**
  - 4 phase states
  - 2 bits/symbol

- **16 QAM**
  - 16 phase states
  - 4 bits/symbol

- **32 QAM**
  - 32 phase states
  - 5 bits/symbol

- **64 QAM**
  - 64 phase states
  - 6 bits/symbol

**What is the Advantage?**

- No down-conversion circuity is needed:
  - The atoms do the down-conversion automatically.

**We can detect and receive phase-modulated signals!**

2047 symbols steam
Sensor/Receiver

We need to keep in mind that the Rydberg atom-based receiver/sensor, in effect, replaces the receiving antenna and front-end components and electronics that are used in a conventional receiver system.

For example, the Rydberg atoms perform some of the same functions as both antennas and demodulators all in one, so this needs to be considered when comparing with traditional systems.

Fully characterize the RF E-field in one compact vapor cell:

- Magnitude
- Phase
- Polarization

1. Detection of fields and modulated signals
2. Direction of arrival
3. Vector fields
4. Waveform characterization (CHIRP signals)
5. DC to THz detection
6. Very Weak fields / Very Strong fields
These results show proof-of-concept for measuring angle-of-arrival of an RF source. While discrepancies between theory and measurements are seen, these results show that it is possible to determine the angle-of-arrival. It is believed that the discrepancies between theory and measurements is due to RF internal cell resonances, causing additional phase shifts (different for different cell sizes). We think we have ways of correcting or calibrating out these discrepancies.
While a Rydberg atom-based approach will not have the uncertainties of the benchtop Josephson voltage standard at 1 V, Rydberg based voltage standards offer the possibility of compact, room temperature, cheap (SWAP-C) alternatives for a large range of AC/DC voltages.

**Amplitude:** 1V – 10V, but possibly could be extended to 1000V at reduced accuracy. This is limited by the choice of Rydberg state and level mixing that occurs at elevated voltage.

**Uncertainty:** Probably 1e-5 fractional uncertainty, and 1e-7 long-term stability, limited by fringing fields.

\[ |E| = \sqrt{\frac{4 \Delta f}{\alpha}} \]

\[ V = |E| \cdot d \]
TE\textsubscript{10} mode in rectangular waveguide
only allowed mode at measurement frequency
\[ \vec{E} = E_0 \sin \frac{\pi x}{a} \left\{ e^{-j\beta z} + \Gamma e^{j\beta z} \right\} \hat{y} \]
½ sinusoid in x, constant in y, partial standing wave in z

Transmitted Power
\[ P_{\text{trans}} = E_0^2 \frac{ab}{4} \frac{\varepsilon_0}{\mu_0} \sqrt{1 - \left( \frac{c}{2af} \right)^2} \]
Depends on E, physical constants ($\varepsilon_0$, $\mu_0$, c), and geometry (a,b)

We measure E with the Rydberg atoms and power is traceable to Planck's constant.
Traceable RF Power Measurements

Holloway, et al., APL, 2018

Transmitted Power

\[ P_{\text{trans}} = E_0^2 \frac{ab}{4} \sqrt{\frac{\varepsilon_0}{\mu_0}} \sqrt{1 - \left( \frac{c}{2af} \right)^2} \]

\[ \vec{E} = E_0 \sin \frac{\pi x}{a} \left\{ e^{-j\beta z} + \Gamma e^{j\beta z} \right\} \hat{y} \]

TE\(_{10}\) mode in rectangular waveguide

19.629 GHz and 26.526 GHz: WR42: Cs atoms

Atom-based measurement

Power-meter (at second coupler)
New Paradigm for RF Power (Calibrated Source)

Current State of the Art

• Energy meter
• Absorption-based
• Energy $\propto \Delta T$
• Calibration through the power meter

Outcome after IMS: Real-time “in situ” traceability

In Situ RF (Rydberg cell)
RF Atomic-Vapor Cell (AVC) Camera

AVC array

Vapor cell pixel

RF Image
RF AVC Camera
or
RF Beam Profiler
Simons et al., IEEE Access, 2019

Holloway et al., APL, 2022

Field Enhancement

New Recorded Sensitivity by NIST:
3 µ V/m Hz^{-1/2}
By using a second RF source we can “dress” (or tune) the Rydberg state to detect any RF frequency.

