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A Technology for Deblurring Astronomical Images

Thomas H. Tidrick

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A Technology for Deblurring Astronomical Images

Author

Thomas H. Tidrick

Advisor

Prof. Nick Wilding

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1 Introduction

“Astronomy”, the English word is from Anglo-Norman, that from French (c1090) “astronomie”, from classical Latin “astronomia”, from ancient Greek “αστρονομια”. Literally, the “science of the stars”; perhaps the oldest natural science. Early on, the acquired knowledge was useful to mark the seasons and navigate the seas. But, how to capture and convey useful knowledge? Presumedly, in ancient times, knowledge would be passed word-of-mouth; stories relating discernable patterns in the sky.

In modern times, we make and process images to capture and communicate significant patterns. In fact, we live in an era of great advances in image acquisition and are creating floods of raw data. The raw data generated by ground-based telescopes equipped with electronic cameras are typically blurry, due in part to ubiquitous atmospheric turbulence. The problem of unclear images has resulted in development of new technologies to reduce blurring and increase image resolution.

This paper focuses on a specific technology for deblurring astronomical images. Data are collected as digital matrices of image pixels. The technology reconstructs the object via computational manipulation of the blurred image. Dr Stuart Jefferies, Professor, Department of Physics and Astronomy, GSU, along with several colleagues developed a sequence of techniques over three decades, based on a single, powerful idea. Drawing on compatible ideas from physics, engineering, mathematics and computer science, they learned to extract more and more useful information from the raw data.

This paper is organized as follows. First, this ’Introduction’. Second, ‘Background’ presents the tools and history of astronomical image making, and the motivation for computation image processing. Third, ‘Beginnings’ discusses the problem and strategy of astronomical image making, and presents the basic idea of the technology. Fourth, ‘Expanding application’ demonstrates the usefulness of the technology by showing its effectiveness in diverse situations. Fifth, ‘Hawaii, U. S. Air Force and Astronomy’ presents the significant opportunity to advance the development of the technology. Sixth, 'Beyond AMOS' and 'State of the art' shows the continuing relevance of the technology in a totally new domain. Seventh, 'Discussion' considers the technology in a broader context of the 21st century enterprise of scientific imaging making generally. Finally, 'CODA - Institution Building'. It is not unheard-of, though not inevitable, that major works, over many years, might bequest institutions to carry on and expand that work.

The paper's final comments asks what we can glean, from the works discussed, about the encouragement of creative 'breakthrough' scientific knowledge making.

2 Background

2.1 The Hardware of Astronomy

Of course, the first tool that comes to mind is the telescope. Over the years, there have been many designs, from Galileo's hand-made, hand-held device to the monster machines that, today, occupy mountain tops and high-altitude plains. The on-going goal is greater resolution: to see more objects, to see more clearly. This requires collecting more light. The obvious means to collect more light is to make bigger apertures. But doing so brings many significant technical challenges. See this reference for a bit of the histories of telescope design.[1]

The next tool, while not so obvious, is also essential: the mount; that is, a mechanical structure that supports the telescope to a fixed foundation. The mount provides three services: 1) a steady view of the sky, 2) a means for collecting angular position data (an elevation angle above the horizon and an azimuth angle from a fixed point on the horizon), and 3) object tracking ability. Object tracking means continuously pointing the telescope at a particular object as it appears to move across the sky. Here is a brief survey of telescope mounts.[2] Notice, also, this is the beginning of the capture of quantitative data about our observations. We will see how quantitative data becomes increasingly important.

Next, consider means for recording observations. There have been three epochs: the human eye and hand drawing on paper, photography and electronics. The next section discusses this in more detail. Finally, we must mention electronic data processing systems as an essential tool of modern astronomy. The night sky is full. From ancient times, when humans looked up at the night sky, we

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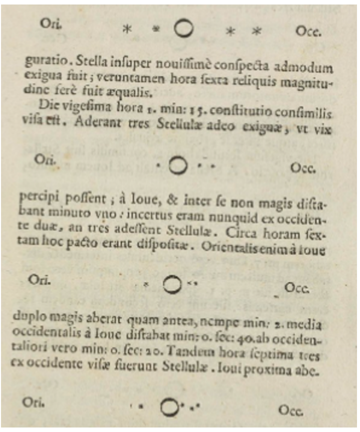
[1] King2011

[2] Re2022

wondered what all that stuff was and what it meant. Always, the sky presents more than we understand. So it is today, we have a torrent of data; and even with our high-performance computing systems (High-performance computing (HPC)), the challenge is that our algorithms, even with the HPCs, are always playing catch-up. This paper traces one scholar's efforts to extract more and more information from the available and expanding data.

2.2 A Brief History of Astronomical Image Making

From ancient times, humans have imagined fantastic things in the night sky. Consider the Zodiac as just one example. This is not our concern. Here we consider what is revealed by telescope. Galileo is celebrated as the first person to publish the results of observing the night sky. Observing the planet Jupiter over several nights in 1609 and 1610, Galileo came to realize four satellites were orbiting Jupiter. He recorded these observations with pen and paper, and subsequently reported them in *'Sidereus Nuncius'*.[3] See Fig 1. Convincing others of the reality of this finding was another matter.



guratio. Stella inſuper nouiſſimè conſpecta admodum exigua fuit; veruntamen hora ſexta reliquis magnitudine ferè fuit æqualis.

Die vigeſima hora 1. min: 15. conſtitutio conſimilis viſa eſt. Aderant tres Stellulæ adeo exiguæ, vt vix

percipi poſſent; à Ioue, & inter ſe non magis diſtabant minuto vno: incertus eram nunquid ex occidente duæ, an tres adeſſent Stellulæ. Circa horam ſextam hoc pacto erant diſpoſitæ. Orientalis enim à Ioue

duplo magis aberat quam antea, nempe min: 2. media occidentalis à Ioue diſtabat min: 0. ſec: 40. ab occidentaliori vero min: 0. ſec: 20. Tandem hora ſeptima tres ex occidente viſæ fuerunt Stellulæ. Ioui proxima abe-

Figure 1: Galileo and images of the satellites of Jupiter

The large 'O' represents Jupiter and the smaller '*' represent the various satellites, which changed position and number at different date-times.

Pen and paper were the only recording medium available for over two hundred years. However long lived, this medium is necessarily subjective and increasingly less accepted as an expectation and demand arose for more objective, repeatable evidence.[4] Daguerreotype photography was introduced in 1839. Various attempts at astro-photography were made during the 1840s through the 1860s, with limited success. The primary limiting issue was the very long exposures required and the associated

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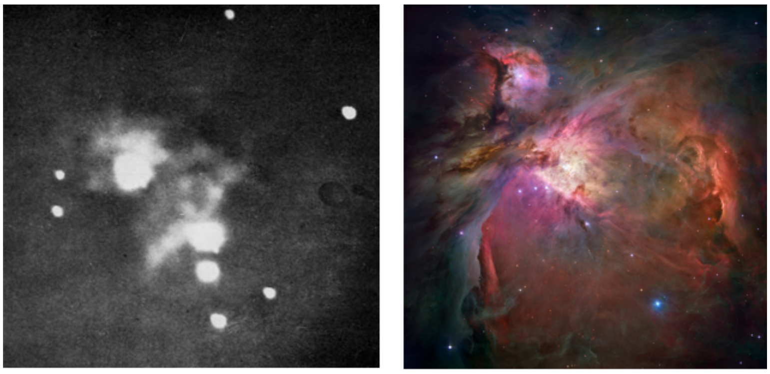
[3] Galileo1989

[4] Daston and Galison2007

problem of tracking object and their apparent movement across the sky. As a serious research tool, astro-photography had to wait for the ‘dry plate’ technology. Fig 2, shows Henry Draper’s 1880 photograph of the Orion Nebula, the first ever taken. Draper’s image was taken with an 11-inch telescope and a 51-minute exposure. Compare that image with one taken by a modern electronic camera, a ‘Charge Coupled Device (CCD)’.



a) Draper’s 1880 photograph b) Modern electronic camera

Figure 2: Early photographic and recent CCD images of Orion nebula

The Charge Couple Device was invented in 1969 at Bell Labs. In 1972, semiconductor maker Fairchild introduced the first experimental CCD for photography.[5] The use of photograph plates has declined significantly since the early 1980s, replaced by CCD (electronics).[6] CCDs are very much more sensitive and faster. By the 1990s we have CCD cameras capturing images as large matrices of pixel data. See Fig 3. The gray scale value of each pixel is interpreted as an amount of light captured, black-no light, white-maximum. These matrices enable computational manipulation of astronomical data. It is significant that the 2009 Nobel Prize in physics was awarded to the inventors of the CCD.[7]

2.3 Motivation for Computational Image Processing

So, the stage is set, modern hardware generates data. Can we build algorithms to extract information? This part of the story begins with a problem in the Hubble Space Telescope (HST). While HST does not observe through atmospheric turbulence, it was clear from first-light in 1990 that there was a fundamental flaw. The primary mirror was off by 1/50th the thickness of a human hair.

