A new quantum technique could enable telescopes the size of planet Earth

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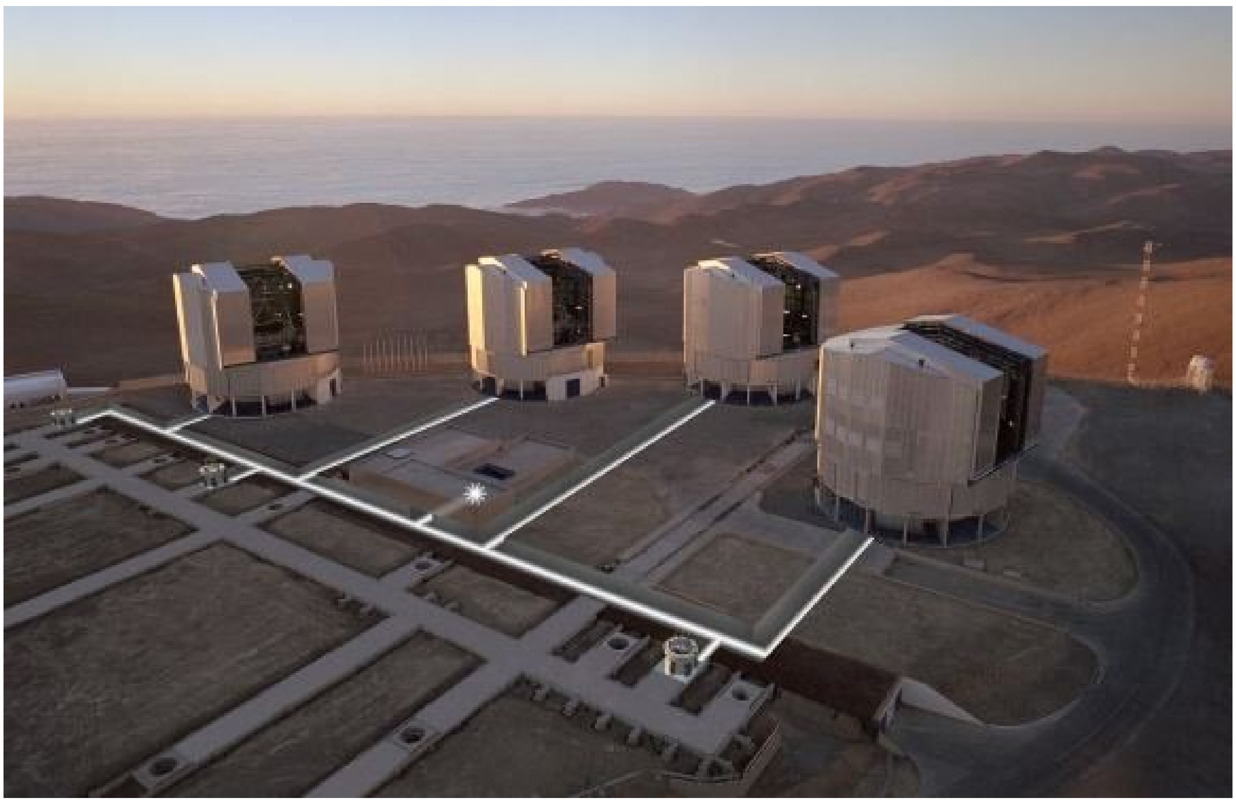


Aerial view of the Paranal Observatory showing the four 8.2-m Unit Telescopes (UTs) and various installations for the VLT Interferometer (VLTI). Credit: ESO

There's a revolution underway in astronomy. In fact, you might say there are several. In the past 10 years, exoplanet studies have advanced considerably, gravitational wave astronomy has emerged as a new field, and the first images of supermassive black holes (SMBHs) have been captured. A related field, interferometry, has also advanced incredibly thanks to highly sensitive instruments and the ability to share and combine data from observatories worldwide. In particular, the science of very-long baseline interferometry (VLBI) is opening entirely new realms of possibility.

According to a recent study by researchers from Australia and Singapore, a new quantum technique could enhance optical VLBI. It's known as Stimulated Raman Adiabatic Passage (STIRAP), which allows quantum information to be transferred without losses. When imprinted into a quantum error correction code, this technique could allow for VLBI observations into previously inaccessible wavelengths. Once integrated with next-generation instruments, this technique could allow for more detailed studies of black holes, exoplanets, the Solar System, and the surfaces of distant stars.

The research was led by Zixin Huang, a postdoctoral research fellow with the Center for Engineered Quantum Systems (EQuS) at Macquarie University in Sydney, Australia. She was joined by Gavin Brennan, a professor of theoretical physics with the Department of Electrical and Computer Engineering and the Center of Quantum Technologies at the National University of Singapore (NUS), and Yingkai Ouyang, a senior research fellow with the Center of Quantum Technologies at NUS.

To put it plainly, the interferometry technique consists of combining light from multiple telescopes to create images of an object that would otherwise be too difficult to resolve. Very Long Baseline Interferometry refers to a specific technique used in radio astronomy where signals from an astronomical radio source (black holes, quasars, pulsars, star-forming nebulae, etc.) are combined to create detailed images of their structure and activity. In recent years, VLBI has yielded the most detailed images of the stars that orbit Sagitarrius A* (Sgr A*), the

SMBH at the center of our galaxy (see above).

