James Wyant's contributions to polarization aberration theory

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ABSTRACT

James Wyant's contributions to the foundations of polarization aberration theory are reviewed and the simplifications it provided relative to polarization ray tracing are emphasized.

Keywords: Aberration theory, polarization

1. INTRODUCTION

Upon joining the Ph. D. program at the College of Optical Sciences in 1982, I was fortunate to join the research group of Jim Wyant. Although Jim Wyant's research group was primarily concerned with developing interferometers and performing interferometric testing, Prof. Wyant shared my interests in aberration theory and optical design.

Instrumental polarization was the term we used for the polarization properties intrinsic to an optical system. Ideally many optical systems would be non-polarizing, the incident and exiting polarizations would be the same. However due the Fresnel coefficients of mirrors and lenses and the polarization effects of diffraction gratings and other components, the polarization is modified on a ray-by-ray basis as the light propagates through the optical system. These effects could be classified into retardance, or polarization dependent phase changes, and diattenuation, polarization dependent amplitude changes. Such retardance and diattenuation effects were not calculated by optical design programs in the 1980s, because their priority had not yet become important in enough systems.

The polarization effects of interfaces are small near normal incidence, where many lenses and mirrors operate, but increase rapidly, typically quadratically, with increasing angle. So folding mirrors, in particular could show significant differences in reflectance amplitude and phase, between incident light which was s or p-polarized. As an example, Figure 1 shows the Fresnel equations for an aluminum fold mirror which has about 4% diattenuation at 45º angle of incidence increasing to 10% at 70º. Diattenuation describes the degree of polarization of an initially unpolarized beam on interaction with optical surfaces.

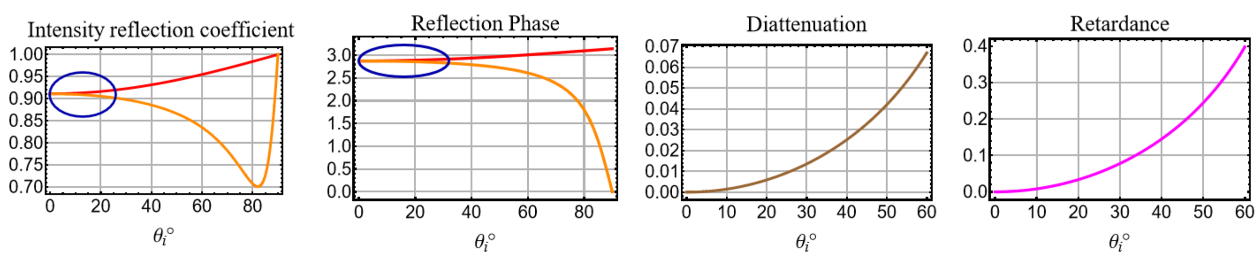

Figure 1 (Left) Fresnel intensity reflection coefficients for Aluminum, 800 nm: red s-polarized, orange p-polarized. (Second) Phase change on reflection in radians. The blue circles highlight the regions of quadratic behavior near normal incidence. (Third) Corresponding diattenuation, degree of polarization when unpolarized light is incident. (Right) Retardance in radians.

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2. CONTEMPORARY POLARIZATION ISSUES

Orbiting spectroradiometers were taking precise radiometric measurements of light scattered from the earth. The desired radiometric accuracy was better than 2%. The earthlight is predominantly unpolarized, but light from water, aerosols, and other smooth surfaces, particularly near Brewster's angle or near the cloud bow angle (138 degrees, where rainbows form) could be highly polarized. The fold mirrors which reflected and scanned earthlight into the instruments, along with the other optical element's diattenuation, were distorting the accuracy of the precision radiometric measurements when the incident light was partially polarized. In one particular system, Landsat 4, which launched in 1982, during instrument calibration the instrumental polarization was discovered to be bad as 12% at some scan angles and wavelengths. This placed instrumental polarization as a more serious issue than the other priority issues of detector noise and pixel gain drift. Thus, NASA had a strong motivation to reduce the instrumental polarization of future remote sensing systems,

Figure 2 (Left) Landsat 4 had significant instrumental polarization issues, which were discovered during calibration. JPL hoped to reduce this problem in future space-based spectroradiometers.

