LTA 10

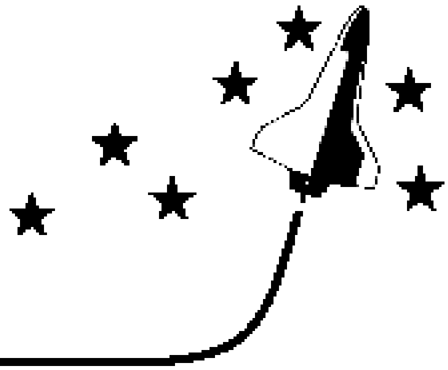
NASA - AMATYC - NSF
Project Coalition

Kennedy Space Center

Exploring NASA's
Automated Window Inspection Device (AWID)

Mathematics for Engineering Technology

Mechanical
Materials
Civil



Capital Community-Technical College

A Shuttle flight comes to a successful close as the Orbiter Columbia touches down on Runway 33 of KSC’s Shuttle Landing Facility

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Mathematics for
Mechanical Engineering Technology
Materials Engineering Technology
Civil Engineering Technology

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Exploring NASA's Automated Window Inspection Device (AWID)

Background

Approximately seven Space Shuttle Missions are launched each year. NASA currently has four Space Shuttle Orbiters (Atlantis, Columbia, Discovery, Endeavour) available for these missions. After a mission, the Orbiter is thoroughly inspected and refurbished for its next mission. Included in that inspection are the thermal windows.

An Orbiter has 6 thermal windowpanes that contribute to the structural integrity of the Orbiter. The windows are 5/8 inch fused quartz, and each costs approximately $100,000 to replace. During a mission, the panes are weakened by defects caused primarily by micrometeorite impacts. As many as 200 hits may occur. Eight to ten of these may be significant defects that require further inspection. Even defects which are only 1/1000 inch in diameter and 6/10,000 inch in depth are reported as significant and require further inspection. Manual inspection for these defects is extremely time consuming and tedious. It is performed during general post-flight servicing operations while the windows are in place on the Orbiter. A manual inspection requires two people a full day to inspect **each** window. Before inspection can occur, windows have to be cleaned and polished which requires two people 5 full days to complete. Damage has been missed in the past because of the difficulty of performing manual inspections.

In 1993, NASA scientists began developing the Automated Window Inspection Device (AWID). During early development a simple document scanner was used to scan a window for defects to test the overall concept. Some of the basic hardware and software worked, but a much better viewing device was needed.

The present version of the AWID locates defects on or below the window surface by using a polarized light imager prior to polishing the window. Additionally, it measures the extent (area and depth) of each defect using a refocus microscope. The AWID takes 8 hours to inspect each of the 4 larger windows and 5 hours to inspect each of the other two smaller windows. It also improves the reliability of the inspection process; the AWID has found significant defects that were missed in the manual inspection.

NASA scientists are already working on a next generation of AWID that promises even better resolution and imaging.

AWID Experiment
Polarized Light and Defects in Transparent Materials

Purpose

To explore the properties of polarized light and how it can be used to find defects in transparent materials.

Equipment

1. Optical bench with leveling screws
2. Regulated incandescent light source
3. Standard component carriers (3)
4. Calibrated polarizing filters (polarizers) (2)
5. Viewing screen with metric scale
6. Transparent materials to put between polarizers

