Quantum-Assisted Observatories in Space: Real-Time Coherence in Space Telescope Arrays via Shared Quantum States

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(Dated: 26 October 2023)

We show how quantum entanglement may be able to improve the joint performance of a system of telescopes, cameras, or other sensors which are widely separated in space. The improvement is relative to any observation strategy that uses only classical coordinating devices. Potential application domains include space-based observatories and multi-frequency interferometry.

I. INTRODUCTION

Distributing a set of astronomical observatories across a vast region of space (e.g., as in the proposed LISA constellation[1,2]) has the potential to capture hit-or-miss events in great detail via appropriate choices of complementary positioning, instruments, and settings.

Some of the most interesting astronomical events can be very quick and unpredictable. For instance, the final moments in a merger of two black holes are detected by gravitational sensors such as LIGO as a brief "chirp"[3,4]. Furthermore, for supernova events there is very little information on the initial phase of that process because it is rare that a telescope would be already pointed in the right direction[5,6,7].

If more than one sensor is active on a target the event can often be resolved in much greater detail, sometimes exploiting the offset between the different views, as with interferometry techniques, and sometimes exploiting the joint information that results from combining the output of complementary sensor types[8,9].

Ideally, then, when multiple observatories become aware of a new event, they will follow a coordinated observation strategy. However, depending on the timeline of each new event, communication among observatories may be too slow to be useful. In this case, the best those observatories can do is to resort to optimal autonomous decisions based on their local information. We represent this decision problem faced by a set of distant observatories as a team game. We then consider a few sample scenarios, and identify the optimal performance that can be obtained with classical observation strategies. We go on to show that, in those scenarios, the availability of a shared quantum state enables the observatories to coordinate their choices in a way that strictly improves on their optimal uncoordinated performance.

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II. OBSERVATORIES WITH RANDOM ORIENTATION

We assume that there are two identical observatories, each randomly (i.e., uniformly and independently) oriented with respect to the other along a common plane, and each with a hemispherical field of view. Each observatory (1 and 2) has a choice of two frequency bands (R and G) that it can alternatively select at any time.

We also assume that the payoff from a joint observational strategy depends on the join (union) and meet (intersection) of the two fields of view. Specifically, when the two observatories look in opposite directions, then they receive a joint payoff of 1 in case they use the same frequency band (e.g., because the two images can be stitched), and 0 otherwise. When they look in the same direction, they receive a payoff of 0 if using the same frequency band (e.g., because the two images are redundant), and 1 otherwise (e.g., because multi-band observations of the same target are more informative). When the overlap (meet) is a fraction $p = \cos^2(\theta/2)$ of the field of view, then the payoff is the convex combination of the two limit cases with weights p and $1-p$.

A (deterministic) strategy for observatory i (for $i = 1,2$) is a function returning a choice of frequency for each orientation.

To find the maximum payoff that the two observatories can obtain, we conceive of the situation as a team decision problem[10]. Using arguments from game theory, we can then classify this team problem as a Kuhn tree with imperfect recall and conclude that the two observatories cannot improve their joint performance by making use of any classical coordinating device (i.e., any classical shared randomness)[11,12,13]. So, we can concentrate on finding the best payoff under deterministic strategies.

Let α and β be the two angles at which the observatories are oriented with respect to a predetermined common direction. Also, let $f(\alpha)$ and $g(\beta)$ be two Boolean functions, representing the respective strategies of the two observatories, depending on the angle at which they are oriented.

The expected payoff is then given by

$$\frac{1}{4\pi^2}\int_0^{2\pi}\int_0^{2\pi}[(1-|1-f(\alpha)-g(\beta)|)\cos^2((\alpha-\beta)/2)+$$

$$|1-f(\alpha)-g(\beta)|\sin^2((\alpha-\beta)/2)]\,\mathrm{d}\alpha\,\mathrm{d}\beta =$$

$$\frac{1}{2}+\frac{1}{4\pi^2}\int_0^{2\pi}\int_0^{2\pi}|1-f(\alpha)-g(\beta)|\cos(\alpha-\beta)\,\mathrm{d}\alpha\,\mathrm{d}\beta.$$

We constrain f to take the value 1 on one semicircle and the value 0 on the opposite semicircle. We constrain g similarly with respect to a (different) semicircle. It can then be shown that the maximum value of this second integral is $2/\pi^2$, obtained by choosing the semicircles for f and g to be out of phase by π. The highest expected payoff obtained with deterministic strategies is therefore $1/2+2/\pi^2 \approx 0.7026$.

Observe that such optimal strategies can only be implemented if there exists a common predetermined direction, from which the two angles are computed. Hence, achieving the classical bound requires absolute positioning capabilities at the two sites.

We now assume that the two observatories share a quantum state, namely, a Bell state pair[14,15], which has the property that its two quantum bits (qubits) always return opposite answers if measured in the same basis. If the two qubits are observed in different bases, then their outcomes agree with probability $1-\cos^2\phi$, where ϕ is the relative angle between the two bases[16].

