

Rydberg Sensors for Advanced RF Payloads (RYDAR) project – from identifying key advantages of Rydberg sensors for Space Situational Awareness (SSA) to results of prototype test campaign

Sebastian Borówka^{a,b}, Mateusz Mazelanik^{a,b}, Michał Parniak^{a,b}, Marcin Jastrzębski^a, Bartosz Kasza^a, Wiktor Krokosz^a, Bartosz Niewelt^a, Jan Nowosielski^a, Mattia Verducci^c, and Tommaso Catuogno^c

^aUniversity of Warsaw, Banacha 2c, 02-097 Warsaw, Poland

^bQuRA.space sp. z o.o., Warsaw, Poland

^cThales Alenia Space Italia S.p.A., Rome, Italy

ABSTRACT

Rydberg atomic RF sensors are a developing quantum technology, leveraging the properties of alkali atom vapours for a sensitive, tunable and self-calibrated detection of RF fields – from sub-Hz to THz domain. Here we focus on the developments achieved in the RYDAR project, where we developed a working mobile prototype of a Rydberg sensor targeted at Space Situational Awareness application. The objective was to demonstrate with a single sensor simultaneous detection in two distant RF bands – a 1.18 GHz simulating signal in Galileo E5a band, and 20.6 GHz simulating an unknown signal to be determined. We conducted a test campaign to find the key performance indices judging the suitability of the technology for the chosen application. Additionally, while the registered RF fields strength can be traced to SI units, some properties of Rydberg sensors, such as sensitivity, cannot be simply determined from theoretical calculations due to many interaction effects present in atomic vapours. The test campaign helped determining these properties to successfully model the behaviour of the prototype in other applications.

Keywords: Rydberg atoms, atomic antenna, microwave sensing, Space Situational Awareness

1. INTRODUCTION

Rydberg atomic radio frequency (RF) sensors are a developing quantum technology, leveraging the properties of alkali atom vapours for a sensitive, tunable and self-calibrated detection of RF fields – from sub-Hz to THz domain. The key component of a Rydberg sensor is a vapour cell containing a gas of alkali atoms. With the use of two or more lasers, the atoms are excited to a very high energy level, one of the so-called Rydberg levels. There, the atomic medium becomes very sensitive to RF fields, as the transitions between the Rydberg levels are in the RF domain. The choice of the transition to be addressed is determined by frequency detuning of the lasers, while on the other hand the transition corresponds to a certain chosen part of the RF spectrum. This means that with laser detuning a single sensor can selectively cover the whole of RF spectrum in a semi-continuous manner.¹ What is more, often times several frequencies can be addressed simultaneously by utilising multiple transitions.² As the strengths of the transitions are determined by the unchanging properties of atoms, determined by the laws of quantum mechanics, the RF fields registered that way can be traceably calibrated to SI units.³ Such property eliminates the need for external calibration and recalibration for Rydberg sensors. For these reasons, as well as the promise of all-optical operation, Rydberg sensors were considered for various RF applications,^{4,5} including space missions^{6,7} and dual-use.⁸

Further author information: (Send correspondence to S.B.)

S.B.: E-mail: s.borowka@cent.uw.edu.pl, sborowka@qura.space

QuRA.space: E-mail: info@qura.space, Website: <https://qura.space>

The “RYDAR: Rydberg Detector for Advanced RF Payloads” project was realised in response to ESA “Development of Quantum Microwave Sensors for RF Payloads” ITT by a joint consortium of UWRC sp. z o.o. (University of Warsaw SPV) and Thales Alenia Space Italia S.p.A. with an objective to assess Rydberg sensing technology, choose a target application, and design, construct and test a prototype sensor for this application. The project focused on the Space Situational Awareness (SSA), taking advantage of the unique capability of Rydberg sensors to simultaneously detect two spectrally different RFs, here considered as a Galileo satellite signal and an unknown signal to be identified.

Here we present the results of test campaign conducted on the mobile prototype demonstrator developed and built in the RYDAR project. We focus on its capability to detect 0.85–1.18 GHz and 20.64 GHz fields, both in a Single Signal Scenario and simultaneously in Multiple Signal Scenario. Additionally, we present the analysis of spatial and polarisational capabilities of the prototype, as well as the capability to discern the linear polarisation of an incoming signal.