Setup

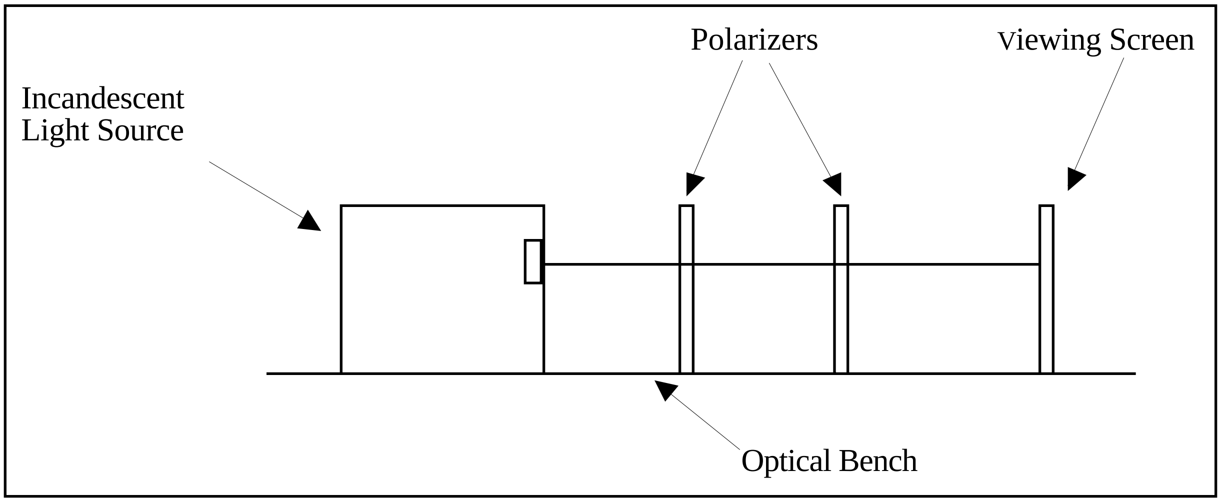


Figure 1 - Setup

Mount the light source at the far end of the optical bench (Figure 1). Mount the filters on component carriers that are 10 - 15 cm apart (Figure 1). Place the viewing screen on the third component carrier. You should see the light source projected onto the viewing screen.

Procedure

1) Rotate the polarizing filters, and watch the image on the viewing screen. Describe how the brightness (intensity) of the image on the viewing screen depends on the polarization directions of the filters.

2) Rotate the filters until their polarization directions are perpendicular to one another (Figure 2). How does this affect the image on the viewing screen?

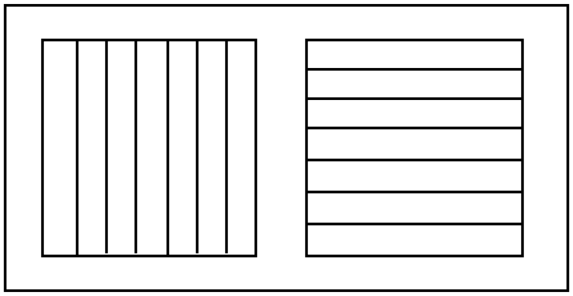


Figure 2 - Perpendicular Polarized Filters

3) With the directions of the polarizers perpendicular to each other, place the transparent materials between the filters one at a time (Figure 3).

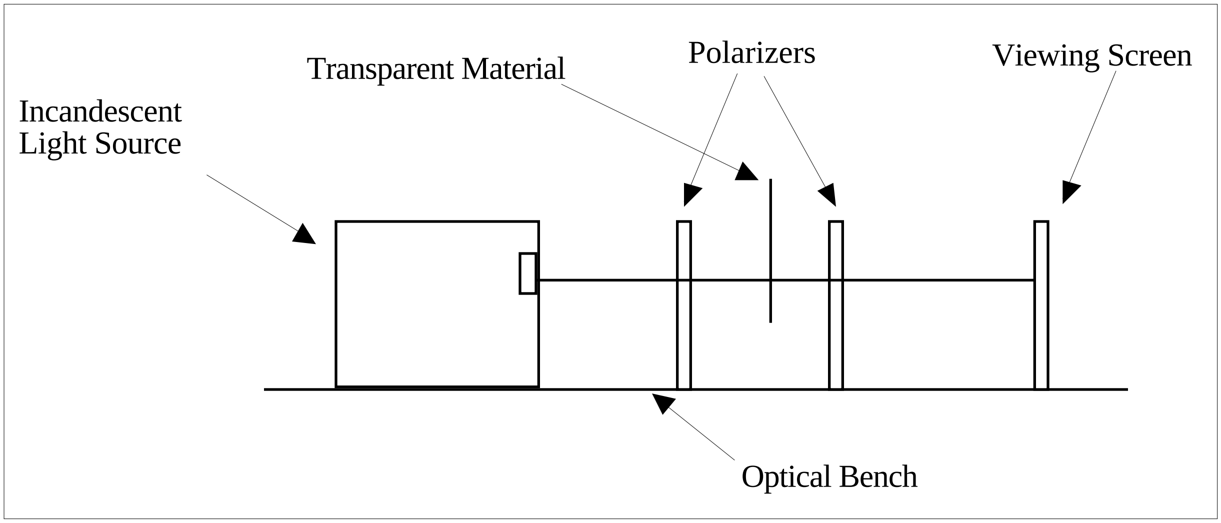


Figure 3 - Placement of Transparent Materials

Record your observations for the different materials in a table with the following column headings.

