Sensing with Quantum Microwaves in Space

PT-UK Quantum Technologies in Space Workshop

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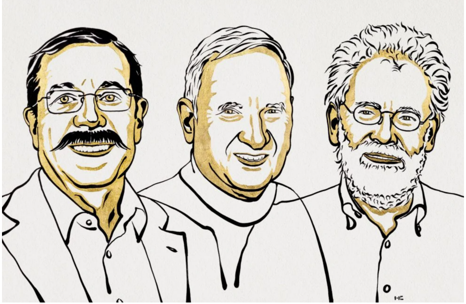
Outline

- Entanglement: from a weird idea to a daily resource
- Quantum parameter estimation and sensing
- Quantum microwaves: tech ‘sota’
- Free propagation: pros & cons of mws vs optical
- Other sensing ideas + roadmap

Introduction

2022 Nobel Prize awarded to A. Aspect, J. Clauser, and A. Zeilinger



"for experiments with **entangled photons**, establishing the violation of Bell inequalities and pioneering quantum information science". (1960s)

Entanglement math

Mathematically, entanglement is a type of quantum correlation arising from:

- Superposition (linearity of Schrödinger's equation)
- Composition rule

Superposition: Take a 2-level system with ONB:

$$|a_1\rangle\,, |a_2\rangle \in \mathcal{H}_A \tag{1}$$

then

$$|a_3\rangle \equiv \alpha\,|a_1\rangle + \beta\,|a_2\rangle \tag{2}$$

is *also* in $\mathcal{H}_A$.
Composition:

$$\mathcal{H}_{AB} \equiv \mathcal{H}_A \otimes \mathcal{H}_B \tag{3}$$

A and B can label any (**distinguishable!**) d.o.f.

Entanglement math

Take bases

$$|a_1\rangle, |a_2\rangle \in \mathcal{H}_A$$

$$|b_1\rangle, |b_2\rangle \in \mathcal{H}_B$$

Then, there should be some $|\psi\rangle_{AB} \in \mathcal{H}_{AB}$ s.t.

$$|\psi\rangle_{AB} = \gamma\, |a_1\rangle \otimes |b_1\rangle + \delta\, |a_2\rangle \otimes |b_2\rangle$$

This state is non-separable!
Despite its mathematical simplicity, entanglement has important consequences, both conceptually[1] and technologically.

[1] A. Peres: *Quantum Theory: Concepts and Methods*, 2002 Kluwer Academic Publishers.

Entanglement history

Two theory papers:

- EPR in 1935: introduced the idea to ‘prove’ QMs incompleteness[2]
- J. Bell[3] in 1964 proposes test to check local realism *experimentally*!

First experimental demonstrations:

- Violation of Bell’s inequalities: J. Clauser in 1972 [4]
- 1980s: Some loopholes closed by A. Aspect [5]
- 1990s: Zeilinger realises quantum teleportation [6]
- 2010s: Entanglement distribution with Micius satellite: 1300 km[7]
  Loophole-free Bell tests: Nature **526**, pp. 682–686 (2015).

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[2] Phys. Rev **47** (10): 777–780 (1935)
[3] Physics Vol. 1, No. 3, pp. 195-290 (1964)
[4] Phys. Rev. Lett. **28**, 938 (1972)
[5] Phys. Rev. Lett. 47, 460 (1981) & Phys. Rev. Lett. **49**, 91 (1982)
[6] Nature **390**, pp 575–579 (1997)
[7] Science, **356**, 6343 pp. 1140-1144 (2017)

Entanglement applications

Quantum **communications** and cryptography

- Security against eavesdropping: BB84[8] (no entanglement), E91 [9]

Quantum **computation**

- Faster than-classical performances
- Shor's algorithm: inverse Quantum Fourier transform implies entangling qbits

Quantum **sensing**

- Quantum illumination & imaging
- NV centers[10]
- Testing quantumness of gravity
- Networked quantum sensors (talk later today by L. Bugalho)
- Quantum CMB signatures

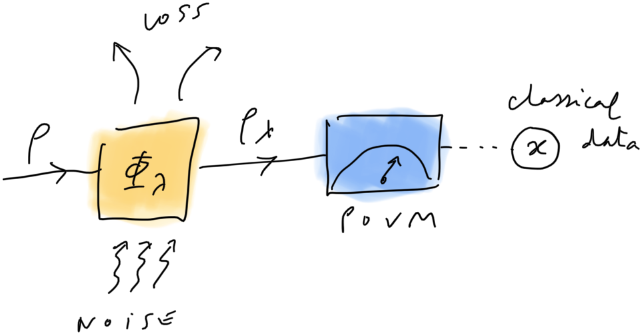
[8] Systems and Signal Processing, **175**, p. 8 (1984)
[9] Phys. Rev. Lett. **67**, 661 (1991)
[10] Nature Commus **12**, 2737 (2021)

