Demonstration of entanglement swapping in a deployable payload

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Abstract: A quantum network spanning intercontinental distances will require satellite payloads that can swap entanglement. We report on results from the Q4S mission, successfully demonstrating entanglement swapping on a deployable payload.

Quantum networks that span intercontinental distances will require hardware that can be deployed to space, such as entangled pair sources and quantum repeaters. Entangled pair sources have been demonstrated in space [1,2], but challenges still remain for space-based quantum repeaters. The base functionality of quantum repeater is to relay quantum information via entanglement swapping [3]. In entanglement swapping, two independent photons, each belonging to a distinct entangled photon pair, become entangled after their twins are jointly measured in a Bell-state measurement (BSM). Demonstrations of entanglement swapping to date have been performed only in laboratory settings, on large tabletop benches due to the size weight, and power (SWaP) of the lasers and detectors, and have required carefully controlled laboratory environments. In order to be able to perform space-based entanglement swapping, a massive reduction in SWaP and increase in robustness is needed, while preserving fidelity. The goal of the Q4S mission is to meet this demand and deploy a satellite payload that performs a self-contained entanglement swapping experiment in low-Earth orbit.

The main challenge of the Q4S mission is to perform entanglement swapping at a sufficient rate and fidelity without an excessive power demand. Whereas space-based entangled photon sources conventionally use a CW diode laser pump, the requirement for indistinguishability at the BSM prohibits this, due to the high degree of spectral entanglement produced by such sources. As a result, we opted to employ a compact mode-locked fiber laser from Menlo Systems, generating 100fs pump pulses and relaxing the ultra-narrow spectral filtering requirement that would be associated with a CW laser. With this moderate filter bandwidth and silicon APD's for detection, a sufficient swap rate is attainable within an integration time window that minimizes the temperature variations from a sun-synchronous orbit.

The Q4S payload entangled photon source is a temperature-controlled ppKTP (periodically-poled potassium titanyl phosphate) crystal, pumped at two distinct locations to generate two polarization-entangled photon pairs via type-II spontaneous parametric down conversion (SPDC). A successful BSM on two of the photons, one from each pair, swaps the entanglement, and heralds the remaining two photons at sites A and B in a polarization Bell state of the form

$$|\Psi\rangle = |H\rangle_A |V\rangle_B + e^{i\phi} |V\rangle_A |H\rangle_B,$$

where H and V denote horizontal and vertical polarization states, respectively, and ϕ is an arbitrary phase acquired from the optical components. Thanks to the BSM configuration, which employs four detectors, two out of the four orthogonal Bell states can be resolved. Entanglement between the photons at A and B is certified via quantum state tomography, which is accomplished by polarization analyzers at each site. Each analyzer consists of a pair of liquid crystal variable retarders (LCVRs), followed by a polarizing beam splitter with a free-space coupled silicon avalanche photodiode single-photon detector at each output. This configuration enables a projective measurement of an incoming photon onto any cardinal polarization basis.

In addition to the optics package, the payload contains module that is responsible for distributing power to the laser, detectors, temperature controllers, and active optical components; regulating control servos; and collecting system health data and photodetection time stamps. The entire payload (Figure 1a) weighs <20 kg with a ~12 L footprint, and consumes <45 W of power in nominal operating conditions.

The payload prototype (the ground twin) was completed in 2025. Upon initial testing, it was found that the free-space single photon detectors were not sufficiently shielded from scattered laser light, necessitating some design modifications to improve the baffling. These improved baffles were implemented on the payload prototype. An additional challenge was optimizing and maintaining mode-matching to ensure indistinguishability between the two entangled photon sources when combined at the BSM module. After overcoming these challenges, we report on the first demonstration of successful entanglement swapping *in situ* on the Q4S payload prototype. We obtain a swapped state fidelity of 0.654 ± 0.015 (Figure 1b), which surpasses the classical limit by nearly 10 standard deviations, with a rate of 24 events per hour.

Additionally, the space-bound payload has completed fabrication and is currently undergoing integration and test. Preliminary results demonstrate improvements in the signal-to-noise ratio and mode-matching as compared to the prototype, due to improvements in the coatings and alignment procedures based on results from the prototype. The Q4S mission is on track to be the first in-orbit demonstration of entanglement swapping, a key step towards a global space-based quantum network.

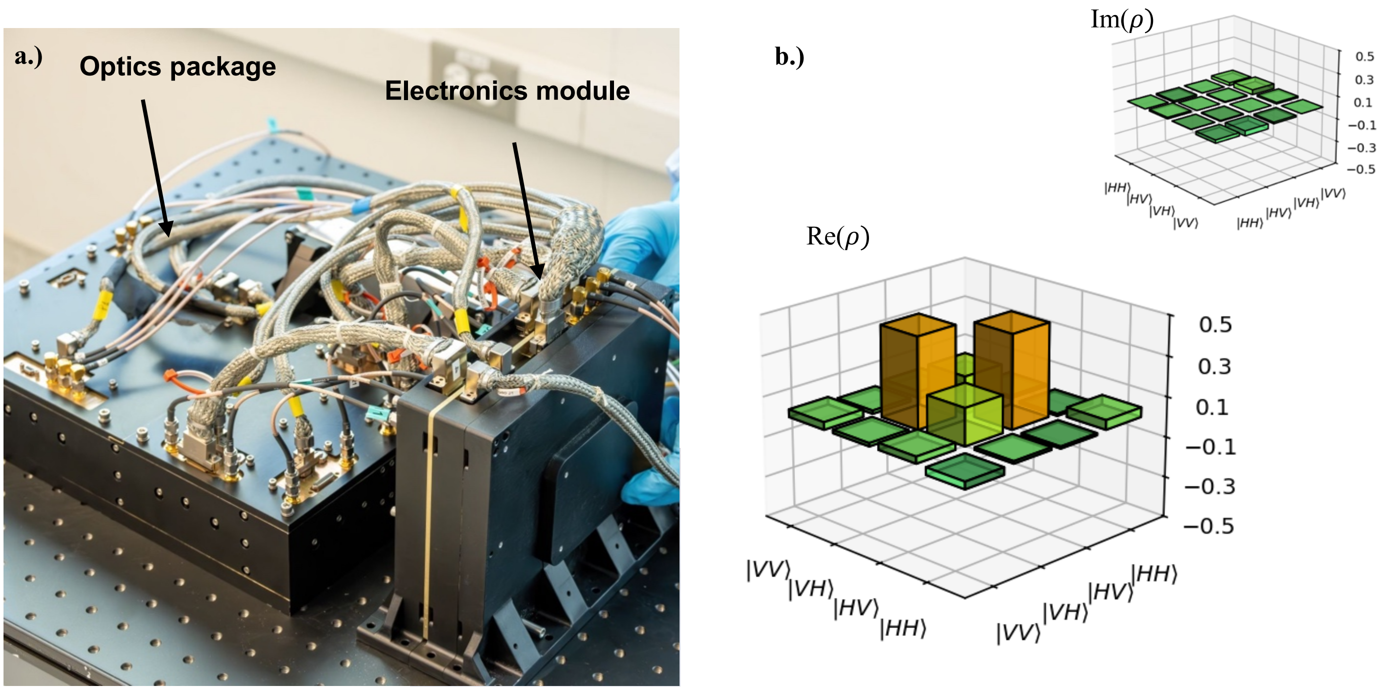

Figure 1. a.) Q4S optics package and electronics module from the payload prototype. b.) Density matrix for a swapped entangled state, *in situ* on the payload prototype, showing fidelity of 0.645 +/- 0.015.

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Boeing and HRL patents and patents pending.

References

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