Transparent material	Sketch of what you observed on the viewing screen	Description of what you observed on the viewing screen

Report

Write a lab report for this experiment using the following format.

A. Title Page
B. Purpose
C. Method with pertinent descriptions and sketches of equipment
D. Data - your observations
E. Conclusions
F. Reflections - Discuss the limitations of the equipment used to analyze the transparent materials. Give your opinion of this technique for detecting defects in transparent materials.

AWID Overview

Window Requirements

While traveling in space, NASA’s Space Shuttle Orbiter circles the earth at about 17,000 mi/hr. (That is 16 times around the earth each day!) Microscopic pieces of space debris may be traveling around the earth at 30,000 - 40,000 mi/hr. Even tiny pieces of space debris could make a major impact on the Orbiter’s windows. Upon reentry into the atmosphere, the outer Shuttle windows must withstand a temperature of up to 2300˚ F. The windows are even subjected to a blast of 25,000 lbs of force for 50 milliseconds when the Solid Rocket Boosters are jettisoned. The booster rockets have to be blown clear of the shuttle, and they weigh a lot even when empty. To add to all that, the windows of the Shuttle contribute to the structural strength of the Orbiter. This is very different from the windows of your house which can be removed without weakening the framework of the house. In the Orbiter, even if the window frame is left in place, the Shuttle structure would be compromised without the 5/8 inch thick fused quartz window. Clearly, it is critical to the Shuttle safety and performance that the windows be maintained in good condition.

AWID Tasks

To check the windows for possible flaws requires a thorough inspection. Defects as small as 1/1000 in diameter and 6/10,000 in depth are considered significant.

The AWID has four major tasks.
1. Locate the defects.
2. Examine the shape, structure and depth of the defects.
3. Determine if the defects are significant.
4. Record the exact location of the defects.

Finding the Defects

Since the defects are so small, the AWID must be able to see tiny marks on the surface of the window. In fact, even dust particles will show up when the AWID scans the surface. During its surface scan, the AWID may pick up 20,000 - 80,000 **possible** defects. Of these only 200 to 300 are real micrometeorite hits. How can the AWID tell the difference between dust and a micrometeorite impact? As Ric Adams, a lab leader at NASA's Kennedy Space Center, explained, a combination of ingenuity, luck and hard work led the NASA scientists to a solution.

Surface vs. Subsurface Effects

The dust that accumulates on the Orbiter after it lands lies on the surface of the quartz and does not damage the window. A real hit by a micrometeorite during flight will leave either an impact crater on the quartz or a bruise within the quartz. The impact craters on the surface are similar to the craters on the moon - except a wee bit smaller (1/1000 inch diameter and 6/10000 inch in depth). The bruises within the quartz barely mar the surface of the window, and they are typically caused by slower, bigger micrometeorites. Micrometeorites either dig a crater in the the quartz or they produce a bruise that is almost completely within the quartz. In either case, micrometeorites cause defects below the surface level of the quartz (subsurface defects). Here was the key to the problem: “if there were no subsurface effects, it could not be a micrometeorite impact”. If the AWID could distinguish surface effects from subsurface effects, it could determine which were the real defects and which were not. To do this, the AWID would have to scan both the surface and the interior of the quartz.

Defects, Polarized Light and Subsurface Scanning

Polarized Light

To see the subsurface effects, the NASA team chose to use “polarized” light. Light normally has no preferred orientation, but by passing it through a certain type of filter, called a polarizer, the light can be given an orientation or “polarization”. (Expensive sunglasses are made with polarized glass.)

Polarized light has some interesting properties. For example, if a beam of light is moving forward, the polarization could be in **any** direction perpendicular to the direction of motion - left, right, up, down, at an angle upward and to the right, etc. (Facing forward with your arms at your side, if you “flap” your arms along your side, any way your arm can point is a possible polarization direction.) The light is moving in the forward direction, but the polarization will be in a perpendicular direction.

