MICHELSON-TYPE RADIO INTERFEROMETER FOR UNIVERSITY EDUCATION

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\section*{ABSTRACT}

We report development of a simple and affordable radio interferometer suitable as an educational laboratory experiment. The design of this interferometer is based on the Michelson & Peace stellar optical interferometer, but operates at a radio wavelength (\(\sim 11\) GHz; \(\sim 2.7\) cm); thus the requirement for optical accuracy is much less stringent. We utilize a commercial broadcast satellite dish and feedhorn. Two flat side mirrors slide on a ladder, providing baseline coverage. This interferometer resolves and measures the diameter of the Sun, a nice daytime experiment which can be carried out even in marginal weather (i.e., partial cloud cover). Commercial broadcast satellites provide convenient point sources for comparison to the Sun’s extended disk. We describe the mathematical background of the intensity interferometer, the design and development of the telescope and receiver system, and measurements of the Sun. We present results from a students’ laboratory report. With the increasing importance of interferometry in astronomy, the lack of educational interferometers is an obstacle to training the future generation of astronomers. This interferometer provides the hands-on experience needed to fully understand the basic concepts of interferometry.

\section{INTRODUCTION}

The future of radio astronomy relies strongly on interferometers (e.g., ALMA, EVLA, VLTI, aperture masking technique). From our experience at interferometer summer schools at the Nobeyama Radio Observatory and at the CARMA Observatory, we are convinced that hands-on experiments are critical to a full understanding of the concepts of interferometry. It is difficult, if not impossible, to obtain guaranteed access to professional interferometers for university courses. Therefore, we built a low-cost radio interferometer for the purpose of education and developed corresponding syllabi for undergraduate and graduate astronomy lab courses.

This experiment teaches the basic concept of interferometry using the technique developed by Michelson & Peace in the early 20th century (Michelson & Pease 1921). They measured the diameter of Betelgeuse, one of the brightest stars in the sky, with a simple optical interferometer. Such optical interferometry needs high precision telescope optics. The same experiment becomes much easier at radio wavelength when measuring the diameter of the Sun; the acceptable errors in the optics scale with the wavelength.

Figure 1 shows a conceptual sketch of the Michelson radio interferometer for education. This type of interferometer, adding signals instead of multiplying them, is called an intensity interferometer. We discuss the mathematical background of the intensity interferometer in §2, design and development of the telescope and receiver system in §3, telescope setup and measurements in §4, and results from a students’ lab report in §5.

\section{MATHEMATICAL BACKGROUND}

We describe the mathematical basis of intensity interferometer. We start from the geometric delay calculation (§2.1) and explain the total power, the parameter that we measure, in §2.2. We will show an example of how a point source (i.e., a commercial broadcast satellite) appears in §2.3. We will then discuss the case of an extended source. We prove that an interferometer measures a Fourier component and define visibility in §2.4. We will explain how the visibility is measured with our interferometer, and how the Sun’s diameter is derived in §2.5.

\subsection{2.1. Geometric Delay}

Interferometers mix signals received at two different positions (position 1 & 2 in Figure 2). In our radio interferometer, the signals that arrive at the two side mirrors (Figure 1) are guided to the antenna and mixed. The separation between the two mirrors, called baseline length \(B\), causes a time delay \(\tau\) in an arrival of signal at position 2 because of the geometry (Figure 2). Using the angles of telescope pointing \(\theta\) and an object in the sky \(\theta_0\), a simple geometric calculation provides the delay,

\[
\tau = \frac{B \sin(\theta - \theta_0)}{c} \sim \frac{B(\theta - \theta_0)}{c}
\]

where \(c\) is the speed of light. We used the small angle approximation \((\theta - \theta_0 \sim 0)\), since most astronomical objects have a small angular size.

\subsection{2.2. Total Power}

Radio signals are electromagnetic radiation and can be described in terms of electric field \(E\) and magnetic field \(B\). For simplicity, we consider only the electric field \(E\) in the following calculations (but this simplification does not lose the generality of the discussion). If we define the radio signal at frequency \(\nu\) that is detected at position 1 (or reflected if a mirror is there) at time \(t\) as,

\[
E_1(t) = E(\theta_0) \cos[2\pi\nu t],
\]
the signal that is detected at position 2 at the same time is,
\[ E_2(t) = E(\theta_0) \cos[2\pi\nu(t - \tau)], \]
(3)
because of the geometric delay \( \tau \).