It also allowed astronomers with the Event Horizon Telescope (EHT) Collaboration to capture the first image of a black hole (M87*) and Sgr A* itself. But as they indicated in their study, classical interferometry is still hindered by several physical limitations, including information loss, noise, and the fact that the light obtained is generally quantum in nature (where photons are entangled). By addressing these limitations, VLBI could be used for much finer astronomical surveys. Said Dr. Huang to universe Today via email:

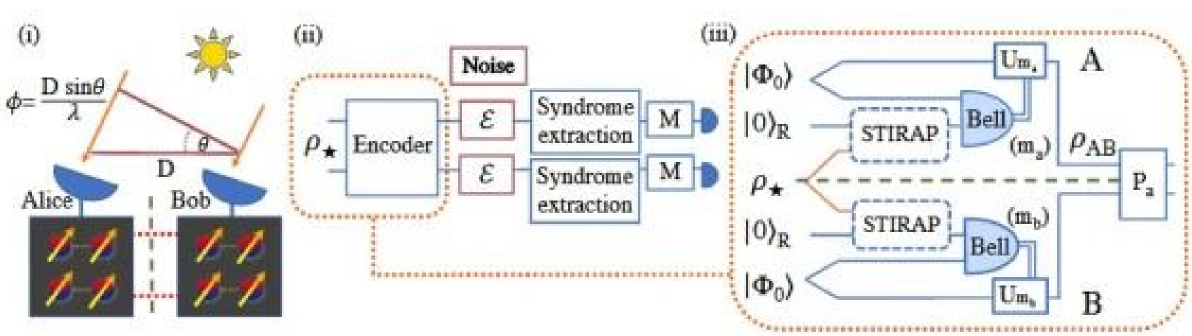
"Current state-of-the-art large baseline imaging systems operate in the microwave band of the electromagnetic spectrum. To realize optical interferometry, you need all parts of the interferometer to be stable to within a fraction of a wavelength of light, so the light can interfere. This is very hard to do over large distances: sources of noise can come from the instrument itself, thermal expansion and contraction, vibration and etc.; and on top of that, there are losses associated with the optical elements."

"The idea of this line of research is to allow us to move into the optical frequencies from microwaves; these techniques equally apply to infrared. We can already do large-baseline interferometry in the microwave. However, this task becomes very difficult in optical frequencies, because even the fastest electronics cannot directly measure the oscillations of the electric field at these frequencies."

The key to overcoming these limitations, says Dr. Huang and her colleagues, is to employ quantum communication techniques like Stimulated Raman Adiabatic Passage. STIRAP consists of using two coherent light pulses to transfer optical information between two applicable quantum states. When applied to VLBI, said Huang, it will allow for efficient and selective population transfers between quantum states without suffering from the usual issues of noise or loss.

As they describe in their paper, "Imaging stars with quantum error correction," the process they envision would involve coherently coupling the starlight into "dark" atomic states that do not radiate. The next step, said Huang, is to couple the light with quantum error correction (QEC), a technique used in quantum computing to protect quantum information from errors due to decoherence and other "quantum noise." But as Huang indicates, this same technique could allow for more detailed and accurate interferometry:

"To mimic a large optical interferometer, the light must be collected and processed coherently, and we propose to use quantum error correction to mitigate errors due to loss and noise in this process. Quantum error correction is a rapidly developing area mainly focused on enabling scalable quantum computing in the presence of errors. In combination with pre-distributed entanglement, we can perform the operations that extract the information we need from starlight while suppressing noise."



Overview of the STIRAP protocol proposed by Dr. Huang and colleagues. Credit: Huang, Z. et al. (2022)

To test their theory, the team considered a scenario where two facilities (Alice and Bob) separated by long distances collect astronomical light. Each share pre-distributed entanglement and contain "quantum memories" into which the light is captured, and each prepare its own set of quantum data (qubits) into some QEC code. The received quantum states are then imprinted onto a shared QEC code by a decoder, which protects the data from subsequent noisy operations.

In the "encoder" stage, the signal is captured into the quantum memories via the STIRAP technique, which allows the incoming light to be coherently coupled into a non-radiative state of an atom. The ability to capture light from astronomical sources that account for quantum states (and eliminates quantum noise and information loss) would be a game-changer for interferometry. Moreover, these improvements would have significant implications for other fields of astronomy that are also being revolutionized today.

"By moving into optical frequencies, such a quantum imaging network will improve imaging resolution by three to five orders of magnitude," said Huang. "It would be powerful enough to image small planets around nearby stars, details of solar systems, kinematics of stellar surfaces, accretion disks, and potentially details around the event horizons of black holes—none of which currently planned projects can resolve."

In the near future, the James Webb Space Telescope (JWST) will use its advanced suite of infrared imaging instruments to characterize exoplanet atmospheres like never before. The same is true of ground-based observatories like the Extremely Large Telescope (ELT), Giant Magellan Telescope (GMT), and Thirty Meter Telescope (TMT). Between their large primary mirrors, adaptive optics, coronagraphs, and spectrometers, these observatories will enable Direct Imaging studies of exoplanets, yielding valuable information about their surfaces and atmospheres.

By taking advantage of new quantum techniques and integrating them with VLBI, observatories will have another way to capture images of some of the most inaccessible and hard-to-see objects in our universe.

More information: Zixin Huang, Gavin K. Brennen, Yingkai Ouyang, Imaging stars with quantum error correction. arXiv:2204.06044v1 [quant-ph], arxiv.org/abs/2204.06044

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