Another property of polarized light is how it reflects off of a flat surface. For example, imagine that you are holding a flashlight pointing forward. For convenience, suppose that the flashlight beam has been given a polarization that points straight up toward the ceiling. If the light were to hit a smooth flat surface straight on (such as a pane of glass or the flat quartz window of the shuttle) and bounce back off the surface, the polarization would flip 180˚ and point downward toward the floor. Figure 4 below shows a side view of an incoming beam of light and its reflected beam with polarization reversed. **Polarized light reflecting back off a flat surface would have its polarization changed 180˚.**

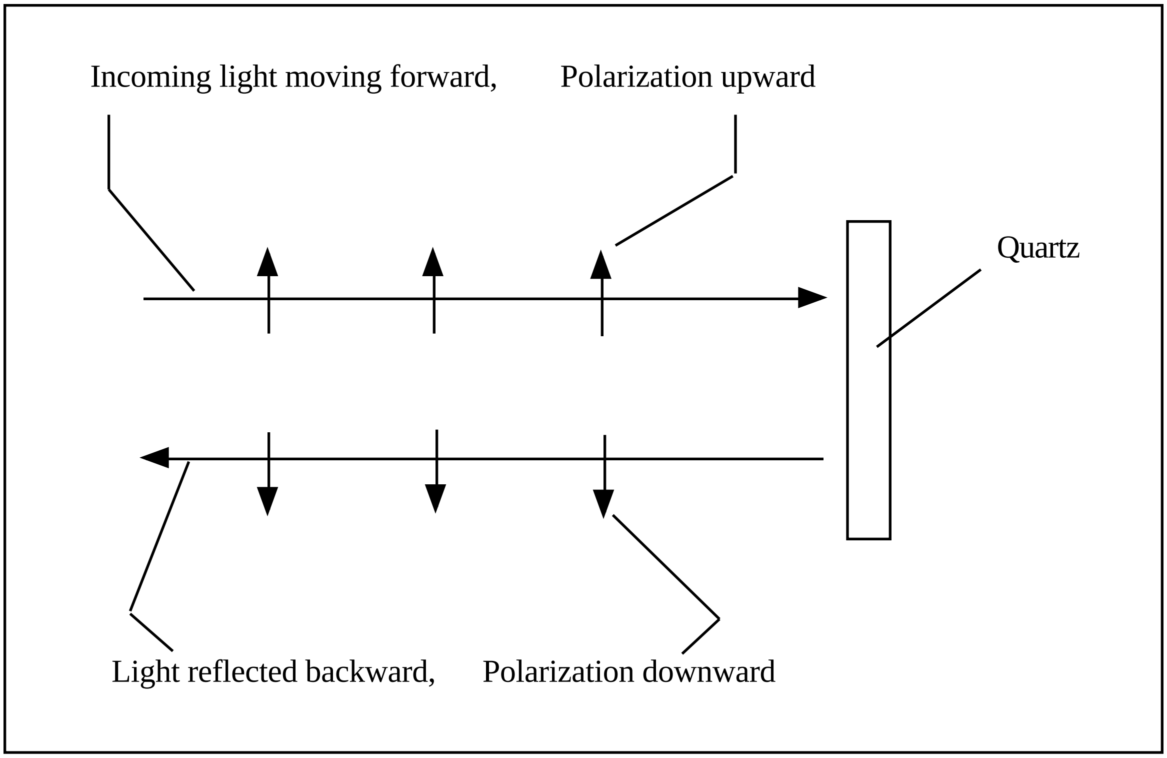


Figure 4 - Reflection of Polarized Light

A third property of polarized light is that two polarizing filters, one placed after the other, with polarization directions perpendicular to one another will block all light. Again, take a beam of light moving forward with its polarization upward. If the light runs into a polarizer that has left or right polarization, **none** of the light would get through. (If you walk forward through fairly widely spaced vertical bars you could pass through. If you walked forward into a series of horizontal bars you could not pass through.)

So, if you pass some generic (non-polarized) light through a polarizer to give it a vertical polarization and then you send the same light through a second polarizer that is horizontal, no light will get through. **In fact, as long as the first polarizer is perpendicular to the second polarizer, no light will get through.** (You observed this in your experiment.)

Now go back and consider all three properties of polarized light just discussed. What happens if you pass some light through a vertical polarizer, bounce it off the flat surface of a window and look at the light that reflects back through a horizontal polarizer?

