

# Atom Camera: Super-resolution scanning microscope of a light pattern with a single ultracold atom

Corresponding Author: Dr Takafumi Tomita

**This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.**

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The authors have clarified several points raised in the previous round of review and have mentioned the potential application of their technique for probing light fields using atoms in an optical tweezer. After reading the revised manuscript, citations, and the authors' responses, I now have a clearer picture of the intended scope of this atom-based microscopy. However, this clarification raises significant concerns regarding the central claims of the work.

## 1. Use of the term "super-resolution"

The term super-resolution refers to imaging that surpasses the diffraction limit of the optical field, where the resolution is fundamentally set by the wavelength. In the present work, atoms are used as local probes of a light field, and the standard spatial resolution is determined by the spatial extent of the atomic wavefunction (or equivalently the de Broglie wavelength), which is on the order of nanometers. It is therefore inappropriate to compare this resolution to the optical wavelength or to claim that the technique overcomes the optical diffraction limit.

This situation is analogous to AFM-based optical probes or nanoparticle-based near-field imaging, where sub-wavelength resolution is run-of-the-mill because the probe itself is nanometric. Such techniques are properly described as sub-optical wavelength imaging, but not as super-resolution methods, since they do not overcome a diffraction limit associated with optical propagation. The terminology used in the manuscript is therefore misleading and should be revised.

## 2. Comparison with existing sub-micron optical imaging techniques.

As noted by Reviewers, when compared with established sub-micron imaging methods such as SNOM, AFM-based techniques, NV-center probes, nanoparticle scattering, and electron-based microscopy the optical tweezer approach suffers from several disadvantages that are not adequately addressed:

### A. Spatial resolution.

The effective "tip size" of a single atom in a tweezer, set by the spatial extent of its wavefunction (tens to 100 nanometers), is substantially larger than the probe size achievable with many solid-state tips, and is also large compared to the electron wavelength used in electron microscopy. As a result, the attainable spatial resolution is comparatively limited.

### B. Spectral bandwidth.

Atoms in optical tweezers are sensitive primarily to near-resonant optical fields and rapidly lose sensitivity for far-off-resonant light fields. In contrast, many solid-state probes offer broadband spectral response and are therefore applicable to a much wider range of optical fields.

### C. Imaging speed.

From the manuscript, scanning a single atom through an optical field is inherently very slow. This limitation is not sufficiently discussed or compared with alternative approaches, such as solid-state scanning probes, NV centers, or electron-based methods, which can achieve orders-of-magnitude faster acquisition and refreshing rates.

### D. Probe robustness.

Atoms in optical tweezers are susceptible to loss and heating during probing. Once the atom is lost or its internal state is altered, it is difficult, if not impossible, to restore the probe to its initial quantum state and continue scanning seamlessly. This

significantly limits the practicality of extended imaging.

### 3. Potential advantages of single-atom tweezer probes.

While the manuscript emphasizes resolution, it does not clearly articulate the genuine strengths of atom-based probes relative to competing techniques. If properly framed, several unique advantages could be highlighted:

#### A. Minimal invasiveness.

A single atom perturbs the optical field far less than macroscopic or solid-state probes, potentially enabling minimally invasive, three-dimensional mapping of optical fields.

#### B. Quantum sensing capabilities.

Atoms offer access to phase-sensitive and mode-selective measurements through coherent quantum control, capabilities that are difficult or impossible to achieve with conventional solid-state probes.

#### C. Multimodal sensing.

Atomic internal states provide simultaneous sensitivity to optical, electric, and magnetic fields, enabling simultaneous multifunctional sensing within a single platform.

These potential advantages, are examples that can be developed or discussed in the manuscript to improve the significance of the manuscript.

In conclusion, the manuscript should provide a compelling case for the claimed significance of “tweezer-based sub-micron microscopy” relative to standard methods on the market. A fair and quantitative comparison is missing, and the unique capabilities of atoms in optical tweezers are not clearly distinguished from competing platforms. As a result, I find that the work, in its current form, still lacks the level of fundamental impact or broad significance required for publication in Nature Communications.

