

# Towards space-ready Rydberg quantum sensors

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## ABSTRACT

Rydberg-atom electrometry enables SI-traceable measurements of radio-frequency (RF) electric fields using an all-dielectric sensor head, with coverage from tens of MHz to several THz. However, reported performance has largely been achieved in laboratory settings with vibration-isolated optical tables. For space deployment, the instrument must also meet stringent constraints on size, weight, power, and cost (SWaP-C). Here we assess the requirements for transferring this capability to a flight instrument, using the ESA-funded RYDAR project as a case study. Across candidate architectures, multiple continuous-wave (CW) lasers and their frequency-locking electronics dominate the SWaP-C budget; achieving simultaneous stabilisation is the primary barrier to flight readiness. In the two-laser baseline architecture used in the RYDAR proof-of-concept, the probe laser and vapour cell are nearing flight readiness, whereas the coupling laser remains the limiting subsystem, occupying a large fraction of the instrument volume and consuming nearly half of the power. An alternative approach based on an all-infrared excitation ladder eliminates the coupling laser at the expense of stabilising a third laser. By contrast, two frontier architectures retain the coupling laser: microwave-to-optical conversion with photon-counting readout, a leading approach for radiometry above 100 GHz, and all-optical-bias superheterodyne detection, which provides phase-sensitive readout for coherent imaging and communications. Both remove the RF local oscillator and enable reception-pattern control via the optical-beam geometry.

**Keywords:** Rydberg atoms, RF sensing, quantum sensors, laser stabilisation, microwave-to-optical conversion, radiometry, space instrumentation

## 1. INTRODUCTION

A Rydberg-atom sensor measures a radio-frequency (RF) electric field by coupling the field to a transition between two highly excited (Rydberg) states and reading out the resulting perturbation optically. The interaction strength is set by the transition dipole moment  $d$ , which scales as  $n^2$  for neighbouring Rydberg states (principal quantum number  $n$ ), yielding a much stronger response than in ground-state systems. In the warm-vapour implementations considered here, two lasers at 780 nm (probe) and 480 nm (coupling) excite rubidium atoms, and the RF field is inferred from changes in probe transmission via electromagnetically induced transparency (EIT) and Autler–Townes (A–T) splitting. Since adjacent Rydberg-level spacings scale as  $n^{-3}$ , this approach can access transitions from tens of MHz to several THz.<sup>1</sup>

This detection principle has three features that are particularly relevant for space instrumentation. The measurement is absolute: the A–T splitting is set by the RF Rabi frequency  $\Omega = dE/\hbar$ , so the field amplitude  $E$  can be obtained from atomic structure without an external calibration chain. The sensor head can be all-dielectric, with its dimensions set by the optics and vapour cell rather than the detected wavelength. Finally, the operating band is selected by the laser wavelengths and chosen Rydberg state, enabling a single head to cover bands that would otherwise require multiple front ends.

The remaining barriers are therefore primarily engineering-driven. Most demonstrations rely on vibration-isolated optical tables and rack-mounted laser systems, whereas a flight instrument must maintain narrow linewidth and long-term frequency stability under launch loads, thermal cycling, and radiation within a constrained payload mass and power budget.

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## 2. SENSOR ARCHITECTURES: FROM THE BASELINE TO THE FRONTIER

Rydberg-atom RF sensing has been demonstrated using a range of detection methods that can be grouped into five architectural families.<sup>1</sup> We focus on the three most relevant to space deployment. The first is a baseline architecture whose miniaturisation is now largely an engineering task; the other two are frontier approaches that could deliver capabilities difficult to realise by other means in orbit, but are not yet at instrument-level. Because the development bottlenecks differ, we treat the baseline and frontier architectures separately below.

### 2.1 The Baseline Architecture

The baseline architecture combines Autler–Townes (A–T) splitting, which provides an absolute field calibration, with superheterodyne detection. A strong RF local oscillator (LO) is applied to the atomic medium and beats with the weak signal field, imprinting a difference-frequency modulation on the probe transmission. The implementation requires two lasers (probe and coupling) and is well characterised. Portable, self-calibrated instruments have been demonstrated,<sup>2,3</sup> and this approach underpins the RYDAR proof-of-concept receiver and much of the current work on compact Rydberg receivers. Its main limitation is the need to deliver the LO to the atoms, which reintroduces metallic structures at the sensing point and constrains the sensor head design.