2. PRINCIPLE OF OPERATION

The operating architecture of the Rydberg microwave sensor is that of a RF mixer,^{9,10} sometimes referred to as superheterodyne,¹¹ in an analogue to classical superheterodyne receivers. We focus two frequency-stabilised laser beams – a 780 nm laser and a 480 nm laser – inside a rubidium-87 vapour cell, in a counter-propagating geometry. To facilitate frequency mixing, we utilise local oscillator (LO) RF field on the energy transition of interest, as well as an auxiliary (AUX) field to access one of the RF transitions. The parts of the rubidium energy level structure are presented in Fig. 1. The **a** configuration is utilised in Single Signal Scenario tests, where only one transition of interest – NAV at 0.85 GHz and DATA at 20.64 GHz – is addressed at a time. The **b** configuration is utilised in Multiple Signal Scenario tests, where both of the transitions are addressed – NAV at 1.18 GHz and DATA at 20.64 GHz.

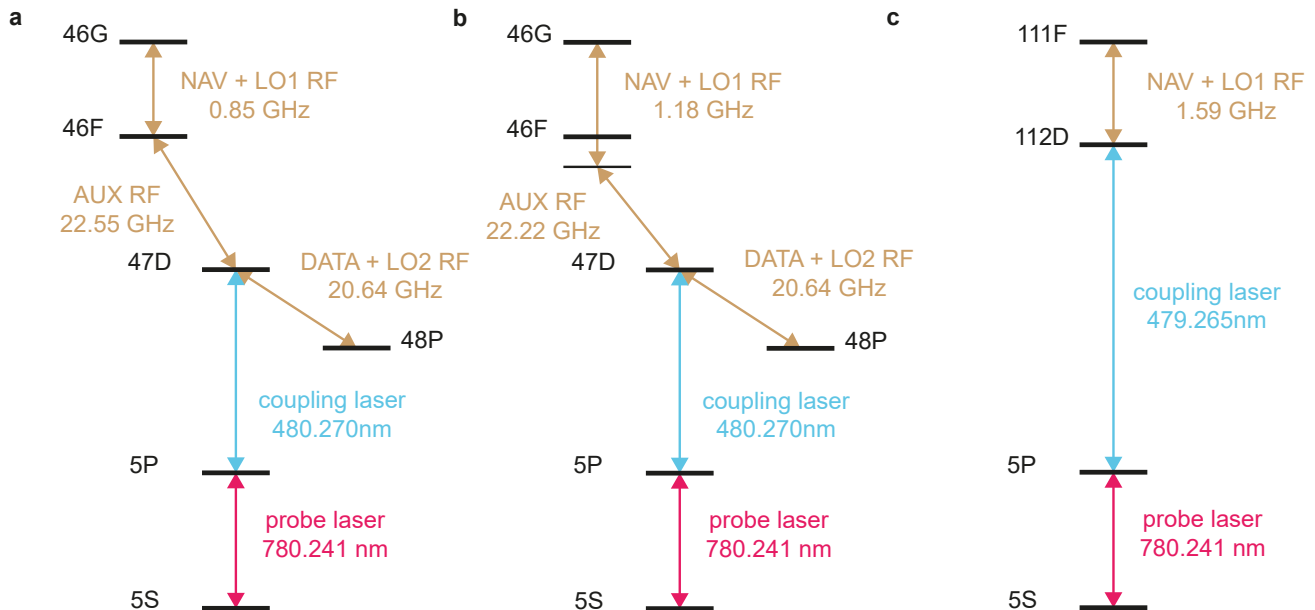


Figure 1. Energy level structure of rubidium utilised in the RYDAR project. **a**, A configuration enabling simultaneous detection of low frequency NAV signal and high frequency DATA signal. **b**, A second similar configuration, where the AUX field was detuned for the NAV frequency to match the Galileo E5a band. **c**, An alternative configuration, where the coupling laser is detuned to a different energy level to address a different transition corresponding to the Galileo E1 band.