### Reviewer #2

#### (Remarks to the Author)

I would like to thank the authors for their thorough review of the manuscript and for addressing all of the comments raised by the other referees and me. I think the authors have clarified the relevant points and significantly improved the manuscript. I recommend the paper for publication essentially as is. I still believe that the work represents a beautiful example of single-atom-based sensing, which is an important result that is certainly of interest to the expert readership of Nature Communications.

One final comment: I think there is a small typo in the caption of Fig. 2 f, where quantum projection noise is shown in the right panel (not left) and data and background are compared in the left panel (not right).

### Reviewer #3

#### (Remarks to the Author)

I have reviewed the authors' reply and revision submitted to Nature communications. The authors have addressed my major comments on the applicability of this method to general cases regarding full characterization of the electric field polarization, and have made amendments and discussions on the limitations of this technique. Overall, I am satisfied with what was discussed in the text. It is well written and the data looks convincing. The manuscript reports an experimental advancement that is particularly useful for cold atoms in tight optical traps which have gathered significant attention in recent years for quantum computations, simulations and sensing. The authors demonstrate both scalar and fictitious field sensing down to an impressive 25nm resolution - a significant improvement with added novelty compared with previous cold atom experiments. In the revised text, the authors have properly acknowledged prior works and have compared their experiment with other material platforms. I also agree with the authors that the demonstrated single atom sensor, albeit more fragile and difficult to prepare in the first place, directly measures the optical field, in vacuum, without the unavoidable material disturbance presented in other solid state platforms or nanoscale probes. This work presents a complementary scheme for applications in quantum science. Given the potential impact in the field and the novelty of the demonstration, I recommend publication of this manuscript in Nature communications.

### Version 1:

#### Reviewer comments:

### Reviewer #1

#### (Remarks to the Author)

Dear Editor,

I have carefully read the authors' revised manuscript and their detailed responses to my previous report. I appreciate the thorough manner in which they have addressed the concerns raised.

In particular, the authors have clarified the scope and positioning of their technique, revised the terminology surrounding

“super-resolution” to avoid potential misinterpretation, and added appropriate discussion comparing their approach with existing sub-wavelength imaging methods. I find their revised framing much clearer and more balanced.

The additional discussion of limitations (spatial resolution, spectral bandwidth, and imaging speed) as well as the clarification of probe robustness significantly improves the manuscript. I also appreciate the expanded discussion of the unique advantages of atom-based probes, including minimal invasiveness and potential extensions toward quantum and multimodal sensing.

Overall, these revisions have substantially strengthened the manuscript and addressed my previous concerns. I now believe the work presents a meaningful and well-contextualized contribution. I therefore recommend publication.

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We would like to thank all the reviewers for their careful reading and reports. We have carefully considered all the points raised and substantially revised the manuscript accordingly. We believe that the revised version will now be suitable for publication in *Nature Communications*.

Below we provide a detailed, point-by-point response to the reviewers' comments. All revisions are summarized at the end of this document ("List of revisions").

#### Reviewer #1:

The authors have clarified several points raised in the previous round of review and have mentioned the potential application of their technique for probing light fields using atoms in an optical tweezer. After reading the revised manuscript, citations, and the authors' responses, I now have a clearer picture of the intended scope of this atom-based microscopy. However, this clarification raises significant concerns regarding the central claims of the work.

##### 1. Use of the term "super-resolution"

The term super-resolution refers to imaging that surpasses the diffraction limit of the optical field, where the resolution is fundamentally set by the wavelength. In the present work, atoms are used as local probes of a light field, and the standard spatial resolution is determined by the spatial extent of the atomic wavefunction (or equivalently the de Broglie wavelength), which is on the order of nanometers. It is therefore inappropriate to compare this resolution to the optical wavelength or to claim that the technique overcomes the optical diffraction limit.

This situation is analogous to AFM-based optical probes or nanoparticle-based near-field imaging, where sub-wavelength resolution is run-of-the-mill because the probe itself is nanometric. Such techniques are properly described as sub-optical wavelength imaging, but not as super-resolution methods, since they do not overcome a diffraction limit associated with optical propagation. The terminology used in the manuscript is therefore misleading and should be revised.