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[5] Boyle and Smith1970

[6] Malin2022

[7] Las-Cumbres-Observatory2022

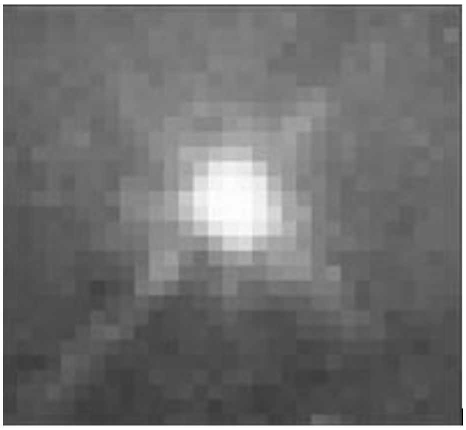
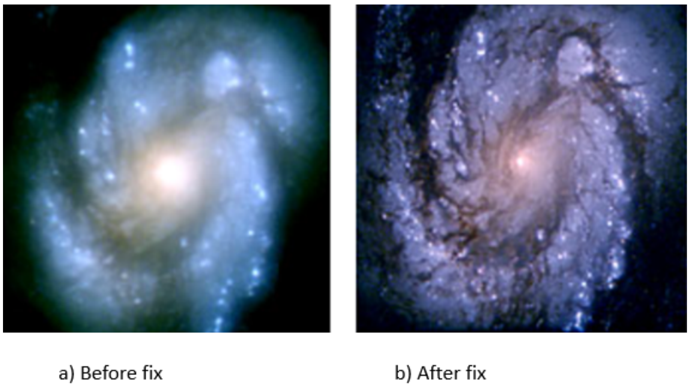


Figure 3: Pixelated CCD image

Doesn’t sound like much, but HST had a serious optical defect. See Fig 4. The image on the left shows the best HST could do originally, and on the right after the flaw was fixed.[8]



a) Before fix

b) After fix

Figure 4: Hubble images, before and after fix

The fix, in 1993, required a spacewalk and the installation of The Corrective Optics Space Telescope Axial Replacement (COSTAR) instrument; essentially corrective lens to compensate for the flaw.[9] In the meantime, National Aeronautics and Space Administration (NASA) had issued an RFP to the imaging community with the challenge: can you improve our blurry images? Thus, began a serious application of computational image processing of astronomical images.

In 1994, The Space Telescope Science Institute, on the behalf of NASA, held a workshop and published the proceedings as: Evaluation of Image Restoration Algorithms Applied to HST Images. This work reports results on intercomparison of image restoration algorithms, when used in the specific context of stellar fields imaged by HST. Properties such as fidelity to the original image and

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[8] ESAHubble2022

[9] NASA2022

photometric linearity, as well as computational performance were evaluated.[10] The lessons learned here, with regard to computational image processing, are direct ancestors to the processing of astronomical images blurred by atmospheric turbulence.

3 Beginnings–the Problem and Strategy of Astronomical Image Making

When light from a source object passes through turbulent atmosphere and telescope optics into the telescope's detector, a CCD camera, the camera produces a matrix of pixel data. The impact of the passage is called a Point Spread Function (PSF). Point spread function is an apt name: each point of light is more-or-less spread out, resulting in a blurring of the light. The image data, then, is a blurred representation of the source object. The task of the astronomer is to start with the data and separate the object from the PSF. Because we have data as a digital matrix, we can take that data as a mathematical convolution of: 1) the object and 2) the PSF. As applied to our problem, mathematical convolution combines a function that represents the object with another function that represents the PSF.

The task becomes a 'de-convolution'. The mathematics of convolution / deconvolution is fairly well understood. In fact, if either the object or the PSF are known exactly, retrieving the other can be fairly easy. In our case neither object nor PSF are known exactly. Thus, our case is a 'blind' deconvolution (BD), a much more difficult task. We have, fortunately, the mathematical techniques of Fourier Transform (FT), which greatly simplify the calculations of blind deconvolution. Specifically, FT turns a calculus integration problem into a simple arithmetic problem. What we need is a computational algorithm that cleverly uses FT to tease apart the object from the PSF.

In 1988, Ayers offered a simple iterative technique for blind deconvolution of two convolved functions. Any iterative technique can be thought of as an algorithm based on a cyclical set of computations. Each cycle improves, hopefully, the estimate of the two functions, in our case, our object and PSF. Inputs to the algorithm include: 1) the image data, 2) an initial guess of the object, 3) various constraints on the object and PSF, and 4) a pre-determined stop criterion. The initial guess of the object is typically arbitrary. Constraints can be based on any prior knowledge. The simplest

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[10] Busco2022

constraint is that pixel values of the object cannot be negative. Negative light is meaningless. The cycle of computations is repeated until the stop criterion is met. Typical stop criteria might be total number of iterations, or some measure of 'goodness' of estimation. [11]

Notice, the algorithm manipulates functions for: 1) the data, 2) the object, and 3) the PSF. That is, we assume the following relation in the Fourier domain: FT (data) = FT (obj) * FT (PSF).

Ayers' algorithm proceeds as follows:

1. Calculate FT (data), and FT (obj); first iteration uses 'initial' object; later iterations use the latest estimate of object
2. Use FT (data) and FT (obj) to estimate FT (PSF); based on the assumed relation
3. Inverse FT (estimate of FT (PSF)), get estimate of PSF
4. Apply appropriate constraints against estimates of PSF
5. Calculate FT (constrained PSF)
6. Use FT (data) and FT (constrained PSF) to estimate FT (obj)
7. Inverse FT (estimate of FT (obj)), get estimate of object
8. Apply appropriate constraints against estimate of object
9. Check stop criterion
10. Repeat, as necessary

Note, with each iterative cycle, the algorithm 1) re-estimates the object and the PSF, 2) applies constraints in the image domain and makes major calculations in the FT domain, and 3) decides to take the next iteration based on pre-determined stop criterion. Make no mistake, this algorithm is computationally intensive. Nevertheless, starting with blurred image data, we have a method to get a best estimate (somehow defined) of the source object.

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[11] Ayers1988

3.1 Turbulence and Seeing

Before considering an improvement to the algorithm, we should say a bit more about turbulence and 'seeing'. 'Seeing' is the astronomer's term for the relative optical quality of the Earth's atmosphere. Optical quality is defined as the steadiness and absence of distortion in a telescopic image. A motionless and optically perfect image indicates excellent seeing; a rapidly changing and grossly distorted image indicates poor seeing. Scientists have been aware of optical turbulence at least since English naturalist Robert Hooke in 1665 attributed the twinkling of stars to small, moving regions of the atmosphere having different refracting powers which act like lenses.[12] Fig 5, shows the resulting image of an hypothetical point source object (such as a single star) after passing through different levels of seeing. Classification V represents the image of a point source object under excellent seeing; whereas class I shows the same object subjected to poor seeing.[13]

Figure 5: Simulated point source object assuming different levels of seeing

The cause of differences in seeing is the high frequency temperature fluctuations of the atmosphere, and the mixing of air parcels of different temperature/densities or the 'refractivity' of the air.[14] In physics, refraction is the change in direction of a wave of light passing from one medium to another.[15] Fig 6, shows the actual image of a beam of light passing through still air, then glass, then still air again.

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[12] MacEvoy2022

[13] Canada2022

[14] Peach2022

[15] Ajizai2014

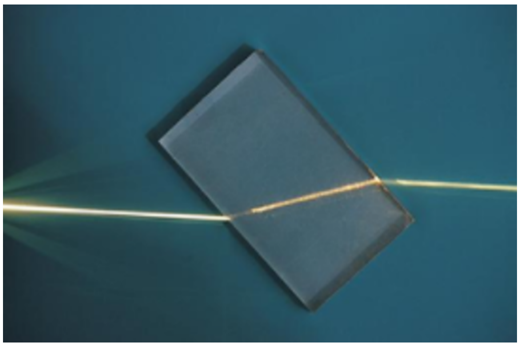

Figure 6: Demonstration of refraction

Fig 7, a schematic diagram, simulates how optical wavefronts from a distant star (assumed to be above the figure) may be perturbed by a layer of turbulent mixing in the atmosphere.[16] Notice the parallel lines at the top of the diagram compared to the squigged lines of the perturbed wavefronts. We say the parallel lines represent ‘in-phase’ light, and squiggled lines represent ‘out-of-phase’ light. It turns out, serendipitously, that the Fourier Transform directly measures the phase shift across pixels of an image.

