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An Optical Believe It or Not: Key Lessons Learned

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Introduction

This conference is the first SPIE conference dedicated to the sharing of key optical lessons learned. Nearly all optical engineers, scientists, researchers, or managers have dealt with the unexpected. Many of these situations in hindsight are quite funny, and have buried within them key optical lessons learned. The problem with simply listing lessons learned is that as a simple listing, they are clearly hard to remember. Thus history repeats itself much to our collective debit. This conference was configured to add humor into the mix where appropriate, and by presenting a collection of small interesting stories or optical parables, help us all remember the important take-aways. We allowed each presentation to be somewhat embellished by the author (within editorial limits). Names, places, and dates were sometimes changed to protect the guilty. But all presentations have a basis in truth as avowed by the Devil's Advocated author, and each included at least one, if not more than one, lesson learned that has serious optical content.

Papers were specifically requested on past, current, and/or evolving optically related systems that met certain conditions:

- Have been subject to surprises, anomalies, and/or unanticipated business factors which, in hindsight, are funny and which have a key optical lesson-learned/take-away;
- Where (optically related) specifications went terribly wrong;
- Any aspect of the build-cycle could be included, be it in conceptualization, design, development, fabrication (any somewhat optically related process), test, or end-use;
- Any technical discipline could be included if/as it ties to optics (e.g. opto-mechanics, thermo-optics, electro-optics, optical-physics, etc.);
- Any personnel problem could be included if/as it relates to an optical truth (this could include training or the lack thereof);
- Any optically related piece-parts could be included, from raw materials to heat treats to coatings to mechanisms, etc.;
- Any optical environment was acceptable, e.g. from underwater to outer-space to child-proof toys to shot-from-a-gun;
- Any size was acceptable, e.g. from nano/MEMS, to deployable multi-meter optics;
- Any unusual scheduling problem was acceptable as long as it was optically driven;
- Inter-company relationships and/or relationships with clients, suppliers, and/or vendors could be included, if the author so dared and could sanitize the text to avoid liability (and as long as there was a key optically related take-away, though these could be in an optical business-based sense);

Of special interest were stories where, despite any humor, the optically related lessons learned were serious and would help to form a body of knowledge that can grow and be used, as an evolving check-list, for other on-going or future optically-related adventures.

We won't trivialize the punch-lines by doing a simple summary here. The authors' papers deserve serious attention and a set of crib-notes doesn't do these sometimes complex subjects justice. It's not so much that the concepts are so terribly complex; it's that the situations that lead to some of the lessons learned have slippery-slope contextual aspects that are relatively subtle, or there are logical short circuits that come into play. Just one example would be from HST. End-to-end testing was eliminated to save money. The presumption was that as long as two totally different piece-part tests agreed, all would eventually be well. But then schedules got tight, logic gave way to what folks knew in their hearts was right—that the Reflecting Null Corrector used to finalize the Primary Mirror was all that really mattered, and that the supposedly less accurate Refracting Null could be ignored. Of course in ignoring the Refracting Null's test results the initial premise was violated that required two different tests which had to agree. (As we know, although on paper the Reflecting Null Corrector was better than the Refractive Null Corrector which was used to rough-in the Primary Mirror, the Reflecting Null Corrector was not built to specifications.).

By not shorting out your need to examine the papers presented, we're actually invoking a lesson learned. Simple Summary Charts often can lead to a false sense of understanding. But with that stated, we do intend to keep tabs on the various lessons learned, and this may well become a future rolling score-card, albeit with a somewhat intentional time-delay to encourage the real-time readers to delve into the details and find the Devil that's hiding in wait for them.

We will state that in this conference, as expected, there were a number of talks on the Hubble Space Telescope (HST), including special insights shared by Domenick Tenerelli of Lockheed Martin Space Systems Co., Greg Davidson of Northrop Grumman Space Technology, and Joe Howard (presenting a paper of his, Lee Feinberg's, and Paul Geithner's) of NASA Goddard Space Flight Center (presentation only), as well as by this author.

Michael Sholl of the University of California/Berkeley discussed several unique aspects of the CHIPS microsatellite optical system.

