Search for temporal coherence in the sky

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ABSTRACT

A new observation mode, a survey of temporal coherence in large fields, is described. Longitudinal coherence can arise in many astrophysical scenarios and at different wave lengths, from plasma effects, scattering of electrons on periodic electromagnetic volumes, to Einstein rings and even extraterrestrial unintended signaling. There is a plurality of coherence seeking devices, developed for military purposes, which can be easily adopted for this task. Many are based on unbalanced interferometers, with a path difference that exceeds the white light envelope. They were shown to be able to discern very weak coherent sources in a heavily cluttered environment. For searches where the coherent wave length was unknown, a signal to background ratio of 1:10,000 was demonstrated. At a known wave length (e.g. molecular lines) one can even expect 1:1,000,000 detection ratio. Once such sources are found, they can be better monitored by most astronomical interferometers, whose field of view is usually rather narrow.

Keywords: temporal coherence, stellar interferometry, SETI

1. INTRODUCTION ON TEMPORAL COHERENCE

Coherence of light describes the correlation between photons arriving from a source. Coherence is three dimensional – lateral and longitudinal. The latter can also be described as temporal coherence, related to longitudinal coherence by the speed of light c: $\tau_c = l_c / c$. Generally, naturally occurring sources such as stars do not have any coherence of their own – the photons emitted from one point at a specific time are not causally related to photons emitted from a different point at another time. However, there might be some clues and suggestions as to where it might be possible to find temporal coherence in astrophysical processes. Among others, synchrotron radiation, known to be polarized, can be also coherent over the scale of electron groups or clumps inside the groups[1,2]. Scattering of relativistic electrons off a periodic grating may also produce coherent photons[3] as was experimentally shown at mm waves[4]. Thus one can think of scattering of fast electrons off plasma waves or spiraling magnetic tubes, similar to free-electron lasers, as a source for coherent radiation.

Extremely strong scintillation was discovered in quasars which can be explained by small spatial dimensions[5] but also by temporal coherence. In masers, (spontaneous) emission occurs because of population inversion and hence photon amplification[6]. The effect can also occur in the visible, such as in planetary nebulae or regions near intense sources such as η Carinae[7]. Coherence in quasars might be due to stimulated emission from rapidly cooled plasma[8]. Stimulated emission is also a suggested explanation to unusual iron lines intensities in the ultra violet, again near η Carinae[9]. Care should be taken when observing forbidden line transitions, whose spectral depth is very narrow which might also seem as a result of stimulated emission[10]. Apart from scattering of relativistic electrons, as mentioned above, there are no known processes which can manufacture coherent photons at the extreme ultra-violet and x-ray regimes (accessible only from space), but then, not much is known about plasma streaming near black holes and other violent processes.

Another interesting possibility for naturally occurring coherence is in gravitational lensing by a small object, where the paths to the observer do not differ significantly (an Einstein ring). In these cases photons arriving from various paths can be interfered and tested for longitudinal coherence, provided the delay is not too large, and the gravitational wave length shift of the beams is the same. Surveys for small lensing galactic objects searched until today only for the intensity enhancement as the focused beam swept Earth, and ignored the coherence of the beams.

No longitudinal coherence was observed in celestial sources, as far as can be traced. Masers are usually discovered by their narrow lines and polarization[11], but the effect of temporal coherence is generally not considered, perhaps because of the assumption of maser line broadening[12, 13].

2. INTERFEROMETRY AND COHERENCE

Since the birth of modern astronomy, interferometers were always involved in different observing modes, be it spatial interferometry (on one or few telescopes), Fourier or Fabry-Perot spectroscopy, etc. While all these devices can also measure temporal (longitudinal) coherence, they are being employed for other purposes, as their names imply. We are interested here in those photons which arrive from a specific direction, but also are coherent temporally, and they are best measured by interferometers with a long path difference between their arms. Most light sources loose their coherence when the delay between the arms is longer than a few waves – the coherence length. In contrast, coherent radiation maintains its phase over many cycles. Laser resonators produce exceedingly long coherence length, but in nature, where no cavities exist, the coherence length is, to first order, the distance over which stimulated emission can occur.