An intensity interferometer adds the two signals and measures total power of the two. The total electric field is
\[ E_{\text{tot}}(t) = E_1(t) + E_2(t). \]
(4)

The radio frequency \( \nu \) is typically large compared to a data sampling rate. Hence, the total power \( P(\theta) \), detected by a receiver, is a time average (or integration). Using the notation \( \langle ... \rangle \) for the time average, we obtain
\[ P(\theta) = \langle E_{\text{tot}}^2(\theta) \rangle = \langle E^2(\theta_0) \left( \cos[2\pi\nu t] + \cos[2\pi\nu(t - \tau)] \right)^2 \rangle = E^2(\theta_0)[1 + \cos(2\pi\nu\tau)] \]
(6)

Because of the high frequency \( \nu \) all terms with \( \langle \cos(\nu t) \rangle \), \( \langle \sin(\nu t) \rangle \), etc, vanished due to the time average. With equation (1) under the small angle approximation, it becomes
\[ P(\theta) = E^2(\theta_0)[1 + \cos(2\pi B\lambda(\theta - \theta_0))] \]
(8)
where \( B\lambda \equiv B/\lambda \) is a normalized baseline length and \( \lambda \) is the wavelength \( (\lambda = c/\nu) \).

Equation (8) can be generalized for an extended object as
\[ P(\theta) = \int E(\theta_0)d\theta_0[1 + \cos(2\pi B\lambda(\theta - \theta_0))], \]
(9)
where \( E(\theta_0) \) is an intensity/energy density distribution of the object. Our intensity interferometer measures \( P(\theta) \); we slew the telescope across the object in the azimuthal direction and obtain fringe, i.e., the power as a function of \( \theta \).

2.3. Point Source

A point source has the energy density of a \( \delta \)-function at the position of the object \( \theta_0 = \theta_c \). By adopting the coordinate origin to make \( \theta_c = 0 \), it is
\[ E(\theta_0) = E_0\delta(\theta_0). \]
(10)
Combining with eq. (9), we obtain
\[ P(\theta) = E_0[1 + \cos(2\pi B\lambda(\theta - \theta_0))]. \]
(11)

We should see a sinusoidal power response as a function of \( \theta \), as we sweep the telescope from one side of the object to the other.

Figure 3 (top) shows the theoretical fringe pattern of a point source. Our satellite dish (and any other radio telescope) has a directivity; its response pattern tapers off away from the center. The pattern that we actually obtain is attenuated by the dish response pattern (beam pattern) as in Figure 3 (bottom). Commercial broadcast satellites are very small in angle and approximate point sources.

Fringe measurements are useful in determining the baseline length \( B\lambda \). The total power is zero when the normalized baseline is \( B\lambda(\theta - \theta_0) = n + 1/2 \), where \( n \) is an integer. The separation between adjacent null positions is \( \delta\theta = 1/B\lambda = \lambda/B \).

2.4. Extended Source and Visibility
An astronomical object often is extended. In general, an interferometer measures the Fourier transformation of the energy density distribution $\mathcal{E}(\theta_0)$. Here we prove this.

From eq. (9) we define the visibility $V_0(B_\lambda)$ as follows:

$$P(\theta) = \int \mathcal{E}(\theta_0) d\theta_0$$
$$+ \int \mathcal{E}(\theta_0) \cos(2\pi B_\lambda(\theta - \theta_0)) d\theta_0$$
$$= S_0[1 + V(\theta, B_\lambda)],$$

where

$$S_0 = \int \mathcal{E}(\theta_0) d\theta_0$$

and

$$V(\theta, B_\lambda) = \frac{1}{S_0} \int \mathcal{E}(\theta_0) \cos[2\pi B_\lambda(\theta - \theta_0)] d\theta_0$$
$$= \frac{1}{S_0} \left[ \cos(2\pi B_\lambda \theta) \int \mathcal{E}(\theta_0) \cos(2\pi B_\lambda \theta_0) d\theta_0$$
$$+ \sin(2\pi B_\lambda \theta) \int \mathcal{E}(\theta_0) \sin(2\pi B_\lambda \theta_0) d\theta_0 \right]$$
$$= V_0(B_\lambda) \cos[2\pi B_\lambda(\theta - \Delta \theta)].$$

