Abstract

The central aim of this project is to build an audio-frequency working model of a phased-array radar as a striking demonstration of time-reversal in optics and acoustics. The model will show how a phased-array radar (essentially a directional antenna), is simply the time-reversed counterpart of a diffraction grating (essentially a large array of coherent radiators). The experiment will be used as a student project in an upper-level course on modern optics that is taught each year at Elmhurst College. The model of a phased-array radar will be constructed using Vernier microphones, two speakers, and a function generator.

A canonical problem in upper level optics is to demonstrate how the sum of fields radiated by a linear array of N coherent oscillators results in the formation of sharp diffraction peaks in intensity in the far-field. Students often do not realize that a time-reversed version of this system, namely N receivers with a fixed phase delay, can be used as a directional antenna. Thus, while demonstrating the principle of time-reversal, the experiment also demonstrates how the mathematical description of wave motion remains unchanged for acoustic or optical waves, thus illustrating the underlying unity of physical phenomena. The experiment will also be used to demonstrate how the phased-array technique is used in radio astronomy to build directional radio telescopes.

(228 words)

Program Description

Program Philosophy, Goals and Objectives

The overarching aim of the Elmhurst College physics program is to graduate *complete physicists* - students who grasp the underlying unity of physical phenomena and recognize when the same physics underlies phenomena or techniques that look very different on the surface. The celebrated physicist Richard Feynman succinctly expressed this as "*The same equations have the same solutions*." Thus, the goal of the Elmhurst Physics program, and my main objective while teaching, is to demonstrate that physics is a *synthetic* science which aims to deduce, from the observations of a large number of phenomena, a small number of underlying unifying principles.

The proposed experiment, constructing a model of a phased-array radar, is a dramatic demonstration of this "underlying unity." It shows how a diffraction grating, a staple of any undergraduate course on optics, and the phased-array radar, a sophisticated and powerful device with uses in radio astronomy, weather forecasting, and aviation, are simply time-reversed counterparts of one another.

The proposed experiment will form a lab activity in PHY414-*Modern Optics,* a course that I teach each fall. Further, the Elmhurst College physics department offers an honors course in Astronomy every alternate year. This lab activity will also be used as a demonstration experiment in *Honors Astronomy* where it will be used to show how techniques developed in one area of physics (diffraction gratings - optics) find applications in other areas (phased-array radio telescopes - radio astronomy), thus once again emphasizing the "underlying unity" of physics.

