Topical: Space clocks and Space VLBI

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ABSTRACT

Very Long Baseline Interferometry (VLBI) is an essential tool for modern astrophysics. Each antenna in a VLBI array requires an atomic clock frequency reference. A future space-based VLBI mission could enable new observations of the immediate environments of supermassive black holes that are not possible with earth-based VLBI. Development of next-generation space clocks, itself a scientific endeavor that explores the foundations of quantum mechanics, would enable such future missions. Space qualification of these new clocks should be a high priority for this decade.

INTRODUCTION

Very Long Baseline Interferometry (VLBI) coherently combines multiple signals from remote antennae over long baselines to achieve exceptional imaging resolution, culminating in the recent imaging of a supermassive black hole at the center of the galaxy M87 by the Event Horizon Telescope (EHT) [1]. VLBI observations were key in complementing one of the primary science goals of NASA's Fermi mission, namely understanding the environments around supermassive black holes [2]. VLBI is also used by NASA to perform navigation of deep space spacecraft by comparing spacecraft positions with those of nearby (distant) radio sources that serve as sky position reference sources [3]. The process of combining VLBI signals requires that each be precisely time tagged at reception so that they can be closely aligned in post-processing. For example, observing at 230 GHz (wavelength 1.3 mm) requires time alignment better than 4 ps. The maximum correlation is obtained using a fringe search whereby the time offsets from different antennae are adjusted relative to each other, but each time series must already be very closely aligned to the others for the fringe search to be successful. To accomplish this precise time tagging for VLBI at radio frequencies, a hydrogen maser is usually installed at each antenna. The hydrogen maser coherence time is generally better than the coherence time of signals passing through Earth's atmosphere and, so even at the 230 GHz detection frequency currently used by the EHT, maser coherence time doesn't limit VLBI performance.

Spatial resolution in current terrestrial VLBI is limited in three ways: atmospheric coherence times, detection frequencies that can propagate through the atmosphere and can overcome interstellar scattering, and terrestrial baselines. For each of these parameters, a larger value would yield higher resolution in VLBI images. Temporal resolution in terrestrial VLBI is also limited to the order of hours by the rotation period of the earth about its own axis, which is used to fill in the u-v plane. Operation of VLBI in space offers the opportunity to probe this parameter space without the limitations imposed by the earth's atmosphere, size, and rotation period. On Earth, averaging times used to improve measurement signal to noise ratios (SNR) are limited by atmospheric perturbations at 10-20 seconds. The current highest frequency typically used is 230 GHz with higher frequencies possible in principle if operating in space where the atmosphere is avoided (higher frequencies are possible on earth in some circumstances but depend critically on atmospheric conditions). Antenna baselines currently limited by the diameter of the earth could be extended to orders of magnitude higher values. Finally, adding a space-based antenna with an orbital period much shorter than Earth's rotation period could improve temporal resolution from hours to minutes. Extending EHT measurements to test general relativity [4], validate the Kerr metric for spacetime around a spinning black hole or resolving details of the first photon ring will require enhancement in one or all of these parameters [5]. Similarly, to study variability on the time scale of the Inner most Stable Circular Orbit (ISCO) of particles falling into a super massive black hole, the temporal resolution will need to be improved from hours for the current terrestrial measurements to order of minutes [6, 7].

With the elimination of atmospheric effects in Space VLBI (SVLBI), the next leading cause of decoherence will probably be the clocks used to time-tag signals. SVLBI also introduces the additional element of orbit determination, which may also limit performance. Here we address the question of clock technology. We will argue that current space clock technology is probably not sufficiently stable to support SVLBI goals and will recommend that next-generation clock technology based on optical clock transitions be adapted to operation in space.

CLOCK PERFORMANCE METRICS

To simplify the discussion of what clock characteristics are required for SVLBI, we note that for most applications envisioned, coherence times will be less than 1000 seconds and frequencies less than 1000 GHz. While it is possible to consider phased arrays of clocks on separations of 100's of kilometers using free space optical links [8], truly long baselines will likely require the traditional approach of simply having very stable clocks free running at each antenna since signal propagation times between antennas will limit phase lock bandwidths for large separations. Which clocks can support SVLBI parameters comes down to a question of what their various coherence times are at a given detection frequency. Here we use an approximate expression for coherence as a function clock Allan deviation [9].

$$\langle C^2(T)\rangle = \frac{2}{T}\int_0^T \left(1-\frac{\tau}{T}\right) exp\left\{-\pi^2 \nu_0^2 \tau^2 \left[\sigma_y^2(\tau) + \sigma_y^2(2\tau) + \cdots\right]\right\} d\tau \tag{1}$$