In radio interferometry, measurement of temporal coherence is simple: a simple long correlator lag, for every dish and between dishes, is sufficient. As the wave length becomes shorter, the number of photons per mode decreases, and near 10 micrometers it drops to a few. This makes correlations inefficient as compared to direct interference of the electromagnetic fields[14]. Still, it was proposed recently to utilize heterodyne intensity interferometry at 1 micrometer to detect coherent radiation[7]. A similar idea is to employ intensity interferometry on extremely large telescopes towards this end[15]. It seems that simple amplitude interferometry will be able to perform this fit as well, and be more efficient at smaller telescope sizes.

The field of view to be searched is thus imaged twice, once through each arm of the interferometer, and the images are made to overlap with each other (zero-shear interferometer). The two arms are not equal, and there is a delay of more than a few waves between them. Objects with a shorter coherence length will have a minimum mutual coherence, and their contrast will be depressed, while those with coherence longer than the delay will still interfere, and their contrast will be measurable.

3. REALIZATIONS

Many interferometers can perform temporal coherence measurements. Thus one has only to choose the best configuration for this purpose. In the first place, since the measurement needs to be sensitive to delays between the beams, a device which does not produce vibrations is preferred. Thus nearly-overlapping path interferometers are preferable to Michelson interferometers with orthogonal arms[16, 17, 18]. In addition, a very wide field of view is required. Finally, the delay has to be changed easily (for a temporal modulation) or be introduced into the stellar images (for spatial coding of the fringes). In general, shearing interferometers, with zero spatial shear and substantial longitudinal shear are good candidates for this task, as are Fabry-Perot etalons with extended cavities[19]. For the spatial-modulation method a small angular shear is also required. Notice that for unequal-path imaging, the two images might suffer different magnifications. In slow beams, they can be balanced instead before and after focus, where the effective focal depth (including speckles or adaptive correction) is usually much longer than the path difference.

As was realized very early on, detection of laser radiation in the battlefield is an essential weapon, and thus there is a wealth of military devices for coherence detection[16, 20, 21, 22, 23]. Many of these use only polarized light. In astronomy this usually means ignoring half of the photons, or constructing two such devices in parallel, one for each polarization.

A lateral-shear interferometer illustrates the principle (Fig. 1): a collimated beam is formed after the telescope focus and crosses two consecutive beams splitters, forming four beams, where each two interfere as a pair. Between the beam splitters we insert two different delays for the two beams, a fixed delay and a variable one. The variable delay can oscillate in time around zero[24, 25]. Finally, two lenses form two images of the stellar field on the detector with mirror symmetry. Since the two images are complementary to each other, inequality of intensity in corresponding pixels will signify coherence longer than the delay between the beams. The fields of view are limited by the size of the beam splitters. Similar designs were constructed, down to the x-ray regime[26, 27]. At these energies, the wave length is easily measured, making the detection easier, compared to the visible.

Spatial fringes (as opposed to temporal modulation) can be formed by either tilting one of the beam splitters around its center (normal to the drawing) or shifting it sideways, which will form angular shear upon interference, thus producing fringes on the stellar images. These images extend over a few pixels, so as to match the fringe period to the pixel size (Fig. 2). A delay is introduced between the beams, so that only long temporal coherence produces fringes. A Fourier transform of the whole image will detect a signal at the highest frequency, that of the fringes. Thus by demodulating the whole image at that high frequency, it is easy to find the location of any fringes in the field of view. Separation of wave lengths is also possible[18].