The visibility $V_0(B_\lambda)$ can be written by defining the phase shift $\Delta \theta$ as

$$V_0(B_\lambda) \cos(2\pi B_\lambda \Delta \theta) = \frac{1}{S_0} \int \mathcal{E}(\theta_0) \cos(2\pi B_\lambda \theta_0) d\theta_0$$
$$V_0(B_\lambda) \sin(2\pi B_\lambda \Delta \theta) = \frac{1}{S_0} \int \mathcal{E}(\theta_0) \sin(2\pi B_\lambda \theta_0) d\theta_0$$

which lead to

$$V_0(B_\lambda) = e^{i2\pi B_\lambda \Delta \theta} \frac{1}{S_0} \int \mathcal{E}(\theta_0) e^{-i2\pi B_\lambda \theta_0} d\theta_0.$$ 

The first term $e^{i2\pi B_\lambda \Delta \theta}$ is a phase shift $\Delta \theta$ of a complex visibility. The visibility amplitude is therefore

$$|V_0(B_\lambda)| = \frac{1}{S_0} \int \mathcal{E}(\theta_0) e^{-i2\pi B_\lambda \theta_0} d\theta_0.$$

This is a Fourier component of the object $\mathcal{E}(\theta_0)$ at the baseline length of $B_\lambda$. The inverse $1/B_\lambda$ is the angular size of the Fourier component in radian.

Figure 4 (top) shows the theoretical fringe pattern of a top-hat function (or the Sun’s disk in 2-dimensions). The pattern is also attenuated by the beam pattern (Figure 4 bottom).

2.5 Visibility Measurements and Sun’s Diameter

We measure $P(\theta)$ and calculate the visibility amplitude $|V_0(B_\lambda)|$. From eqs. (13) and (17), we have

$$P(\theta) = S_0[1 + V_0(B_\lambda) \cos(2\pi B_\lambda(\theta - \Delta \theta))]$$

Figure 4 (bottom) is what we see toward the Sun — we sweep the Sun by slewing the telescope in the azimuthal direction (i.e., changing $\theta$). The fringe pattern is attenuated by the antenna response pattern, but we assume that the antenna response is approximately constant around the peak of the response pattern. The maximum and minimum powers of the sinusoidal curve (see Figure 4 bottom) are

$$P_{\text{max}} = S_0[1 + V_0(B_\lambda)]$$
$$P_{\text{min}} = S_0[1 - V_0(B_\lambda)].$$

From these, we calculate

$$|V_0(B_\lambda)| = \frac{P_{\text{max}} - P_{\text{min}}}{P_{\text{max}} + P_{\text{min}}}.$$

This is the visibility amplitude at the baseline length of $B_\lambda$.

Two side mirrors slide on the ladder in Figure 1 and change the baseline length. We repeat measurements of $|V_0(B_\lambda)|$ at different baseline lengths and make a plot of $|V_0(B_\lambda)|$ as a function of $B_\lambda$. $|V_0(B_\lambda)|$ is a Fourier
component of $\mathcal{E}(\theta_0)$; therefore, we should see the Fourier transformation of the emission distribution in the plot. Sun’s $\mathcal{E}(\theta_0)$ can be approximated as a top-hat function. Assuming Sun’s diameter is $\alpha$, it is

$$\mathcal{E}(\theta_0) = \begin{cases} 1, & \text{if } |\theta_0| < \alpha/2 \\ 0, & \text{otherwise} \end{cases}$$ \hfill (26)

The Fourier transformation is

$$|V_0(B_\lambda)| = \frac{\sin(\pi B_\lambda \alpha)}{\pi B_\lambda}.$$ \hfill (27)

This is a $sinc$ function (Figure 5). By fitting, we determine the parameters of this $sinc$ function, which can be translated to the diameter of the Sun $\alpha$.

3. INSTRUMENTS

We describe the construction of the telescope and receiver system. We used a commercial broadcast satellite dish and feedhorn operating at radio X-band. The budget is often the limitation in development of student lab experiments. We utilized low-cost parts and materials. The system was constructed in our machine and electronics shops, but an assembly of each component could be offered as a student lab component.

3.1. Telescope and Optics

Figure 1 shows the design of the Michelson stellar radio interferometer. Radio signals from the Sun hit two flat mirrors at the sides and are reflected to a satellite dish antenna through the central flat mirrors. The signals from both sides are mixed as detected. Figure 6 shows photos of the telescope. It was built with mostly commercial products and materials. A broadcast satellite dish and feedhorn (blue in Figure 1; Figure 6a,b) operates at the frequency of $\nu \sim 11$ GHz ($\lambda \sim 2.7$ cm in wavelength). The required accuracy of optics at this wavelength is about $\sim 3$-5 mm, which is relatively easy to achieve with flat mirrors (without curvature).

