Cover Page

Topical White Paper: Quantum Enhanced Very Long Baseline Interferometry (QE-VLBI)

Primary Author: Michael G. Raymer, 541-790-1928, University of Oregon, raymer@uoregon.edu

Co-Authors:

Matthew Brown, University of Oregon, mbrown9@uoregon.edu

Paul Kwiat, University of Illinois Urbana-Champaign, kwiat@illinois.edu

Virginia Lorenz, University of Illinois Urbana-Champaign, vlorenz@illinois.edu

John Monnier, University of Michigan, monnier@umich.edu

Topic: Increasing the baseline of interferometric optical telescopy using quantum technology

 Abstract:

Current advances in quantum information science make it feasible in the next decade to construct quantum enhanced Very Long Baseline Interferometry in the optical regime, surpassing the baseline limits now imposed by signal loss and decoherence. Such telescopes will have orders-of-magnitude greater angular resolution than conventional ones, with applications in astronomy, geodesy, and defense. The fundamental principle on which such telescopes will be built is quantum-assisted nonlocal optical measurements and will rely on entanglement distribution via quantum networks now being developed.

Quantum Enhanced Very Long Baseline Interferometry (QE-VLBI) in the Optical Spectrum

The angular resolution of a telescope is limited ultimately by its aperture size as a consequence of well-known principles of wave optics. Synthetic-aperture telescopes overcome the challenge of creating ever-larger single-element lenses or mirrors by combining light coherently from two or more telescopes separated by a distance called the baseline, analogous to Young’s double-slit experiment. [mon03] The proof-of-principle experiment was demonstrated by Michelson exactly 100 years ago. [mic21] Large arrays, such as CHARA, have raised the technique of optical stellar interferometry to a high art, allowing researchers to resolve spatial detail of astronomical objects in the optical (visible or near-visible) spectrum with resolutions in the milli-arcsecond regime. [ped09]

The main fundamental impediments to creating arrays of *optical* telescopes larger than a few kilometers are signal loss and phase-stability degradation during transmission of stellar optical signals from the telescopes to a central receiving site where they are combined coherently. An alternative to combining stellar signals directly is offered by optical heterodyne detection at each collector site with subsequent coherent combination of the resulting electronic signals, as pioneered by Townes. [joh74] While this method avoids the need for weak stellar light to travel to the combining site, the shot noise created during heterodyne detection limits the sensitivity and precision of such methods, equivalent to noise from >1000 K thermal background (kT = hν). [mon03] Radio telescope arrays do not suffer from these limitations, as amplitude-and-phase signals can be recorded directly to magnetic storage using atomic clocks for timing synchronization, and shot noise is not an issue at low frequencies. Signals from radio telescopes spread across the Earth can now be combined to form astounding images of objects such as black holes. [bou20] At present, such clock-based schemes are not feasible in the optical spectrum, as distributed clock signals are not sufficiently stable and, more importantly, no detector exists that can record amplitude and phase without introducing large levels of shot noise (as in heterodyne detection).

Costs for telescopes built in traditional ways are reaching new extremes, as the 39 m Extremely Large Telescope will cost >1.3B euros and the 6.5 m NASA JWST over $10B. Astronomers require significantly bigger telescopes/interferometers to pursue the most exciting astronomical topics, such as recent Nobel-winning pursuits as exoplanets and black holes. For example, hunting for water vapor and detecting signs of life around nearby Earth-like exoplanets will likely require greater <1 milliarcsecond angular resolution (> 100meter baselines) to separate and block out the strong background flux from host stars. Even harder, zooming into the event horizon of black holes requires orders of magnitude greater resolution still (> 100 km baselines). We need engineering breakthroughs in how light is manipulated and combined in space to push ahead, and quantum-enhanced very long baseline interferometry (QE-VLBI) will offer new paths to practical solutions.

Here we outline a disruptive new interferometer architecture that leverages advances in quantum theory, entangled light sources, high-speed and high-efficiency photon-counting detector arrays, and space accessibility that could enable addressing fundamental scientific questions and significantly expanding the parameter space of discovery [rin20, rid20]. Research areas that will benefit from these advances (resolution and increased sensitivity) include planet formation and imaging [mon20a, mon20b, rin20], stellar formation and structure and the study of their physical parameters [roe20, van20], probing the inner structure of active galaxies, the matter accreting into black holes [kis20], as well as the equation of state of degenerate matter in white dwarf stars [rin20].

