Manipulation of Phase Shifts in Big-Bang Interferometry

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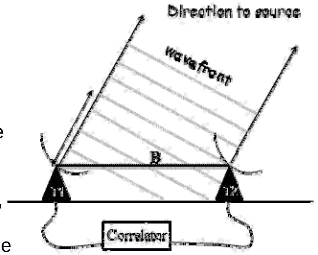
The CMB

The CMB – or Cosmic Background Radiation – is an early relic of the embryonic stages of the universe. 380,000 years after the big bang, matter cooled enough to allow for the first unobstructed passage of hot, energetic photons. These photons reach us now with a mean temperature of 2.73 K.

WMAP

The WMAP satellite, or the Wilkinson Microwave Anisotropy Probe, offered a detailed portrait of the CMB by measuring the intensity of the radiation from around the night sky, offering us information about the density of matter in the early universe. Unfortunately, study of the intensity of the CMB intensity tells us nothing about the time immediately after the big bang, when matter was still too hot to combine into atoms. Determining the polarization of the light as it leaves the CMB, however, can push the limit of our knowledge back even closer to the birth of the universe, the undisputed "Holy Grail" of astrophysics.



The CMB Polarization

According to the inflationary theory of the universe, gravitational waves were produced in the very early Universe along with the density perturbations that caused the temperature change. By slightly squeezing space in some directions and stretching it in others, these gravitational waves should have produced an imprint in the polarization of the CMB. Finding this polarization offers both confirmation that inflation actually occurred, and gives us access to a cosmological fingerprint of a universe less than than 10-30 second old.

Measuring the Polarization

A multi-university group is developing a satellite (the Einstein Polarimeter for Inflationary Cosmology, or EPIC) to measure this polarization using interferometry. By using an array of detector horns spaced at varying distances and angles to each other, the EPIC satellite will measure the CMB polarization of a range of length scales over the entire sky.

Importance of the Polarization

Until about 10^{-30} seconds after the big bang, cosmologists believe the universe was undergoing a period of rapid expansion called inflation. As distances expanded at rates faster than the speed of light, gravitational waves—ripples in space-time—constricted light in some directions while expanding it in other directions. The net result was 'squished' light, with one direction more prominent than the other: a result we would see as polarization in the CMB. Finding this polarization and its properties offers evidence for inflation and gives us information about the very early universe.

Interferometry

Interferometry compares favorably with other methods of CMB measurement with both higher resolution and less systematic error. In an interferometer, the light from the CMB is processed by the detector horns as electromagnetic fields. The E-field from each detector is then put together with the others in the array using a combiner. The signal we receive from the array is the square of this summed E-field. Say we have an *n*-detector array, with each detector contributing an E-field E_i. Then the signal we get is:

$$S = (E_1 + E_2 + \ldots + E_n)^2$$

The information about the polarization, however, is contained in the cross terms, or *visibilities*, $E_i E_j$. Phase-shifting offers a means of obtaining these visibilities from the signal data.

180° Phase Shifting

Phase shifting involves adding a time-delay operator to the E-field of one or more of the detectors in order to manipulate the resulting signal. One possible method involves switching the sign of the E-field, or phase shifting by 180°. This leads to possible signals of the form:

$$S = (E_1 \pm E_2 \pm \ldots \pm E_n)^2$$

We can then combine these signals to get each visibility in the following way, making sure to use each signal only once to minimize error:

$$E_i E_j \propto S_1 \pm S_2 \pm \ldots$$

Finding the Visibilities

To find each visibility, we created a mask $\vec{M}$ for each cross term $E_i E_j$ with the property:

$$\vec{M}_{i,j} \bullet \vec{S} \propto E_i E_j$$

where $\vec{S}$ is the vector consisting of $S_1, \ldots, S_n$. To make sure that these masks solely depend on $E_i E_j$ there needs to be an algorithmic way to ensure they are not equal.

180° Phase Shifting

# of S_i	# of antenna
2	2
4	3
8	4
16	6
32	7
64	9
128	12
256	16
512	21

Number of antennas retrievable as a function of signals

Case: $m = 2^u$

For the case where the number of signals is a power of 2, we have developed a set of basis vectors which allow for all masks $\vec{M}$ to be nonequal. These vectors take the form:

Where αi is the *i*th row of the matrix formed by writing all numbers from 1 to *u* in base 2, as columns, from left to right, and the j's take the value of either 0 or 1. To ensure that the masks *M* are not equal, we want to choose a subspace of these vectors such that:

$$\vec{\beta}_\alpha \vec{\beta}_\beta \neq \vec{\beta}_\phi \vec{\beta}_\varphi$$

Most of my research this summer concentrated on finding largest possible subset of these basis vectors for a given *u*. This is equivalent to maximizing the number of independent detector horns for a given number of signals—important for optimizing the satellite.

90° Phase Shifting

A similar process can be done for any degree phase shifting that is an integer divisor of 360. Specifically, 90° Phase Shifting, which consists of multiplying the E-field from each detector by 1, -1, *i*, or -*i*. A Butler Combiner, which offers certain advantages over other types of interferometry, uses this type of phase shifting.

A Look Ahead

90° Phase Shifting opens up the possibility of studying equivalent base pairings, or where two visibilities can be treated as equal. This occurs when two visibilities are parallel and have equal seperation. In the future, looking into the possible geometries of the detector arrays should allow for even better optimization.

- http://fringes.org/INT.JPG