Quantum Optics

Can we build a space-based quantum network? While there are many challenges, a new model for low-cost satellites is bringing global quantum communication a step closer to reality.

for SPACE PLATFORMS

William Morong, Alexander Ling and Daniel Oi

Experimental physicists generally prize having complete control over the laboratory environment above all else. In our quest for ever-more precise results, even the slightest stray variable can mean ruin. So, as our team of quantum physicists cruised through the German countryside last May to track a weather balloon, we encountered what would normally be considered a worst-case scenario: The free-flying balloon carried a quantum optics experiment that had reached an altitude of 37.5 km and was now falling to the ground at a speed of 6 m/s with the aid of a parachute, and recovery was based on our ability to track faint radio beacons.

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Sounding balloons are a cheap and effective method for testing nanosatellite components. Their low cost and ease of use has made them popular among hobbyists. They weigh less than 2 kg; have a range of less than 100 km; and can reach an altitude over 35 km. We teamed up with an amateur group based at the Susso Gymnasium in Konstanz, Germany, for our first high-altitude test.

Daniel Oi

Fortunately, the radio signal never fully vanished, and we eventually spotted the slim test package in a bushy farm field about three hours after we launched.

Welcome to the world of outdoor quantum technology experimentation.

Why leave the comfort of our lab benches to subject a delicate optical alignment to the ups and downs of a high-altitude weather balloon test? Our group is among a growing number of physicists who are taking quantum optics into the larger world, where we plan to use it as a basis for new technologies. In fact, our weather balloon tests—which were intended to assess the system's response to pressure and temperature changes—are the lower limit of our ambitions. Our goal is to demonstrate a working source of entangled photon pairs in space and one day develop inter-satellite communications systems based on quantum technology.

It all goes back to a series of discoveries made nearly 30 years ago that married two seemingly unrelated disciplines: quantum mechanics and cryptography.

Quantum cryptography and photons

The possibility that we might be able to distribute cryptographic keys using quantum mechanics was first raised in the 1980s. In this proposal, researchers suggested that single quantum systems—typically single photons—could be used to encode a random string of numbers for a cryptographic scheme called the one-time pad. Since then, many practical realizations of such protocols have been implemented, mostly by optical means. In 1991, Artur Ekert introduced an additional twist when he showed that a quantum correlation known as entanglement could be exploited as a resource for quantum cryptography. This has also been demonstrated

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via quantum-entangled photon pairs generated through nonlinear optics processes.

There are many advantages to using photons to encode a quantum message: They are largely non-interacting, which preserves the quantum coherence of the system, yet they can be readily controlled using standard optical components. They can also be individually detected using commercially available avalanche photodiodes.

In addition, we have an increasingly sophisticated understanding of techniques for improving the brightness of entangled photon sources and techniques to correct for quantum-state errors during transmission. Moreover, quantum cryptography is already a reality, and several companies are producing commercial quantum key distribution (QKD) kits.

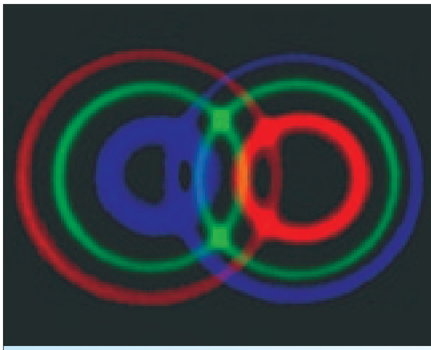
Nevertheless, there are still many challenges to be overcome if quantum communication is to become widespread; the most significant is distance.

Free-space communication

Would-be quantum communicators who want to span continental-scale distances currently rely mostly on line-of-sight communication techniques. To date, the farthest transmission of quantum correlations in this way has been 144 km. However, in recent years, some physicists have begun to turn their attention toward the heavens. Between ground and low-earth orbit, signals only pass through the equivalent of approximately 10 km of sea-level atmosphere, after which a quantum signal could travel indefinitely through a near-perfect vacuum.