In addition, looking down instead of up is useful for geodesy—the science of accurately measuring, mapping, and understanding the Earth's geometric shape, orientation in space, and gravity field, as well as measuring the movement of tectonic plates and thickness of ice sheets.

There is growing confidence that quantum information technology (QIT) can provide the needed fundamental resources and techniques to overcome the challenges in extending baseline distances for synthetic telescope arrays in the optical spectrum. The essence of optical QIT is the use of entangled states of light to enable sensing, communicating, or computing to extend capabilities beyond those allowed by ‘classical’ techniques. The rapid growth of this field is embodied in the U.S. National Quantum Initiative (NQI). [mon19, NSTC21] The emphasis of the NQI is to focus on ‘science first,’ with the idea that technical and commercial applications will follow naturally. [OSTP18]

It is known that QIT techniques can, in principle, extend the baseline of optical arrays to arbitrarily large distances, [tsa19, kha19a, kha19b, czu21], although the path to practical implementation is arduous, requiring optimized sources of entangled photons, massively parallel quantum light detectors, and high-capacity quantum memories. The path to success may take a decade or longer to traverse, but the community’s view is that now is the ideal time to begin serious work given the rapid progress now being seen in QIT R&D. Nascent efforts in this direction are already being undertaken, either funded by or being considered by NSF, DOE, NIST, NASA, and other agencies.

There are several principal proposals currently for QE-VLBI in the optical spectrum. One is analogous to the radio-telescope scheme and involves recording optical signals from an astronomical source in coherent quantum memories located at each telescope and physically moving those memories to a central location for coherent quantum processing. [bla21] That method requires an extreme level of quantum hardware to be fully functional and so is seen as a long-term solution at best. A more practical approach, relying on nearer-term quantum technology is that proposed by Gottesman, et. al. [got12] and refined by Khabiboulline et. al. [kha19a, kha19b], and further improved by Czupryniak, et al. [czu21]. Both rest on a fundamental theorem proved by Tsang that “in the case of weak thermal light, any local measurement scheme must be significantly inferior to a nonlocal one for the estimation of the mutual coherence according to quantum mechanics.” [tsa19] Nonlocal schemes include the standard Michelson approach, wherein signals are brought together spatially to interfere, and notably the use of quantum information resources to mimic a nonlocal scheme fully while not being required to bring the stellar optical signal together. In particular, Tsang showed that the spatial structure of a distant thermal or incoherent source (such as a star) can be obtained with high precision and resolution by combining the incoming signals locally at each telescope with light fields that are quantum entangled with one another. Tsang showed, using Fisher information, that such a scheme yields (within a factor of two) the same information per source photon as the direct combining (Michelson) technique, but does not need to suffer from signal transmission losses as occurs in the direct method.



The figure shows schematically the quantum enhanced VLBI scheme using *N* telescopes, where the inner details of only two telescopes are shown (the others being indicated by dashed lines). A laser (CW or pulsed) drives a nonlinear-optical crystal to emit pairs of photons entangled in time and energy (frequency), meaning that the energies within each pair sum to the fixed energy of a laser photon while the members of each pair are also tightly correlated in time. Such a state is analogous to the famous Einstein-Podolsky-Rosen state and can be used to violate a Bell inequality verifying nonlocal quantum correlations. The photons in each pair are broadband, permitting multichannel frequency-correlated joint detection. One of them from each pair is sent to a spectrally resolved single-photon detection array (frequency demultiplexer), the activation of a single pixel of which serves as a ‘herald,’ giving quantum information about its partner photon that has been distributed equally using beam splitters among all the telescope sites. At each telescope site the stellar light is spectrally demultiplexed (say with a diffraction grating) and interfered with the corresponding spectral channel of the heralded single photon (which acts as a ‘quantum nonlocal oscillator’, satisfying Tsang’s requirement mentioned above.) In particular, if the light in the spatial modes detected by two telescopes is coherent, then the coincidence rate between same-color detectors at the two telescopes (i.e., detecting one photon at each) will display two-photon interference fringes as the relative phase of the terrestrial-produced photon propagating to the two telescopes is varied.