The polarization of interest for these orbiting optical system analyses were not the strong polarization of polarizers and retarders, but weaker polarization effects from uncoated and antireflection coated interfaces and from on-axis and fold mirrors of Aluminum, Silver, Gold, with and without overcoatings.

3. RESEARCH FUNDING

As a graduate student I was fortunate to receive research funding through Jim Breckenridge at NASA Jet Propulsion Laboratories to investigate methods for polarization ray tracing the instrumental polarization of space instrumentation. Such instrumental polarization is not usually a large effect, and optical designers had been mostly ignoring it, but it was important at that time to JPL.

Our original plan was to write a computer program to explore polarization ray tracing algorithms and apply this to components and systems of interest to JPL. Such a polarization ray tracing program would encompass the conventional ray tracing algorithms to find ray intercepts, directions, and optical path lengths. But it would also need to, at each ray intercept, calculate a Jones polarization matrix, to describe the local polarization change of the surface. The polarization matrices would be calculated using Fresnel coefficients or thin film amplitude coefficients.

While working on my dissertation research I was also learning aberration theory from Rolland Shack as well as thin film theory from Angus Macleod. Thus, the research project was an excellent opportunity to pull together ideas from Professors Wyant, Shack, and Macleod. What a wonderful combination!

4. POLARIZATION RAY TRACING

The research progressed to the point where I began to polarization ray trace my first optical systems, basic lenses and reflecting telescopes. With the algorithms working, grids of rays were being traced from the entrance to exit pupils of these optical systems creating the grids of Jones matrices which optical designers now call Jones pupils. Optical design programs always create so many numbers that optical designers complain that they never even look at most of them. In fact, the polarization calculations were creating even larger arrays of numbers, since polarization optical design replaces the scalar wavefront aberration function with an 8-parameter Jones matrix. So, the polarization analysis had eight times the large number problem of conventional ray tracing. I was swamped in numbers. This was evident every time I would provide my weekly update to Jim Wyant on the progress of the polarization ray tracing simulations.

5. POLARIZATION ABERRATIONS

Since we were just starting on this new form of optical design, I lacked the data reduction algorithms to quickly reduce and visualize these multidimensional pupil functions; I was trying to create these graphical forms as I progressed. In frustration, Jim Wyant pleaded with me to find ways to simplify the polarization ray trace data to find the underlying behaviors. Over the course of a year of these simulations he helped me formulate a more direct method of understanding the instrumental polarization of these optical systems. Jim had been directing graduate students for more than ten years at this point, and with his expert coaching, we developed a new perspective on instrumental polarization. He urged me to return to aberration theory, such as the Seidel aberration terms in Figure 3 to gain a broader perspective.

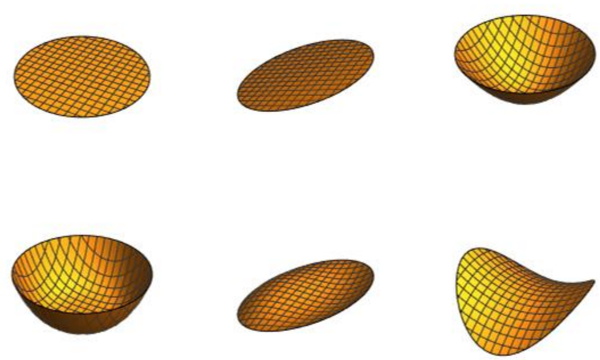

Figure 3 **The** second and fourth order wavefront aberrations: piston, tilt, defocus, spherical aberration, coma, and astigmatism. Jim Wyant and I performed research to generalize these aberration forms to handle the diattenuation and retardance patterns in instrumental polarization.

