ISSN : 2249-5762 (Online) | ISSN : 2249-5770 (Print)

Satellite-based Quantum Communications Tests in Space

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Abstract
Will space be the final frontier of quantum optics? Only time will tell. Several groups worldwide have been making important progress in the area and reporting their latest results. One of the main research objectives is the realization of reliable satellite to ground quantum communications, which might eventually lead to a global quantum network. What is certain is that the classical satellite optical communication channels that are already in place would benefit from the secure data transmission afforded by quantum Protocols.

Keyword
Quantum Optics, Spacecraft, Quantum Enlargement, Quantum Communications

I. Introduction

In this context, the Chinese led quantum experiments at space scale (QUESS) project, which launched its satellite in August1,2016, ticked an important box — carrying a source of entangled photons into space for the first time. Elsewhere, collaboration between Singapore and the UK, and teams from Japan, Italy and Germany are all pursuing approaches for conducting quantum experiments between Earth and space.

From a general perspective, it might be argued that taking quantum optical technologies into space is a natural evolution. The quantum toolbox has been put to the test over many decades on Earth: Researchers have refined schemes for entanglement generation and manipulation, achieved quantum teleportation and performed Quantum Key Distribution (QKD) over long distances (up to around 300 km with optical fibres2). However, a terrestrial fiber based global quantum network for communications would require quantum repeaters that are not available at present and some experts believe that satellite to ground channels represent a promising alternative [3].

Despite the impressive progress with terrestrial quantum experiments, one should not be misled into thinking that space based quantum protocols are trivial extensions of Earth based research. Alexander Ling, assistant professor at the National University of Singapore, leads a research team that is currently operating a source of correlated photon pairs aboard a Cube Sat (a common nano satellite standard), and some of the challenges they are facing.

Owing to weight and space limitations aboard the larger spacecraft that took the experiment into a low Earth orbit, Ling and collaborators knew that they would not be able to shield their setup against ionizing radiation. “We had expected there to be radiation damage [to the equipment] and had model led it,” explains Ling. Nevertheless, the data showed that the background rate for the detectors was higher than in the simulations4, indicating that “the radiation damage was accumulating at twice the predicted rate,” states Ling. The discrepancies between simulated and observed phenomena are a major challenge for quantum experiments in space, where “the radiation environment is not fully understood, and the only way to mitigate [damage] is to shield, or to design the mission so that it operates within the lifetime of the electronics,” comments Ling. Still, hope is not lost as radiation hardening is commonly used for scientific equipment in space when limitations on payloads are less strict. Ling was also positively surprised by the performance of their unshielded source, polarization rotators and photo detectors: “nine months after launch [we are still] fully operational,” he notes.

Another technical challenge is optical losses. During the experimental demonstration of single photon interference originating from the coherent superposition of temporal modes reflected by a moving satellite 1,000 km away from a receiving ground telescope explains that imperfect satellite tracking, laser beam divergence and the size of the telescope are all sources of optical loss, which affect the quality of the received data and are especially damaging to fragile photon entanglement. “To realize QKD ground space experiments it will be necessary to minimize losses as much as possible.”

II. Quantum Theory: The Basic

Here’s a quick refresher in case you haven’t thought about physics in a few years, because this story is cooler when you understand these basics. Skip ahead if you’re already a quantum geek.Most human technology is built around the classical physics that Isaac Newton and his inheritors came up with (equal and opposite reactions, that sort of thing). When engineers hit on electricity, Michalakis says, they perceived it in aggregate as a kind of a force; it’s either on, or it’s off. This understanding led to electric switches, which became transistors, and when you put all those transistors in a box and start turning them off and on with instructions encoded “11010001101”… it’s a computer. But as scientists were developing electric computers in the 20th century, theorists beginning with Max Planck were ripping up the rule books.

Their experiments with light suggested that something about classical physics didn’t quite add up. Soon they developed mathematical proofs to explain that the tiny particles that make up matter protons, neutrons, and electrons—don’t necessarily behave like you would expect particles to behave. They can act as if they are in two places at once, for instance. (That’s one of those “bizarre features” the Chinese are talking about.) This is quantum theory.

The first and most famous application of these ideas came in nuclear weaponry and energy.

Physicists are still trying to agree on how classical and quantum physics come together coherently. But quantum theory already underlies a lot of modern technology; the transistors on a silicon chip, in fact, wouldn’t work without it. Now engineers are trying to apply it to more futuristic things.

III. Spooky Action at a Distance

Let’s say that you take a very small particle, and set it up so that it could be in either one of two states. Let’s call one state “up,” and the other one “down.” (Quantum computers do something like this, using single atoms trapped in a magnetic field to represent either a “0” or a “1”.)

If you do this, quantum theory says that two things will happen. The first is that, although the particle will always be either “up” or “down” if you look at it, when you’re not looking, it will be in a kind of combination of the two, called a superposition. In quantum mechanics, the act of measuring something changes it; the superposition “collapses,” in the parlance, to either up or down.

The second thing is that two or more of these particles can be put in a situation of “quantum entanglement,” where they form a single superposition together. Then their physical properties are correlated. For instance, you can set them up in advance so that if you look at one particle and find it’s up, then you know, without looking, that the other must be down, and vice versa.

Here’s where it gets really interesting. Let’s say you entangle two particles. Then you move one of them far, far away—to the other side of the planet, or to the moon. No matter the distance, quantum mechanics says, they remain entangled. If you look at the first one, and in doing so change it—collapsing the superposition—you will also change the other one. And this will happen instantaneously, however far apart they are. Let that sink in, because this technique, called “quantum teleportation,” is crazy to think about. Light has a speed limit, and normally information cannot travel faster than light. Quantum teleportation is, in a sense, information traveling outside of space and time. Einstein called it “spooky action at a distance.”