### 2.2 Microwave-to-optical Conversion and High-frequency Radiometry

In the conversion architecture, the RF field is coherently mapped onto an optical field via wave mixing in the atomic medium, rather than being inferred from a perturbation of probe transmission. This shifts the signal to an optical band where single-photon detectors are available, enabling photon-counting readout. Microwave demonstrations report a 57 dB conversion dynamic range and a 3.8 K noise-equivalent temperature at room temperature,<sup>4</sup> consistent with radiometric requirements. Conversion is therefore a leading candidate for radiometry,<sup>1</sup> particularly above 100 GHz,<sup>5,6</sup> where conventional electronic front ends become challenging. Relative to the baseline architecture, conversion places greater demands on the photonic chain, including narrow-band optical filtering, single-photon detection, and simultaneous stabilisation of three continuous-wave lasers (including the coupling laser).

### 2.3 All-optical Superheterodyne

The second frontier architecture replaces the RF local oscillator with additional optical fields. The phase-sensitive bias is then applied optically, so no metallic structure is introduced into the interaction volume. The implementation reported to date uses four lasers and achieves performance comparable to conventional superheterodyne detection on the same apparatus.<sup>7</sup>

Because the readout relies on wave mixing, phase matching makes the response direction-dependent. The reception pattern is therefore set by the laser-beam geometry and has been calculated for the reported configuration.<sup>7</sup> Phase matching also applies to conventional superheterodyne detection,<sup>1</sup> but the available control is different: with a microwave LO the pattern can be adjusted mainly through LO mode and polarisation, whereas in an all-optical scheme the relevant wavevectors are three to five orders of magnitude larger than that of the detected RF field, so small angular changes in a beam can strongly reshape the response. The same mechanism enables pattern control in the conversion scheme of Sec. 2.2 and underpins coherent terahertz field tomography.<sup>8</sup>

Because both amplitude and phase are preserved, the architecture supports coherent imaging<sup>9</sup> and, in principle, arrayed sensors. An all-dielectric head perturbs the incident field less than a metallic antenna, and optical-domain outputs from multiple heads could be combined using fibre splitters and integrated phase shifters rather than an RF feed network. To date, multi-element and distributed demonstrations use simpler architectures,<sup>10–12</sup> so a fibre-combined dielectric array remains an open opportunity.

The principal cost is reduced phase stability, which arises from the topology of the wave-mixing loop rather than from the absence of a microwave oscillator. In conventional superheterodyne detection, probe and coupling fields each act twice in the loop and their phase noise cancels. In the all-optical loop used here, every field other than the probe acts only once, so laser phase fluctuations add and appear directly on the detected signal. Coherence has been recovered using nonlinear interferometry,<sup>7</sup> but this requires an additional nonlinear crystal, a separate reference arm, and an extra detection chain; moreover, the reference is derived from the blue field and therefore still presupposes the coupling laser.

## 2.4 The Obstacle

Both frontier architectures must stabilise three or four optical fields on distinct transitions (versus two in the baseline) and both retain the 480 nm coupling laser, because their wave-mixing loops close through the blue leg. The all-infrared ladder discussed in Sec. 3.3 removes blue light only for the baseline. The baseline can therefore trade the coupling laser for an additional lock, whereas the frontier schemes require both. Even in the baseline, this trade is not free: a third laser adds a frequency reference, control electronics, and another optical path.

## 3. MINIATURISING THE BASELINE: THE RYDAR PROOF OF CONCEPT

### 3.1 The Proof-of-concept Design

RYDAR (Rydberg Detector for Advanced RF Payloads) is an ESA-contracted project aimed at validating Rydberg RF sensing for space applications, targeting Technology Readiness Level 4. The proof-of-concept receiver was built around a Space Situational Awareness use case to provide concrete requirements. The architecture itself is application-agnostic, with anticipated competition in Earth observation, navigation, and telecommunications.

The receiver implements five modes within the two-laser baseline architecture: absolute field calibration, single-band superheterodyne detection, dual-band superheterodyne detection, polarisation sensing, and manually tunable coverage of the GNSS band. It is split into a Rack Module (lasers, locking electronics, and control hardware) and a fibre-linked Sensor Head Module containing the vapour cell (Fig. 1b,c). This partition matches an eventual flight instrument, where only the head must be located at the measurement point. However, the breadboard scale (Fig. 1a) highlights the remaining gap: about 126 kg including ground support equipment, and up to 540 W electrical demand, with the coupling laser alone accounting for 250 W.