A natural arrangement would be to have a space-based source of entangled photons that beams the entangled photon pairs down to ground stations out of sight of each other but within sight of the satellite. This transmission geometry offers advantages over other arrangements, such as reduced beam wander due to atmospheric turbulence. Thus, this is the concept that would most likely be pursued in the long term.

Other arrangements may still be useful for testing various aspects of the system or for demonstrating key capabilities. Quantum technology could also be used for inter-satellite communication. To pursue these goals, a number of research groups worldwide have formed consortia to take quantum cryptography towards this final frontier.



One standard method for generating entangled photons is to use pairs of photons emerging from the intersections of laser-generated rings. These photons have a long-distance connection to one another.

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THE SPOOKY SCIENCE OF ENTANGLEMENT

One of the hallmarks of quantum objects, such as photons, is that they can be entangled—that is, the behavior of multiple field modes or particles can be correlated to a much greater degree than is allowed for by classical physics, despite being fundamentally random in each individually.

For example, the polarization-entangled photons that we create each have a fundamentally random polarization value when measured, but the two photons in the entangled pair always get the same random result. Einstein famously described this as "spooky action at a distance," since it seems that each particle is somehow instantly letting the other know what it is measured to be.

In fact, no information is transmitted, avoiding the faster-than-light signaling that is forbidden by special relativity. Nonetheless, Einstein and others believed that this apparent paradox posed by random yet agreeing measurements was an indication that quantum theory was lacking since it did not account for the factors which might actually be causing the photons to "pick" one polarization or another.

Several decades later, John Bell addressed these concerns with his celebrated theorem. Roughly speaking, it showed that the kind of explanation sought by Einstein was incompatible with the predictions (and experimental results) of quantum physics and that any alternative theory must depart from our classical ideas of how the world works in similar ways.

This finding kicked off a wave of research into entanglement, both experimental and theoretical, which eventually became closely joined with the study of quantum information science, which asks how quantum properties such as entanglement affect the principles of information transfer that we've developed.

Finally, in several seminal papers in the late 1980s and early 1990s, it became apparent that one could in fact use a stream of entangled pairs of particles to send an encrypted message between two people. Moreover, because all of the information in the message is contained in the quantum correlations between the entangled pairs, instead of the individual streams of particles, it is in principle possible to arrange things so that a third party can never intercept and decode the message. Nature's laws themselves guarantee its safety.

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Why global quantum communications doesn't work today

While classical optical communication via fiber networks now spans the globe, quantum optical systems cannot readily take advantage of the existing infrastructure. Unlike classical optical communication, quantum information carriers can exist in a coherent quantum superposition of 0 and 1, with some amplitude of each. This fragile quantum state leads to vulnerabilities called "phase errors;" a single photon in a superposition of two linear polarizations is sensitive to changes in the birefringence of standard optical fibers. This sets an upper limit to the distribution distance for the photons via fiber, even with compensation techniques.

In addition, quantum states must be preserved until the final measurement is made. This eliminates another standard industry tool, the optical repeater. A classical signal traveling a long distance is typically amplified and rebroadcast by repeaters positioned at intervals to overcome attenuation.

However, in quantum mechanics, the "no-cloning theorem" of Wooters and Zurek disallows the creation of perfect copies of an unknown quantum state; any attempt to "read" the state to be copied will almost always change it! This is the basic reason why a third party cannot spy on quantum messages without their presence being revealed; it also makes quantum repeater design a challenge. Intensive research work is being done on quantum repeaters, but to date no satisfactory technological solution has been found.

There are many barriers to a quantum space network, but we see a huge opportunity to quickly ascend the ladder of development necessary by taking small steps in rapid succession. In our opinion, the first exploratory steps to space-based quantum key distribution should be done via low-cost satellites called CubeSats, with an iterative design cycle that incorporates the lessons gleaned from each launch. This new model for conducting space experiments is enabling us to take space-based QKD a step closer to reality.