We have constructed a working mobile prototype capable of generating the required laser and RF fields, and detect the incoming signal fields. The design of the prototype involves a Rack Module pictured in Fig. 2 **left** – consisting of Laser Submodule and Electronics Submodule – as well as Sensor Head Module, pictured in

Fig. 2 **left**, standing at the top. The modules are connected with optical fibres and RF cables, thus enabling the delivery of the required laser and RF fields to the vapour cell inside the Sensor Head Module. The sensor is capable of detecting continuous wave (CW), pulsed and modulated fields with full phase retrieval capability, at both NAV and DATA frequencies, by registering the transition of probe field the atomic medium, and performing Fourier transform to analyse the beating signal. An additional capability enables the retrieval of polarisation of DATA field.

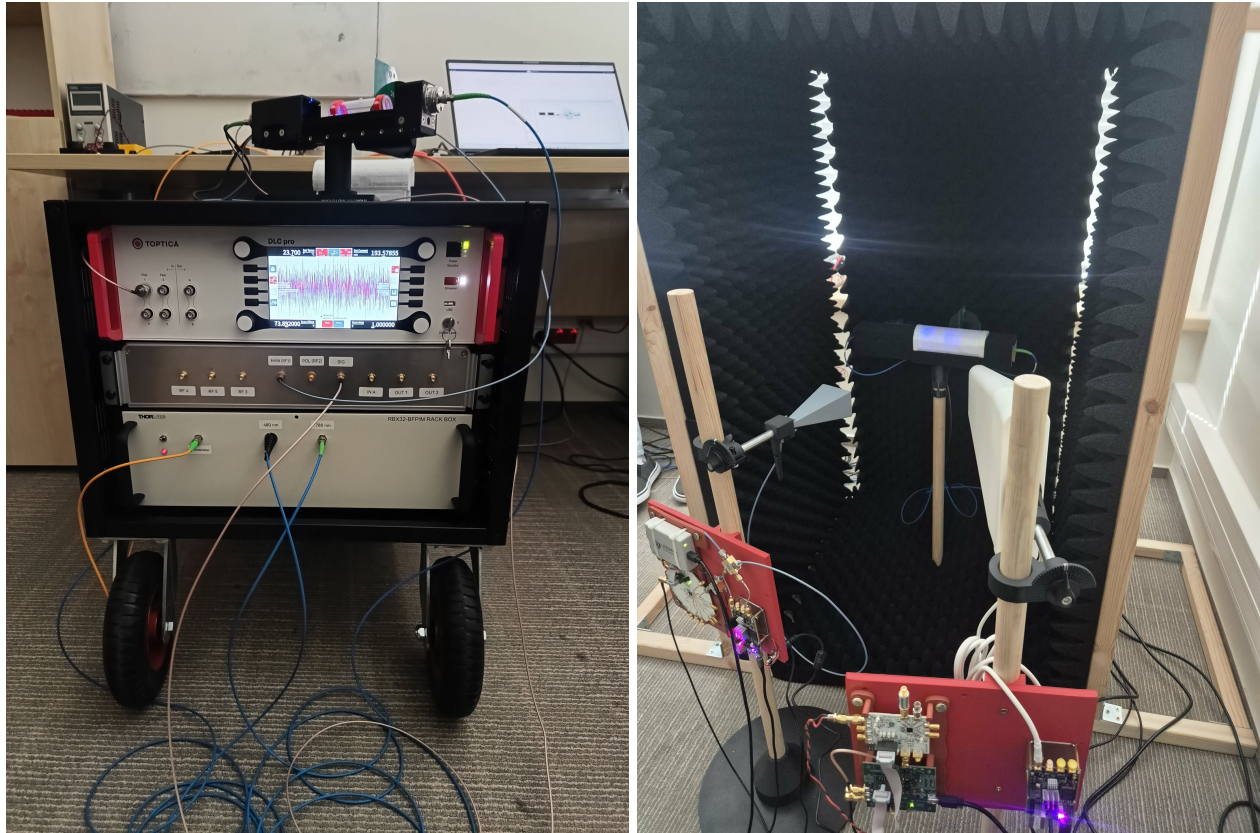


Figure 2. **left**, The Rack Module, containing Laser Submodules and Electronics Submodule, contained in standard 9U 19" rack compartment with enabled mobility. The fibre-connected Sensor Head Module can be seen on the top of Rack Module. **right**, The Sensor Head Module inside an anechoic box in a configuration for the testing of Multiple Signal Scenario. NAV and DATA antennas can be seen outside of the anechoic box as parts of Testing Subsystem.