Thus, by taking ideas I was learning from Roland Shack and Angus Macleod, Jim helped me formulate an extension to wavefront aberration theory which treated the linear diattenuation and linear retardance of coated and uncoated surfaces as separate aberrations terms whose strength depended on a Taylor series approximation to the Fresnel coefficients and amplitude coefficients. Thus, we created the foundation of polarization ray aberration theory, which developed into my Ph. D. dissertation, “Polarization Aberrations” in 1987.

Here is an outline of the core idea Jim and I came up with for polarization aberration theory. An on-axis lens or mirror surface, spherical or conic, has a paraxial angle of incidence distribution as shown in the following Figure 4, where the magnitude of the angle of incidence increases linearly, while the plane of incidence is radial. The paraxial polarization aberrations for a single lens or mirror surface are obtained by combining the paraxial angle of incidence with a quadratic expression for diattenuation or retardance as a function of angle of incidence. By combining the angle of incidence functions with approximations for the Jones matrix of a surface or coating, an approximate expression for the Jones matrix of a surface is developed. Referring to the Fresnel equations in Figure 1, the diattenuation and retardance of surfaces have a leading quadratic term about normal incidence. Thus, as shown in Figure 5, for such an on-axis surface, the approximate form of the diattenuation or retardance polarization aberration for the on-axis wavefront should be the square of the angle of incidence function, taking one of the two forms, positive (left figure) or negative (right).

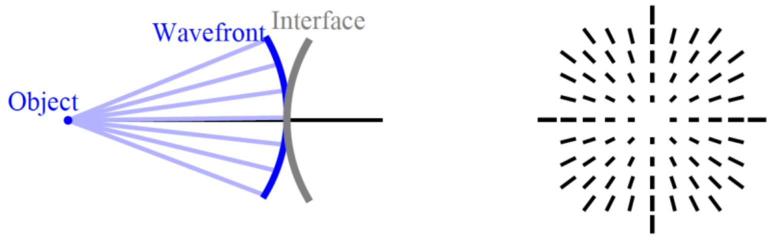

Figure 4 (Left) The spherical wavefront from an on-axis object point incident on a spherical interface has an angle of incidence of zero at the center of the beam. (Right) The paraxial angle of incidence for an on-axis wavefront at a spherical surface increases linearly from the center and equals the marginal ray angle of incidence at the edge. Line lengths indicate the angle of incidence and the orientation indicates the plane of incidence.

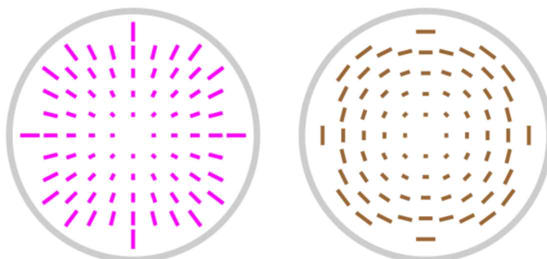

Figure 5 The on-axis form for the polarization aberration (Left) when the p-component is greater than the s-component, (right) or, when the s-component is greater than the p-component. These forms are called diattenuation defocus or retardance defocus depending on which effect is being described.

The analysis is extended to off-axis wavefronts at interfaces by considering the behavior of the paraxial angle of incidence as the object moves off-axis. Figure 6 shows a spherical wavefront incident on a spherical surface as the object moves away from the axis. Since both are spherical, the functional form of the angle of incidence remains like Figure 4, but shifted, as shown in Figure 7. The corresponding diattenuation or retardance magnitude is proportional to the angle of incidence (Fig. 7) squared, taking the form of a shifted quadratic.