CubeSat: Small science, small satellites

The prevailing trend for space science has been for larger and more capable satellites, by working with space agencies to propose a mission with many milestones. This can take several years from proposal to the delivery of a space-qualified science experiment. There are many good reasons why the traditional route is expensive and takes a long time: Many quality-control steps ensure that costly launch systems are not compromised and are able to run for years.

However, this approach may not be suited to small-scale science experiments intended as technology pathfinders and operating only a few months in low-earth orbit. Out of the need for more affordable access to space, scientists at California Polytechnic State University and Stanford University launched the CubeSat initiative in 1999. Currently, there are more than 40 universities with publicized interest in CubeSats. In our proposal,

In order to fit our source aboard a CubeSat, we are restricted to a volume of about 300 ml, which is smaller than a can of soda.

the satellite itself is being designed by colleagues at the Nanyang Technological University in Singapore. We are working in close collaboration with them.

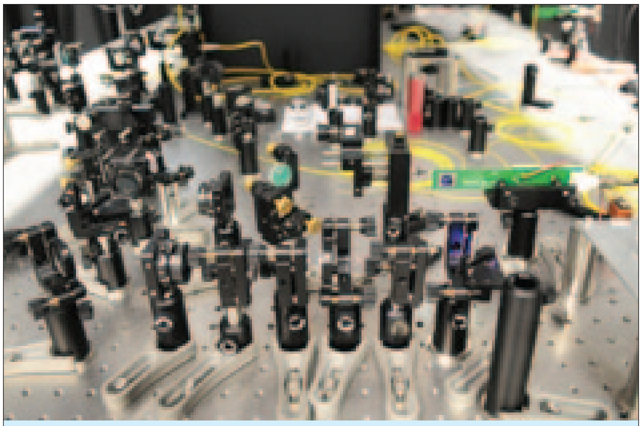
The CubeSat is a 1 U cube-shaped module with 10 cm to a side and up to 1 kg in mass. CubeSats can ride into orbit piggy-backed upon commercial satellite launches. Typically they are deployed in groups of three using something called a Poly-PicoSatellite orbital deployer, which uses a spring to eject the CubeSats away from the main satellite deployment bus. Hitching a ride into space means that the launch costs are three to four orders of magnitude less for a CubeSat than for a conventional satellite. Because of the small size and standardization of the CubeSat specifications, development can be completed in months for a few tens of thousands of dollars, instead of years and tens of millions of dollars.

The planned short orbital lifetime of CubeSats also means that less costly conventional off-the-shelf components can be used instead of special space-rated equipment. Commercial satellite launches are also fairly regular, so it is not too difficult to book a “seat.” We foresee that, in the next decade, dedicated launch vehicles will be available with the express purpose of placing payloads into a low earth orbit of 400 km. This may bring the cost of launch down to the range of $10,000 per kg.

Moving from table-top to spacecraft

As a first step, we propose to demonstrate a working source of entangled photon pairs in space, onboard a CubeSat that should be operational for at least a few weeks. In this experiment, all photons should be detected onboard (i.e., no transmission), as it is necessary to monitor the behavior of the apparatus in the space environment. Follow-up missions can then be planned for studying how best to transmit photons from the satellite.

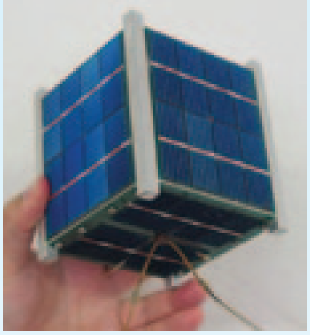
Although entanglement correlation experiments are now found even in some undergraduate labs, they are often very hard to align and to maintain. Our proposal, although modest in scope as a space experiment, is a major technological challenge requiring a redesign of the typical sprawl in an optics lab such that it can be incorporated into a satellite that is running autonomously. This is a tremendous challenge, requiring a multidisciplinary team of specialists in quantum optics, satellite physics and electrical engineering.