The test campaign was conducted in an office environment to demonstrate the capability of the prototype to operate in less stringent conditions than in a laboratory environment. However, for testing the Sensor Head was placed inside an anechoic box to negate possible reflections. The testing environment is pictured in Fig. 2 **right**.

3. RESULTS

3.1 Single Signal Scenario – NAV

The first part of test campaign involved a detection of CW NAV signal with tunable frequency and power to obtain the reception bandwidth and dynamic range of the sensor - from atomic saturation to the noise level. The results are presented in Fig. 3.

The next test involved a detection and retrieval of BPSK encoded signal at NAV frequency. The bit-error rate (BER) from the retrieval can be then derived directly or estimated from the widths of constellation diagram to consider the achievable performance enhancement when error-correction is applied. The results are presented in Fig. 4.

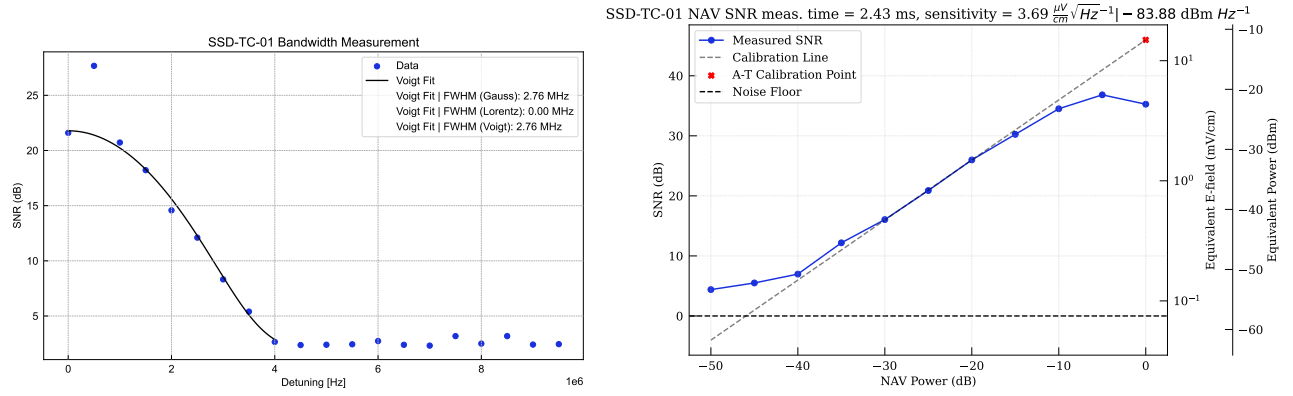


Figure 3. **left**, The measurement of bandwidth response for the NAV signal. **right**, The measurement of dynamic range response for the NAV signal.