Quantum Sensing/Metrology

- Problem of highest resolution and sensitivity in measurement
- Non-classical resources: entanglement, squeezing
- Mathematical tools: quantum statistical inference theory (q info + probability)
- Interesting both from foundational and technological perspectives
- Wide range of applications

Parameter estimation

Single run:



Parameter estimation

- Probe $\boldsymbol{\rho}$
- Encoding: quantum channel (interaction + possible partial loss of info + possible noise):

$$\boldsymbol{\rho} \mapsto \Phi_\lambda[\boldsymbol{\rho}] \equiv \boldsymbol{\rho}_\lambda$$

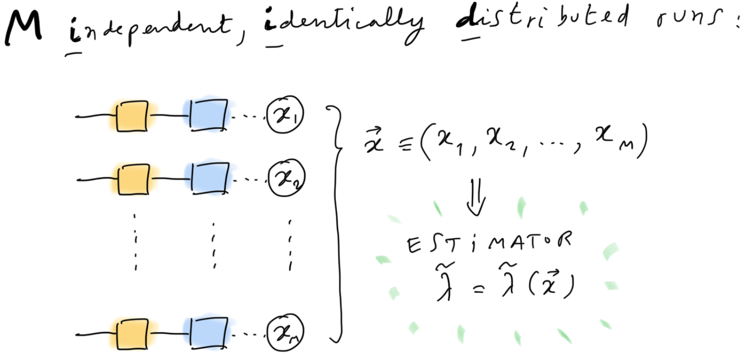
- Measurement
  - Extract info X from system via POVM[11]
  - Update state via Born's rule, collect statistics $p(x|\lambda) = \mathrm{Tr}(\Pi_x \boldsymbol{\rho}_\lambda)$.
  - Repeat
- Optimal (classical) estimator $\hat{\lambda}$ approaches λ.

1st optimisation: best POVM (optimal detection).

[11] Positive-operator valued measure $\{\Pi_x\}_x$.

Parameter estimation

Assume we have iid process and repeat M times:



Quantum parameter estimation

Minimum variance estimator saturates quantum **Cramér-Rao bound** :

$$(\Delta\hat{\lambda}_{\boldsymbol{O}_\lambda})^2 \geq \frac{1}{MH(\lambda)}$$

Quantum Fisher information

$$H(\lambda) = 2\sum_{m,n} \frac{|\langle\rho_m|\,\partial_\lambda \boldsymbol{\rho}_\lambda\,|\rho_n\rangle\,|^2}{\rho_m + \rho_n} \tag{4}$$

And

$$\boldsymbol{O}_\lambda = \lambda\mathbb{1} + \frac{\boldsymbol{L}_\lambda}{H(\lambda)}, \tag{5}$$

where $\boldsymbol{L}_\lambda$ is a symmetric logarithmic derivative[12] .

Solves the equation $\{\boldsymbol{L}_\lambda, \boldsymbol{\rho}_\lambda\} = 2\partial_\lambda \boldsymbol{\rho}_\lambda$

[12] **M. C.** et al, Adv Quantum Technol. **5**, 2100051 (2022)

Quantum parameter estimation

The QFI implicitly depends on *the way* parameter λ is imprinted onto $\boldsymbol{\rho}$ by means of the quantum channel Φ_λ.

- Further optimize over probes $\boldsymbol{\rho}$! (optimal state preparation)
- Some probes are more *sensitive* to the channel.
- "Information content of probe $\boldsymbol{\rho}$ wrt a specific estimation problem characterised by Φ_λ".
- This is the **sensing** aspect of metrology.

Motivation for quantum microwaves

Some technological reasons to exploit quantum properties of microwaves for comms and sensing

- Superconducting chips naturally operate at ~ 5 GHz (aim: zero ω conversion loss)
- Low energy
- Atmospheric transparency

Needs:

- Cryogenics for entanglement generation
- Good squeezing sources
- Advances in photocounters for propagating modes[13]

Still missing:

- Room-temperature entanglement + detection
- Understanding of open-air and free space propagation of quantum microwaves (antenna + collimators, etc)

[13] R. Dassonneville et al, Phys. Rev. Appl. **14**, 044022 (2020).