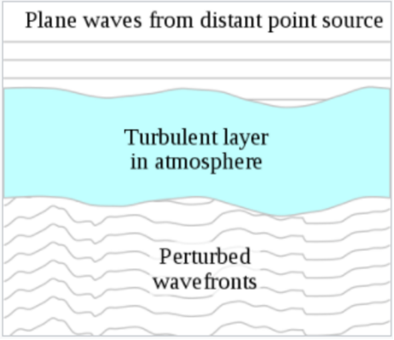

Figure 7: Simulation of effect of atmospheric turbulence

3.2 Algorithm Improvement

In 1991, Lang provided an improved algorithm, leading to a more effective and efficient image reconstruction technology. Lane modified Ayers’ iterative algorithm by using the phase values of the Fast Fourier Transform (FFT). This yielded a different error metric when comparing the original image data with the new estimate of image data at each iteration. Understand, at each iteration, every pixel value is re-calculated for both the estimated object and the psf. Then, these estimates are convoluted to produce the new estimate of the image data. The error metric is a summation of the pixel-by-pixel

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[16] Gringer2008

error of the original image data minus the new estimate. So, at each iteration step, our error metric is compared with our stop criteria to decide if we should take another iteration step. That is, when the error metric gets less than the stop criteria, we stop. (Actually, there is the possibility of never reaching the stop criteria; so, typically, there must be another/fail-safe stop criteria, such as total number of iteration cycles.) Lane offered another modification. Recall, all pixel values must be re-calculated during each iteration. There exists a mathematical technique to guide this re-calculation called Conjugate Gradient Minimization (CG).[17] The assumptions of the CG minimization theorem are fairly simple; and, when met guarantee convergence to a solution via an iterative algorithm.[18]

In 1992, Lane expanded his modifications. He showed how to incorporate additional constrains, how to use ensembles of images, and how to focus on speckle images.[19]

In 1993 Jefferies and a colleague adapted Lane's techniques to astronomical image processing. They developed a modified version of the Iteative Blind Deconvolution (IBD) algorithm of Lane, applicable to different types of astronomical data. Besides using positivity, convolution, and support constraints, they also applied band-limit and Fourier modulus constraints. By using all the available image constraining information, they were able successfully to recover object and point spread function information from noisy data. They presented results for: 1) simulated data, 2) a nearby binary star system, 3) the asteroid 4 Vesta, 4) a high-resolution image of Capella, and 5) an infrared image of the Galactic center.[20]

At this point in time, Jefferies had the essential components of an image reconstruction algorithm, and he had demonstrated that the algorithm was effective. Two extensions for further development were available: 1) application to new observation situations, and 2) improving the sensitivity of the algorithm. We will see that there is a virtuous-circle feedback loop at work between application and improved algorithm. Simply stated, seeking new application revealed new challenges, which leads to technical improvements.

As might be expected, research concerning astronomical imaging takes place at the limit of the capability of the instruments. The diameter of the primary optics of telescopes determines how much light enters, and the sensitivity of the detectors/cameras determines how much of that is recorded.

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[17] Lane1991

[18] Hestenes1952

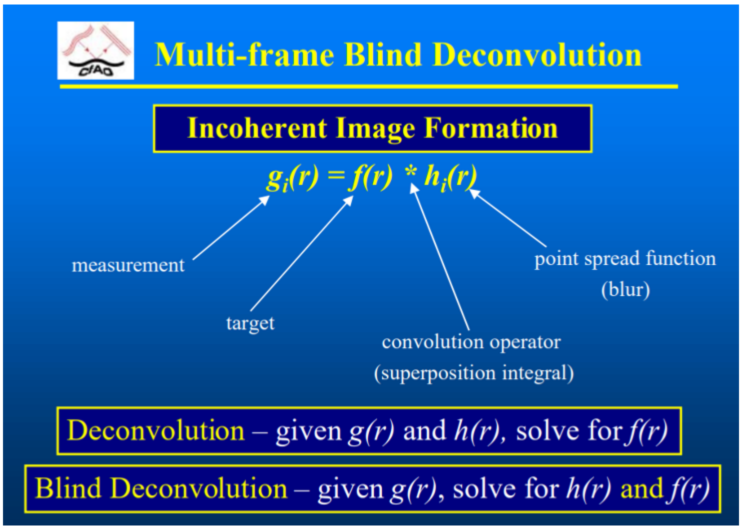
[19] Lane1992

[20] Jefferies and Christou1993

Finally, it is with this recorded light that image processing must analyze. And, also as might be expected, more recorded light provides potentially more information to be recovered. Bigger telescopes and more sensitive detectors might be wished for; but when working with existing instruments, more light can be captured by: 1) longer exposure time, and 2) collecting ensembles of short exposures. The drawback to capturing light over extended time is that the impact of atmospheric turbulence naturally changes with time. A long exposure, single image becomes increasingly blurry.

Recall that turbulence is caused by moving coherent cells of air. With the ensemble approach, if each short exposure image is taken in less time than the moving cells can change, the blurring is reduced. The cells are still moving, so that the light from particular objects tends to fall on different pixels of the detector with each successive image. Instead of a single blurred image, we get fairly sharp speckles distributed across different pixels of the ensemble of images. The trick is to decide which pixels, among the ensemble, belong to which objects. It turns out that the Fourier Transform embedded in an Iterative Blind Deconvolution algorithm does the trick.[21]

The basic problem of finding a source object (target) in a blurred image and the basic strategy of the solution is represented in Fig 8; from a lecture by one of Jefferies' colleagues.[22] Much of what follows comes from examining the ramifications and extensions of ideas in this slide.



Multi-frame Blind Deconvolution

Incoherent Image Formation

$g_i(r) = f(r) * h_i(r)$

measurement

target

convolution operator
(superposition integral)

point spread function
(blur)

Deconvolution – given $g(r)$ and $h(r)$, solve for $f(r)$

Blind Deconvolution – given $g(r)$, solve for $h(r)$ and $f(r)$

Figure 8: Schematic of Multi-frame Blind Deconvolution (MFBD)

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[21] Christou1995

[22] Christou2022

4 Expanding Application

4.1 Diffraction Limit

Image resolution of any image-forming device relates to the ability to distinguish small details. And while resolution improves with larger apertures, every device has a theoretical limit.[23] The figure below shows the natural effect of light passing through a circular aperture; e.g., a telescope. Instead of a bright spot, we get a spot with a fuzzy edge; i.e., Fig 9. This effect is called diffraction.[24] Diffraction is unavoidable; it is due to the size of the (optics) compared to the wavelength of the light.[25] A telescope with resolution performance at the instrument's theoretical limit is said to be diffraction-limited. The objects in Fig 9b are just resolved at the diffraction-limit; those in Fig 9c are not.

a) Single point source b) Binary, barely resolved c) Binary, Not resolved

Figure 9: Demonstration of diffraction-limited resolution

4.2 Adaptive Optics

Adaptive Optics (AO) is a technology used to improve the performance of optical systems. Adaptive Optics works to reduce the effect of incoming wavefront distortions by deforming a mirror in order to compensate for the distortion. It is used by some of our largest telescopes. An AO system has the following components: 1) a wavefront sensor, 2) a mechanical set of actuators literally to displace or deform the telescope's mirror and 3) a computer to calculate the distortion and calculate the appropriate compensation. AO systems operate in real time and are considered very effective.[26] It is worth noting, however, there is always deficiencies in the operation, and compensation is not complete. Post processing of the data is still useful, if not essential.

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[23] Rayleigh1879

[24] Lumen-Learning-Physics2022

[25] Badolato2022

[26] Beckers1993

4.3 Algorithms for AO

AO has the capability of providing diffraction-limited images from ground-based telescopes through turbulent atmosphere. Because of limitations in the AO system, the PSF of the AO system suffers from incomplete compensation. (Many factors contribute to this deficiency.) Thus, AO compensated imaging generally requires post-processing to extract the maximum possible information. Algorithms recently developed and applied to HST imaging were applied to AO post-processing. These algorithms require a stationary PSF, which is not often the case, and are then, not applicable.[27]

In 1996, Jefferies and colleagues applied the algorithm they had developed in 1993 to AO images complicated with variable PSF. The results of preliminary analysis (show promise). The reconstructed PSF's show a similar variability as the convolution images ... (but) convergence in not yet achieved.[28] Blind deconvolution with conjugate gradient minimization had proved useful in a new situation. Useful, and better than other recognized algorithms. What else can we do with this thing?

Astronomical interferometry is, essentially, a technology for leveraging a number of smaller telescopes to make them act as one large telescope, with a correspondent greater diffraction-limit. To make this work, the light is collected by the set of telescopes and, then, combined via very high precision optical and electronic backend instruments. Large Binocular Telescope (LBT) in Arizona is one such interferometer. LBT has two 8.4m mirrors (hence the name 'Binocular'), with centers 14.4m apart; and as a consequence, the effective resolution of a telescope with an aperture of 22.8m.[29]

In 1999, while LBT was under construction, Jefferies and colleagues applied the tools of their algorithm to simulations of LBT. The important lesson of this exercise was that the larger tool kit of the algorithm could be used for purposes other than object recovery. In particular, the tool kit could be used to make prediction about the performance limits of a particular telescope system. With the LBT, they predicted when background noise would prohibit achievement of diffraction-limited resolution at its full potential of an equivalent aperture of 22.8m.[30]

In addition to these early successes, engagement with these recent applications raised questions and inspired further investigation. As noted above, AO technology includes direct sensing of wavefronts. So, the question is: can the result of wavefront sensing inform constraints within the

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[27] Christou1996

[28] Christou1998

[29] BBC-News2008

[30] Hege1999

reconstruction algorithm? And how effective are alternative methods for sensing wavefronts?