Phil Hinz of the University of Arizona & Steward Observatory covered the Sine Condition and also what it meant for the Large Binocular Telescope (LBT). Interestingly, Jim Harvey of the University of Central Florida/CREOL had run into some X-Ray optical problems where violation of the Sine Condition was actually a preferred approach. Jim presented his material in an evening Session we had arranged for members of the audience to speak on their own lessons learned, if they so dared.

Al DeCew of MIT Lincoln Lab. presented a paper on Total Redundancy, and John Rogers of Optical Research Associates discussed three-bar resolution versus MTF, and how the difference can be quite important. Dave Redding of JPL provided some interesting insights into lessons learned as part of an optical analysis of a radio-frequency lens, and Bob Parks of the Optical Perspectives Group, LLC showed there are times when specifications for figure and finish are simply not enough.

John Caulfield of Fisk University had a number of interesting lessons learned that extended to image processing and the nature and value of fuzzy metrology, and Roger Paquin, an Advanced Materials Consultant, covered an unusual situation entitled "Now what happens?" when managerial changes were not only unanticipated, they were rather unprecedented.

Al Hatheway of Alson E. Hatheway, Inc. gave an interesting paper on lessons learned entitled "A rondo in three flats," and Claus Hoff of JPL discussed some of the partially validation-related lessons learned that came from JPL's work on the SIM thermo/opto/mechanical test-bed validation using Cielo (a totally new and revamped tool that is in the process of replacing IMOS). A related paper on hooking up integrated models (i.e. Thermal Desktop®, NASTRAN®, and CODE V®) via a new Integrated Modeling Dashboard Tool called Comet® was presented by Mal Panthaki of Comet Solutions, Inc. These papers had a number of contributors as noted on the papers themselves.

This author, Mark A. Kahan of Optical Research Associates, presented a series of vignettes in three parts that covered a mix of comical (in hindsight) adventures, each of which gave rise to lessons learned. This paper was entitled "From the Navy to the Three Little Pigs." (The second part of the paper covered some general Optical Systems Engineering/OSE Lessons applicable to many programs, and the third part of this talk related to specific OSE examples as related to HST, as was noted earlier.). Also, Bob Fisher of OPTICS 1, Inc. presented a large collection of lessons learned in a paper nicely entitled "Bloopers and Blunders in Optics."

The session ended with the author presenting the work of Jeff Hecht of Laser Focus World/Pennwell on lessons learned from Theodore Maiman's success in making the first laser, as well as an interview he recorded with Frank Leard of Rockwell Automation, Inc. on how to solve problems with borrowed technology.

A mini-evening session was held with a judging panel (the author) evaluating selected stories resulting from the Monday/Tuesday Optical Believe It Or Not: Key lessons learned sessions, and other audience inputs. Jim Harvey won the technical award for his spur-of-the-moment treatise on the Sine Condition. This award, which is still in the "I owe you stage," is a lessons learned t-shirt with a Cassegrain telescope oriented so that light goes from right to left; we all know this is clearly impossible. Alan DeCew won the lessons learned Management Award, which is also in a similar stage of production, for his story about corporate short-sightedness in zeroing-out engineering budgets and the resulting aftermath. (This author was sufficiently familiar with this story; he recessed himself from voting). Alan will be presented with his lessons learned award at a future date. (The award consists of a doll with its head removed and placed at a new location within the doll's body).

Current plans call for us to deepen and expand this lessons learned conference in 2010 (alternating years with the Optical Modeling and Performance Predictions Conference), and to emphasize, even more heavily, the managerial aspects which are a key to success.

Mark A. Kahan

Satisfying the Abbe Sine Condition can Result in Inferior Optical Performance

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Abstract

It has been stated that satisfying the Abbe sine condition is not just a good idea; it's the law! And indeed there is a wide-spread perception among optical designers/engineers that an optical design that strictly satisfies the Abbe sine condition is always better than a design that does not satisfy the Abbe sine condition. There is likewise a widespread perception that an aplanatic optical design is always better than a non-aplanatic design. Believe it or not, in this paper on key lessons learned, I will dispel those widespread perceptions by demonstrating that the Abbe sine condition is not a law, and sometimes it is not even a good idea! I will do this by discussing several imaging applications where an optical design strictly satisfying the Abbe sine condition (or an aplanatic design) actually results in optical performance inferior to that of an optical design with the same 1st-order properties that does not satisfy the Abbe sine condition (or the aplanatic condition).