Implementation of Data Collection Technology

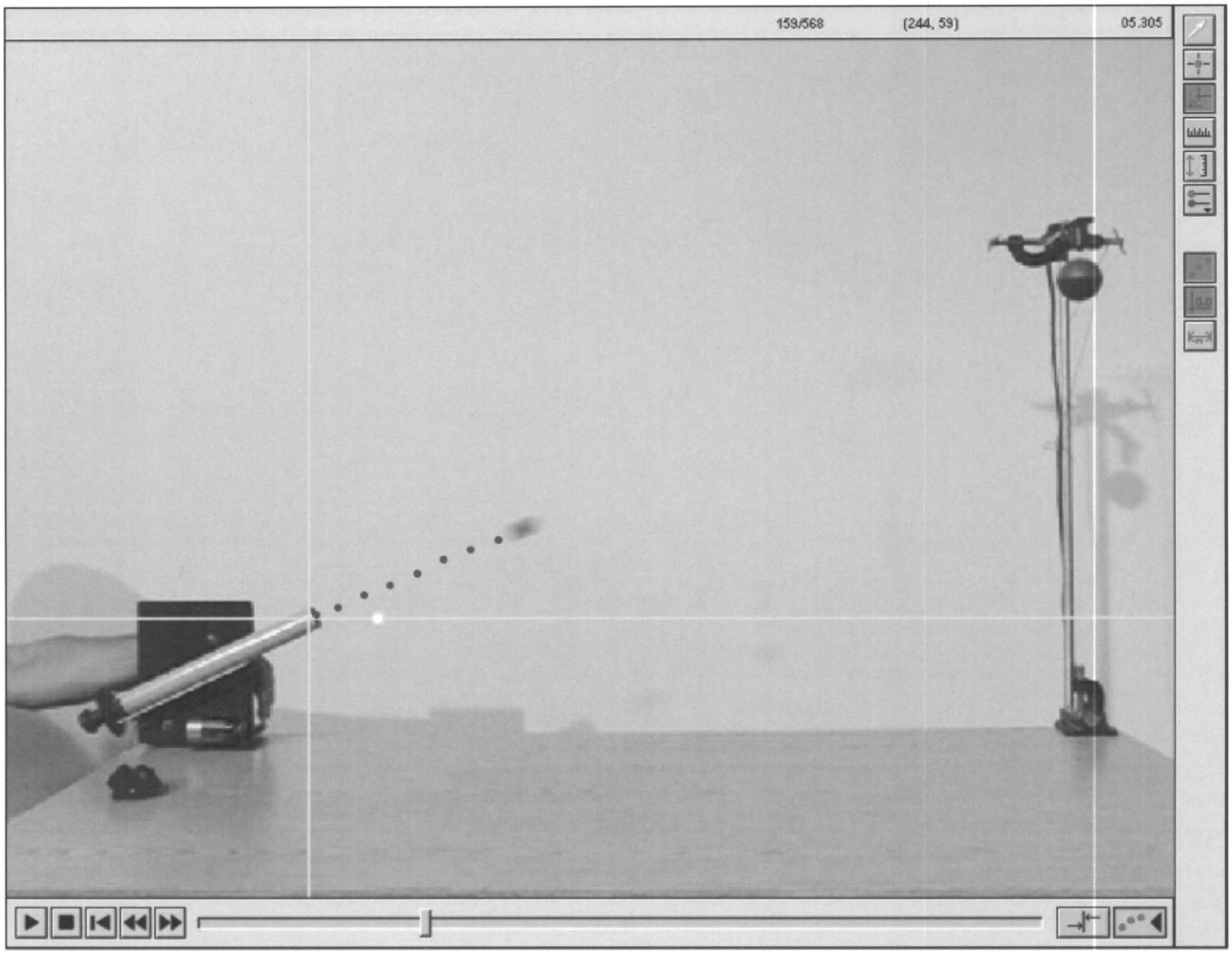
I have made significant implementation of Data Collection Technology in my classes since starting at my current position at Elmhurst College in 2008. Having no knowledge of such technology prior to my arrival at Elmhurst, I first gained expertise by attending the following two specialized training courses in the use of data collection technology:

1. *Chatauqua course on Promoting Active Learning in Introductory Physics Courses With Research-Based Curricula and Tools* - Summer 2009, University of Oregon at Eugene. Instructors: Priscilla Laws, David Thornton and David Sokoloff
2. NSF Sponsored Workshop - LivePhoto Physics: Video-Based Motion Analysis - Summer 2010, Vernier Software, Beaverton OR. Instructors: Priscilla Laws, Maxine Willis, Patrick Cooney, and Robert Teese

Almost all the labs in my introductory calculus-based physics courses (PHY121 and PHY122) that I teach each year now use either probeware with data collection technology or video analysis.

A particular interest of mine has been in developing high-speed videos for video analysis for use in introductory physics classrooms. This work has been supported by two internal grants of $4000 each by Elmhurst College in Summer 2009 and Summer 2010. An example of a high-quality video that I have produced with my students can be seen at : http://eclabs.wordpress.com/2011/08/18/linearmotion/. These videos are produced using low-cost consumer cameras (Casio Exilim series) and components that can be obtained at any hardware store. I am also developing an open-access website with an alphabetically organized collection of high-speed videos illustrating physical concepts.

The website is expected to be completed and online by July 2012. The eventual goal of this project is to make a complete suite of open-source videos and labs for introductory physics courses at the high-school and college level.