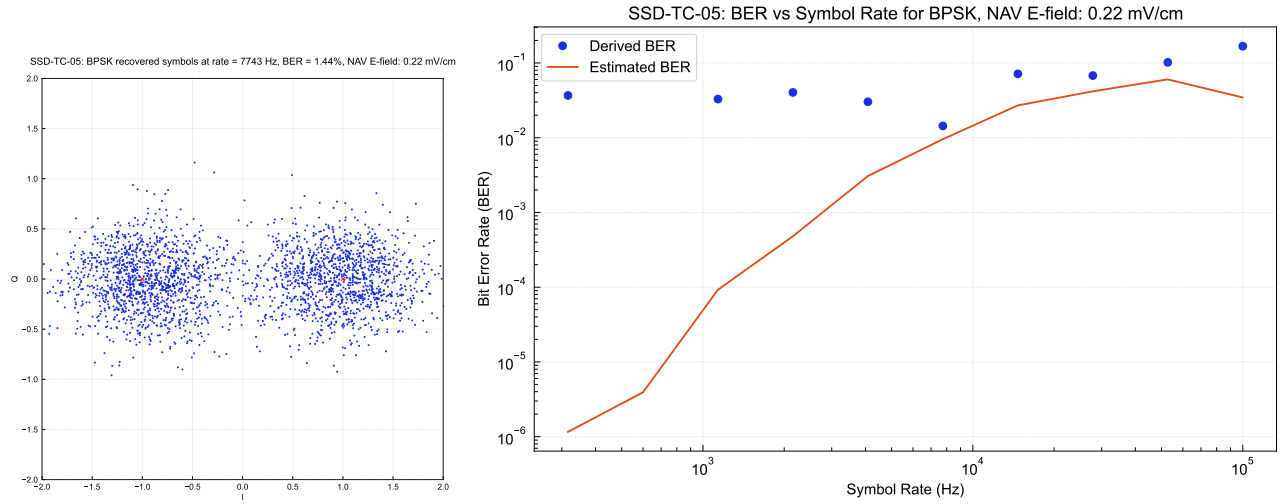


Figure 4. **left** The constellation diagram for BPSK modulated NAV signal reception. **right** The bit-error rate, both directly derived and estimated for BPSK modulated NAV signal reception.

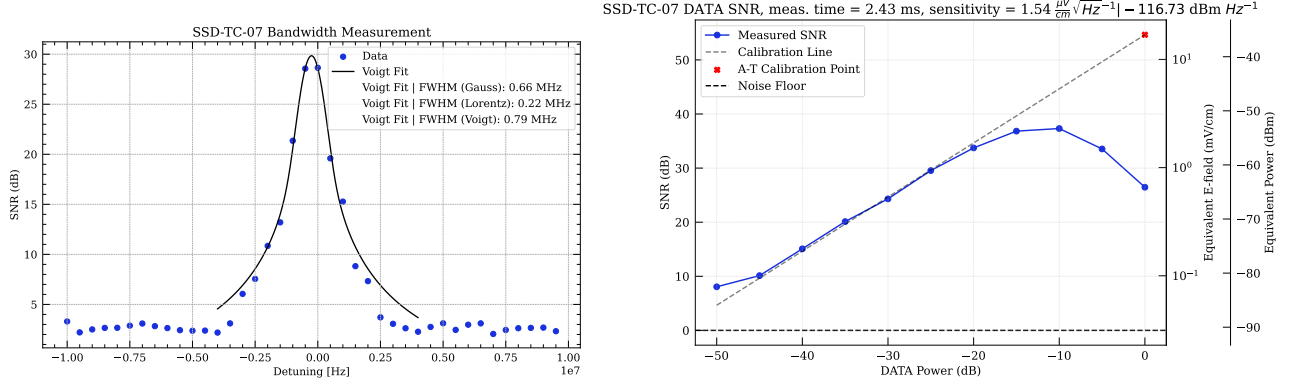


Figure 5. **left**, The measurement of bandwidth response for the DATA signal. **right**, The measurement of dynamic range response for the DATA signal.

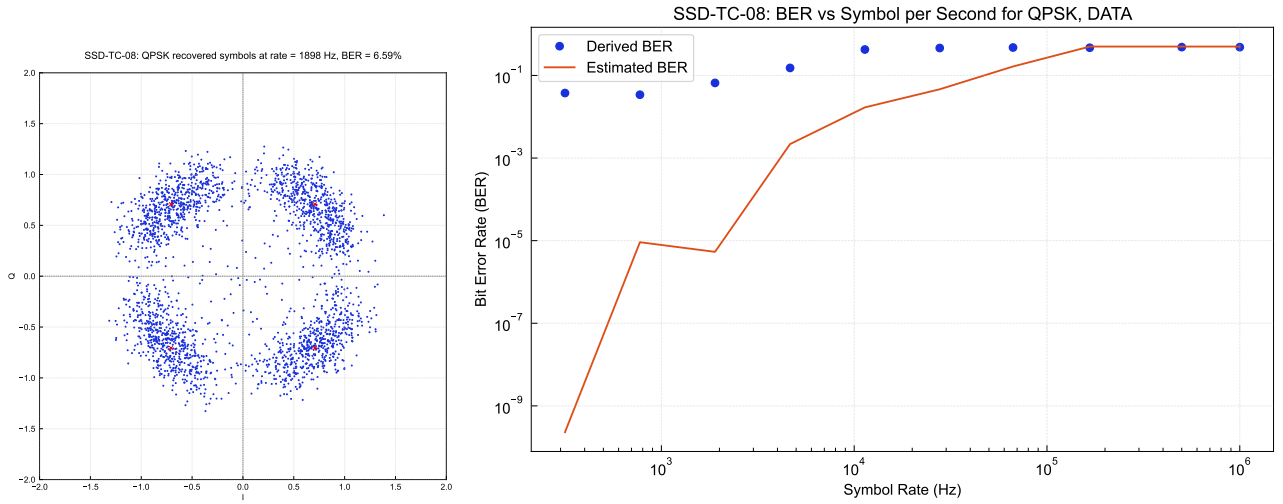


Figure 6. **left** The constellation diagram for QPSK modulated DATA signal reception. **right** The bit-error rate, both directly derived and estimated for QPSK modulated DATA signal reception.