Keywords: Abbe Sine Condition, Aplanatic Optical Designs.

1.0 Introduction

Conference 7071, entitled *An Optical Believe It or Not: Key Lessons Learned*, at the 2008 International Symposium on Optics and Photonics provided a good forum for optical engineers to report on key lessons learned on specific optical programs. These reports will perhaps help other optical engineers from repeating costly and time-consuming mistakes on future optical programs. However, because of different system requirements, there is a danger in taking the lessons learned in one specific program and asserting that they are applicable to a broad range of different optical applications.

An example is paper 7071-03 entitled *The Sine Condition: It's not just a Good Idea; It's the Law*.[1] Does this mean that the Abbe sine condition should be considered as irrevocable as the Second Law of Thermodynamics or Newton's Laws of Motion? I think not. I did not disagree with anything in the content of the paper, only with the implication of the title. The paper dealt with phased telescope arrays, which are inherently very small field-of-view (FOV) imaging systems. And satisfying the Abbe sine is indeed necessary to achieve the top-level image quality requirements for many such systems. However this does not make the Abbe sine condition a law that should necessarily be applied to a wide variety of imaging applications.

Although definitions vary somewhat among different authors, any order of linear coma is an offense against the Abbe sine condition, and an aplanatic design is usually considered to be one in which there is zero 3rd-order spherical aberration and zero 3rd-order coma.

I will now proceed to describe three different major optical programs in which the key lesson learned was: not only is the Abbe sine condition not a law, it is sometimes not even a good idea.

2.0 An Optical Fabrication Feasibility Study for the Far Ultraviolet Spectroscopic Explorer

In October of 1986 NASA's Goddard Space Flight Center awarded a study contract to the Space Sciences Division of the Perkin-Elmer Corporation a manufacturing feasibility study for the Far Ultraviolet Spectroscopic Explorer (FUSE) telescope. I served as the FUSE Study Contract Manager. The FUSE telescope reference design put forth in the NASA Request for Proposal (RFP) was a 1.0 meter diameter Wolter-Schwarzschild Type II grazing incidence telescope as illustrated in the center of Figure 1.

The classical Wolter Type II telescope[2-3] is the grazing incidence analog of the classical Cassegrain telescope. It consists of a confocal concave grazing incidence paraboloid (primary mirror) and a convex grazing incidence hyperboloid (secondary mirror). Although corrected for spherical aberration, the classical Wolter Type II telescope suffers from severe coma, astigmatism and field curvature. It thus violets the Abbe sine condition.

The Wolter-Schwarzschild Type II telescope[4-5] strictly satisfies the Abbe sine condition and is therefore aplantic (corrected for 3rd-order spherical aberration and coma). It requires general aspheric (non-conic) surfaces that can be specified by a set of parametric equations.