In this scenario, the action taken by each observatory can be made dependent on the outcome of measurement of its respective qubit. Consider the following strategy: Each observatory measures its respective qubit in the basis defined by the direction at $1/2$ of its current angle, and its orthogonal complement along the plane. If the outcome is 0 then the chosen action is R, otherwise it is G. In this case the two outcomes agree with probability $1-\cos^2(\theta/2)$, where $\theta=\alpha-\beta$ is the relative angle at which the two observatories are oriented. Therefore, the expected payoff is now given by

$$\frac{1}{\pi}\int_0^{2\pi}\cos^4(\theta/2)\,d\theta=\frac{3}{4}=0.75,$$

a strict improvement over the classical bound.

III. N OBSERVATORIES WITH COSTLY ACTIONS

Consider a set-up with N (pairwise distant) observatories. The current state of each observatory belongs to a set X (including all possible combinations of current positioning, instruments, and settings, as well as the output from recent observations). There is a set of (mutually exclusive) actions A available to each observatory (e.g., a choice of positioning, instruments, and settings) which may be taken by an observatory as a function of its current state.

We assume that, whenever a new event E occurs, it will be detected with probability $p_x(E)$ by an observatory in state $x \in X$. We further assume that detections are independent. There is a cost $c(a)$ associated to each action $a \in A$. The overall team payoff is a function of the combined output of different observatories. The payoff function can be nonlinear: For instance, tracking the same event in complementary frequency bands could reveal additional detail, and hence be more valuable compared with tracking it all in the same band. Moreover, two or more images in the same frequency band could sometimes be redundant (depending, for instance, on the relative position of the observatories with respect to the event), while other times they could be strictly more valuable than a single one.

As before, this situation can be conceived of as a Kuhn tree with imperfect recall, and the observatories cannot, therefore, benefit from classical coordinating devices[13]. There is then at least one optimal classical strategy that is purely deterministic.

We now give two examples of situations where the best performance that the observatories can achieve under a classical strategy is strictly lower than the performance achievable when the observatories share a multipartite quantum state, and make their choices of action contingent on the outcome of measurement on their respective qubit.

Specifically, let us consider N observatories, where each observatory can be in one of several possible states. For example, there may be exactly one of three types of target in its field of view. Each observatory can take a costly action (e.g., actively tracking a target) or a costless one (e.g., no tracking). In reality, actively tracking a target is only part of the full action set of a telescope, together with a choice of instruments and settings, but for simplicity in our model we concentrate on only two of those actions: tracking or not.

We further suppose that each observatory can be in any of the possible states with equal probability, and independently of other observatories.

Next, we assume that the payoff from observing any given event, in the case that k observatories happen to track it, is given by $v-kp$, where $p<v<2p$. Thus, it is always worthwhile tracking an event, but only via a single observatory and not more. We define $s=v-p$ to be the net benefit from a single observation. We can therefore write the (overall) payoff as $s-(k-1)p$.

Finally, we assume that the payoff from tracking m different events simultaneously via k observatories is given by $mv-kp+\varepsilon_m$, where $\varepsilon_1=0$ and ε_m (for $m>1$) is a strictly positive and increasing payoff contribution that reflects complementarity (e.g., the additional value of combining synchronous observations of multiple targets).

If the cost of redundancy is sufficiently high, that is, if $p>>s,\varepsilon_m$, then the best deterministic (and hence, best classical) strategies all involve assigning separate players to become active on different types of event.

With two observatories and two types of event, the best deterministic (and hence, the best classical) strategy is therefore for each observatory to become active on a separate type. With three types of event, the best classical strategy is to make one observatory active for a single type of event, and the other active on the two remaining ones. In the latter case, the two observatories generate an expected payoff of

$$s+(8/36)\varepsilon_2.$$

This payoff can be strictly improved on if the two observatories share a quantum state, and they are able to make measurements on one or more quantum bits (qubits) before deciding which action to take given the type of event that has occurred.

In particular, let us assume that the two observatories share a Bell state pair of qubits, so that, when measured in the same basis, the two qubits always give opposite outcomes. Now, before deciding whether or not to track a new object of a given type, an observatory can measure its respective quantum bit in a basis corresponding to the type of event, and make its choice of action contingent on the outcome. Specifically, measuring their respective qubits at 0, 120, and 240 degrees, depending on the realized type, allows the two observatories always to take opposite actions if measuring in the same direction, while taking the same action with probability $1-\cos^2(2\pi/3)$ if measuring in different directions. The best expected payoff generated by such quantum-assisted strategies is given by

$$s+(9/36)\varepsilon_2,$$

which strictly exceeds the classical bound.

With three observatories and three types, the best classical strategy is once again to appoint each player to become active on a different type of event. With three players and four types, the best classical strategy assigns a single type to each observatory, except for one observatory that also becomes active on an additional type. The best classical payoff in this case is given by

$$s+(56/256)\varepsilon_2+(8/256)\varepsilon_3.$$

A quantum-assisted strategy which generates a strictly higher payoff is the following: One player is assigned to one type, and the two others coordinate on the remaining three types by means of a Bell state pair, just as in the two-observatories, three-types scenario. This leads to a payoff of

$$s+(57/256)\varepsilon_2+(9/256)\varepsilon_3,$$

which is again strictly higher than the best payoff in the classical case.