4.4 Laser Guide Star (LGS)

A Laser guide star (also called a Rayleigh Guide Beacon) is an artificial star image created for use in astronomical adaptive optics systems, in order to correct atmospheric distortion of light (called astronomical seeing). Adaptive optics (AO) systems require a wavefront reference source of light called a guide star. One can create an artificial guide star by shining a laser into the atmosphere. Light from the beam is reflected by components in the upper atmosphere back into the telescope.[31] Fig 10, shows two telescopes on Mauna Kea, HI with their laser guide star systems activated.[32]

Figure 10: Laser guide star/beacon

4.5 Tomography

The term 'tomography' is most commonly associated with medical imaging. '[...] computed tomography (CT) imaging, also known as Computerized Axial Tomography (CAT). "CAT scanning" , provides a form of imaging known as cross-sectional imaging.'[33] Typically, a CAT scan results in a series of cross-section images, each at a slightly different depth in the object. In an astronomical setting, tomography means making a series of images at slightly different altitudes through a turbulent and/or turbid atmosphere.

4.6 Algorithms for Guide Stars and Tomography

In 2000 and 2002, Jefferies and colleagues adapted their algorithm tool kit to study pulsed guide star lasers. Laser light naturally forms as a narrow beam. A pulsed laser creates a narrow column of

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[31] Olivier and Max1993

[32] Max2022

[33] FDA2022

light. As the laser light passes upward through the atmosphere, some light is reflected back to the telescope at each instance. When the telescope camera has sufficiently fast readout, a series of images result each from a different altitude. Call that ensemble No.1. When the cadence of recording is timed to the next pulse, the next pulse results in a second ensemble; and so on. A ‘movie’ can be recorded through the full telescope aperture. With full aperture, diffraction-limited images are achieved. The images of each ensemble are indexed to a secession of altitudes. So, bring together all images for each altitude and analyze them with the tool kit. A tomographic representation results from the impact on a wavefront passing through the atmosphere.[34]

Another application of the blind deconvolution tool kit studies optical diffusion tomography. Jefferies and colleagues achieved important advances over previous technologies. ’Specifically, optical diffusion tomography reconstructs images of objects imbedded in or located behind turbid media from measurements of the scattered light transmitted through the media. [...] a blind deconvolution imaging algorithm determines both a deblurred image of the object and the depth of the object inside the turbid medium [...] producing better reconstructions than can be obtained using backpropagation techniques.’[35] Moreover, it does so without requiring prior knowledge of the characteristics of the turbid medium or of what the blur-free target should look like: important advances over backpropagation.[36]

Before going further with the evolution of Jefferies’ tool kit, we should introduce an important venue for his research, namely: AMOS. The Air Force Maui Optical Supercomputing Site (AMOS) is an Air Force facility in Hawaii and the name of an annual technical conference held in Hawaii. The work just reported was first presented at an early AMOS technical conference.

5 Hawaii, U. S. Air Force and Astronomy

The ancient Polynesians were highly skilled sailors and navigators who sailed thousands of miles over open ocean (for example, from the Society Islands to Hawaii) ... accomplished primarily, it is believed, by a thorough knowledge of the stars, their rising and setting points along the horizon and their meridian passage as a function of latitude. Fast forward to the International Geo-physical Year (IGY) (1957-58), Hawaii was a perfect location for tracking the first artificial Earth satellites. Also,

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[34] Lloyd-Hart2000

[35] Jefferies and Hege2002

[36] Jefferies and Okada2002

during the IGY the U.S. Weather bureau established a facility on Mauna Loa; which generated data that lead to the realization that Hawaii's mountains offered the best seeing condition available in Earth's northern hemisphere.[37]

5.1 AF's Mission

For over 60 years, the Air Force Maui Optical and Supercomputing Site (AMOS) has provided the Department of Defense (DoD) with Space Situational Awareness (SSA) capabilities from the island of Maui, Hawaii. AMOS is comprised of two separate facilities: the Maui Space Surveillance Complex (MSSC) and the Maui High Performance Computing Center (MHPCC). The MSSC is located on the top of the Haleakala volcano and is operated by the Air Force Research Laboratory (AFRL). See Fig 11. MSSC has three large (meter-class) optical telescopes that were designed to provide situational awareness for missile tests and orbiting man-made objects. MHPCC is located in Kihei and is one of the five DoD Supercomputing Resource Centers. MHPCC provides computational resources, high-speed communications infrastructure, and support services to MSSC. Although they are separate facilities, MHPCC and MSSC are often referred to together as AMOS, due to a strong collaboration that exists between them. The site opened in 1966 as the ARPA Midcourse Observation Station (AMOS) for tracking Intercontinental Ballistic Missiles (ICBMs) across the Pacific. In 1977 the Air Force Strategic Air Command took over and re-named it Air Force Maui Optical Station (AMOS). Then, with the introduction of the MHPCC, the name was changed again to the Air Force Maui Optical and Supercomputing Site (AMOS). Now, in addition to SSA, AMOS is a center for basic and applied 'near-Earth' astronomy research.[38]

For the U.S. Air Force (USAF), the SSA mission has evolved over time, beginning with tracking ICBMs, then tracking man-made satellites. Today, the non-profit Space Foundation reports the U.S. Strategic Command (USSTRATCOM) Space Surveillance Network maintains a Space Object Catalog of tens of thousands of objects in Earth orbit. The European Space Agency has a similar program; as does the Russian military. The stated goal of these efforts is to 'enhance the accuracy and timeliness of collision notifications'.[39] Additionally, in the 2021 AMOS Technical Papers, T. Harris reported on Astroscale's ELSA-d mission. Astroscale is a private orbital debris removal company, and the mission

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[37] Steiger2022

[38] Clifford and Welser2013

[39] Space-Foundation-Editorial-Team2022

demonstrated the core technology for debris docking and removal.[40] Presumedly, China has an SSA program as well; since China is reported to be planning a 13,000-satellite near-Earth megaconstellation.[41] So, the USAF's SSA military mission has been an on-going and increasingly difficult technical challenge; thereby, justifying the R&D component in their budget. For example, for roughly two decades AMOS has been holding technical conferences and publishing the results. As we will see, Jefferies and colleagues have been regular participants.

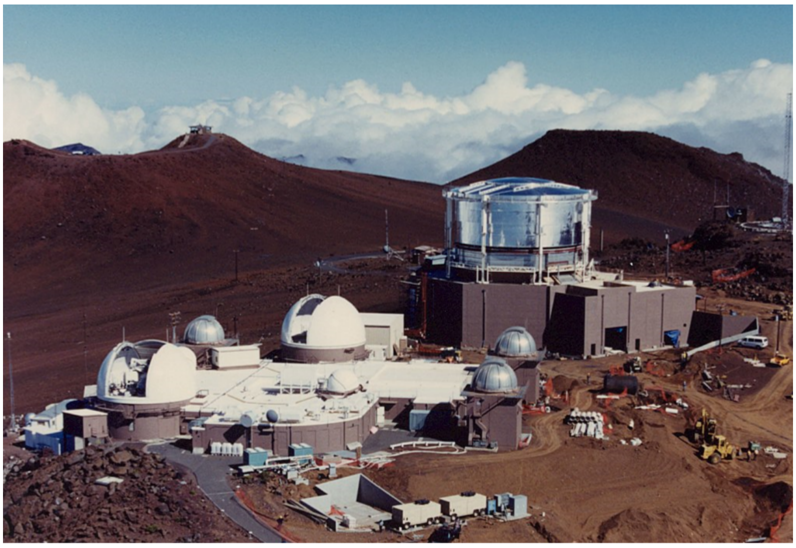

Figure 11: AMOS MSSC, Haleakala Observatory

5.2 AF's Project

In particular, Jefferies and colleagues made significant advances under Air Force Office of Scientific Research (AFOSR) grant F49620-02-1-0107: 'Advanced Concepts in Space Situational Awareness (AC-SSA)'. In Abstract, 'Important original advances were made in the areas of information theoretic image assessment, algorithm development, [...] large-scale optimization methods [....] Physically Constrained Image Deconvolution (PCID) algorithms transitioned to AMOS. In Overview, 'This grant was a five-year, multi-institution Partnership for Research Excellence and Transition (PERT). 'The goals of the grant were: a) original research in a variety of areas of interest to DoD's space surveillance mission, b) transition of research results to AMOS, and c) enhancing the research environment on Maui. 'These goals were well achieved [...].' [42]

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[40] Harris2022

[41] Jones2022

[42] Prasad2022

Let's speculate, for a moment, on the technical challenges to creating and maintaining a Space Object Catalog of tens of thousands of objects. One must be able to resolve each object. One must be able to identify each object uniquely. One must be able to return to each object repeatedly over time and precisely measure its position and, then, to establish its orbit. Recall, Kepler needed years of Brahe's data and further years of his own analysis to establish properly the orbit of a single object, Mars. Today, AMOS has supercomputers and excellent orbital equations. Still, tracking tens of thousands of objects, predicting close encounters and keeping the Catalog in near-real-time is a monumental computation task. More to the point at hand, however, the Catalog depends on the data; that is, repeatedly returning to specific objects and precisely measuring their positions. The data, of course, come from deblurred images. Better resolution matters.