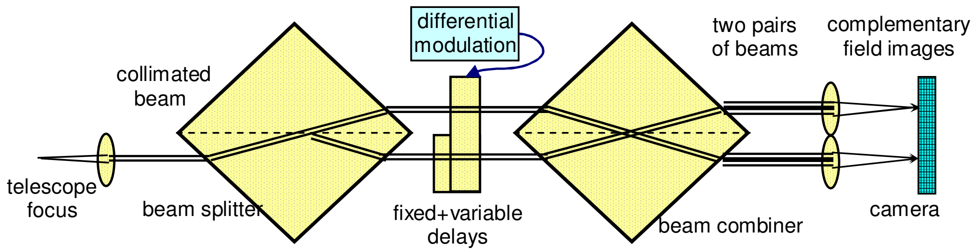

Fig. 1. A zero-shear, large delay interferometer, with temporally modulated fringes, for detection of coherent radiation. Also, tilting the beams introduces spatial fringe modulation.

4. DATA COLLECTION

Continuing from the zero-shear, large delay interferometer described here, and assuming now temporal measurements, a large CCD detector is placed at the re-imaged focal plane of the telescope, and collects the two fields. The pixel size is equal to the point-spread function of the atmosphere and the telescope (including an adaptive optics system if one exists). A fixed delay is introduced, $d_0 = n\lambda_{avrg}$, where n ? 1 and λ_{avrg} is the mean wave length. The whole field is observed and then shifted under a cover, and at the same time the delay is changed by $d_1 = \lambda_{min}/4$, one quarter of the minimum wave length observed (Fig. 3). At λ_{min} this will change any bright fringe to gray, gray to dark, dark to gray, and gray to bright. After an equal period of observation, the second image is shifted away and the first is restored, as is the original delay. The whole process is repeated for a number of cycles. Every few cycles the duration of the integration period can be changed, keeping the two halves equal, to avoid any coincidences with amplitude modulation of the source. Finally the two images, each including two fields of view at opposite interference, are stored away. The same field of view is now observed in the same mode, now with a delay of $d_2 = \lambda_{avrg}/4$, near the mean wave length. Finally, the whole process is repeated at $d_3 = \lambda_{max}/4$, near the maximum wave length. This combination of three wave lengths ensures that some coherent fringes might hardly be affected by the wrong phase delay, and by trying at different delays all signals can be detected. Both series of the delay values and the delay times should not be simply related in order to avoid any harmonics coincidences. Their terms should be chosen at random or as irrational fractions of each other.

The pixel size is equal to the point-spread function of the atmosphere and the telescope (including an adaptive optics system if one exists). The total field observed is limited by current detector technology – the number of pixels available that can be shifted under a cover and back out. The technology also sets the period, so that the image shift will take a small portion of the cycle. It also sets the total integration time, limited by the maximum number of photons per pixel. Finally, cosmic events might wrongly be interpreted as fringe maxima, and they need to be sifted out (e.g. by comparison to nearby pixels).

Notice that it is advantageous to read and subtract corresponding pixels from the two images before digitization, as this reduces significantly the background. If the two images are digitized separately, the background cancellation is limited by the accuracy of digitization.

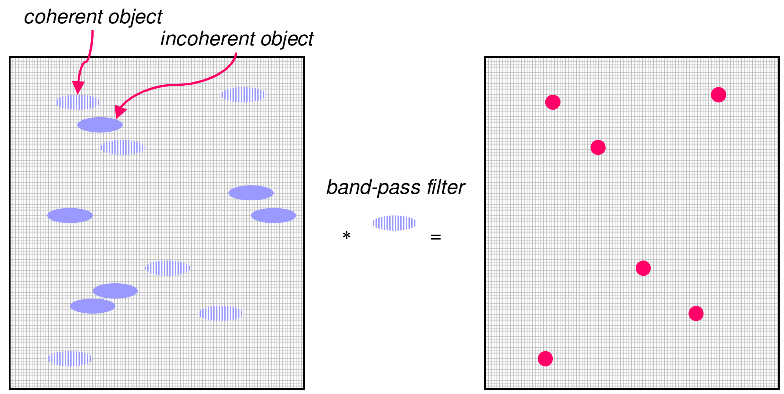

Fig. 2. After subtraction of the complementary image, fringes are clearer on coherent objects (left box). A band-pass matched filter will reveal the locations of fringes at the expected frequency band.