New Recorded Sensitivity:
3 $\mu$V/m Hz$^{-1/2}$
Rydberg Engineering: “Low-Frequency” detection

• Idea: Tune splitting $\Omega_{\text{tuner}}$ to match applied Low Frequency $\omega_{\text{LF}}$
• Measure $|E_{\text{LF}}|$ via non-linear “Floquet” sideband states’ absorption dip
• Enables new experiments:
  • DC field component (at half frequency)
  • Multiple tones “Spectrum analyzer”
  • Audio transmission: AM mod on LF field
• Takeaways:
  • Receives long waves in a cm-sized sensor
  • Far off-resonant Low Frequency fields are made “pseudo-resonant” using tuning field
Two photon vs. three photon approach

\[ \text{Doppler resid}_2 = \frac{|k_{850} - k_{510}|}{|k_{850}|} \cdot \gamma_{12} = 0.667 \cdot \gamma_{12} \]

\[ \text{Doppler resid}_3 = \frac{|k_{895} - k_{636} + k_{2224}|}{|k_{850}|} \cdot \gamma_{12} = 0.0048 \cdot \gamma_{12} \]
Sensitivity Estimation

(Dashed) Two photon
(Solid) Three photon

\[ \Delta \text{Absorption (at zero C-detuning)} \]

\[ \Omega_{RF} (2\pi \text{KHz}) \]

\[ \Omega_p=0.20, \Omega_d=10.00, \Omega_c=0.95 \ (2\pi \text{MHz}) \]

\[ \Omega_p=0.20, \Omega_d=16.00, \Omega_c=0.95 \ (2\pi \text{MHz}) \]

\[ \Omega_p=0.20, \Omega_d=22.00, \Omega_c=0.95 \ (2\pi \text{MHz}) \]

\[ \Omega_p=0.20, \Omega_d=22.00 \ (2\pi \text{MHz}) \]

\[ \Omega_{C/2\pi} = 2.5 \text{MHz} \]

Two photon
Three photon

RF Sensitivity

\[ \Omega_{p/2\pi} \ (\text{MHz}) \]
Development of Technologies for Commercialization

Miniaturize Vapor Cells

Miniaturize Visible Lasers (blue and/or green)
Over the past few years, great progress has been made in using Rydberg atoms for electrical field sensors. Because of the success of this program, several groups around the world (including National Metrology Institutes, private companies, universities, and other government laboratories) have started programs in the area of Rydberg atom-based sensors.

- SI traceable electric-field probe
- SI traceable power calibration
- Blackbody radiation detection

- Atom-based receivers/antennas
  - AM/FM
  - BPSK, QPSK, QAM signals

- RF imaging and visualization technology (RF camera)
- Near-field imaging
- Sub-wavelength imaging

- Voltage standards
- Plasma sensors
- Waveform/Spectrum Analyzer
- Atomic thermal field sensing and measurement (blackbody radiation calibrations)
- Measuring noise sources
- Video Streaming and Recording music
Autler-Townes Splitting in Rydberg Atoms from Extreme RF Fields
Summary

Fundamentally new approach for E-field and Power measurements

E-Fields
• **Broadband probe/sensor**: 10 MHz-to-500 GHz (possibly to 1 THz)
  • Will allow direct SI units linked RF electric field (E-field) measurements
  • Would provide RF field measurements independent of current techniques
  • Very small and compact probe: fiber-coupled atom-based probe
  • Measure *weak* and *large* E-field strengths over a large range of frequencies:
    \[ < 1 \, \mu \text{V/m} \quad \text{and} \quad > 10 \, \text{kV/m} \]

Power
• SI traceable Power measurements
• Calibrations above 110 GHz
• Real-time power calibrations

Unique and Unforeseen Applications
Perseverance

*Quote from Nobel Laureate* for inspiration for early career scientists

“There is no success like Failure, but Failure is no success at ALL”

- *Bob Dylan*

*To be successful:*, you need to adapt, be willing to do and learn new things, and take every opportunity that comes your way.
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Various postdocs and students at U. of Colorado, U. of Michigan, U of Oklahoma
Bottom-line: Rydberg Atoms are “cool” and we can do “cool” things with them, leading to many unforeseen applications.