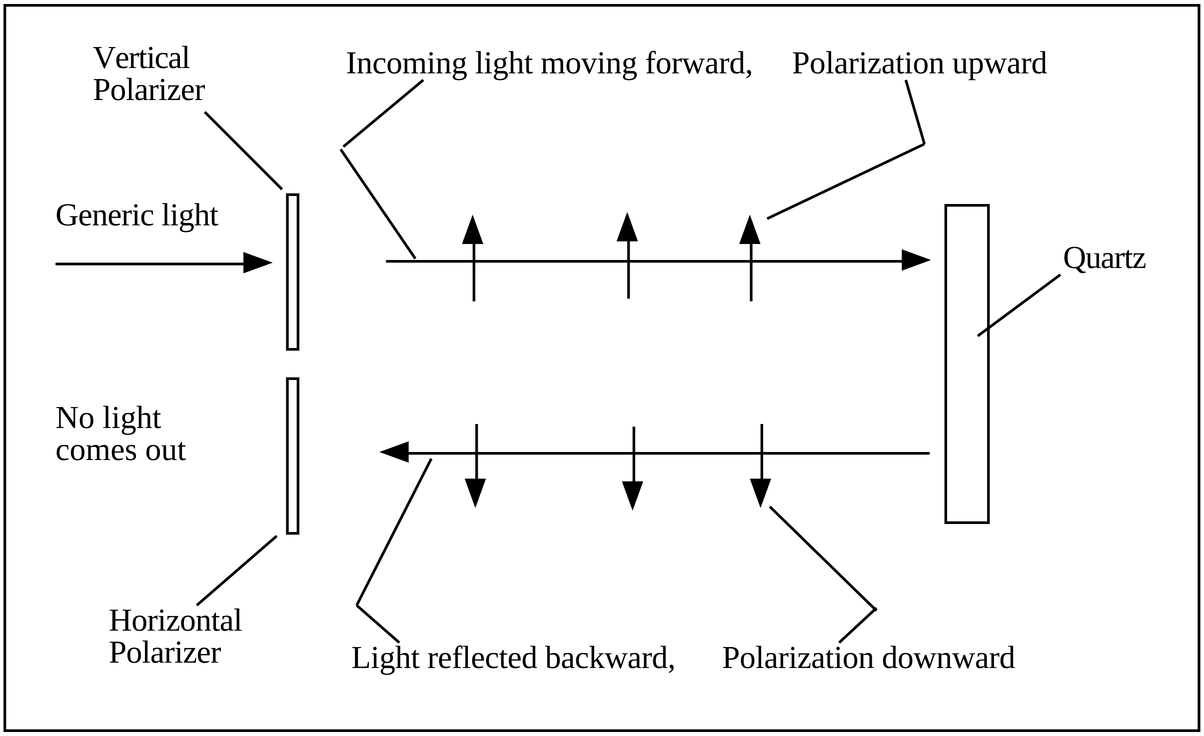


Figure 5 - Vertical and Horizontal Polarizers

No light should get back through the horizontal polarizer.

So, if you bounce polarized light off the surface of a smooth flat window, the reflected light will return with its polarization flipped 180˚. However, the reflected light will still be vertically polarized. Put a horizontal polarizer in the way and you will not see any light return. By a smooth, flat window we mean that no defects are present on the surface of the window. This is precisely what the NASA team did. They directed polarized light on the surface of the window and put a perpendicular polarizer in the way of the reflected light. They could then say, **"No defect means no polarized light comes back off the window."**, and they could tell where there were no defects.

Recognizing Defects and Subsurface Scanning

What if the incoming, vertically polarized light hits a defect? The light is no longer hitting something smooth and flat. Instead, the light is hitting a surface crater or a bruise within the quartz caused by a micrometeorite impact. Recall that both of these are referred to as subsurface defects because they are below the surface level of the window. Subsurface defects do change the polarization of the reflected light. The reflected light will no longer have vertical polarization. The direction of the polarization changes a little or a lot depending on the size, shape, and type of defect. So, if you take the light which has hit a defect and pass it through a second filter perpendicular to the original polarization, instead of no light getting through, some light will make it through the filter. The NASA scientists could then conclude, **If there is a significant defect, then some polarized light will be seen.**