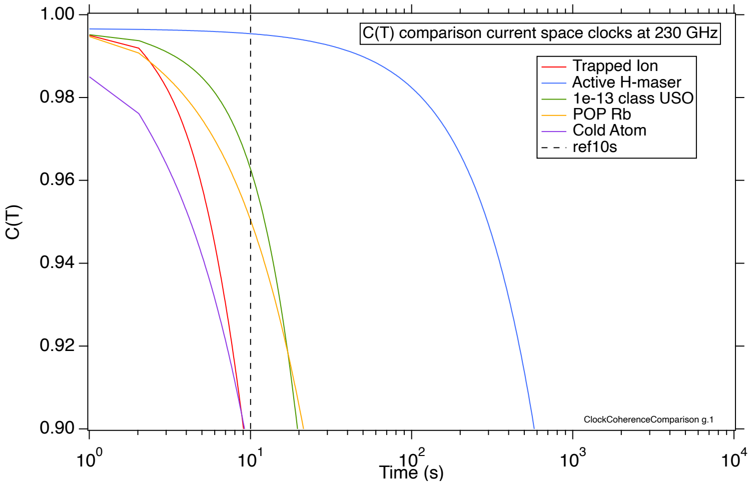
For some noise types, this integral can be calculated exactly, but most clocks exhibit a combination of noise types and the integral is usually solved numerically.

SURVEY OF CURRENT SPACE CLOCKS

The list of current space clocks includes quartz crystals [10] GNSS clocks including rubidium cell clocks, cesium beam tube clocks, passive hydrogen masers [11], active hydrogen masers [12], cold atom beam clocks [13], and trapped ion clocks [14]. All of these probe atoms using microwaves except USO's, which are simply mechanical oscillators.

Short-term clock performance for averaging times less than 1000 seconds is the characteristic most important for VLBI applications. Active hydrogen masers have traditionally been the frequency standard of choice for VLBI. Even though some space clocks out-perform masers in the long term (eg., [14]**)**, superior active maser performance in the short-term results in significantly longer coherence times. To date, there have been several active H-masers in space including one used by the Gravity Probe A experiment [12] and one used by the SVLBI telescope RADIOASTRON [15]. While active hydrogen masers have been operated in space, their performance has not yet matched what has been achieved on the ground. An important aspect of active masers is that in contrast to most atomic clocks, they are active oscillators. In addition to having excellent stability at 1 second – about 1e-13 – the short-term noise type is white phase, such that frequency stability improves with averaging time as $1/\tau$. This characteristic means that masers maintain coherence (no excess phase accumulated) longer than all other currently operating space clocks, which are passive (do not oscillate) such that their frequency stability improves with averaging time as $1/\sqrt{\tau}$.

The following graph shows a comparison of equation (1) calculated for several of the space clocks listed above (rubidium cells, cesium beam tubes, and passive hydrogen masers all have a one second instability of 1 to 2 orders of magnitude higher than active masers and are not included.) This data indicates that virtually all current space clocks except active masers are already exhibiting significant decoherence after only 10 s of integration time, while the maser (here ground performance is taken as a proxy for potential space performance) retains a high degree of coherence for times greater than 100 s.



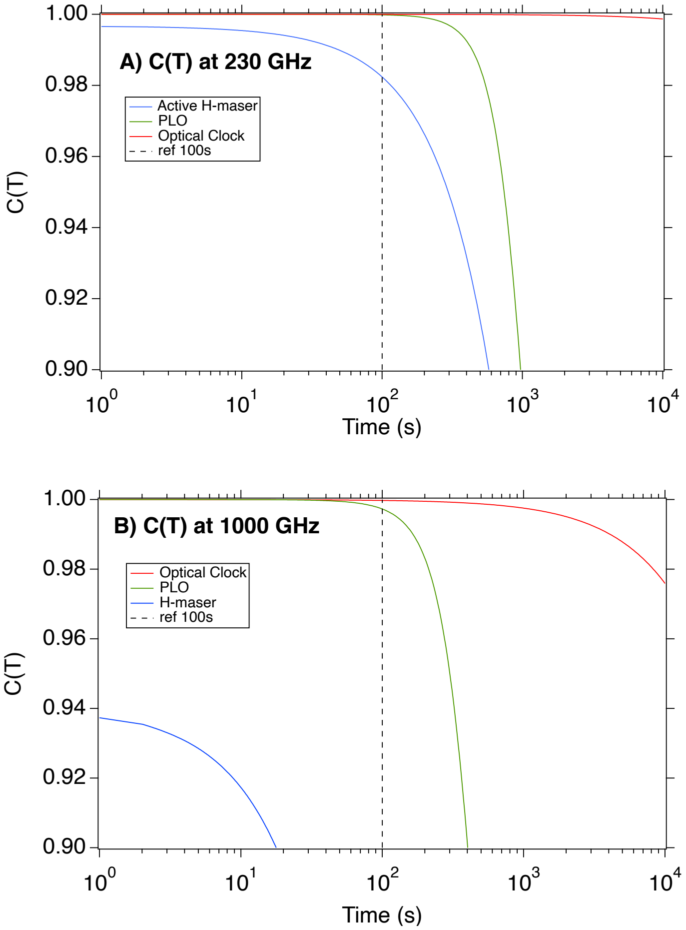
Clock coherence vs. time at a detection frequency of 230 GHz for current space clocks showing a distinct difference between the maser and all others. A value of nearly 1 is required for VLBI – less than one indicates coherence loss. The dashed vertical line is at 10 s, the approximate requirement for EHT observations.