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IV. Tangled up in Space

Scientists have done experiments with quantum teleportation already. They have instantaneously exchanged information about the quantum states of photons, which are particles of light, transmitted 143 km between two of the Canary Islands. But testing quantum teleportation at extremely long distances requires going to space. It’s the easiest way to set up laser communication between two distant points on the earth’s surface. That’s what the Chinese satellite, developed in cooperation with the Austrian Academy of Science, intends to do.

The satellite contains a machine that generates entangled pairs of photons by shooting a laser beam through a specially designed crystal. Each entangled pair will be split up and beamed down to stations on Earth approximately 1,200 km apart. If all goes as planned, researchers at those stations will share access to an entangled system. Any measurement on one of those photons will be instantaneously reflected in its opposite number at the other station.

A US company had partnered with researchers in Denmark and Singapore to launch a small satellite, or cube sat, with similar goals, but it was destroyed when the rocket taking it to the International Space Station exploded in 2014.

V. The Key is the Key

Besides demonstrating a super-long entanglement, the scientists working with the satellite want to test new communications technology. It’s important to realize that we can’t send information like “Hey, how are you?” through quantum teleportation, much less teleport actual things. But smart thinkers realized that being able to share basic information about the state of atomic particles across distance could create a powerful encryption tool.

“It’s very secure from the point of view that if your eavesdropper wants to listen in, usually they are within space and time.” This is where the unbreakable code comes in. Perhaps the most powerful method of encryption is the “one-time pad,” where messages are encoded using a private key known to both parties; theoretically, if the key is random, is as long as the message, is never reused, and is kept completely secret, it cannot be broken. Which sounds really good, code-wise, but it has long been impractical to ensure that two parties can always access a key that meets those standards.

Quantum entanglement could help. If people on two ground stations share access to a large enough set of entangled photons, beamed to them from a satellite in space, they can generate a sufficiently long, random key by teleporting quantum information between the entangled particles. Nobody would be able to detect the transmission of the key. “It’s very secure from the point of view that if your eavesdropper wants to listen in, usually they are within space and time,” Michalakis says. “The data is not transmitted through space time, it goes underneath in mathematical subspace.”Once the people in the two stations have created a key, using their entangled particles, they can use it to encrypt a message. This can be sent by whatever method they want. “You can use a telephone the moment you are sharing a key that nobody has access to,” Michalakis says. But what if someone managed to intercept the laser beam from the satellite that had originally shared the entangled photons between the two stations? Here’s what is truly amazing: Thanks to the laws of quantum mechanics, any attempt by a third party to measure the particles in the entangled system would be immediately detected by the other two, making them aware that their code could be broken.

VI. Quantum Supremacy

The field of quantum information is still in its infancy. As we continue to learn the fundamentals of how quantum phenomena work at a large scale, the data collected will help physicists understand “the process that takes you from the quantum richness of the universe to the classical world we see around us,” Michalakis says. It may be easy to see in this shades of the Cold War race for technological dominance, but Michalakis is confident that research will be shared within the scientific community. His hope is that this experiment is the first step toward a global network of research facilities sharing access to entangled particles beamed down from space—a kind of global, cloud-based quantum computer.

VII. Conclusions

Although the development of secure quantum communications based on a satellite network is widely recognized as one of the primary goals, there are other stimulating opportunities for this research. The realization of space based quantum protocols would open the way to fundamental tests of physics in unexplored conditions, such as investigating the persistence of quantum correlations over long distances. Other studies could look at the effects of general relativity on quantum systems and entanglement. the distribution of quantum entanglement via optical free-space links to independent receivers separated by 600 m, with no line of sight between each other. A Bell inequality between those receivers is violated by more than four standard deviations, confirming the quality of the entanglement. This outdoor experiment represents a step toward satellite-based distributed quantum entanglement. The consequences of space-time being curved on space-based quantum communication protocols. We analyze tasks that require either the exchange of single photons in a certain entanglement distribution protocol or beams of light in a continuous-variable quantum key distribution scheme. We find that gravity affects the propagation of photons, therefore adding additional noise

ISSN : 2249-5762 (Online) | ISSN : 2249-5770 (Print)

to the channel for the transmission of information. The effects could be measured with current technology. At present, using optical QKD is limited to a distance of approximately hundreds kilometers, however, free-space quantum cryptography makes it possible transmitting photons over long distances. We examined the physical properties of the Earth-space and space-space channels to give some prescriptions about the possible losses and to give some useful ideas about the implementation of such a channel. We also developed an analytical model which describes a few photons' behavior to simulate the communication process over a satellite quantum channel. Based on our mathematical models, we were able to examine selected parameters of quantum satellite communication. According to our results, the distance between two satellites should be maximum 15,000 km to handle a successful BB84. These results show that we can realize quantum communication over intercontinental distances. However, after analyzing of LEO (Low Earth Orbit) and GEO (Geostationary Earth Orbit) satellite orbit, we can say that a BB84 supported equipment running on a LEO satellite cannot reach a GEO satellite. We examined the super dense coding in both space-space and space-Earth communication. From our calculations based on the optical losses we can conclude, that deep space links and uplinks cannot be realized with super dense coding. We also examined the BB84 protocol's performance in downlinks. Our results show that satellites at low earth orbit can produce secure keys even at large zenith angles, and hazy weather. Another interesting question is related to quantum error correction. Currently many techniques are introduced but in these proposals redundancy is required for successful error correction. If we could use redundancy-free solutions, they would be very useful in the long-distance aerial communication. We developed different redundancy-free solutions for free-space quantum communications. Our protocols achieve the redundancy-free quantum communication using local unitary operations and unitary matrices.

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