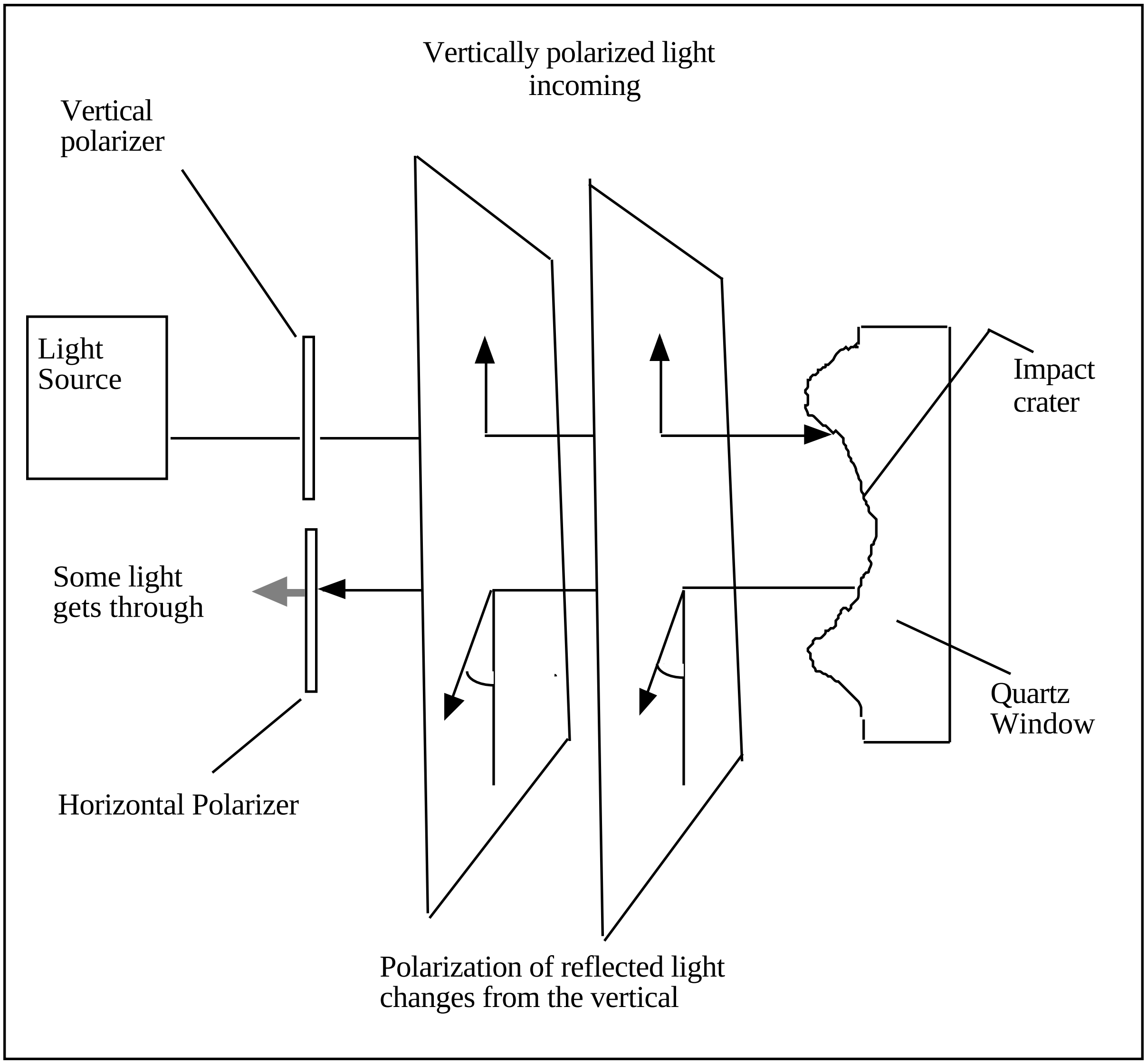


Figure 6 - Polarized Light and a Defect

The drawing in Figure 6 only shows the effects of a surface impact crater. For bruises within the quartz, the NASA scientists had to work a lot harder. To see bruises or cracks beneath the surface when there was no telltale sign on the surface, the NASA team let the polarized light go through the smooth front surface of the window, hit the defects, bounce off the back surface of the window and then return through the perpendicular polarizer. Passing through a smooth surface does NOT affect the polarization, and bouncing off the (presumably) smooth back surface only flips the polarization. (The back surface is facing away from the impacts.) The only way for the polarization to change anything but 180° is for a defect to be present. The polarized light will definitely see the REAL defects, whether they are surface impact craters or bruises within the quartz, since these have an effect upon the polarization of the light.

The last major problem involved insignificant surface effects, such as dust. When the AWID scans a window without polarized light, it basically photographs the surface one small section at a time and identifies up to 80,000 surface marks. What effect does the dust have on the polarized light? None. Regular light reflects off the dust, or else we couldn't see it, but the polarized light does not have its polarization changed. Because of this, the original marks the AWID found can be narrowed down to about 200 to 300 real hits. The AWID therefore takes a series of pictures of the surface of the window and separates out real defects from dust.