Single frame taken from a high-speed video (400 frames per second) of the classic "Monkey and the Hunter" experiment. The launcher on the left fires a projectile at the ball on the right. Students track the trajectory of the projectile and the ball and measure the downward acceleration. They find that both the projectile and the ball are in free fall, i.e. accelerating at 9.8 m/s^2.

Another example of my use of data collection technology is shown in the figure above. When learning projectile motion, students often have difficulty grasping that a projectile launched upwards is actually in "free fall" in that the only force acting on it is the force of gravity pulling it downwards. To demonstrate that the projectile is also “falling” no differently than an object dropped from rest, I made a high-speed video of the classic “Monkey and the Hunter” experiment. Here, a projectile is aimed and fired at a target, a ball (seen at the top right corner of Figure 1) that is suspended from an electromagnet. In the absence of gravity, the projectile would simply travel along a straight line and hit the ball. However, at the instant that the projectile is launched, a switch turns off the electromagnet causing the ball to drop. As the projectile and the ball are both dropping at the same rate, they will still collide if the launcher was aimed correctly at the ball. Even the most skeptical students are convinced after analyzing this video that the ball and the projectile are indeed falling at the same rate!

Impact on Student Learning

I will illustrate the impact of data collection technology on student learning with another example taken from PHY414 - *Modern Optics* that I taught this year (Fall 2011). Nearly a third of the course is spent on discussing interference and diffraction phenomena which are an important consequence of the linear superposition of electric fields. A particularly important example discussed in the course is the calculation of the far-field intensity of a double slit of finite width. The far-field intensity is a sinusoidally varying intensity pattern due to the two slits which is modulated by a *sinc* squared variation in the intensity due to the finite width of the slits.

This year, I disassembled a flat-bed scanner to scan the entire diffraction pattern in one sweep, imported the image file to Matlab, and plotted the intensity values as a three-dimensional graph. The students were stunned to see the modulation in intensity clearly visible in 3D. Although the students routinely plot the far-field intensity in twodimensions in the lab, the simple matter of visualizing the intensity pattern in 3D left a vivid impression on the students and we are now writing up this experiment for publication to a pedagogical physics journal. I have had similar experiences in a number of labs where data collection technology allows students to interact with the data in a much more direct manner by rapidly changing variables and obtaining results quickly.

Evolution of Practices in Applicant's Classroom

Teaching at Elmhurst College was my first sustained exposure to teaching and it would be an understatement to say that I was bewildered! I had very little idea about how to be an effective teacher, how to address the common misconceptions that students had while learning physics, and I had no knowledge of the existence of data collection technology. After my first semester, I became aware of the large body of work on Physics Education Research (PER) and I carefully read a number of papers along with the book by Edward Redish (*Teaching Physics with the Physics Suite*) on using data collection technology in the classroom. After that, I began to develop Interactive Lecture Demonstrations (ILD) for my classes which I used to great effect. The faculty development program at Elmhurst College also supported my efforts by sponsoring me to attend the two workshops listed above and also to buy equipment for data collection and video analysis via two internal grants. Over the past two years, I have used departmental funds to acquire a number of sensors and accessories to teach introductory physics. My classes improved dramatically as evidenced by the number of positive reviews I got, and this year, I was awarded the President's Award for Excellence in Teaching.

Proposed Lab Activity

Motivation

The proposed lab activity is the construction of a working model of a simplified version of a phased-array radar that operates at audio frequencies. The experiment will be implemented as a lab activity in an upper-level course on modern optics that is taught at Elmhurst College each fall. The lab activity has two primary aims:

1. **Aim 1- Demonstrate the mathematical equivalence of sound and light waves.** While the experiment is performed with audio waves, the results are valid for light waves as well. A mathematical analysis of the experiment will be described that is independent of the type of wave used.