We thank the reviewer for pointing out this important point regarding this terminology. Indeed we agree that, in our approach, the ultimate spatial resolution is determined by the spatial extent of the atomic probe within the sub-wavelength scale.

At the same time, we note that the present measurement system is constructed with far-field optical elements (such as an objective lens) and laser field (Fig. 1), motivating us to use the term "super-resolution". We also note that the term "super-resolution" has been used to describe similar imaging beyond the diffraction limit, even when the resolution is determined by the size of a probe (e.g., *Nature* **237**, 510 (1972); *PRL* **128**, 083201 (2022)).

We have therefore revised “super-resolution imaging” to “super-resolution (sub-wavelength) imaging”.

The revisions are summarized at the end of this document (“List of revisions”).

## 2. Comparison with existing sub-micron optical imaging techniques.

As noted by Reviewers, when compared with established sub-micron imaging methods such as SNOM, AFM-based techniques, NV-center probes, nanoparticle scattering, and electron-based microscopy the optical tweezer approach suffers from several disadvantages that are not adequately addressed:

### A. Spatial resolution.

The effective “tip size” of a single atom in a tweezer, set by the spatial extent of its wavefunction (tens to 100 nanometers), is substantially larger than the probe size achievable with many solid-state tips, and is also large compared to the electron wavelength used in electron microscopy. As a result, the attainable spatial resolution is comparatively limited.

We thank the reviewer for this comment. We agree that the size of the atomic probe is larger than that achievable with solid-state tips. To clarify this point, we have added a sentence in the Discussion section of the main text, while also mentioning that it is not a limiting factor for our sub-wavelength imaging.

(The corresponding revisions are described in the response to point C.)

### B. Spectral bandwidth.

Atoms in optical tweezers are sensitive primarily to near-resonant optical fields and rapidly lose sensitivity for far-off-resonant light fields. In contrast, many solid-state probes offer broadband spectral response and are therefore applicable to a much wider range of optical fields.

We thank the reviewer for this important comment regarding spectral bandwidth. We agree that atoms are intrinsically sensitive only within a limited spectral range around specific atomic transitions and thereby less versatile than broadband solid-state probes. However, in cold-atom applications such as quantum simulation and quantum computation, the relevant optical fields that we aim to image are inherently close to the atomic resonances. The spectrally selective response of atomic probes is therefore not a practical limitation in this field of application. We have clarified this point in the revised manuscript.

(The corresponding revisions are described in the response to point C.)

### C. Imaging speed.

From the manuscript, scanning a single atom through an optical field is inherently very slow. This limitation is not sufficiently discussed or compared with alternative approaches, such as solid-state scanning probes, NV centers, or electron-based methods, which can achieve orders-of-magnitude faster acquisition and refreshing rates.

We thank the reviewer for this comment regarding imaging speed. We agree that the present implementation require longer acquisition times than solid-state or electron-based techniques. In cold-atom experiments, however, the optical fields are typically stable and do not require rapid refreshing, making this timescale acceptable with practical needs. Future improvements, such as parallelization or optimized readout protocols (discussed in the Discussion part), may significantly reduce the imaging time.

To address the points A-C, we have added sentences in the Discussion part as follows:

- The atomic probe is larger than solid-state tips, intrinsically spectrally selective around specific atomic transitions, and requires longer data acquisition times due to sequential scanning. The achievable spatial resolution is still well below the optical wavelength that determines the characteristic spatial scale of the light-field structure. While the spectral selectivity limits its applicability to broadband imaging, this method is well suited to cold-atom applications, where the relevant optical fields we aim to image are inherently close to the atomic resonances.

#### D. Probe robustness.

Atoms in optical tweezers are susceptible to loss and heating during probing. Once the atom is lost or its internal state is altered, it is difficult, if not impossible, to restore the probe to its initial quantum state and continue scanning seamlessly. This significantly limits the practicality of extended imaging.