Location and Type of Defect

When the AWID finds a real defect, it notes its location on the window. The AWID then automatically deploys a refocus microscope (one that focuses at several different depths) which takes a series of close-in pictures of the defect at several different depths. From this the NASA team will have a multilayered snapshot of each defect and can study the defect's structure. This information will be passed on to another NASA team that will use it in their model of the Orbiter's entire structure. Whether the window can be used or must be replaced is determined using this model.

Conclusion

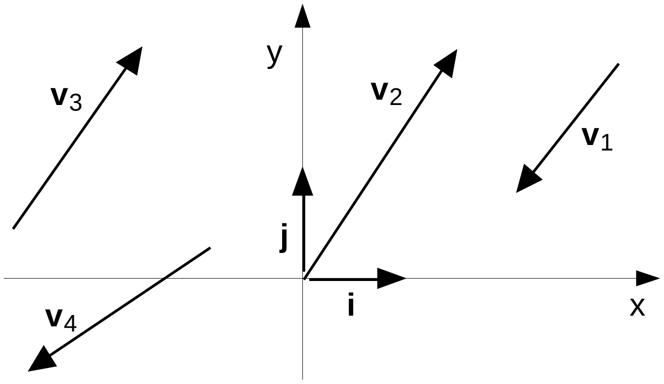
There are many other interesting aspects of the AWID such as finding ways to modify the optics so that they fit within the scaffolding around the Shuttle, to minimize the weight so that hanging the AWID from the Shuttle does not warp the window frame, and to determine exactly where a defect is located, not just its nature, etc. These are topics for future experiments, activities and explorations.

Vector Worksheet

Purpose: To review vectors and vector components.

Recall the following:

A **vector** in the plane can be represented by a directed line segment. Two vectors are equal if they have the same length and direction no matter where they are located. These are called free vectors. (Figure 1)



Note: **i** and **j** are standard unit vectors in the positive x and positive y directions respectively.

Figure 1 - Examples of Vectors

Any non-zero vector can be written as a sum of two vectors called **components** of **v**. In particular, **v** can be expressed in terms of the unit vectors **i** and **j**, i.e. $\mathbf{v} = v_x\mathbf{i} + v_y\mathbf{j}$ where v_x and v_y are scalar horizontal and vertical components, respectively (Figure 2). Vectors will be written using boldface type; scalars will be in standard type.

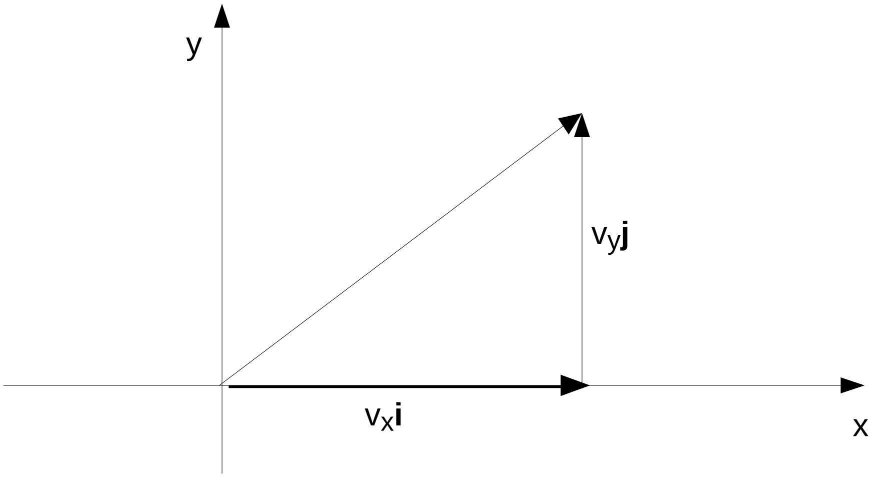


Figure 2 - Example of Vector Components

The **magnitude** or **length** of a vector, **v** is $|\mathbf{v}| = \sqrt{v_x^2 + v_y^2}$.
Also, $v_x = |\mathbf{v}|\cos(\theta)$ and $v_y = |\mathbf{v}|\sin(\theta)$, where θ is the angle formed by the vector and the positive x-axis.

Practice Problems:

Given the magnitude and angle θ, sketch the following vectors and find their scalar components, v_x and v_y.