First, we will show how the results of the work of Jefferies and colleagues fit into the AF's AMOS mission. Then we will discuss the technology innovations that made the new AMOS system such a game changer. Finally, we will introduce further innovations that were made possible and inspired by Space Object Catalog project.

The Maui Scientific Research Center, with Jefferies as director, was the original locus for the AC-SSA project. In 2006, that transitioned to the Institute for Astronomy, Univ of Hawaii, Maui (IfA), with Jefferies' acceptance to a professorial appointment to IfA. The following is a summary of AC-SSA project accomplishments:

- establish the importance of fundamental research for generating new technologies and development concepts in SSA;
- enhance the research environment of AMOS/MSSS by bringing in a number of distinguished research scientists from around the world to AMOS;
- raise the awareness of the excellent facilities available at AMOS for conducting imaging and non-imaging research and data analysis;
- transition advanced mathematical concepts and software resulting directly from the original research performed under the project; and
- educate and train a new generation of scientists to carry on SSA research. [43]

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[43] Prasad2022

While the project included several areas of original research, we will focus on a few that directly involved Jefferies. These will be outlined here and discussed in more detail below.

- Jefferies continued his AO research ... resulting in a very important paper ... demonstrating feasibility of AO wavefront sensing;
- Advanced algorithm development, ... modification of PCID code, ... high-performance computing research ...;
- Development of (robust) toolbox of methods for blind deconvolution ... and a well-defined approach for deciding which tool for which scenario ....

In 2007, Matson et als., presented an AMOS Technical Paper on the next generation AMOS image processing environment PCID and ASPIRE 2.0. PCID is a set of algorithms for deblurring images of space objects collected using AMOS telescopes, and ASPIRE 2.0, a Graphical User Interface (GUI) front end. AMOS uses both AO and image (post-processing) to overcome atmospheric turbulence. PCID is able to produce image restoration in as little as a few seconds; and achieves or closely approaches the theoretical limits of image restoration quality. ASPIRE enables technicians to investigate the raw data and the reconstructed images.[44]

In 2014, Werth et als., reported on 'Recent Developments in Advanced Automated Post-Processing at AMOS'. Werth worked for the defense contractor (Boeing) that had assumed management of the MHPCC and was reporting on the status of the AMOS system. This new data handling and processing system has significantly enhanced the capabilities of the AMOS site while also reducing the time that it takes for data to be processed and disseminated. Raw data is automatically transferred (from the telescopes on Haleakala) to a high-performance computing facility (in Kihei) for processing and analysis. Advanced post-processing algorithms are applied to the raw data, allowing analysts to more rapidly view, annotate, and disseminate imagery. The PCID processing pipeline results in high-quality image reconstructions and allows user to explore the parameter space.[45]

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[44] Matson2007

[45] Werth and Thompson2022

5.3 Algorithm Innovations Built into New AMOS System

With the AMOS system developed, installed, operational and approved, it's time to look at the several algorithm innovations build into the new processing system. First, note that the atmosphere, turbulent or not, has two dimensions as seen by a telescope: depth and breath. We considered depth above with the discussion of laser guide stars and atmospheric tomography. As to breath, we consider what is called spatially varying blur. The task of sensing the wavefront properly requires consideration of both.

5.3.1 Spatially Varying Blur

All of the research problems considered so far assume the blurring function, the PSF, is spatially invariant. That is, a constant PSF applies across the entire aperture of the telescope. A spatially varying blur means the PSF is not constant across the aperture. This presents an ill-posed, more difficult problem. Based on a few reasonable assumption (the blurring effects vary according to a Gaussian function, and they are only of local extent), Nagy and O'Leary demonstrated closure for an appropriate mathematical theorem, and then developed an effective algorithm for this problem.[46] Once the diameter of an aperture is large enough, the assumption of a spatially invariant PSF is no longer tenable. Imagine the cause of light refraction, and thus blurring, is a self-sustaining vortex embedded in dissimilar air. If the aperture is large enough, multiple vortices are captured in each image; thus, spatially varying blur. Incorporating techniques derived from the Nagy and O'Leary theorem proved useful.

5.3.2 Algorithms for Spatially Varying Blur

Gonsalvas presents a survey of a technique called Phase Diversity (PD). Phase diversity is an unconventional imaging technique which uses two or more distorted views of an object to perform wavefront sensing. It was one-of-many techniques used in 1990 to remove the flaw in the HST.[47] Paxman and Thelen studied the PD technique for at least 20 years, from 1988 to 2009.[48] Essentially, PD captures a time-series of two or more images of the same object. Then in post-processing, the algorithm calculates the phase of the wavefront for each frame and uses a maximum-likelihood

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[46] Nagy1998

[47] Gonsalves2018

[48] Thelen2009

estimator to get the best wavefront phase. PD is first mentioned with respect to Jefferies' technology in 2001, citing Paxman (1992).[49]

In the 2001 article, Jefferies and colleagues use PD in a novel way with an AO guide star for tomographic effects. Jefferies and colleagues applied PD in various situations.[50] Then, in 2006, Jefferies and colleagues uses PD on spatially varying blur.[51] So, we see Jefferies applying a particular technique to capture phase shifting effects of turbulence vertically through the atmosphere and horizontally across the aperture. They are satisfied that direct sensing of the wavefront is possible and useful in image reconstruction. The hunt for more effective wavefront sensing is on. More on that later.

Another concept important to the new AMOS system is generally known as the use of 'prior information' about the object, the instrumentation and the physics of the observing conditions. Examples of such information include a positivity constraint on the object, a constraint on its spatial extent (commonly referred to as support), and any partial knowledge of the PSF, possibly obtained from a wave-front sensor. All such information is pertinent and can be used to constrain the solution space that must be searched by the algorithm. We spoke of positivity earlier; that is, negative light makes no sense. So, to preserve positivity, all light values are squared, then at the appropriate time the resultant calculation uses the square root. Support means the physical size of an object, and how large an image should be in our detector. Recall, the blurring PSF spreads the light across many pixels. The reconstructed image should fit into a smaller, known number of pixels. The AMOS PCID algorithm uses a combination of techniques. Always, the data is a collection of multiple frames. To apply PD, the algorithm sections each image, and then treats the sections as a sequence of frames with unknown PSFs that are correlated and approximately spatially-invariant. PD is applied to an ensemble of frames for each section, resulting in a best PSF estimate. With the resulting PSF estimate in hand, we then use a technique by Nagy and O'Leary for the restoration of images with a known, spatially-varying blur to reconstructed the image globally.[52]

Another technique included in the AMOS system is the use of sequences of images obtained simultaneously at different wavelengths and then prior information on the distribution of the sources of low intensity in the data.[53] And finally, the AMOS system has been parallelized to a significant degree

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[49] Lloyd-Hart and Hege2001

[50] Jefferies and Georges2002

[51] Bardsley and Plemmons2006

[52] Hope and Jefferies2006

[53] Hope and Giebink2007

for execution on high-performance computers, with an emphasis on distributed-memory systems so that it can be hosted on commodity clusters. As a result, post-processing image restorations can be obtained in seconds to minutes.[54]

5.4 Exploring the New AMOS System

This section showcases some of the capabilities of the new AMSO system. Recall the AMOS system consists of AO-equipped, specialized telescopes, high-bandwidth communication links, high performance computer clusters, the PCID algorithm and the custom GUI.

While AMOS was optimized for imaging objects from low-Earth orbit to geostationary orbit, it has proven an excellent tool for finding asteroids that happen to be further out. The AMOS web site shared a link to a ScienceDaily 2011 article.[55] The Pan–STARRS PS1 telescope on Haleakala, Maui, discovered 19 near-Earth asteroids on the night of January 29, the most asteroids discovered by one telescope on a single night. This record number of discoveries shows that PS1 is the world's most powerful telescope for this kind of study, said Nick Kaiser, head of the Pan–STARRS project. NASA and the U.S. Air Force Research Laboratory's support of this project illustrates how seriously they are taking the threat from near-Earth asteroids.