We thank the reviewer for this important comment. We agree that, in general, atoms in optical tweezers can be susceptible to loss or heating. However, under our experimental conditions, these effects are not practical limitations.

The loss timescale (i.e., vacuum limited lifetime) is on the order of minutes, which is sufficiently longer than the measurement timescale of 200 ms for one experimental shot. We have added a sentence in the Methods section to clarify it:

- Atom loss is negligible, given the minute-scale trap lifetime.

The dominant sources of heating are photon scattering from the tweezer light and the potential change induced by ramping up/down the light pattern during the Ramsey interrogation. Since the tweezer light is sufficiently detuned from the atomic resonance, the scattering time scale is on the order of a second, which is much longer than the Ramsey interrogation time of 40 ms (i.e., the time during which the atom interacts with the light pattern). Also, the target light is linearly ramped up and down in 1 ms to minimize the heating of the probe atom, with the trap frequency of  $\omega \simeq 2\pi \times 100$  kHz

ensuring the adiabaticity. We have added a sentence in the Methods section to clarify these points:

- The timescale of photon scattering is on the order of a second, much longer than the 40 ms Ramsey interrogation time, and thus heating due to scattering is negligible.
- (added the underlined part) The target light is linearly ramped up and down in 1 ms to minimize the heating of the probe atom (the trap frequency  $\omega \simeq 2\pi \times 100$  kHz).

The relevant timescale for the state change should be compared with the coherence time. The Ramsey interrogation time (40 ms) is chosen to be sufficiently shorter than the coherence time ( $T_2 > 100$  ms). The spin relaxation timescale  $T_1$  is even longer than  $T_2$ , further ensuring robustness of the probe state during interrogation. We have revised the sentence in the Methods section to mention it:

- The Ramsey interferometer is completed well within both the coherence time of the clock transition ( $T_2^{\text{XY4}} > 100$  ms) and the spin relaxation time ( $T_1$  on the order of seconds).

### 3. Potential advantages of single-atom tweezer probes.

While the manuscript emphasizes resolution, it does not clearly articulate the genuine strengths of atom-based probes relative to competing techniques. If properly framed, several unique advantages could be highlighted:

#### A. Minimal invasiveness.

A single atom perturbs the optical field far less than macroscopic or solid-state probes, potentially enabling minimally invasive, three-dimensional mapping of optical fields.

We thank the reviewer for highlighting this aspect. We agree that minimal invasiveness is a key advantage of our approach. This is already stated in the 2<sup>nd</sup> paragraph of the Discussion part of the main text in the context of the comparison from the solid-state system:

- Unlike SNOM-like approaches employing a tapered optical fiber, our single-atom technique does not require any solid interface, ensuring non-perturbative imaging of nanoscale optical fields, although its application is naturally restricted to environments compatible with a cold-atom system.

Also, the possible extension of this technique to the three-dimensional mapping is mentioned in the 5<sup>th</sup> paragraph of the Discussion part of the main text:

- The technique can also be extended to image three-dimensional light patterns by scanning the atom along the optical axis using a holographic Fresnel lens.

#### B. Quantum sensing capabilities.

Atoms offer access to phase-sensitive and mode-selective measurements through coherent quantum control, capabilities that are difficult or impossible to achieve with conventional solid-state probes.

### C. Multimodal sensing.

Atomic internal states provide simultaneous sensitivity to optical, electric, and magnetic fields, enabling simultaneous multifunctional sensing within a single platform.

These potential advantages, are examples that can be developed or discussed in the manuscript to improve the significance of the manuscript.

We thank the reviewer for highlighting the potential advantages of our approach.

Regarding quantum sensing capabilities (B), we note that some degree of mode selectivity is demonstrated in the present work: our measurement selectively probes specific polarization modes depending on the transitions, though limited to extracting the ellipticity. As discussed in the manuscript, the current implementation does not provide sensitivity to the relative optical phase of different spatial modes, which remains an interesting direction for future work.