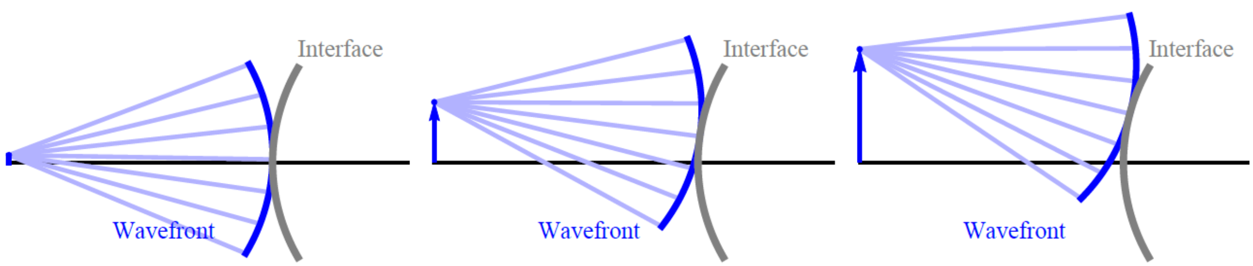

Figure 6 Wavefronts from an on-axis and two off-axis objects incident on a spherical surface. All three cases are a spherical wavefront tangent to a spherical interface.

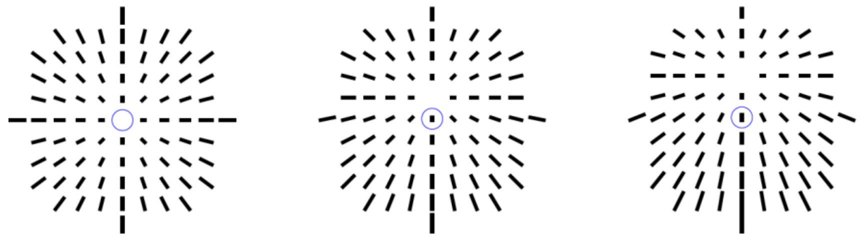

Figure 7 Angle of incidence maps as the wavefronts of Figure 4 move off-axis. The patterns shift, but otherwise are unchanged. The ray through the center of each pattern (inside blue circle) is the chief ray for that field.

A shifted or decentered quadratic function can be decomposed into a quadratic, linear and constant terms, as shown in Figure 8. In aberration theory these terms would be named defocus, tilt, and piston. Jim and I named the corresponding terms for diattenuation polarization aberrations in the paraxial regime: diattenuation defocus, diattenuation tilt, and diattenuation piston. These are graphed on the right side of Figure 9. When these are combined as Jones matrices, the result is a shifted quadratic function, as shown on the left side of Figure 9. The same three functional forms will describe the retardance of coatings in the paraxial region: retardance defocus, retardance tilt, and retardance piston. On-axis, an uncoated or coated interface only contributes diattenuation defocus and retardance defocus. As the object moves off-axis the diattenuation tilt and retardance tilt aberrations increase linearly, while the diattenuation piston and the retardance piston increase quadratically.

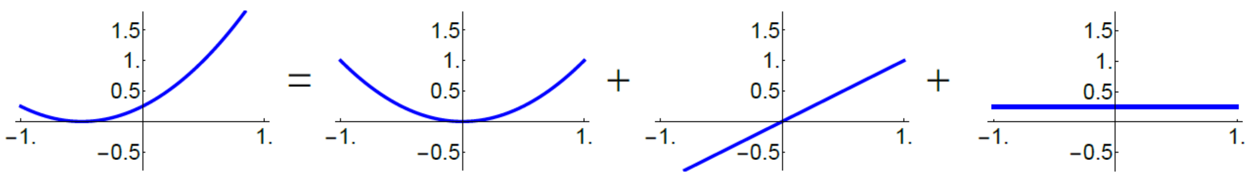

Figure 8 A decentered quadratic equation expressed as the sum of quadratic, linear, and constant components.

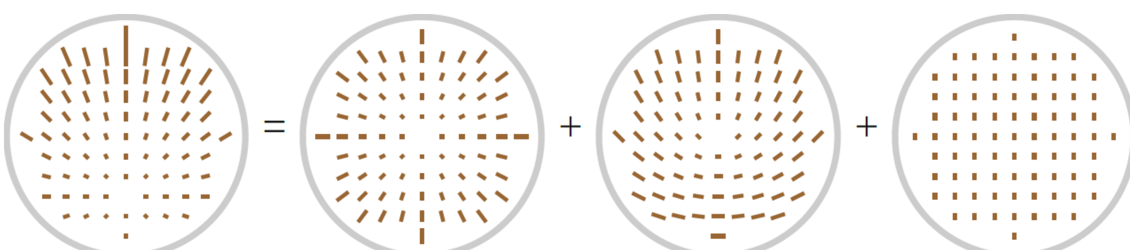

Figure 9 The diattenuation map for an off-axis beam (left) has a quadratic variation along the *y*-axis. This map can be expressed as the sum of a quadratic variation, linear variation, and constant diattenuation. These are diattenuation defocus, diattenuation tilt, and diattenuation piston aberrations. Parallel components add, while crossed components cancel.