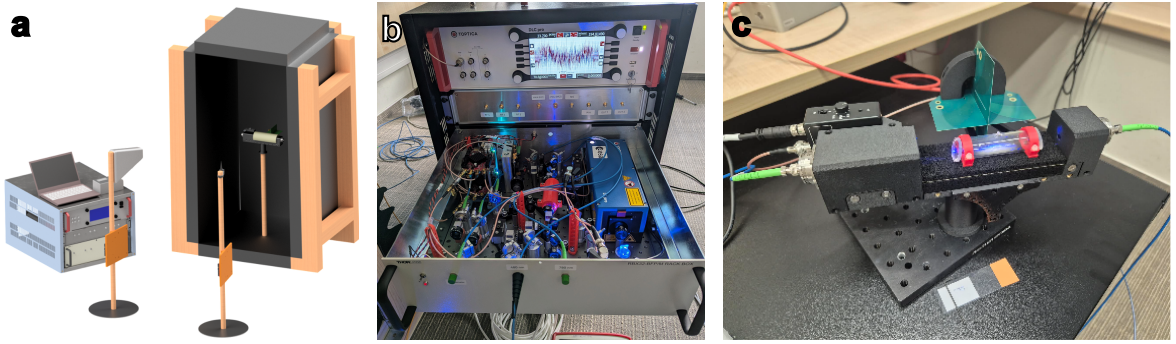


Figure 1. **a** The RYDAR proof-of-concept receiver in a testing scenario (design). A free-standing Rack Module provides laser generation, control, and readout processing, while a detached Sensor Head Module performs sensing in a controlled environment. **b** The Rack Module contains the laser systems and control electronics, including the coupling-laser controller. **c** The Sensor Head Module is connected by optical fibres and RF cables, so only the vapour cell and its optics must be placed at the measurement point.

### 3.2 Mature Elements: the Probe Chain and the Vapour Cell

The 780 nm branch is close to resolved. RYDAR uses a butterfly-packaged external-cavity diode laser with a compact driver, digitally stabilised on an FPGA platform, yielding a linewidth on the order of 100 kHz. Cavity- and comb-based locks were rejected for the breadboard due to cost and complexity. The literature indicates substantial headroom for further reduction: micro-integrated rubidium frequency references have been realised in 35 cm<sup>3</sup> at 73 g and 780 mW,<sup>13</sup> as a 12.4 × 10.4 × 3.1 cm<sup>3</sup> plug-and-play unit,<sup>14</sup> and as a two-photon reference of similar volume.<sup>15</sup> For qualification (rather than size), a mounted reference cavity in a transportable cavity-stabilised laser has reached TRL6 under vibration, shock, and radiation tests.<sup>16</sup>

On the sensor head side, fibre-coupled all-dielectric heads have been operated away from the optical table,<sup>17</sup> additively manufactured ceramic benches enable rigid micro-integrated physics packages,<sup>18</sup> and wafer-level fabrication has produced all-glass cells that avoid silicon-associated RF loss,<sup>19</sup> alongside MEMS glass-silicon-glass cells using high-resistivity silicon.<sup>20</sup>

### 3.3 The Limiting Component: the Coupling Laser

The main exception to this favourable picture is the coupling laser (480 nm in rubidium, 510 nm in caesium), referred to below as the blue laser. RYDAR baselines a full-size external-cavity diode laser, chosen over second-harmonic solutions because direct blue diodes offer straightforward tuning between Rydberg levels with lower SWaP-C. The deeper issue is ecosystem maturity: the required wavelength lies between established diode platforms (532 nm green and 405 nm violet). Although InGaN emitters in the blue-green have only recently exceeded 100 mW, no commercial source currently meets the combined space-driven requirements of power, compactness, low electrical demand, narrow linewidth, and long-term frequency stability.

Three routes exist, but none is complete. Injection locking a free-running blue diode with a low-power ECDL has produced 263 mW at a 591 kHz linewidth in a  $20 \times 21 \times 4 \text{ cm}^3$  package without nonlinear conversion,<sup>21</sup> but remains laboratory hardware. Second-harmonic generation from 960 nm in a nonlinear waveguide is attractive in principle because both the infrared seed and the waveguide can be compact and space-compatible; the present limitation is power handling, as state-of-the-art devices tolerate  $\sim 50 \text{ mW}$  and likely below 100 mW, short of the coupling-transition requirement. Finally, an all-infrared three-photon ladder avoids blue light: in rubidium, 780 nm is followed by 776 nm and  $\sim 1260 \text{ nm}$ , where 100 mW at 480 nm corresponds to about 9 mW at 1260 nm in Rabi frequency. This comparison concerns the final leg only (not a full power budget), but the margin is substantial.