Centre for Quantum Technologies

THE INCREDIBLE SHRINKING LAB BENCH

The typical equipment used to test optically generated quantum entanglement is done on a crowded lab bench. The optical axes of the birefringent crystals must be aligned and the crystals are adjusted by bulky tip-tilt mounts.



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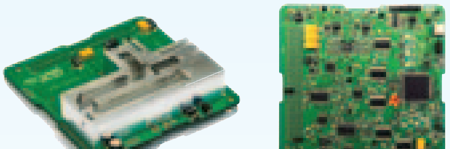
But our experiment must be made to fit in the much smaller confines of the CubeSat, which is roughly 10 cm to a side and up to 1 kg in mass. Typically, 30 percent of its volume is available for a customized payload.



Daniel Oi

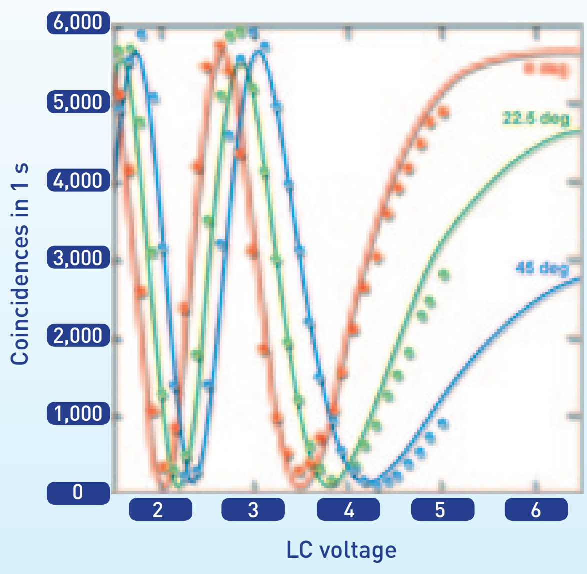
So, we engineered an experiment that would normally take up a whole bench down into this sandwich-sized electro-optical package (nicknamed “Alice”) to test quantum correlations. It includes a dummy aluminum mount indicating the position of the final optical components. The reverse side of the “Alice” board (right) holds all the microelectronics needed to operate our quantum entanglement experiment.

On the optics side, two of the authors (William and Alexander), based at the Centre for Quantum Technologies in the National University of Singapore, are working on the Small Photon-Entangling Quantum System (SPEQS). This is an entangled photon source that is modular, compact, versatile and suitable for spaceflight.

Our photon source itself is fairly conventional, using a nonlinear process called spontaneous parametric down Conversion (SPDC). In the laboratory, SPDC-based sources have been used in many ground-breaking experiments, demonstrating their viability. However, the constraints of our satellite platform have forced us to reexamine nearly every aspect of the design. In order to fit our source aboard a CubeSat, we are restricted to a volume of about 300 ml, which is smaller than a can of soda. Our entangled photon source must weigh less than 300 g and draw less than 1.5 W of power. It must also be able to withstand the vibration of launch, the 30° C temperature swing that it will experience in each 90-min. orbit, and the radiation in space.

To accommodate these constraints, we have designed a compact aluminum mount for our crystals and a set of specialized tools to precisely align them before they are secured. Another challenge was finding a suitable adhesive to attach the crystals, which must not expand or contract as it cures or allow for even minute angular drifts. On the electronics side, we had to design a low-power feedback system that would regulate the voltage applied to the single photon detectors (based on silicon avalanche photodiodes), to adjust for their temperature-dependent breakdown voltages. Finally, ensuring that our components are all stable in a vacuum and against the radiation exposure has required extensive and careful testing.