The flat mirrors (green in Figure 1) are made with fiberboard with wood frame structures (Figure 6e). The mirror surfaces are all angled 45 deg from the optical path. We originally covered their surfaces with kitchen aluminum foil, which has an appropriate thickness with respect to the skin depth ($\sim 0.8\mu$m) at the operating wavelength (reflectivity $\sim 96\%$ from our lab measurements). Later, we replaced it with thin aluminum plates for student-proofing (Figure 6d). The two side mirrors slide on a ladder to change the baseline length.

The azimuth-elevation mount structure is made with plywood (red in Figure 1 and blue and yellow in Figure 6). The azimuthal and elevation angles are driven with motors (Figure 6c), which are controlled by a paddle (i.e., handset in Figure 6b). The protractor (Figure 6f) is placed at the center of the bottom mount plate (yellow in Figure 6b) for measurement of the azimuthal angle of the telescope. Figure 6a shows the whole structure of the telescope. A metal pole is mounted perpendicular to the top mount plate (Figure 6b) and aluminum frame (Figure 6c), and supports the dish. Note that the pole should be perpendicular, which makes the pointing adjustment easier as discussed later.

Sweeping the Sun in azimuth permits fringe measurements. This telescope can be converted to a single-dish telescope by flipping the satellite dish by 180 degrees around the metal pole (see Figure 6b). Single-dish and interferometer measurements can be easily made and compared, which is essential to appreciate the high angular resolution possible with the interferometer.

3.2. Receiver System

The signal detection system in radio astronomy is a series of electronic components. Figure 7 shows the design and photos of the receiver. Again, these are mostly commercial products.

Signals from the sky are at too high a frequency ($\sim 11$ GHz) to be handled electronically. Hence the Low Noise Block Feedhorn (LNBF) down-converts the frequency to a lower frequency, called the intermediate frequency (IF; 950-1950MHz), by mixing reference signal at a slightly-offset frequency and taking the beat of the sky and reference signals. This is called heterodyne receiving. The LNBF works as a heterodyne mixer.

Figure 7 shows the flow of signal. In sequence, an amplifier, two attenuators, and bandpass filter adjust the signal amplitude to the input range of a square-law detector. A filter with a 100 MHz width narrows the frequency range, since the bandwidth of the IF (1GHz at the operating frequency of $\sim 11$ GHz) is too broad for detection of null fringes in interferometry. Output from the detector is then amplified to the whole dynamic range of the analog-to-digital (A/D) converter. We assembled all these components inside a metal box for protection. A power supply is also in the box, providing the power to the LNBF and amplifiers.

The output from the receiver box goes to the commercial LabPro A/D convertor. The LabPro is connected via USB to, and controlled by, a laptop computer with the LabPro software installed. It takes care of time integration to record voltage measurements.

Table 1 lists the electronics components that we purchased. The square-law detector (schottky diode detector) was purchased through eBay, and similar devices...
Figure 6. Photographs of the telescope. (a) Overall view. (b) Mount structure. The blue box at the bottom (with handles) and yellow plates are made with woods. The entire yellow part rotates in the azimuthal direction on the blue box. The two yellow plates are attached with hinges, and the top plate moves up to change the elevation angle. The telescope is mounted for a "single-dish" mode, and its pointing would be rotated by 180 deg for the "interferometer" experiment. (c) Support structure. The aluminum frame supports the telescope. A screw rod and elevation drive motor also appear. (d) Side mirror from the front side. Kitchen aluminum foil has an enough skin depth, but we glued a thin aluminum plate, instead, for student-proof. (e) Side mirror from the backside. It’s supported by a wood frame. (f) Protactor to measure the azimuthal angle of the telescope.

4. SETUP AND MEASUREMENTS

4.1. Setup

The mount structure, ladder, and mirrors of the telescope (Figure 6) are detached when it is stored in a storage area in our physics building. We move them with a cart to the front of the building and assemble them there in the morning of experiment. We make sure that the flat mirrors are angled 45 deg with respect to the optical path and 90 deg vertically, using a triangle. We then set the ladder and mirrors on the mount structure.