The advantages of such a scheme are that the stellar photons do not need to travel long distances from each telescope to a central site to be interfered, and the quantum nonlocal oscillator light does not introduce shot noise ideally, as it contains a fixed number of photons in each detection event. Image reconstruction follows the standard method of varying the baseline and computing a Fourier transform of the interference visibility observed as a function of baseline. While much remains to be done, a single-channel implementation of this ‘Gottesman’ scheme has been demonstrated and reported at a NASA meeting. [ray21] and at Frontiers in Optics 2021 [bro21, dia21].

The ‘Gottesman’ scheme suffers in practice from major barriers: the nonlocal oscillator light can suffer losses during distribution to the telescope sites, and the stellar photons are sparse in the time-frequency domain, making it an inefficient strategy to create nonlocal oscillator photons at a rate high enough to fill all time-frequency (phase-space) slots, most of which are ‘empty’. Note that the implementation in the figure is without quantum memories. Khabiboulline et. al. proposed that using multichannel memories that could store many nonlocal oscillator photons at each site could overcome these barriers. [kha19a] Steady streams of nonlocal oscillator photons would be sent from a central location to be stored as entangled memory elements. If a photon is lost in transmission or if detection of the partner photon fails, another pair could immediately replace it, building up a buffered collection of photons that would be used on demand as needed at each site. Implementing such a scheme is perhaps tens years out, as it requires massively parallel (multimode) quantum memories. If the telescopy community begins working now with the quantum-memory community, the needs for attributes of the developing technology can be targeted at successful implementation of optical VLBI arrays in the optical.

In the meantime, there is much groundwork to be demonstrated leading in a well-planned path to deployment of a quantum enhanced VLBI system. Several groups or consortia in the U.S. are now working to construct the elements of a quantum communications network or a Quantum Internet. [paper Eden sent me] A main task of such networks will be to provide entangled states of light to remote users as a ‘resource’ (analogous to a power grid providing energy as a resource). Such a network could, when operational, provide the entangled photon pairs at the high rates needed to implement tests of the memoryless ‘Gottesman’ scheme, already under development without such a network, as mentioned earlier. Thus, a logical path to the final configuration is available: memoryless ‘Gottesman’ scheme over single optical fiber lengths; then ‘Gottesman’ scheme with Quantum Internet distribution of nonlocal oscillator photons; then Gottesman/Khabiboulline/Czupryniak scheme with quantum memories. As a point of progress, recently two quantum memories have been entangled over dozens of kilometers via fibers. [yu20]

To develop a quantum enhanced VLBI system that will outperform conventional ones, several technical advances will be needed, all of which have applications reaching far beyond VLBI itself:

• Low-noise, high-efficiency single-photon detector arrays.

 Superconducting nanowire detectors have become the workhorse of quantum optical experimental systems, as they have high (0.98) quantum efficiency across the visible and near infrared. [red20] Compact collections of such detectors have been fabricated in large arrays.

• High-rate efficient sources of heralded single photons.

 Sources based on spontaneous parametric down conversion or four-wave mixing enable the preparation of heralded single-photon states. However, to be efficient it is necessary to introduce some form of multiplexing (spatial, temporal or spectral), to suppress multi-photon events while maintaining a high rate of single photons.

• Massively parallel (multimode) quantum memories.

 There are many approaches to creating quantum memories to store coherently the states of photons. Parallelism is achieved in various ways, including a spatial array of many single-qubit storage elements (such as single atoms or ions in individual microcavities) or spectral multiplexing wherein photons of distinct colors are stored in a single bulk crystal doped with inhomogeneously broadened impurity ions. [sim10]

• Quantum communication network to distribute entangled photons to telescope sites with low loss and high fidelity.

 Several groups, centers, and agencies in the U.S. are actively pursuing the creation of quantum networks capable of distributing entangled photon pairs over distances exceeding 1000 km.

• Fast computer and hardware systems for control and data analysis.

 Time-tagging event loggers are becoming very powerful and are available from several companies. Single-photon arrivals can be recorded with 10-ps resolution and processed in real time using FPGAs or sent to hard disk for later processing.