1) $|\mathbf{v}| = 2.398, \qquad \theta = 32.7^\circ$

2) $|\mathbf{v}| = 12.89, \qquad \theta = \frac{8\pi}{7}$ radians

3) $|\mathbf{v}| = 8.9823, \qquad \theta = -108.72^\circ$

Find the magnitude of the following vectors:

4) $\mathbf{v} = 3.34\mathbf{i} + 7.891\mathbf{j}$

5) $\mathbf{v} = -2.268\mathbf{i} + 0.23\mathbf{j}$

6) $\mathbf{v} = (4.764 \times 10^{-3})\mathbf{i} + (-3.124 \times 10^{7})\mathbf{j}$

AWID - Polarization of Light - The Vector Connection

Light has a property called **polarization**. Polarization is confined to a plane and can be described by a vector. Light that we usually encounter is made up of a large number of individual vector components which are polarized in different directions. The vector components of non-polarized light tend to cancel one another so that there is no preferred direction. (If all the polarization vectors cancel out, what is their resultant vector?) Figure 3 below shows a few of the vector components of non-polarized light.

In Figures 3, 4, and 5 that follow, assume that the light is coming out of the page directly towards your eye, as if you were looking into the beam of a flashlight.

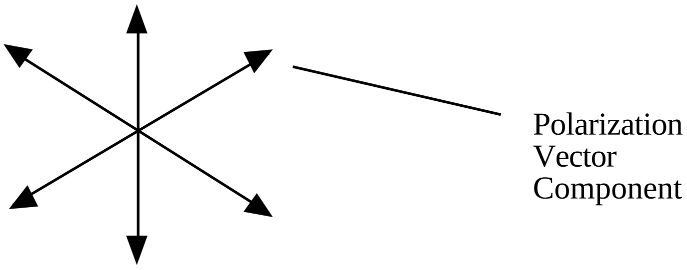


Figure 3 - Non-polarized light

If the light is passed through a polarizer (a special type of filter), one vector direction is selected. The light is said to be polarized in that direction.

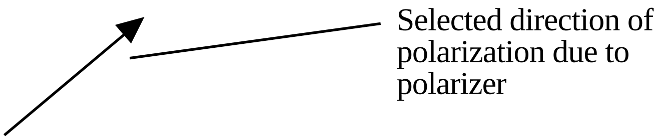


Figure 4 - Polarized Light Vector

When light is then passed through a second polarizer in a different polarization direction, only the component of the light's polarization along the direction of the second polarizer will get through.

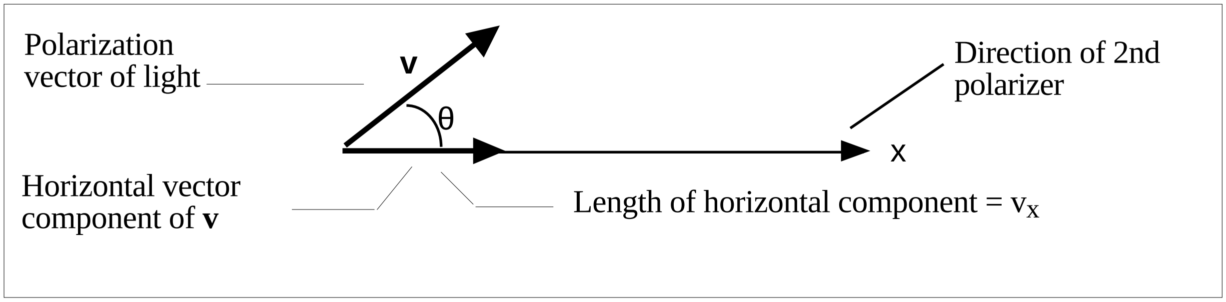


Figure 5 - Horizontal Component of Polarization Vector

In Figure 5 above, only the horizontal component of the light's polarization would get through the polarizer. The component of the polarization vector along the direction of the second polarizer is dependent on the angle between the light's polarization vector and the preset direction of the second polarizer.

7) If θ is the angle between the polarizer and the polarization vector of the light, write an equation for the fraction of the polarization along the polarizer.

8) In the **Experiment - Polarized Light and Defects in Transparent Materials** you adjusted the polarizers to eliminate all light passing through the second filter. Show, using vector components, how you were able to do this.

9) What should be the difference in the angles of polarization between two polarizers if you only wanted half the polarization to be along the direction of the second polarizer? 2/3 of the polarization?