3.2 Single Signal Scenario – DATA

Similar tests were repeated for DATA frequency. The measurement of bandwidth and dynamic range is presented in Fig. 5, while the reception of QPSK signal at DATA frequency is presented in Fig. 6.

3.3 Multiple Signal Scenario

In the next part of testing campaign we checked the capability of the sensor to simultaneously detect NAV and DATA frequencies, which correspond to the SSA application of detecting and positioning an unknown signal in relation to a known Galileo satellite signal. The results, detailing the bandwidths for NAV and DATA frequencies, as well as the simultaneous detection and demodulation of modulated signals is presented in Fig. 7.

3.4 Signal reception at various directions and polarisations

In an auxiliary test, the reception pattern of sensor was measured by rotating the sensor for a known angle. The results are presented in Fig. 8 **left**. Furthermore, we conducted a test to measure the sensitivity to various linear polarisations by rotating the NAV and DATA antennas. The results are presented in Fig. 8 **right**.

3.5 Detection of polarisation angle

In a separate tests, we enabled two cross-polarised LO fields at the DATA transition, which allowed us the discrimination between different linear polarisations of DATA signal field, with mirror symmetry.¹² We present

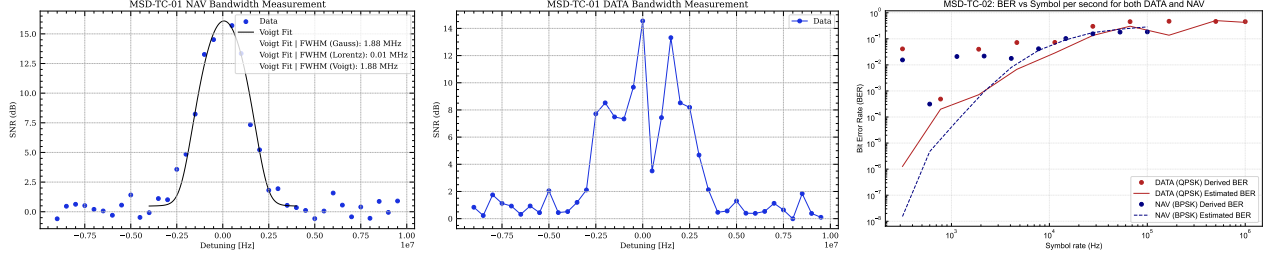


Figure 7. **left**, The measurement of bandwidth response for the NAV signal in the Multiple Signal Scenario. **centre**, The measurement of bandwidth response for the DATA signal in the Multiple Signal Scenario. **right**, The bit-error rates, both directly derived and estimated for modulated NAV and DATA signal reception in the Multiple Signal Scenario.