Finally, to point out the broader interest in advancing optical imaging and VLBI, we point out other approaches that are inspired by quantum information science while not using quantum entangled states or quantum communication. One is a proposal by Stankus et. al. [sta21], in which two photons from different point-like stellar sources are interfered at two separate and decoupled stations, requiring only a slow classical information link between them. This scheme can be seen as a generalization of the conventional Hanbury Brown & Twiss (HBT) pair-intensity interferometry, as it introduces interference effects inspired by quantum information science. A second novel method uses recent advances in optical detectors. Superconducting transition-edge sensors that allow one to distinguish, with high efficiency, between integer numbers of photons arriving in a short pulse, up to around 15 photons. [mor20] This technology has been demonstrated to improve single-aperture imaging. [how19]

In summary, the rapid advances being made in quantum information science—in particular single-photon sources and detectors, and entanglement distribution via quantum networks—make the present decade the right time to begin serious development efforts of quantum enhanced VLBI in the optical regime.

**References**

[bla21] Bland-Hawthorn, Joss, Matthew Sellars, and John Bartholomew. "Quantum memories and the double-slit experiment: implications for astronomical imaging.” Journal of the Optical Society of America B, 38, pp. A86-A98 (2021)

 [*https://doi.org/10.1364/JOSAB.424651*](https://doi.org/10.1364/JOSAB.424651)

[bou20] Bouman, Katherine L. "Portrait of a black hole: Here's how the event horizon telescope team pieced together a now-famous image." *IEEE Spectrum* 57, no. 2 (2020): 22-29.

DOI: [10.1109/MSPEC.2020.8976898](https://doi.org/10.1109/MSPEC.2020.8976898)

[bro21] Matthew Brown et/ al., “Interferometry-Based Astronomical Imaging Using Nonlocal Interference with Single-Photon States”. Frontiers in Optics Conference, (FTh6D.4), 04 November (2021)

[che11] Che, X., J. D. Monnier, M. Zhao, E. Pedretti, N. Thureau, A. Mérand, T. Ten Brummelaar et al. "Colder and hotter: interferometric imaging of β Cassiopeiae and α Leonis." *The Astrophysical Journal* 732, no. 2 (2011): 68. <https://doi.org/10.1088/0004-637X/732/2/68>

[czu21] Czupryniak, Robert, John Steinmetz, Paul G. Kwiat, and Andrew N. Jordan. "Optimal photonic gates for quantum-enhanced telescopes." *arXiv preprint* (2021).

<https://arxiv.org/abs/2108.01170>

[dia21] David Diaz et. al., “Emulating Quantum-Enhanced Long-Baseline Interferometric Telescopy.” Frontiers in Optics Conference, (FTh6D.7), 04 November (2021)

[got12] Gottesman, Daniel, Thomas Jennewein, and Sarah Croke. "Longer-baseline telescopes using quantum repeaters." *Physical review letters* 109, no. 7 (2012): 070503. <https://doi.org/10.1103/PhysRevLett.109.070503>

[how19] Howard, L. A., G. G. Gillett, M. E. Pearce, R. A. Abrahao, T. J. Weinhold, P. Kok, and A. G. White. "Optimal imaging of remote bodies using quantum detectors." *Physical review letters* 123, no. 14 (2019): 143604. <https://doi.org/10.1103/PhysRevLett.123.143604>

[joh74] Johnson, M. A., A. L. Betz, and C. H. Townes. "10-μm heterodyne stellar interferometer." *Physical Review Letters* 33, no. 27 (1974): 1617.

<https://doi.org/10.1103/PhysRevLett.33.1617>

[kha19a] Khabiboulline, Emil T., Johannes Borregaard, Kristiaan De Greve, and Mikhail D. Lukin. "Optical interferometry with quantum networks." *Physical Review Letters* 123, no. 7 (2019): 070504. <https://doi.org/10.1103/PhysRevLett.123.070504>

[kha19b] Khabiboulline, Emil T., Johannes Borregaard, Kristiaan De Greve, and Mikhail D. Lukin. "Quantum-assisted telescope arrays." *Physical Review A* 100, no. 2 (2019): 022316.

<https://doi.org/10.1103/PhysRevA.100.022316>

[kis20] Kishimoto, M., et al. “Exploring active supermassive black holes at 100 micro-arsec resolution,” Astro2020, <https://baas.aas.org/pub/2020n3i156/release/1>

[mic21] Michelson, Albert A., and Francis G. Pease. "Measurement of the diameter of Alpha-Orionis by the interferometer." *Proceedings of the National Academy of Sciences of the United States of America* 7, no. 5 (1921): 143. doi: [10.1073/pnas.7.5.143](https://dx.doi.org/10.1073/pnas.7.5.143)

[mon03] Monnier, John D. "Optical interferometry in astronomy." *Reports on Progress in Physics* 66, no. 5 (2003): 789-857.