5. BASIC LIMITS

Experiments performed with military devices already give us some very good clues as to the ratio of the coherent signal to the incoherent clutter (here, the celestial field). A 100% coherent beam, at a known wave length, was discernible against an incoherent one 10^5 brighter[20, 22, 23, 17] and under favorable conditions even 10^7 brighter[16]. If the wave length is not known, more images need to be taken at various delays, slowing the detection process. If the wave length is known, a narrow band filter reduces the background, and the path difference has to be longer correspondingly.

The basic requirement is to receive at least two coherent photons within the integration time, and to be able to discern them against an incoherent background. As an example, let us take a 2 arcsec pixel size (system without adaptive optics), and a camera with 4,000 pixels across. The well depth of each pixel is assumed to be 125,000 electrons, and the signals are subtracted off-chip. If the coherent signal occurs at the same pixel as the maximum intensity, then very long integration will allow a pixel dynamic range of 1:125,000, as the incoherent photons are averaged away outside the modulation frequency band. Assuming a 2.5 m telescope, this number of photons can be accumulated for a field with a bright (magnitude 5) star and 10% total efficiency in one minute, and for three wave length delays in three minutes. The total sky is approximately $4\pi/0.01 \approx 1250$ times the size of this field, and requires 20 hours of scan. Deeper searches can be made (ignoring saturation near the brightest stars) for much longer times.

In order to enhance the detection chance over a wide band at a specific direction, one can bin down the pixels, or better still, use a single pixel detector – an avalanche photodiode. In this case, the current from the detector is demodulated from the delay frequency directly[24, 25]. Here indeed the coherent to incoherent ratio of better than 10^7 obtained in the lab can be realized[16]. Thus by lumping all the objects in the field into one incoherent background, it is possible to discern the coherent signal above it. As the density of stars in the field is low, this might be an advantageous strategy, as long as there are less than $\sim 10^4$ objects in the field.

6. INTENDED SIGNAL

While temporally coherent natural sources are in question, the search goes on for artificial sources. Great effort is being invested in the search for extra-terrestrial intelligence (SETI), which might be trying to communicate with whoever might be watching its pulsed beacons[28]. Historically initiated in the radio, the visible regime is a serious contender[29, 30]. A recent search for pulsed optical signals found no candidates[31]. It might make sense to look for unintended such signals, look for their temporal coherence and perhaps in addition for time sequence signatures. If such beings have indeed produced a laser, they might also have tried to use it at shorter wave lengths, down to x-rays. These should be detected on a much quieter background, such as that introduced by a nearby sun. Thus the survey for natural temporal coherence should supplement SETI, with the great advantage that it does not have to be directed at a specially chosen source.

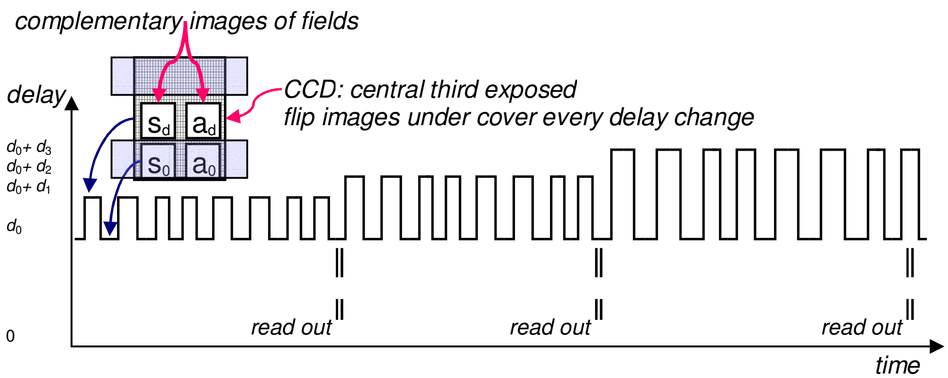

Fig. 3. The symmetric and antisymmetric image pair is shifted under the cover every half-cycle, and the other complementary pair is shifted during the second half. When the delay is changed, the four images are read out and subtracted. The frequency is varied slightly against unknown modulation, but the amount spent in each half-cycle is the same.

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