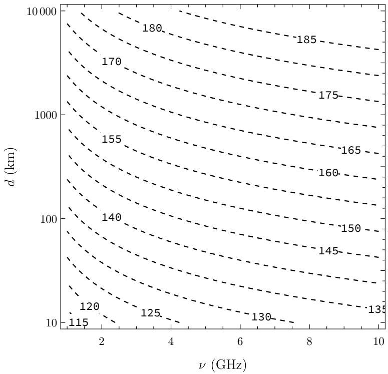
Non-guided quantum microwaves[14]

Free-space path loss (FSPL):

$$L_{\mathrm{FSPL}}(\mathrm{dB}) = 20\log_{10}(4\pi d\nu/c)$$

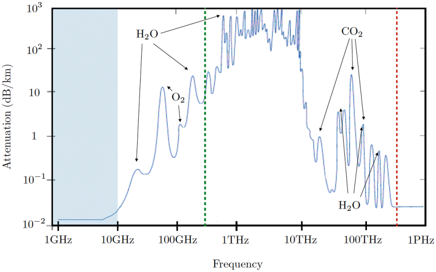
- Quantifies 3D spread of a signal in the far-field limit
- d is emitter-receiver distance
- Quadratic ν dependence: MWs (1–10 GHz) over optical

Needed: Entanglement degradation by atmospheric diffraction, turbulence, etc



[14] T. Gonzalez-Raya, **M. C.**, et al, Phys. Rev. Applied **18**, 044002 (2022)

Atmospheric mw-transparency window



15 FIG. 2. Atmospheric attenuation (dB/km) as a function of the frequency (at 20C, 1 atm and 7.5 g/m^3 of water). The red dashed line at right separates visible frequencies from infrared, while the green dashed line separates infrared from microwaves. The blue area corresponds to the frequencies in which the technology of propagating quantum microwaves and superconducting circuits operates. This plot uses data taken from Ref. [28].

[15] From M. Sanz et al *Challenges in Open-air Microwave Quantum Communication and Sensing*, [arXiv:1809.02979]

Quantum microwaves: Noise

Photons follow Bose-Einstein statistics.
Expected thermal photon number is:

$$n(\nu, T) = \frac{1}{e^{h\nu/k_B T} - 1}$$

Earth's surface, $T = 300K$:

- Optical (400-790 THz): $n \sim 10^{-28}$–10^{-55} photons
- MWs (1–10 GHz) $n \sim 6250$–625 photons

Space, $T = 2.7K$:

- Optical (400-790 THz): Absolute darkness
- MWs (1–10 GHz) $n \sim 56$–5 photons

Quantum microwaves: review and prospects

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TOPICAL REVIEW • OPEN ACCESS

Propagating quantum microwaves: towards applications in communication and sensing

Mateo Casariego[20,1,2], Emmanuel Zambrini Cruzeiro[3], Stefano Gherardini[4,5], Tasio Gonzalez-Raya[6,7], Rui André[3], Gonçalo Frazão[1,3], Giacomo Catto[8], Mikko Möttönen[8,9], Debopam Datta[9], Klaara Viisanen[9] + Show full author list

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Roadmap

Time →

Quantum Communication			
Model of 1st generation quantum repeaters (E1, E2) Quantum compression models for communications	Inter-fridge COW-QKD with time-bins (SG1, D1) 2D QLAN realization (SP1, SP2)	Inter-fridge remote state preparation (SG4, D1) Inter-fridge quantum teleportation (SG4, D1)	Open-air quantum teleportation (SP4, D1, D2) Open-air QKD: one decoy BB84 (SP2, SP4, SP5, E4)
Quantum Sensing			
Bath-system interaction learning protocols (E3, E3) Dark matter and quantum microwaves (SG2)	Intra-fridge all-microwave quantum illumination (E3) Models of inter-fridge quantum illumination (SP4)	Open-air quantum illumination (SP4, D2) Haloscopic axion searches (D1, D3 E3)	Quantum radar and quantum Doppler radar (SG4, SG5, SP2, SP3, SP4, D1, D2) Distributed quantum computing (SP1, SG3, E1, E4)

Technological and theoretical developments required:

State Generation (SG)	State Propagation (SP)	Detection (D)	Elements (E)
1. Propagating time-bins & Single photon emitter 2. Polarization-entangled sources/3D cavities 3. Deterministic non-Gaussian sources 4. Improved JPAs 5. Frequency-entangled sources	1. Guided: Ni/Al flexibility advances required 2. Non-guided: receiving antenna + emitter 3. Focalization methods: collimators, SAR-like approaches 4. Rigorous study of MW in open-air (including turbulence, etc) 5. 3D waveguides	1. Improve single-shot homodyne measurements with photocounters for propagating modes 2. Non-cryogenic detection 3. Bolometers and calorimeters: improvements for photon-counting	1. Circulators: compatibility with superconducting platforms 2. Heralded noiseless amplifiers to restore entanglement in dissipative channels 3. MW quantum memory 4. SiGe heterojunction bipolar transistors: make more compatible with CMOS tech.

Review and prospects

Take-home: Microwaves are entering the 2nd quantum revolution and this brings opportunities

- Antennas + collimators + atmospheric turbulence
- Noise-resilient sensing protocols
- Fully-mw implementation of quantum illumination
- Room-temperature entanglement generation + distribution
- Space: inter-satellite quantum ranging?
- Radar-like protocols
- Gravimetry, Doppler & gravitational redshifts, Dark Matter, CMB physics. . .

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