<https://iopscience.iop.org/article/10.1088/0034-4885/66/5/203>

[mon19] Monroe, Christopher, Michael G. Raymer, and Jacob Taylor. "The us national quantum initiative: From act to action." *Science* 364, no. 6439 (2019): 440-442.

[DOI: 10.1126/science.aax0578](https://doi.org/10.1126/science.aax0578)

[mon20a] Monnier, J., et al. “The future of exoplanet direct detection,” Astro2020, <https://baas.aas.org/pub/2020n3i514/release/1>

[mon20b] Monnier, J., et al. “Imaging the key stages of planet formation,” Astro2020, <https://baas.aas.org/pub/2020n3i498/release/1>

[mor20] Morais, Leonardo Assis, Till Weinhold, Marcelo P. de Almeida, Adriana Lita, Thomas Gerrits, Sae Woo Nam, Andrew G. White, and Geoff Gillett. "Precisely determining photon-number in real-time." (2020). <https://arxiv.org/abs/2012.10158>

[NSTC21] [A Coordinated Approach to Quantum Networking Research](https://www.quantum.gov/wp-content/uploads/2021/01/A-Coordinated-Approach-to-Quantum-Networking.pdf), January 19, 2021

<https://www.quantum.gov>

[OSTP18] [National Strategic Overview for Quantum Information Science](https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf), September 24, 2018

<https://www.quantum.gov>

[ped09] Pedretti, Ettore, John D. Monnier, Theo Ten Brummelaar, and Nathalie D. Thureau. "Imaging with the CHARA interferometer." *New Astronomy Reviews* 53, no. 11-12 (2009): 353-362. <https://doi.org/10.1016/j.newar.2010.07.008>

[ray21] Michael Raymer, Matthew Brown, Valerian Thiel, Markus Allgaier, Brian Smith, Paul Kwiat, and John Monnier, “Interferometric Imaging Using Single-Photon States as a Nonlocal Oscillator,” NASA Quantum Conference, Virtual Event, August 17-19, 2021

[red20] Reddy, Dileep V., Robert R. Nerem, Sae Woo Nam, Richard P. Mirin, and Varun B. Verma. "Superconducting nanowire single-photon detectors with 98% system detection efficiency at 1550 nm." *Optica* 7, no. 12 (2020): 1649-1653.

<https://doi.org/10.1364/OPTICA.400751>

[rid20] Ridgway, S., et al. “Revitalizing the optical/infrared interferometry community in the US,” Astro2020, https://baas.aas.org/pub/2020n7i157/release/1

[rin20] Rinehart, S. A., et al. “A long-term vision for space-based interferometry,” Astro2020, <https://baas.aas.org/pub/2020n7i222/release/1>

[roe20] Roettenbacher, R., et al. “High angular-resolution astrophysics: resolving stellar surface features,” Astro2020, <https://baas.aas.org/pub/2020n3i181/release/1>

[sim10] Simon, Christoph, Mikael Afzelius, Jürgen Appel, A. Boyer De La Giroday, S. J. Dewhurst, Nicolas Gisin, C. Y. Hu et al. "Quantum memories." *The European Physical Journal D* 58, no. 1 (2010): 1-22. doi <https://doi.org/10.1140/epjd/e2010-00103-y>

[sta21] Stankus, Paul, Andrei Nomerotski, Anže Slosar, and Stephen Vintskevich. "Two-photon amplitude interferometry for precision astrometry." *arXiv preprint* (2021)

<https://arxiv.org/abs/2010.09100>

[tsa19] Tsang, Mankei. "Resolving starlight: a quantum perspective." *Contemporary Physics* 60, no. 4 (2019): 279-298. <https://doi.org/10.1080/00107514.2020.1736375>

[yu20] Yu, Yong, Fei Ma, Xi-Yu Luo, Bo Jing, Peng-Fei Sun, Ren-Zhou Fang, Chao-Wei Yang et al. "Entanglement of two quantum memories via fibres over dozens of kilometres." *Nature* 578, no. 7794 (2020): 240-245. <https://doi.org/10.1038/s41586-020-1976-7>

[van20] van Belle, G. “High-angular resolution astrophysics: Fundamental stellar parameters,” Astro2020, <https://baas.aas.org/pub/2020n3i381/release/1>