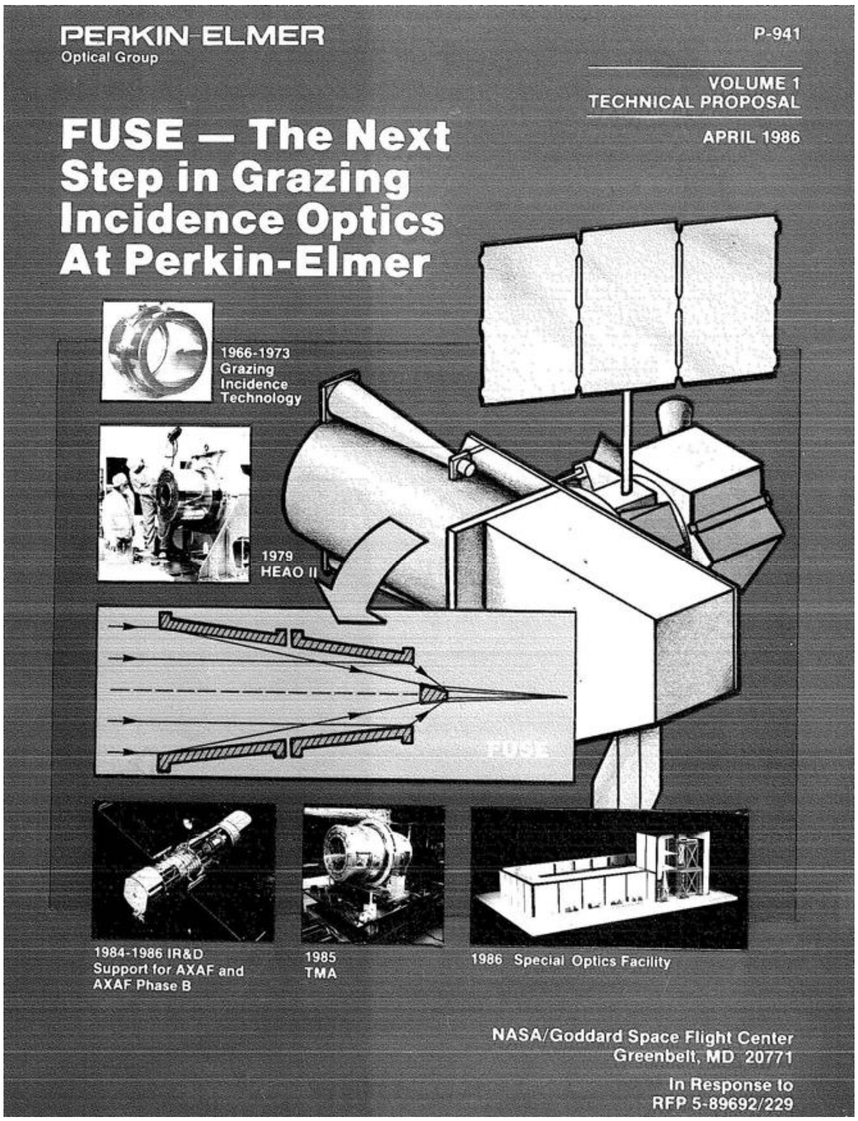

Figure 1. FUSE—The Next Step in Grazing Incidence Optics at Perkin-Elmer.

The detailed analysis performed by Perkin-Elmer in this study contract[6] indicated that indeed the optical design of the Wolter-Schwarzschild Type II telescope is superior to that of the classical Wolter Type II telescope at small field angles (see Figure 2) where science data will be taken. However, when reasonable optical fabrication errors are included in the image quality predictions, the system performance is no better throughout the small science FOV and only insignificantly better throughout the larger tracking FOV (see Figure 3).

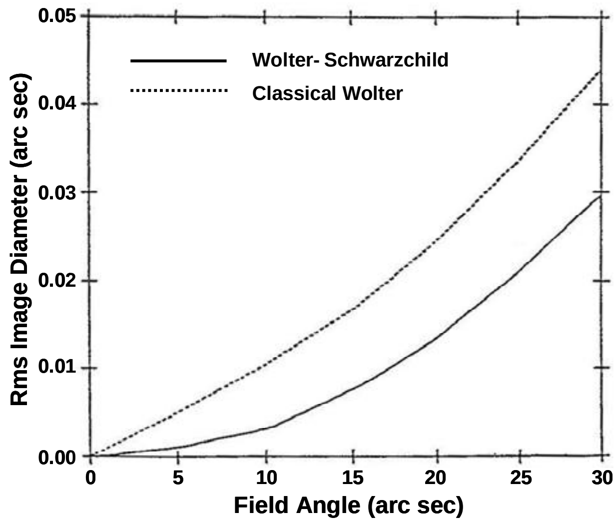

Figure 2. Illustration of the superior performance of the Wolter Schwarzschild design over the small science field when only residual design errors (geometrical aberrations) are considered.