The US has significant civilian and military assets in geostationary orbit. High-resolution, ground-based imaging of these assets enables us to monitor in detail their health and safety and to detect the presence of any foreign microsatellites that might be in proximity. Although adaptive optics compensation of ground-based imagery imparts some level of mitigation of the deleterious effects due to the Earth's turbulent atmosphere, the correction is far from optimal and there is usually ample room for further improvement in resolution through image post processing. Jefferies and colleagues show that significant gains in image fidelity and detection sensitivity can be achieved during the image post processing by the injection of prior information on the wave-front phases via wave-front sensing data and wave/phase-diverse data. The gains are such that it is possible that AEOS could become a practical resource for high-fidelity imaging and detection of GEO targets.[56]

The Frozen Flow Hypothesis (FFH) assumes that the turbulence can be modeled by a series of independent static layers, each moving across the telescope aperture with the prevailing wind at the

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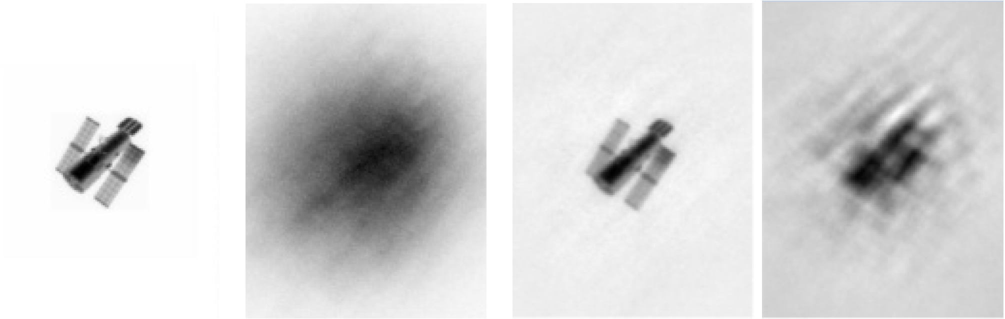
[54] Matson and Lloyd-Hart2009

[55] SPACEDAILY2022

[56] Hope and Giebink2008

altitude of the layer.[57] Deconvolution from wave front sensing requires the simultaneous recording of high cadence, short-exposure images and wave-front sensor data.[58] By capturing the inherent correlations present in the consecutive wave fronts, using the Frozen flow hypothesis (FFH) during the modeling, high-quality object estimates may be recovered in conditions of heavy turbulence. Fig 12 presents an example of post-processing assuming FFH. From left to right: a) truth object, b) image data (convolution of truth object and PSF), c) recovered object assuming FFH, and d) recovered object without FFN.[59]



(a) HST truth image for this test
(b) Actual CCD data to be recovered
(c) Recovered image with FFH
(d) Recovered image without FFH

Figure 12: Recovered image with and without FFH based compensation

One of the more dramatic capabilities of the AMOS system is its ability to produce excellent results while deconvolving images from data collection in daylight and under strong turbulence.[60] Daylight conditions and diurnal solar heating greatly increase turbulence even in places with excellent nighttime seeing. Fig 13, is an example of post-processing of a daylight image. The central frame is the actual data. The third frame is the output from AMOS. This compares with a truth image of the source object on the left. D/r0 is a common measure of turbulence, and a value of 70 is very high.[61]

'Performance' is another area of interest when evaluating the AMOS system; that is, the time between capturing image data and delivering deconvolved product. This is essentially post-processing computation time. We already mentioned that PCID incorporated parallelism to speed computation. Here we discuss two variations on basic multi-frame blind deconvolution (MFBD). The first is a multi-channel MFBD algorithm. Multi-channel MFBD uses images from two telescopes with different

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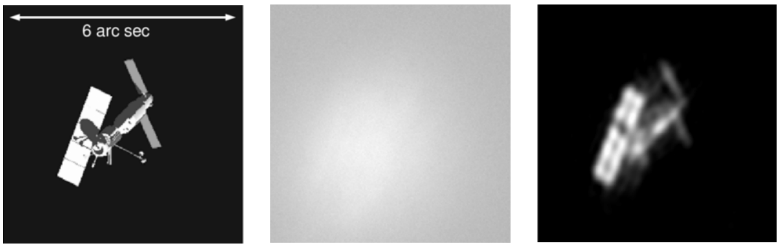
[57] Nagy and Chu2010
[58] Chu2011
[59] Jefferies and Hart2011
[60] Hart and Xompero2011
[61] Hart2011



(a) Truth image (b) Actual CCD data (c) Recovered image

Figure 13: Recovered image from data taken in daylight

apertures, taken of a single target at the same time. The PSFs of telescopes with different apertures are naturally different. Recall the total PSF comes from the atmospheric turbulence and from the optics of the telescopes. Knowing the difference due to the telescopes facilitates determination of that part of total PSF due to turbulence; thus, yielding better results over the larger telescope alone.[62]

6 Beyond AMOS–Further Research

As might be expected, the experience of developing, implementing and using the new AMOS system inspired several avenues for further research. Among these are: a) alternative techniques for wavefront sensing, b) alternative methods of applying prior knowledge, c) alternative minimizers and other computational techniques, d) investigation of mathematical proofs associated with the numerical analyses applied to the data, and e) re-consideration of the physical assumptions of the basic model. Here we relate several papers in which Jefferies and colleagues explored these ideas. There are experimental explorations using real and simulated data, and there are theoretical explorations.

We see two themes (goals): higher quality results and faster performance. Higher quality is the traditional astronomical desideratum: higher resolution, seeing more, seeing more clearly. But nominally, performance is an Air Force desideratum, deliver the product faster. And, of course, there is a tradeoff between quality and performance. Higher quality, typically, requires longer computation; and thus, performance costs money. So, exploration of new ideas is driven by research curiosity and by practical consideration.

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[62] Hope2011

6.1 Quality–Wavefront Sensors

A 2014 paper introduced a pivotal improvement to the Wavefront Sensor (WFS). Data acquired from a Shack-Hartmann (SH) micro-lens array opens the door for both a beacon-less WFS and for imaging over wide fields-of-view (FOV). To review, quality image reconstruction depends on how well one can approximate the PSF ... which depends on how well one can approximate the phase shift of the wave front across the full aperture. A WFS can measure gradients of the wavefront, from which to get the phase. The problem is that with a large aperture (i.e., a wide FOV) a singular PSF doesn't work. Experiments with SH WFSs proved fruitful.[63]

Now, SH arrays are common in many optical systems, and their physics well understood, as is the mathematics of the algorithms used to manipulate their data. SH WFSs are arrays of micro-lens placed between the perturbed wavefront and the detector. See Fig 14. In a sense, each individual lens measures a portion of the wavefront, which are knitted together to approximate the total PSF.[64]

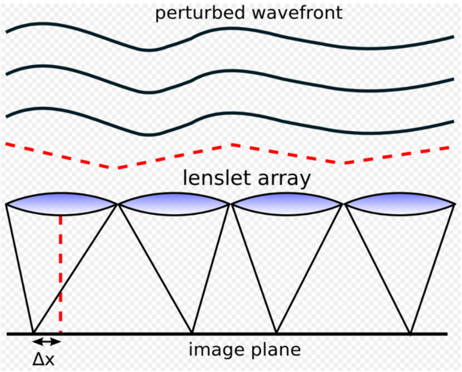

Figure 14: Schematic of SH WFS

Papers from 2016 and 2017 report an alternative method of creating a series of sub-apertures, which also leads to better PSF approximation. The method is called aperture-diversity and is achieved as a series of concentric partitions of the full aperture. The MFBD algorithm is modified to first approximate the PSF associated with the inner sub-aperture; then to approximate with each successively larger sub-aperture. The experiments tested methods of aperture-diversity and SH WFS vs. a control (based on singular PSF). Both methods achieved significantly better-quality results than the control. [65]

Note, aperture-diversity is wholly based in algorithmic manipulation of the data, whereas SH WFS