Call if you want to join the team!
Rydberg-Atom Sensor Papers:


RF Radiation Pressure papers:

3. Ryger, et al., “MEMS non-absorbing electromagnetic power sensor employing the effect of radiation pressure”, Eurosensors 2018, Sept 9-12, Graz, Austria, 2018
Development of Technologies for Commercialization

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Miniaturize Visible Lasers (blue and/or green)
Multi-Band/Channel Receiver: Dual Atomic Species for Stereo Reception

**Instrumental on Rb atoms**

**Vocals on Cs atoms**

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![Diagram of multi-band/channel receiver with dual atomic species for stereo reception](image-url)
Dual Atomic Species Stereo Reception

Holloway et al., IEEE APS Mag., 2021.

Instrumental on Rb atoms
Vocals on Cs atoms

Original Waveform

Received Waveform
IoT: Chamber Characterization
A Little Atomic Physics: The Hydrogen Atom

Bohr Model

1. Electrons orbit the nucleus in discrete radii.
2. The ground state is n=1
3. Need to supply or released energy (or photons) to change state (or orbit)

\[ \Delta E = h \nu \]
\[ \nu = -13.6 \left( \frac{1}{n^2} - \frac{1}{nf^2} \right) \text{ eV} \]
\[ \frac{1}{\lambda} = R_H \left[ \frac{1}{n^2} - \frac{1}{nf^2} \right] \frac{1}{m} \quad R_H = 1.0973731 \times 10^{-7} \text{ m}^{-1} \]

Transition from ground state: n=1 to n=2

\[ \lambda = 121.6 \text{ nm} \quad (f = 2 \times 10^{15} \text{ Hz}) \quad : \Delta E = h \nu = 10.2 \text{ eV} \]

Energy in a 20 GHz photon:

\[ \Delta E = h \nu = 8.27 \times 10^{-5} \text{ eV} \]

Ground state: photons at RF to lower THz will not change the state (or orbit)
Alkali Atoms and Rydberg Atoms

Atom will respond to their environment.

So, the BIG question is:
How do we use the atom to measures E-fields?

by Generating Rydbergs Atoms
and
Electromagnetically Induced Transparency (EIT)

Alkali metals or atoms
• One electron in the outer shell
• The outer electron can be predictably excited
• We can used theoretical calculations of the hydrogen atom to predict interactions
• This is especially true for Rydberg Atoms (excited atoms to a very large n)

Rubidium
one electron in outer shell
ground state: n=5

Sulfur
Development of Technologies for Commercialization

Miniaturize Vapor Cells

Miniaturize Visible Lasers (blue and/or green)
Applications

- **New SI Traceable Power Calibration**
- Atom-based receivers/antennas
- Quantum RF imaging and visualization technology (RF camera)
- Quantum-enabled medical imaging and diagnostics
- Plasma sensors
- Atomic DC/AC voltage and current references
- Atomic thermal field sensing and measurement (blackbody radiation calibrations)
- Single microwave photon detection
- Quantum storage of radio frequency, microwave, and THz photons using slow light effects in Rydberg gases. (Quantum encrypted Rydberg atom quantum receivers from 1 GHz to 1 THz)
- Waveguide Power Measurements: Power Calibrations
- Sub-wavelength imaging
- Near-field imaging
- Measuring Noise sources

And many other unforeseen applications.
New Paradigm for RF Power (Calibrated Source)

**Current State of the Art**
- Energy meter
- Absorption-based
- Energy $\propto \Delta T$
- Calibration through the power meter

**Outcome after IMS:** *Real-time “in situ” traceability*

In Situ RF (Rydberg cell)