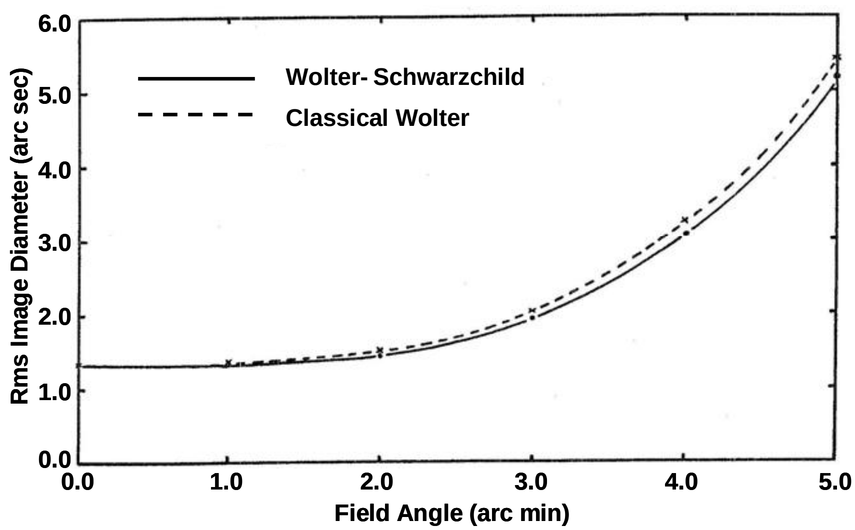

Figure 3. Illustration that the Wolter Schwarzschild design loses its advantage when an optical systems analysis is performed that includes optical fabrication errors as well as residual design errors.

The lesson learned here is that if scattering effects from residual optical fabrication errors dominate coma at small field angles and astigmatism and field curvature dominates coma at large field angles, then there is no merit to an optical design that strictly obeys the Abbe sine condition (zero coma) In fact, there is a disadvantage to the design that satisfies the Abbe sine condition as optical fabrication and metrology costs and schedule will probably increase due to the more complicated surface figure requirements. Based upon the Perkin-Elmer analysis, NASA changed their reference optical design in their FUSE Phase A Study Report published in 1989.[7]

3.0 The Solar X-ray Imager (SXI)

The Solar X-ray Imager (SXI) is a staring grazing incidence X-ray telescope being flown on all future Geosynchronous Operational Environmental Satellites (GOES) operated by the National Oceanic & Atmospheric Administration (NOAA). SXI provides full solar disc images over the spectral range 10Å < λ < 60Å that will be used to monitor and predict space weather.[8] The Lockheed Martin Solar and Astrophysical Laboratory (LMSAL) was the prime contractor responsible for designing and building the SXI instrument. Goodrich

Electro-Optical Systems in Danbury, CT was selected as the subcontractor for fabricating the super-smooth grazing incidence mirrors. NASA/GSFC was the contract monitor for the SXI program. There were thus two federal agencies and two large aerospace companies involved in the SXI program. I served as a technical consultant to Lockheed Martin, through a small contract to the Center for Research and Education in Optics and Lasers (CREOL) at the University of Central Florida. My role was to look over the shoulder of the subcontractor manufacturing the mirrors, to examine the metrology data, and to advise LMSAL concerning optical fabrication tolerances and scattering effects upon the resulting image quality.

The baseline design of a classical Wolter Type I X-ray telescope presented in the RFP was essentially dictated by the top-level image quality requirement imposed upon the on-axis fractional encircled energy. This image quality requirement, and the resulting Wolter Type I design, had previously been used for NASA's Chandra Observatory which was a small FOV stellar telescope. However, SXI is a wide-field staring solar telescope (pointed at the center of the sun and taking full solar disc snapshots) and the off-axis aberrations of the Wolter Type I baseline design caused severely degraded images over much of the solar disc.

A *field-weighted-average* measure of resolution is more appropriate as the image quality requirement for a wide-field application. Optimizing the field-weighted-average resolution over a wide FOV has traditionally been done by merely despacing the focal plane of the classical Wolter Type I design or the corresponding Wolter-Swartzschild (WS) Type I design that strictly satisfies the Abbe sine condition. This, of course, results in a defocused image on-axis image.

Optimizing the field-weighted-average geometrical rms image size produced by a two-mirror grazing incidence X-ray telescope resulted in a whole new family of generalized Wolter Type I (hyperboloid-hyperboloid) optical designs, where each member of the family was optimized for a different operational field-of-view (OFOV). This field-weighted-average rms image radius is readily converted to an approximate number of spatial resolution elements in a given operational field-of-view (OFOV) that, in turn, can be associated with the total information content in that OFOV.