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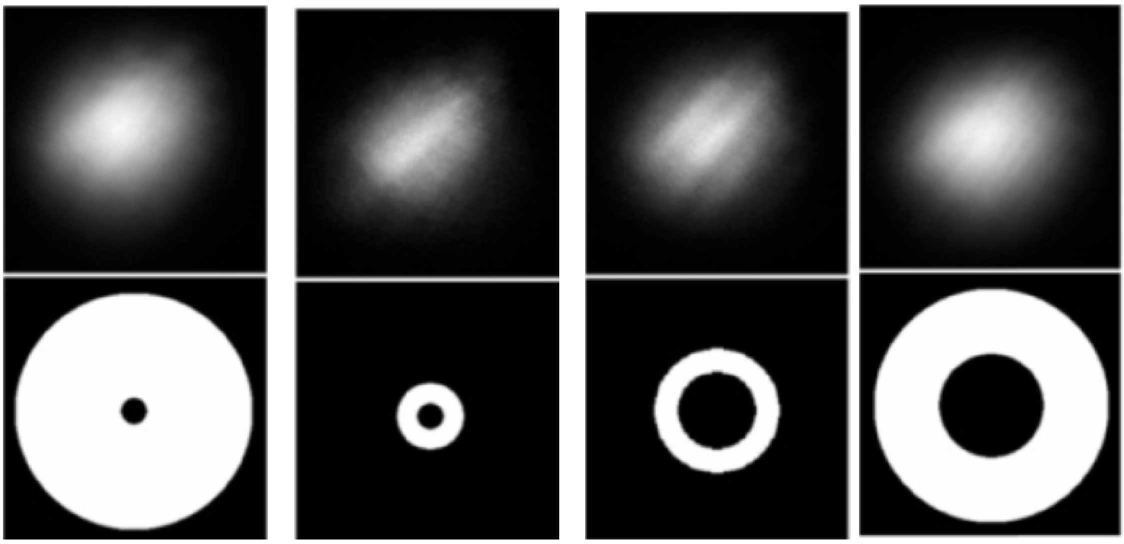
[63] Nagy and Hope2014

[64] 2pem2011

[65] Jefferies and Hope2017



(a) Full aperture (b) Inner sub-aperture (c) Mid sub-aperture (d) Outer sub-aperture

Figure 15: Example of CCD data from various aperture-diversity. Top row, actual CCD data captured through specific aperture/sub-aperture. Bottom row, representation of portion of aperture utilized for each image data

requires the additional instrument hardware. So, the innovative methods would be applied in different situations. Fig 15, is an example of aperture-diversity and associated data. From left to right, bottom row, full aperture, sub-apertures, smallest to largest. Top row, shows the raw data associated with respective apertures.

6.2 Performance

A series of papers from 2011 to 2019 examined possible means for improving performance. Two strategies are evident. Use a) an alternative minimizer and/or b) appropriately reduce the number of pixels requiring re-calculation. Recall, for each iteration step the minimizer decides how to change the pixel values, so as to reduce the error metric. The faster the error gets below the threshold, the less computation time, the faster performance. In mathematical terms, this is a question of convergence. And ideally, a mathematical theorem that guarantees convergence would be nice. The mathematics of interest here is called numerical linear analysis. It is well studied, with alternative minimizers for matrices of various structure. When the data matrix at hand does not satisfy the assumptions of the various minimizers, convergence cannot be guaranteed; and an experimental approach is necessary to compare the minimizers. In the end, Jefferies stayed with a minimizer called non-linear conjugate gradient (NLCG).[66]

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[66] Vorontsov et al.2011

Papers in 2011, 2017 and 2019 discuss the second strategy for improving performance, reducing the number of pixels re-calculated. It is called 'compact MFBD (cMFBD)'. Compact MFBD is difficult to describe simply. Suffice it to say, compact MFBD leverages ratios of Fourier spectra between two data frames and ignores data below the measured signal-to-noise ratio. The ignored data means a reduction in the number of variables to calculate, speeding the overall calculation and hinting at the possibility of producing higher-fidelity results.[67]

In 2017, Jefferies reports higher performance than basic MFBD, as well as higher-quality results in certain observing situations.[68] In 2019, Hope, Smith and Jefferies reports further improved performance of cMFBD having introduced a new 'internal consistency' constrains to the algorithm. The paper reports evidence from a proof-of-concept example, and asserts an expectation of analogous improvement in performance by other algorithms using cMFBD.[69]

6.3 Application, Daytime

A critical element of the AF AMOS mission is continuous 24/7 operation. This means during daylight. We have already seen that AMOS fulfills that requirement. As Jefferies investigates new ideas, they are checked against daylight requirements. Here are several papers reporting results of these investigations. A 2014 paper reports brightness measurement recorded in the near infrared (near-IR) for the AEOS telescope. At visible wavelengths, brightness had already been well measured; but not so for the near-IR. Once it had been determined that near-IR data could improve PSF approximations; measuring brightness in the near-IR became important. The goal was not to undertake a survey that is in any sense complete across all time scales and viewing geometries, but rather to assure the viability of the IR WFS. Encouraged by results, Jefferies built and delivered a near-IR WFS for the AEOS telescope.[70]

Several papers in 2016 reported experimental work on daylight operations with sodium laser guide stars (LGS) for wave front sensing. Recall, an LGS is part of an AO system. The laser is pointed in the (nearly) same direction as the telescope. The laser light reflects off various layers of the atmosphere, and being a single frequency of light can be filtered and isolated in the detectors. Thus, the LGS

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[67] Hope and Jefferies2011

[68] Jefferies and Smith2017

[69] Hope and Smith2019

[70] Hart and Williams2014

provides special information about the turbulence. First, the authors report on careful performance measurements of the AO-LGS system. These are technical measurements: how much flux from the laser, how much returned to the detector, the state of the atmosphere, time of day, angle above the horizon, etc. (As an aside, the authors interpreted their result in terms of an AO system on proposed, next-generation large telescopes.)[71]

The fundamental problem of daylight imaging of near-earth objects is the scattering of sun light by the atmosphere. It was shown 'the problem can be alleviated, to a large extent, by using a laser guide star (LGS) that is located above the dominant layers of atmospheric turbulence and that can be detected with a good signal-to-noise ratio against a bright sky [...] a sodium-LGS viewed through a magneto-optical filter fulfills these requirements.' [72]

The authors turned their attentions to the AF's mission of SSA. Beyond the problem of atmospheric scattering of sun light, the objects of interest in near-earth orbit are moving relative to the telescope, when compared to normal, background stars. Also, it is normal for near-earth orbit objects to rotate, thus changing their profile in the detector. This motion limits exposure time to avoid another source of blur. Shorter exposure means collecting less light, which means lower signal-to-noise ratios (SNR). The authors propose a method based on short-exposure, high-cadence imaging, supported with the LGS approximation of the wave front, to achieve an improvement of 3-4 stellar magnitudes in the faintest satellites. A significant improvement.[73, 74]

In 2018, the authors report on an additional innovation to support daylight SSA. The paper begins by considering the challenge of ground-based daylight imaging of satellites to be due to two sources: a) strong turbulence, and b) high background noise from scattered sun light. Then the authors combine techniques they had developed for each source. Aperture partitioning enables a reduction in the turbulence induced noise; and as we have seen, high-cadence imaging supports the approximation of the wave front in daylight. Together, these techniques help recover the high spatial frequency components of the object. That is another way of saying the techniques help recover the fine detail of the object.[75]

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[71] Hart and Murphy2016a

[72] Hart and Murphy2016b

[73] Hart and Nagy2016

[74] Hart and Hope2016

[75] Swindle and Jefferies2018

6.4 Momentary Digression into Astrology

Consider a fantasy. Perhaps the new AMOS system satisfies an ancient wish. When astrologers look at the heavens, sometimes they see danger. For example, one of the most dangerous and violent aspects is an adverse aspect between Mars and Pluto.[76] Now with AMOS, if the trajectory of one of 'our' satellite assets is predicted to intersect with that of one of 'our enemies' satellite assets, we see danger. The ancient (and eternal) wish is for knowledge to inform decision/policy.

Suppose some satellite is in some position and on some trajectory at some time. And, another satellite is in a position and on a trajectory at a time. Those are facts, as best as our instruments can measure. Now, we predict where the two satellites will be at some time in the future, at an intersection of trajectories! Next, what does the prediction mean, how shall we interpret? And, then, what should we do?

6.5 Application, Small Objects

Another aspect of the AF mission with AMOS is the identification of small, high-contrast objects close-to or on trajectories that intersect with satellite assets. Small objects approaching satellite assets raises the suspicion of an anti-satellite weapon (or just dangerous orbiting debris) poised to attack the satellite asset.[77] In a 2019 paper, Jefferies and colleagues turned their attention to this problem. Overcoming this problem of detecting a faint source embedded in the noise of another source requires both high-resolution and high-contrast imaging. Indeed, this is similar to the challenge astronomers have when trying to resolve closely spaced objects with high-contrast ratios; for example, finding exoplanets close to (bright) host stars. And so, it is a well-studied problem. Another 2019 paper reports that the MFBD toolkit is able to recover secondary targets with a contrast of 5 x 10^{-4}; that's a brightness ratio of 10,000.[78]

6.6 State of the Art and the Research Frontier

A 2022 paper on 'arXiv', to be published in *Astrophysical Journal*, lays out the state of Jefferies' MFBD toolkit and demonstrates its capability. In the context of extreme AO for large telescopes, MFBD for processing high-cadence acquisitions can produce diffraction-limited estimation of the source