The electronic components are also connected: along the flow of signal, the feedhorn is connected to the receiver (Figure 7), to the A/D converter LabPro, and then, to a computer via USB. We use the software, which comes with LabPro, to control sampling frequency (integration time) and duration of recording.

Telescope pointing adjustment is the next step. We prepare a table of Sun’s azimuthal and elevation angles as a function of time (e.g., each 10min interval) using a tool found on web before the experiment. The antenna is set to the single-dish mode (i.e., dish facing toward the Sun). We align the planes of the mount’s top plate and ladder parallel to sunlight using their shadows. The azimuthal direction of the top plate is also adjusted toward the Sun. We then adjust the elevation angle of the dish (with the top plate fixed) to maximize the readout signal of the Sun. Our dish is the offset Cassegrain antenna, and the direction of the dish looks very offset from the direction of the Sun. We therefore need to use the radio readout. To simplify, we later installed a foot-long rod on the dish and marked a point (on the dish) at which the shadow of the rod tip falls when pointed toward the Sun. [We then flip the dish by 180 deg around the metal pole for interferometer measurements.]

The signal amplitudes from the two side mirrors need balanced. We check readout with each side mirror separately by blocking an optical path of the other (or by removing one mirror at a time). We move the central mirror toward the side of stronger signal to decrease its effective surface area.

4.2. Measurements

Once the mirrors are set and the telescope is pointed toward the Sun, we start interferometer measurements. We should see fringes from the Sun (e.g., Figure 4) as we slew the telescope and sweep the Sun in the azimuthal direction. The pattern may be seen as a voltage readout goes up and down, or as a fringe pattern in a plot (Figure 4) if LabPro and computer are already started. LabPro and the computer do not know about telescope pointing and record only the readout voltage as a function of time. We thereby need to convert the time to azimuthal angle after the measurements. We record the start and end azimuthal angles in sweeping the Sun – we start from a far-off position, say 10-20 deg away in azimuth, and sweep the Sun in azimuth. We assume that the telescope slew speed is constant (approximately correct when we record for a long time, e.g. 20-30 seconds). The projection effect, i.e., the cos(elevation) term, should be accounted for in calculation of arc length in the sky.

We change baseline length by sliding the side mirrors on the ladder and repeat fringe measurements. The baseline length could be determined from the fringe pattern,
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**Figure 7.** Photographs and schematic of the receiver. (a) Inside receiver box. Most components are commercial. (b) Front side of the receiver box. Two critical plugs are for an input from the feedhorn and output to LabPro (i.e., a commercial analog/digital converter often used in physics lab courses, which outputs digital numbers to a computer through a USB connection). (c) Back side. We installed an analog voltage meter, so that signal detection can be easily checked during observations. (d) Schematic diagram of receiver components.
Radio interferometer for education

but for reference, we record the side mirror separation using measure taped on the ladder.

4.3. Miscellaneous

Radio interference was initially a problem. We conducted a site search across the campus. We brought the dish and a commercial receiver (called satellite finder $\sim$ $10-20$, which is used to find a commercial television satellite when a dish is installed) and compared the strengths of the Sun and ambient radio signals. We conveniently found that a spot in front of our building was radio quiet.

The current mount structure is slightly wider than a standard doorway. It cannot be carried with most of our elevators and does not pass through our entrance doors to get out. We have to carry it out from a loading deck. This could have been taken into account when the telescope is designed.

The telescope can be used as a single-dish radio telescope by pointing the dish directly toward the sky. The beam size of our dish is roughly $\sim 1$ deg in X band, with which we can barely resolve the Sun (the $\sim 1/2$ deg diameter). We can compare the profiles of the Sun and a commercial satellite (a point source) to find this experimentally. The Sun’s diameter can be resolved and determined with the interferometer. The comparison of the single-dish and interferometer measurements permits students to appreciate the superiority of interferometry in terms of spatial resolution.

5. RESULTS FROM A LAB REPORT

Figure 8 shows results from a students’ lab report. Panel (a) is an example of a fringe pattern of the Sun. They determined the baseline length by measuring the interval between peaks and troughs (and from their reads of the side mirror separation). Panel (b) shows a fit of the sinc function, i.e., the Fourier transform of the Sun. This group repeated fringe measurements three times at each of 10 different baseline lengths. They obtained the diameter of the Sun to be $31.'1 \pm 0.'6$.

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REFERENCES