We thus performed an exhaustive comparison of the field-weighted-average geometrical rms image size of that family of optimal grazing incidence hyperboloid-hyperboloid (HH) designs to the optimally despaced classical Wolter Type I design and the optimally despaced Wolter-Swartzschild Type I (WS) design that strictly satisfies the Abbe sine condition.[9] The results are shown in Figure 4.

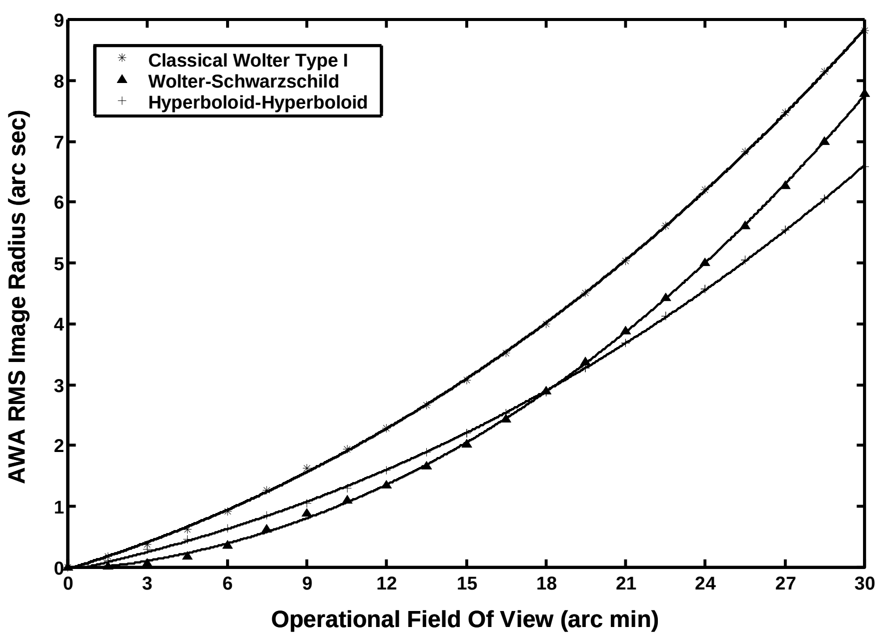

Figure 4. Comparison of the field-weighted-average rms image radius versus OFOV for three different types of grazing incidence X-ray telescope for wide-field imaging applications.

As expected, the optimally despaced WS design and the optimum HH design significantly outperforms the optimally despaced classical Wolter Type I design for all OFOV's. However, perhaps surprisingly, the optimum HH design outperforms the optimally despaced WS design for OFOV's greater than approximately 18 arc min for the SXI telescope 1st-order design parameters. When surface scatter effects and detector effects are included in a complete systems engineering analysis of image quality for such systems, there is often even less merit to an optical design that satisfies the Abbe sine condition.[10-11] Our complete systems engineering analysis of image quality indicated that our optimum non-aplanatic HH SXI design would result in an 80% increase in the number of spatial resolution elements in the solar disc over what could be achieved by the classical Wolter Type I baseline design. Figure 5 is an on-orbit image recorded with the GOES-13 SXI instrument utilizing a non-aplanatic HH grazing incidence X-ray telescope design optimized for an 18 arc min OFOV. At least one solar physicist described is as "exquisite".