6. COMBINING POLARIZATION ABERRATIONS OF SURFACES

As a light ray propagates through series of surfaces with weak polarization aberration, such as camera lenses, microscope objectives, and radially symmetric telescopes, the aberration contributions at each surface, either retardance or diattenuation, can be summed to calculate the overall aberration. We discovered by the use of Pauli matrices, that the combination of weak polarizations was essentially order dependent. Thus, although Jones matrix multiplication is order dependent, as is all matrix multiplication, the multiplication of weakly polarizing Jones matrices, those close to the identity matrix, was nearly order independent. Thus, the diattenuation and retardance aberrations, the piston, tilt, and defocus aberrations could be simply added. The order dependence was a "higher order term" which could be calculated separately, and usually safely ignored.

Figure 10 shows an example of paraxial aberrations accumulation for an off-axis beam cascaded over three surfaces. The first column shows the net polarization, retardance or diattenuation, for each surface, and the total aberration from the three surfaces (bottom, left). The centers of the individual surface patterns are shifted due to the off-axis beam. Since the beam is off-axis, the patterns for each surface can be decomposed into a polarization defocus (second column), polarization tilt (third column), and a polarization piston term (right column). The defocus terms can be separately added to yield the total defocus (bottom row, second column). Similarly, the tilt terms can be separately added, and the piston terms can be separately added. So, the net polarization aberration (bottom, left) is (1) the sum of the nine terms in the upper right, (2) or the sum of the three surface contributions in the first column, or (3) the sum of the total defocus, tilt, and piston in the bottom row. The summation is performed with the Pauli representation of the polarization,