The third route has two limitations. First, it benefits only the baseline, since the conversion and all-optical schemes close their wave-mixing loops through the blue transition. Second, it shifts the problem from a hard component to a hard system: three lasers must now be stabilised simultaneously. The closest demonstration is a photonic integrated platform in which a 780 nm laser was locked to an ultra-high- $Q$  silicon nitride resonator disciplined to the rubidium D2 line, the same resonator served as a transfer cavity for a 776 nm laser, and a third laser near 1270 nm was scanned rather than locked.<sup>22</sup>

## 4. PATHS FORWARD

### 4.1 Simultaneous Stabilisation of Several Lasers

Simultaneous stabilisation of multiple lasers is the pivotal system problem: it separates today's compact subsystems from an instrument-level receiver, and integrated photonics offers the most direct route.<sup>22</sup> A single chip-scale reference resonator, disciplined to an atomic transition and used as a transfer cavity, scales to three or four wavelengths more naturally than multiple independent locks, and it has already been shown at the wavelengths required by the all-infrared ladder. Other chip-scale spectroscopy and stabilisation platforms point in the same direction.<sup>23–25</sup> Extending such schemes to include the Rydberg laser is the natural next step.

### 4.2 The Coupling Laser

Near term, injection locking remains the most credible option for two-laser baseline instruments.<sup>21</sup> Waveguide second-harmonic generation becomes compelling once power handling improves, because it would generate blue light from an infrared source that is already space-compatible. For the baseline specifically, the all-infrared ladder circumvents the blue requirement at the cost of an additional lock. If extended tunability is not required (i.e., operation on a fixed Rydberg transition), the ideal component is a butterfly-packaged blue diode laser akin to mature 780 nm modules. Given recent InGaN progress, this is a realistic near-term objective and would remove the coupling laser as the dominant contributor to instrument volume and power.

### 4.3 Phase Stability of Multi-field Schemes

In multi-field schemes, laser phase noise is set by the wave-mixing loop: every field other than the probe enters once, so fluctuations add rather than cancel as in conventional superheterodyne detection. The impact is measurement-dependent. For phase-sensitive readout (e.g., coherent imaging or field reconstruction), coherence must be restored; for photon-counting radiometry it is largely irrelevant. For the phase-sensitive case, nonlinear interferometry is the demonstrated solution,<sup>7</sup> while locking several lasers to a shared optical frequency comb is a plausible alternative as integrated comb technology matures.<sup>26</sup>

#### 4.4 Ruggedisation and Packaging

Compactness and robustness are distinct, and the literature is stronger on the former. The vibration-insensitive cubic cavity qualified to TRL6 provides a benchmark for what ruggedisation entails in practice.<sup>16</sup> At the component level, adhesive bonding for micro-integrated optics has been qualified under thermal cycling and gamma dose via standardised shear testing,<sup>27</sup> and additively manufactured ceramic benches provide rigid, thermally stable mounts.<sup>18</sup> On the atomic side, wafer-level and MEMS cell fabrication offers the reproducibility that qualification campaigns presuppose.<sup>19,20,28</sup>

### 5. A WISHLIST FOR THE INDUSTRY

The recommendations, in general terms, are that compact laser sources, integrated control electronics, vapour-cell assemblies and ruggedised physics packages be developed, and that common performance benchmarks be agreed.<sup>1</sup> The experience gained in RYDAR suggests more specific requirements, ordered approximately according to the difference they would make.

1. **Blue and blue-green sources as products.** Compact and reliable lasers at 480 and 510 nm should be available as integration-ready subsystems rather than as laboratory instruments. Every architecture discussed in this paper depends on this component, and none of the alternatives to it is complete.
2. **Multi-laser stabilisation.** Locking systems should be designed from the outset to discipline three or four lasers simultaneously. This is the principal obstacle to a complete compact receiver, and it is at present addressed one laser at a time.
3. **Nonlinear waveguides with higher power handling.** Raising the optical power tolerated by such waveguides well above 100 mW would render second-harmonic generation a practical route to blue light and would reduce the dependence on direct blue diodes.
4. **Vapour cells as qualified components.** Wafer-scale, fully dielectric cells should be procurable against a specification rather than fabricated as prototypes for individual experiments.

### 6. CONCLUSIONS

No Rydberg receiver has yet been reported that is sufficiently compact and robust for flight, and this remains true even of the simplest architecture. The goal is attainable with current technology, but the coupling laser remains the limiting factor, and it constrains the baseline architecture as much as it does the more advanced schemes. For the baseline, the all-infrared three-photon ladder is the most practical means of circumventing it, since compact sources exist at all three wavelengths, yet with a missing stabilisation system covering all three.

Regarding the miniaturisation of the baseline architecture, the necessary components exist and their integration is the remaining step, which is an engineering statement rather than a physical one. The integration effort is necessary, since it is a precondition for the capabilities that would render Rydberg receivers distinctive in orbit: radiometry above 100 GHz by means of microwave-to-optical conversion, and coherent imaging with a reception pattern determined by the geometry of the optical beams, in a sensor head containing no metal. Solving the laser problem does not by itself guarantee these capabilities, but none of them is reachable without it.

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