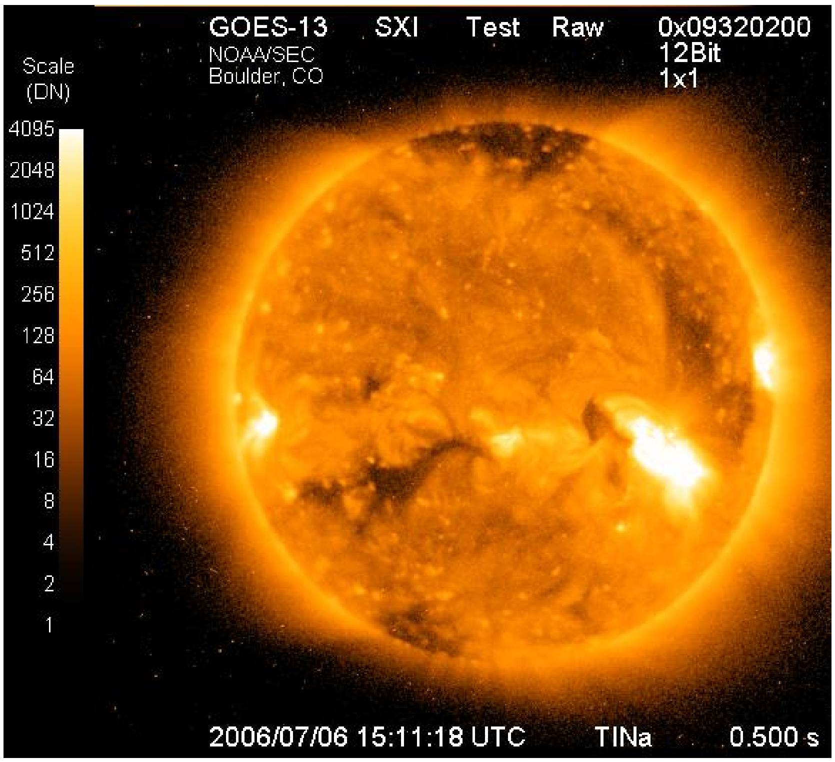

Figure 5. On-orbit image recorded with the GOES-13 Solar X-ray Imager (SXI) instrument utilizing an optimized hyperboloid-hyperboloid grazing incidence X-ray telescope design.

The lesson learned here is that even when only image degradation due to geometrical aberrations is considered, an optical design that strictly satisfies the Abbe sine condition is not always superior to one that does not satisfy the Abbe sine condition; i.e., not only is the Abbe sine condition not a law, it is sometimes not even a good idea.

4.0 The Solar UltraViolet Imager (SUVI)

The Solar UltraViolet Imager (SUVI) is one of several instruments on board the NASA/NOAA Geostationary Operational Environment Satellites (GOES)-R Series that will provide important information on solar activity and the effects of the Sun on the Earth and the near-Earth space environment. The SUVI will use a generalized Cassegrain telescope to image the sun at six different wavelengths in the extreme ultraviolet/soft X-ray region of the spectrum. Wavelength selection and enhanced reflectivity in this spectral range will be provided by multi-layer mirror coatings and the images will be sensed by a CCD detector system. The aperture of the finished instrument will be divided into six sectors, each carrying a different coating.

Figure 6 illustrates the SUVI telescope optical layout indicating rays traced through one sector of the wavelength-selecting aperture plate.

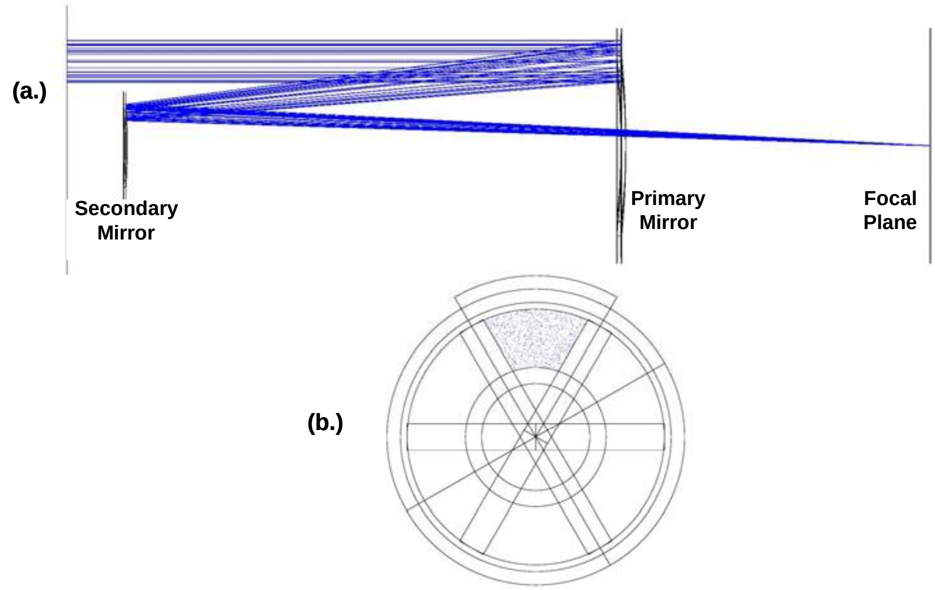

Figure 6. (a.) Optical layout of the SUVI telescope with spiders and aperture plate in place, (b.) illustration of the size and shape of the operating telescope aperture.