HIGH-VISIBILITY CURVES OF QUANTUM CORRELATIONS



Quantum correlations are measured by looking at the number of photon pairs that manage to pass through two independently oriented polarizing filters. The filters are built from liquid-crystal–based polarization rotators coupled to linear polarizers. Typically one of the photons in the pair is subjected to three different polarization settings, while its twin is subjected to a fine polarization scan. This graph shows our measured high-visibility curves, which indicate the presence of high-quality quantum entanglement correlations.

Using spontaneous parametric down conversion to generate entanglement

A number of optical arrangements can be used to generate entangled photon pairs. We chose one design that could be compacted readily. It is based on a nonlinear crystal called beta-barium borate (BBO). When exposed to a pump laser at a relatively short wavelength—in our case, 405 nm—each pump photon has some probability to be downconverted into two longer-wavelength daughter photons, which are conventionally called the signal and idler.

Because the process is parametric, or results in no change to the BBO crystal, the signal and the idler must together contain all of the pump photon's energy and momentum. At a given tilt of the BBO crystal relative to the pump laser, this creates a set of phase-matching conditions, which determine the signal and idler wavelengths. We chose an angle such that the signal and idler pairs are created collinear to the pump laser at the wavelengths of 760 and 867 nm.

The key characteristic of SPDC that allows entanglement is that it is polarization-dependent. Photons are downconverted at a maximum rate from laser light whose polarization is aligned with the nonlinear crystal axis, while if they are orthogonal, there is no downconversion.

The key to the design is to place two BBO crystals in a row, with crystal axes that are oriented horizontally and vertically, and shine a pump laser that is polarized at 45 degrees through both. This polarization corresponds to a quantum state of the light that is a superposition of

We are currently testing our experiment, conducting durability trials by exposing the electronics and optics to vacuum and radiation and monitoring any degradation.

horizontal and vertical, and when this passes through both crystals, the resulting signal and idler are a superposition of two possibilities—a pair of vertically polarized photons or a pair of horizontally polarized photons, depending on which crystal they are downconverted in. Each individual photon has an indefinite polarization until measured, but it is guaranteed that both in the pair will share the same polarization. Therefore, they are said to be polarization-entangled.

The verification of this is straightforward. Since the beams of the signal and idler photons are of different wavelengths, they are easily separated using a dichroic mirror, and the polarization of each of the pair of photons is measured along several directions. If the amount that the photon pairs share the same polarization along different directions exceeds a certain value and violates what is known as Bell's inequality, this guarantees that our photons are strongly entangled.

For the signal and idler to be strongly polarization-entangled, both possible polarizations in the superposition must propagate with a constant phase difference. This is equivalent to requiring that no information about which crystal a photon came from exists, even in principle, except for that which is contained in the polarization degree of freedom.

As a result, we also need several additional crystals after the two downconverted BBOs, which correct subtle ways that the photons created in each crystal differ besides their polarization, such as slight differences in total travel. With these "compensation crystals," we are able to reach near-maximal entanglement.

Prospects and conclusions

We are currently testing our experiment, conducting durability trials by exposing the electronics and optics to vacuum and radiation and monitoring any degradation. In May 2012, we also tested an experimental package on a high-altitude weather balloon launched in southern Germany, as mentioned at the beginning of the article.

After retrieval, the package was subjected to optical and electronic testing back in the labs, where it was revealed that no damage had been incurred. The data stored during the balloon flight also revealed that the system tracked the changes in the environment and corrected for them, allowing the electronics systems to continue optimal operation. This has built confidence in our design choices, and we are targeting a launch for our CubeSat in the next two years.

Once the satellite has achieved a stable orbit and satisfied some preliminary calibrations, we will begin the Bell violation experiment over an expected lifetime of approximately six months, looking for variations of the quality of the entangled state generated. A reliable source will be used as a basis for future long-distance experiments. It may one day enable us to create long-distance entanglement and realize a future that includes global quantum communications. OPN

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