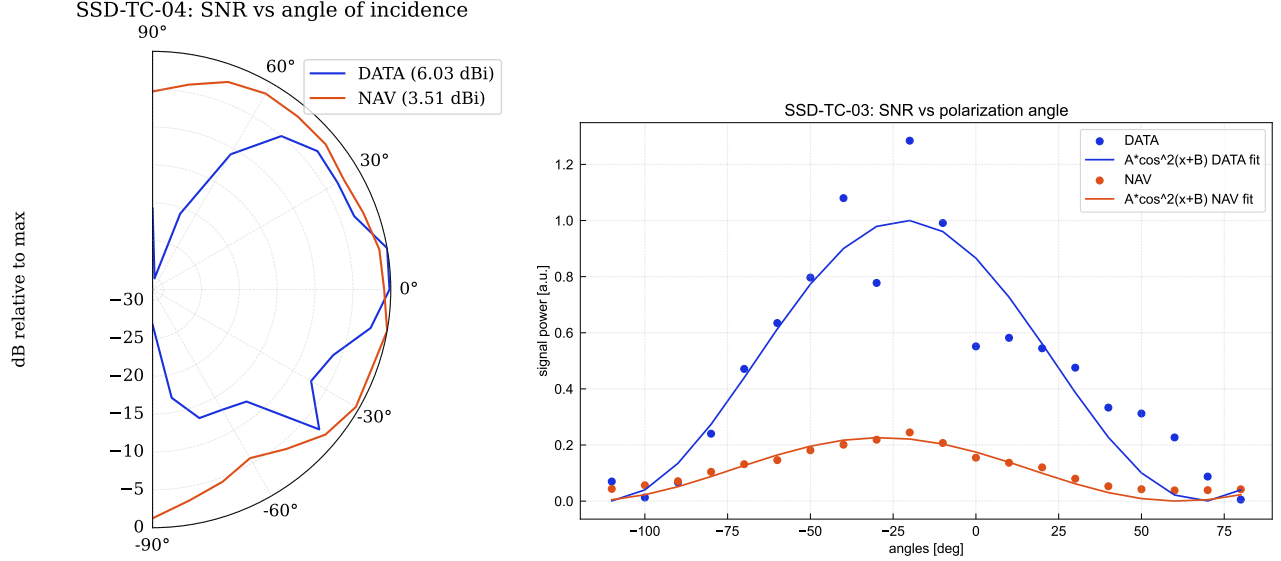


Figure 8. **left**, The antenna reception pattern measured by rotation of the sensor in relation to NAV and DATA signal sources. **right**, The reception of linear polarisation measure by rotation of the NAV and DATA antennas.

the raw results of detecting various polarisation in Fig. 9 **left**, while in Fig. 9 **right** we show the difference between the set angle and measured angle of polarisation, to estimate the possible range for errors.

4. SUMMARY AND DISCUSSION

The presented comprehensive results achieve two objectives. Firstly, they demonstrate unique capabilities of Rydberg sensors in an advanced prototype, moving the Technology Readiness Level (TRL) to targeted 3–4, from laboratory environment to a mobile demonstrator. Secondly, a set of parameters is obtained, including bandwidths, sensitivity levels and BER. These parameters may lead further development of Rydberg sensors for RF payloads.

Some improvements are still possible in the demonstrated system. A technological challenge of developing a miniaturised 480 nm laser currently prohibits significant reduction of SWaP-C. We also anticipate that further optimisation of laser power and field geometry is possible to obtain significantly better sensitivity and bandwidths. Nevertheless, the overall results can be considered successful, given the limited time frame of the project.

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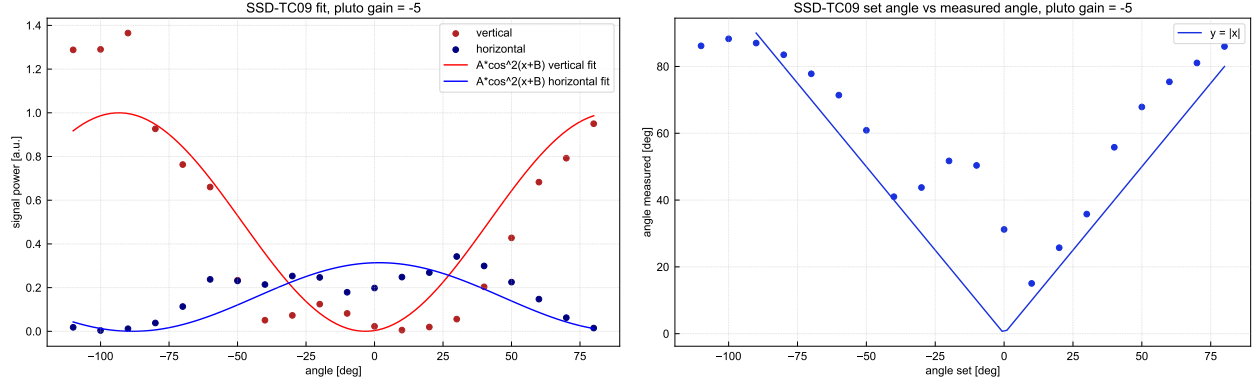


Figure 9. **left**, The results of detection of set polarisation angle, presented for vertical and horizontal readouts. **right**, The calculated readout presenting set angle vs. detected angle of polarisation.

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