The optical prescription of the SUVI telescope started as an aplanatic Ritchey-Chretien design, which was then optimized over a large FOV with a commercially available optical design and analysis code. The resulting optical design consists of a hyperboloid primary mirror and a hyperboloid secondary mirror; however, not the unique hyperboloid-hyperboloid design that would constitute the popular aplanatic Ritchey-Chretien design used for so many small-field stellar telescopes. Instead, the generalized Cassegrain telescope was optimized to balance the geometrical performance over five field angles ranging from zero to 0.5 degrees as illustrated in Figure 7.

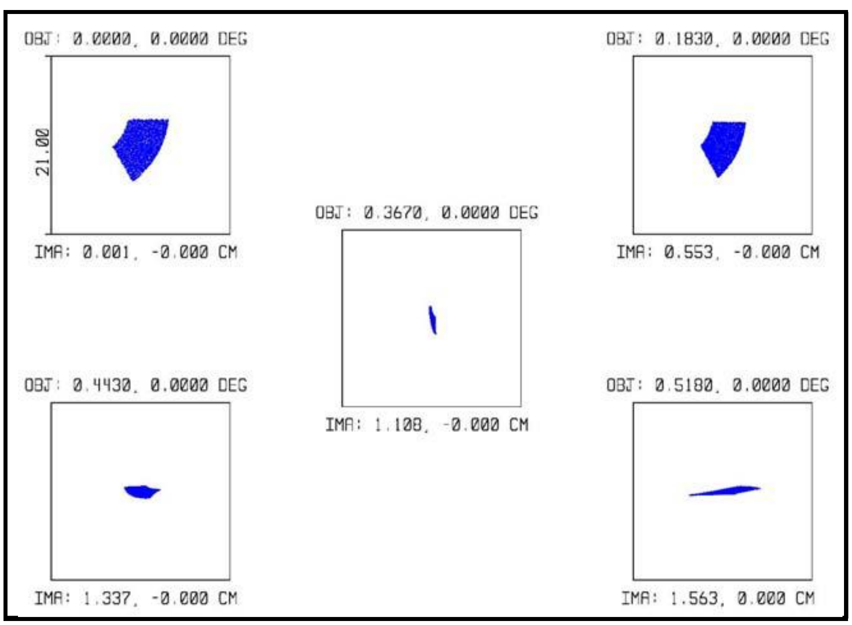

Figure 7. Geometrical spot diagrams for the SUVI telescope when the spiders and aperture plates are in place. Clearly detector effects will dominate geometrical aberrations for all field angles.

The individual geometrical spot diagrams are shown relative to a square representing the actual 21 μm CCD pixel size. Clearly detector effects will dominate geometrical aberrations for all field angles. Due to the short wavelengths involved, surface scatter effects will be substantial, and will be included in the analysis of impixelated energy requirements.

5.0 Results and Conclusions

We have described three different major optical programs that required state-of-the-art optical design, fabrication, and metrology technology; and yet, there was absolutely no merit in an optical design that satisfied the Abbe sine condition (or the aplanatic condition).

In the first application we found that surface scatter effects dominated coma at small field angles, and astigmatism and field curvature dominated coma at large field angles; hence there was no significant increase in image quality with an optical design that strictly satisfied the Abbe sine condition. The second application, a wide-field non-aplanatic hyperboloid-hyperboloid grazing incidence X-ray telescope, was shown to have superior geometrical performance than an optimally despaced Wolter-Schwarzschild design that strictly satisfied the Abbe sine condition. And finally, the third application was a solar ultraviolet imager of the aplanatic Ritchey-Chretien type that when optimized over a large FOV lost its aplanatic characteristic.

Thus the key lesson learned was repeatably that: although the Abbe sine condition may sometimes be a good idea for small-field applications; it is certainly not a law. And for many wide-field imaging applications, or applications where image degradation mechanisms other than geometrical aberrations (surface scatter or detector effects) are significant, it is not even a good idea. The best optical design is not always the one with the smallest design errors, it is the design that results in the best *system performance*.

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