2. **Aim 2 - Demonstrate the concept of time-reversibility in optics and acoustics** Time-reversibility is a central concept in wave propagation. In elementary geometrical optics, we see that if rays can propagate in an optical system in one direction, then propagation in the opposite direction is also allowed. In college-level optics, simple arguments based on reversibility are used to derive the Stokes' relations that show that a wave reflected from a denser medium must undergo a phase shift of π.

Background

Figure 1 shows a schematic diagram of a phased-array antenna assembly. Plane waves from a distant source on the right arrive at the array of detectors on the left. As can be seen from the figure, the path length difference for the rays arriving at each

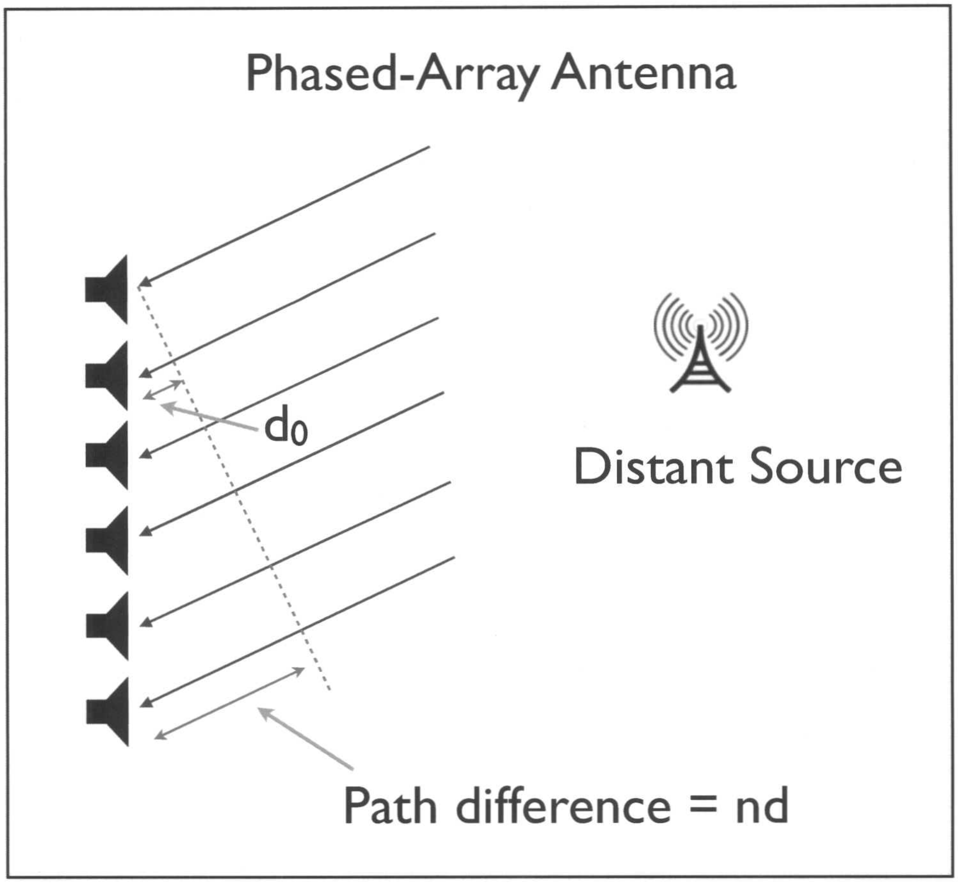


Figure 1 Schematic diagram of a phased-array antenna. Plane waves from a distant source on the right are incident on an antenna array on the left.

detector is simply an integer multiple of the path length difference between the first and second detectors (d_0 in Figure 1). This path length corresponds to a phase difference $\Delta = 2\pi nd/\lambda$, where λ is the wavelength of the incoming wave. If the output of each receiver is retarded in phase by the delay for that detector and the signals are then combined, the result is a signal that is a copy of the original signal that is amplified 'N' times, where 'N' is the number of detectors.