Regarding multimodal sensing (C), the stretched transition is sensitive to real magnetic fields, enabling magnetic-field sensing within the same platform. Extensions to Rydberg states would additionally allow sensing of static electric fields via DC Stark shifts, as demonstrated in single-atom tweezer experiments (e.g., Nat. Phys. **10**, 914 (2014), Nat. Phys. **20**, 1744 (2024)). These capabilities extend the functionality of single-atom probes beyond optical imaging.

To emphasize these points, we have added sentences in the Discussion part of the main text:

- Furthermore, the internal structure of the atom provides transition-dependent mode selectivity. The stretched transition is sensitive not only to the fictitious magnetic field associated with circular polarization but also to real magnetic fields, enabling magnetic-field sensing within the same platform. Extension to Rydberg states would additionally allow sensing of static electric fields via DC Stark shifts [Ravets et al., Nat. Phys. **10**, 914 (2014), Anand et al., Nat. Phys. **20**, 1744 (2024)]. These capabilities extend the functionality of single-atom probes beyond optical imaging.

In conclusion, the manuscript should provide a compelling case for the claimed significance of “tweezer-based sub-micron microscopy” relative to standard methods on the market. A fair and quantitative comparison is missing, and the unique capabilities of atoms in optical tweezers are not clearly distinguished from competing platforms. As a result, I find that the work, in its current form, still lacks the level of fundamental impact or broad significance required for publication in Nature Communications.

We thank the reviewer for the comprehensive assessment of the significance and positioning of our work. We have carefully considered these points and substantially revised the manuscript accordingly. We hope that these revisions more clearly convey the

significance of our platform and its distinct role within the broader landscape of optical imaging and quantum sensing platforms.

**Reviewer #2:**

I would like to thank the authors for their thorough review of the manuscript and for addressing all of the comments raised by the other referees and me. I think the authors have clarified the relevant points and significantly improved the manuscript.

I recommend the paper for publication essentially as is. I still believe that the work represents a beautiful example of single-atom-based sensing, which is an important result that is certainly of interest to the expert readership of Nature Communications.

One final comment: I think there is a small typo in the caption of Fig. 2 f, where quantum projection noise is shown in the right panel (not left) and data and background are compared in the left panel (not right).

We thank the reviewer for the positive assessment and for the careful reading of the revised manuscript. Regarding the typo in the caption of Fig. 2f, we have corrected the labeling as pointed out.

**Reviewer #3:**

I have reviewed the authors' reply and revision submitted to Nature communications. The authors have addressed my major comments on the applicability of this method to general cases regarding full characterization of the electric field polarization, and have made amendments and discussions on the limitations of this technique. Overall, I am satisfied with what was discussed in the text. It is well written and the data looks convincing. The manuscript reports an experimental advancement that is particularly useful for cold atoms in tight optical traps which have gathered significant attention in recent years for quantum computations, simulations and sensing. The authors demonstrate both scalar and fictitious field sensing down to an impressive 25nm resolution - a significant improvement with added novelty compared with previous cold atom experiments. In the revised text, the authors have properly acknowledged prior works and have compared their experiment with other material platforms. I also agree with the authors that the demonstrated single atom sensor, albeit more fragile and difficult to prepare in the first place, directly measures the optical field, in vacuum, without the unavoidable material disturbance presented in other solid state platforms or nanoscale probes. This work presents a complementary scheme for applications in quantum science. Given the potential impact in the field and the novelty of the demonstration, I recommend publication of this manuscript in Nature communications.

We thank the reviewer for the positive evaluation and constructive feedback. We appreciate the recognition of the significance and novelty of our work.

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List of revisions:

1. L39, L221, L320: added “(sub-wavelength imaging)” after “super-resolution”.
2. L331: Added sentences to provide a clearer and more quantitative comparison with existing techniques, as well as to better articulate the unique capabilities of single-atom tweezer probes relative to competing platforms.
3. L473: Added a sentence to clarify that the heating effect due to the scattering is negligible.
4. L494: Added the number of the trap frequency to discuss the adiabaticity more quantitatively.
5. L501: Added explanation to discuss the state change and the atom loss.
6. Caption for the Figure 2: corrected the typo (left  $\leftrightarrow$  right)