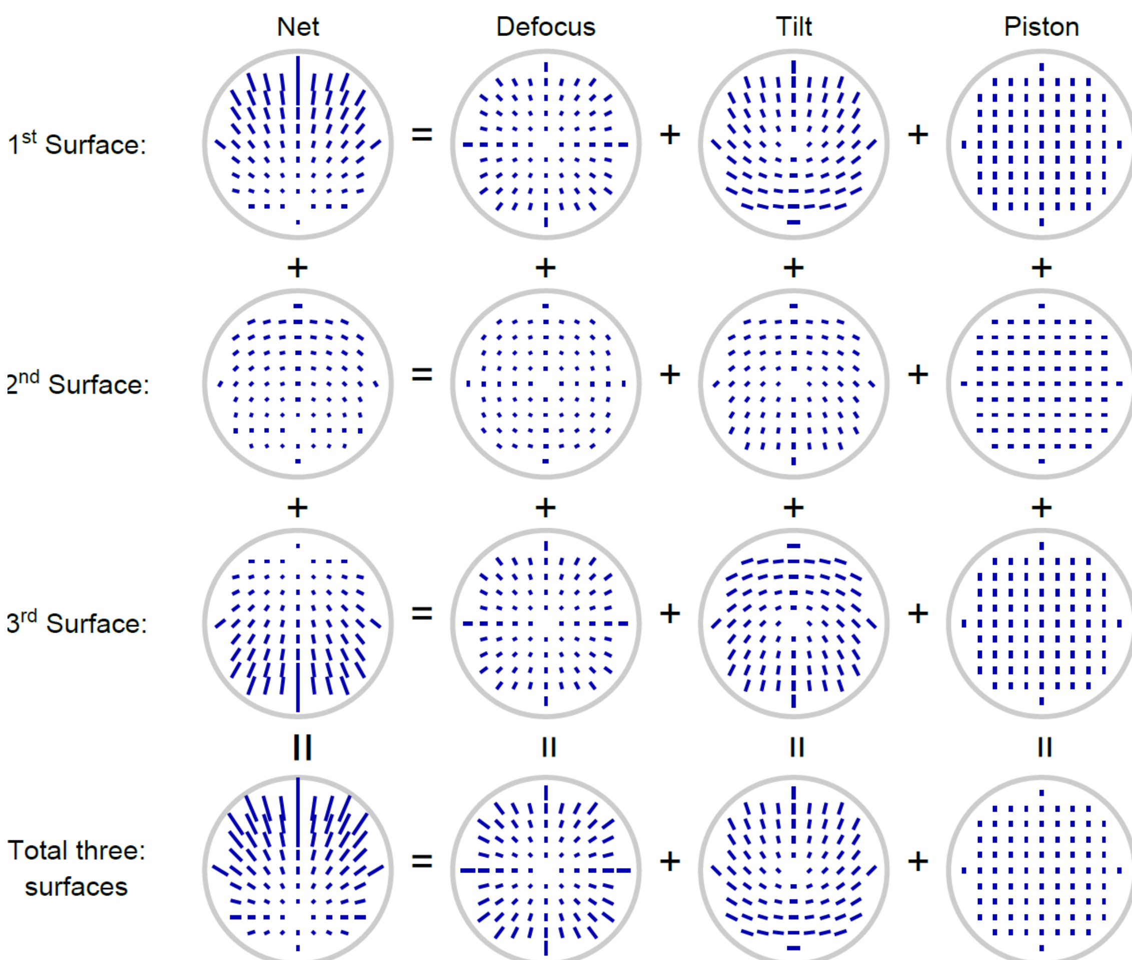

Figure 10 The polarization contribution from three surfaces is shown in the left column. Each of these polarization aberration maps can be decomposed into the summation of a defocus term (second column), a tilt term (third column) and a piston term (right column). These defocus, tilt, and piston columns can also be summed separately, by adding columns, to equal the bottom row's defocus, tilt, and piston terms, which sum to the overall polarization aberration map (lower left).

For the on-axis beam, the tilt and piston terms would be zero, so the net polarization aberration would be just the sum of the defocus terms (bottom row, second column). For a radially symmetric system, the tilt increases linearly with the field, the piston quadratically with the field, and the defocus is constant. The flow and logical continuity of the sections above helps show the power of seeking simplifying principles which Jim Wyant brought to this analysis.

SUMMARY

The Seidel aberrations are defined as deviations from paraxial performance. Similarly, for the derivation of polarization aberrations, paraxial optics forms an excellent basis for deriving the low order forms of polarization aberration.

The benefit of the polarization aberration approach to instrumental polarization is its ability to help optical engineers to clarify a complex situation and communicate better. This was Jim Wyant's point when we confronted the complexities of analyzing reams of polarization ray tracing calculations. The language used to discuss optical phenomena should be clear. Then it will be best understood through the whole cycle of development and production, from those who specify optical systems, the optical designers who perform the analysis, the engineers who perform detailed design of all the parts and subsystems, the subcontractors and vendors making components, metrology and quality control testing these parts, to the system integration and test team.

Jim Wyant played an important role in the original formulation of polarization aberration theory. This theory arose out of the roots of polarization ray tracing results, and provided an important simplification in polarization analysis, explained previous optical system measurement anomalies, and contributed to the community's toolkit to understand and solve problems in instrumental polarization. This tool, which Jim Wyant helped nurture, simplifies the analysis of coatings in optical systems, clarifies the polarization issues, and improves communication among optical system engineers.

In addition to my Optical Sciences dissertation[1], descriptions of this research originally appeared in two proceedings publications: one at the 1985 International Lens Design Conference Cherry Hill, NJ[2] and another manuscript at the SPIE 1987 annual meeting[3]. Another treatment of this material can be found in my textbook "Polarized Light and Optical Systems"[4], Chapter 15.

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