More generally, for this family of scenarios we conjecture that a quantum advantage exists just in case the number of types is strictly higher than the number of players. Our examples above assumed independent distributions of types across observatories, but we conjecture that the quantum advantage also carries over to scenarios with exchangeable distributions. In this regard, we note that exchangeability puts a lower bound on the negative correlation possible across pairs of states.

IV. DISCUSSION

Space systems are in many ways the ideal application domain for wide-scale quantum state distribution, since different elements are typically at great distance from each other, making rapid communication impossible.

Moreover, quantum signals can travel undisturbed in the void of space. Wide-area distribution of entangled quantum states from space was demonstrated in the QUESS experiment, which successfully established a quantum link across distant Earth-based locations[17,18].

While coordination via sharing a quantum state is limited by the no-signaling principle[19], it nevertheless enables patterns of activity that are not available classically. We have demonstrated analytically the existence of a quantum advantage in a few abstract scenarios. In many other scenarios that are not analytically tractable, a quantum advantage may also exist.

In the sample scenarios we presented, a quantum advantage can already be obtained by distributing simple Bell pairs. It may be even more desirable to make use of more general multi-party entangled states such the GHZ state[20]. However, relative to other types of entangled states, Bell state pairs would seem to be among the easiest to generate and distribute in space-based applications.

ACKNOWLEDGEMENTS

We are grateful to David Pérez García and Rafael Miñano Rubio for mathematical advice and to the audience at the 69th International Astronautical Congress, Bremen, Germany, 2018, for helpful comments. Brandenburger acknowledges financial support from NYU Stern School of Business, NYU Shanghai, and J.P. Valles. La Mura acknowledges financial support from the Deutsche Bundesbank. Scarpa acknowledges the support of QUITEMAD-CM P2018/TCS4342 funded by CAM/FEDER, MTM2014-54240-P, ICMAT Severo Ochoa project SEV-2015-0554, and PID2020-113523GB-I00 funded by MCIN/AEI/10.13039/501100011033 and by “ERDF A way of making Europe.”

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

PRIOR PUBLICATION

This paper was originally presented at the International Astronautical Congress (IAC 2018), October 1-5, 2018, Bremen, Germany, `www.iafastro.org`, and was included in the IAC Proceedings and the International Astronautical Federation Digital Library, at `https://dl.iafastro.directory/`. It is submitted here with permission from the IAF.

FINANCIAL INTEREST

Brandenburger, La Mura, and New York University hold U.S. patent #10056983, “Quantum-Assisted Load Balancing in Communication-Constrained Wide-Area Physical Networks,” which referenced 13 in its application.

[1] LISA: Laser Interferometer Space Antenna, LISA Consortium, at `https://www.elisascience.org`.

[2] A. Belenchia et al., *Phys. Rep.*, **951**, 1-70 (2022).

[3] B.P. Abbott et al., *Phys. Rev. Lett*, **116**, 061102 (2016).
[4] R. Abbott et al., *Phys. Rev. Lett*, **125**, 101102 (2020).
[5] M.C. Bersten et al., *Nature*, **554**, pp. 497-499 (2018).
[6] M. Modjaz, C.P. Gutiérrez, and I. Arcavi, *Nat. Astron.*, **3**, pp. 717–724 (2019).
[7] S. Al Kharusi et al., *New J. Phys.*, **23**, 031201 (2021).
[8] B. P. Abbott et al., *ApJL*, **848**, L12 (2017).
[9] R. Margutti and R. Chornock, *Annu. Rev. Astron. Astrophys.*, **59**, pp. 155-202 (2021).
[10] J. Marschak and R. Radner, *Economic Theory of Teams* (Yale University Press, 1972).
[11] H.W. Kuhn, *Proc. Natl. Acad. Sci. USA*, **36**, pp. 570-576 (1950).
[12] H.W. Kuhn, “Extensive games and the problem of information,” in *Contributions to the Theory of Games*, Vol. II, edited by H.J. Kuhn and A. Tucker (Princeton University Press, 1953) pp. 193-216.
[13] A.M. Brandenburger and P. La Mura, *Phil. Trans. R. Soc. A*, **374**, 20150096 (2016).
[14] J.S. Bell, *Physics*, **1**, pp. 195-200 (1964).
[15] V. Scarini, *Bell Nonlocality* (Oxford University Press, 2019).
[16] R. de Wolf, *Quantum Computing: Lecture Notes*, Chap. 17, p. 145, at `https://arxiv.org/pdf/1907.09415v5.pdf` (2023).
[17] J. Yin et al., *Science*, **356**, pp. 1140-1144 (2017).
[18] S. Khatri et al., *npj Quantum Inf.*, **7**, 4 (2021).
[19] S. Popescu and D. Rohrlich, *Found. Phys.*, **24**, pp. 379-385 (1994).
[20] D.M. Greenberger, M.A. Horne, and A. Zeilinger, “Going beyond Bell’s theorem,” in *Bell’s Theorem, Quantum Theory and Conceptions of the Universe*, edited by M. Kafatos (Kluwer, 1989), pp. 69-72.