RECOMMENDATIONS FOR FUTURE CLOCK WORK IN SUPPORT OF SVLBI

The previous graph shows that most current space clocks will not be able to support SVLBI goals of extending averaging times beyond 10-20 s. The exception is the active hydrogen maser. With additional effort, it is possible that the maser could achieve ground maser performance levels while in space. While the coherence of active masers clearly exceeds that of other current space clocks, it will also become limiting for averaging times greater than several hundred seconds. In addition, and perhaps most important, if detection frequencies are increased beyond 230 GHz (shown above), then the maser will no longer be adequate even at shorter times. For long averaging times and detection frequencies above 230 GHz, emerging optical clock technology will be required [16]. While these clocks are passive in that they steer a local oscillator and exhibit white frequency noise, which improves with $1/\sqrt{\tau}$ instead of τ as does the maser, at 1e-15 or below their 1 second instability is more than 2 orders of magnitude better than that of the maser so their accumulated phase error is much smaller.

Optical frequency standard technology consists of two types: a photonic LO [17] (PLO) alone or PLO coupled to an optical atomic discriminator (in both cases, a frequency comb is required to phase coherently down-convert the optical frequency into the microwave). As with their microwave counterparts, the atomic discriminator is used to steer out LO drift in the long-term. Since VLBI depends primarily on short-term performance, it may be possible to support some SVLBI applications with the PLO alone without the atomic discriminator.

The following graph shows the C(T) for optical frequency standards as compared to the maser at a detection frequency of 230 GHz and 1 THz.



Comparison of clock coherence vs. time with a detection frequency of a) 230 GHz and b) 1000 GHz for emerging optical clock technologies (not yet operating in space.) The active H-maser is included for comparison. A value near 1 is required for VLBI. The dashed black line is at 100 s, a desirable SVLBI coherence time.

To support all envisioned SVLBI goals, optical technologies should be developed. This includes both PLO's (optical local oscillators consisting of ultra-stable lasers locked to high finesse optical cavities, optical frequency combs [18] used to down convert the optical frequency into radio frequencies that can be used by the antenna) and optical atomic discriminators used to steer PLO's that can enable separated antennae with free running frequency standards to operate as if effectively part of a phased array for periods of a day or more.

As a pathfinder and intermediate step, existing space clocks could be used in a hybrid ground VLBI array combined with one or more space antennae [6]. If the active hydrogen maser performance in space matures to that on the ground, this could even support averaging times over 100 s at 230 GHz and 10's of seconds for higher frequencies. This combination requiring very little technology advancement in the clocks could result in imaging with significantly higher resolution (spatial and temporal) than is currently possible on the ground. In addition to the maser, current trapped ion clocks and USOs, both with space heritage, could support long space baselines and averaging times of 10-20 seconds at 230 GHz.

In support of SVLBI goals, work aimed at refining SVLBI requirements needed to reach scientific objectives as a function of different mission classes should be continued. For example, a mission combining the EHT with an antenna at LEO will address improved temporal resolution [6], and wouldn't require increased coherence time, while a mission with an array of antennae all in space and much longer baselines would have a different set of requirements and would set completely different constraints on the frequency reference used.

It is likely that a fully optically referenced SVLBI is many years away. In the near term, several ground-based pathfinder projects will be highly desirable. These include portable optical atomic clocks, which can serve as an intermediate step to evolving this technology towards flight, and free space optical links (FSOL) [8]. The latter can be used to phase lock oscillators across free space at distances in excess of 100 km on the ground and have already demonstrated noise floors at or below optical clock levels (in space FSOL's would probably need to be combined with a new level of precision in orbit determination and would not be feasible over very long baselines). With an optical clock at one antenna, it is possible to phase lock a simple USO at another antenna in line of sight using a FSOL such that the USO exhibits optical clock level performance. This makes it possible to have an optical clock performance at two sites with only one optical clock and can serve as a test bed to work out details of operating VLBI with optical clock references.

CONCLUSION

SVLBI presents many technical challenges including the frequency reference maturity discussed in this white paper, orbit determination, and exceptionally high space-to-ground data rates or high data storage capacity in space. Each of these may require years of development before reaching the maturity level required for operation in space. In this white paper we recommend a strong development program aimed at maturing optical clock technologies to support ultimate SVLBI as well as high-performance microwave space clocks to support intermediate SVLBI development or pathfinder missions. In addition, we recommend further study on clock requirements needed to support different SVLBI mission classes that place antennae at locations ranging from LEO to sun-earth Lagrange points.

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