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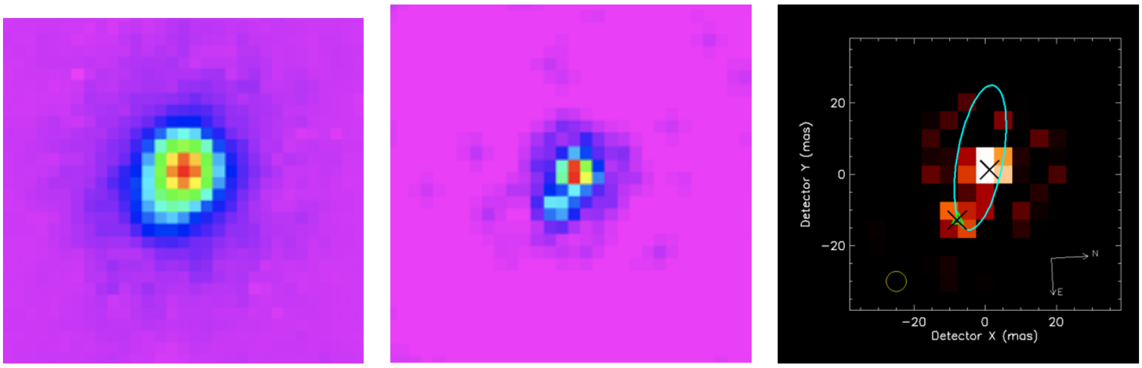
[76] Astrograph2022

[77] Hope and Antoniucci2019

[78] Hope and Testa2019

brightness distribution. This is achieved by a data modeling of each frame in the sequence driven by the estimation of the instantaneous wavefront at the entrance pupil. Under suitable physical constraints, numerical convergence is guaranteed by an iterative scheme starting from a Compact MFBD (cMFBD) which provides a very robust initial guess which only employs a few frames. The authors describe the mathematics behind the process and report a high-resolution reconstruction of actual data of a binary star system named: 'α-Andromeda' ('α-And'), having a very small separation (16.3 mas). Note, 'α-And' is a first identified binary star system in the Andromeda galaxy. The source data for the reconstruction was acquired using the precursor of an upcoming high-contrast camera for the Large Binocular Telescope.[79] Fig 16, shows reconstructed images of the binary star system. From the left, the first reconstruction was published in 2019 using an alternative technique called Speckle Free Imaging (SFI).[80] The middle image from the MFBD toolkit starts with the same data. Recall the discussion of resolution given above (see Fig 9). Observe the MFBD image distinguishes the two members of the binary star system. The SFI does not. Finally, image on the right shows the enlarged MFBD image with further information overlaid. Currently the MFBD toolkit provides one-order-of-magnitude improvement (ie, 10x) over the next best technique.



(a) SFI restoration; binary NOT resolved

(b) MFBD restoration; binary resolved

(c) Further analysis of MFBD restoration

Figure 16: α-Andromeda binary star system, restored images and analysis

The MFBD toolkit contains a rich set of algorithms. It has been developed over thirty years, met many challenges, and proved worthy. In looking to the future, Jefferies and his current colleagues are exploring new possibilities. Exploration includes looking at alternative minimizers available in the mathematic literature. Another is looking at alternative techniques for incorporating a variety of priors

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[79] Hope et al.2022

[80] Mattioli et al.2019

and constraints. One important existing limitation of MFBD is its computation cost. One interesting alternative framework and is called Alternating Direction Methods of Multipliers (ADMM). That name ADMM may be a mouthful of math speak; but the framework promises to provide fast optimization algorithms with simple methods for incorporating alternative minimizers and multiple prior knowledge/constraints.[81] An additional avenue of exploration is looking for new ways to parallelize computation, particularly taking advantage of the newer GPU hardware.

7 Discussion–Knowledge Making

In 'Objectivity', Daston and Galison offer a history of scientific imaging making. They specifically focus on atlases of images from various disciplines, but their real concern is the epistemic values built into the atlases; that is, how a particular style of image making derives from a particular set of values. The authors identify three epochs of image making, which they label: truth-to-nature, mechanical objectivity and trained judgment. The truth-to-nature epoch preceded an interest in scientific objectivity. During this epoch, original images were hand-drawn by a 'naturalist'; who, typically, would jealously supervise the translation of the original into published form. Naturalists presented their personal representation of 'nature'.[82]

Galileo was one of the first to look at the night sky through a telescope, see something of interest, and hand-draw what he saw. And Galileo was the first to see his drawings published. See Fig 1. He wasn't the last. Up until photography, there was no other way to publish images of what was seen through a telescope. Say it again, what was seen, by an individual, through a telescope. Frivolously, this included images of canals on Mars.[83] This among other incidents lead to the epistemic goal of removing subjectivity from image making. Which led to the epoch of mechanical objectivity. Photographic image making was viewed as objectivity par excellence. Indeed, it removed the personal point-of-view, the personal perspective, the personal interpretation. But, hand-in-hand, we lost emphasis, interpretation, a signal of what is important in a particular image of the myriad diversity of nature. See Fig 2. According to Daston and Galison, over time mechanical objectivity also came to be seen as unsatisfactory, and morphed into the epoch of trained judgment. Here, professional training

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[81] Prasad and Tyler2018
[82] Daston and Galison2007
[83] Lowell and UVa1985

and peer review would allow, and then constrain personal judgment.[84]

The subject of this paper: Jefferies, his colleagues and the AMOS project fit well in the epoch of trained judgment. Consider, light coming from above the atmosphere, is blurred (beyond recognition?) by ubiquitous, ever changing, turbulence, and captured as the large matrix of pixels. See Fig 13. Then, by the artifice of highly trained individuals and the magic of algorithms and high-performance computers, objects in space are revealed with sufficient clarity to inform critical operational decision making.

In ‘Image and Logic’, Galison took on a very much broader project: roughly the history of 20th century microphysics. The subtitle ‘A Material Culture of Microphysics’ directs attention to physical components necessary for scientific knowledge making: first, experimental apparatus; then, data collection instrumentation; finally, computational hardware/software for analysis. But that book covers so much more. At the beginning of the century, new knowledge came from individuals (or a professor and his grad students) working in a small laboratory using (mostly) self-made apparatus. Not so very different from Galileo. By the end of the century, dozens, nay hundreds, contributed to specific projects associated with vast, expensive, purpose build apparatus.[85] So, what Galison gives us is an analysis of the evolution of the scientific enterprise over the century. By the end of the century, we see how vast projects are conceived; what scientific question are asked; what apparatus is needed: how to design, build and locate the apparatus; who will take the data; who will analyze the data (and where); and finally, who will manage these enterprises. Galison is particularly keen on understanding how this tower of babel communicates. How do the various disciplines coordinate? In short, Galison gives us ‘the rise of big science’. Next is a brief look at a three government projects derived from military necessity of which the AMOS project is a direct descendant.

7.1 Public Funding of Big Projects

7.1.1 Jet Propulsion Laboratory (JPL), the Military and Science

It is probably the case that there has always been tension over government spending for military vs. scientific research. With respect to space exploration, a precedent was established early on for the US. That is, the US government budget for such research should not be solely for military interests. In

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[84] Daston and Galison2007

[85] Galison1997

the face of the PR competition between the Soviet Union and the US over who would be first to launch an artificial satellite, Eisenhower maintained that the US space efforts would include scientific purposes. The Army was convinced it could beat the Russians with a simple launch. Eisenhower held steadfast. See, for example, the JPL documentary series on the space-age, particularly episode-2 about the first US satellite Explorer 1. Also, when Ike established NASA, he took JPL off the US Army's books in favor of NASA's.[86] NASA was to be responsible for unique scientific and technological achievements in human spaceflight, aeronautics, space science, and space.[87]

JPL had begun as a rocket project of a Caltech professor in the 1930s. The US Army soon began funding 'jet propulsion' research. During WWII there were projects for technical advice, on the German V-2, among others. So, into the 1950's JPL focused on military projects for the US Army. After Sputnik, the first US satellite was by JPL and was launched on an Army rocket. And, the satellite carried a Geiger counter to measure and report data. Sputnik had been simpler, a demonstration of capability and a basic radio beacon. We should note that the data from the Geiger counter enabled the discovery of the Van Allen Belts of trapped radiation encircling Earth.[88] Not to belabor the point, the first US satellite demonstrated capability and yielded scientific knowledge.

7.1.2 The Manhattan Project, Grandaddy of Them All

Perhaps, the archetype of a public supported, big science project was the WWII Manhattan project. In 1905, Einstein gave us $E=mc^2$. Once in power in Germany in the 1930s, the Nazi party purged 'Jewish science' from their universities. The US benefitted. Among others, we got Einstein and Szilard. Apparently, Szilard was the first to realize $E=mc^2$ and fissionable uranium could make a big bomb. In 1939, Szilard convinced Einstein to write a letter to FDR warning of the possibility and of Germany's interest. FDR empaneled a committee of scientists and military at Columbia Univ to consider Einstein's letter. The Manhattan project resulted. Early government support put Szilard and Fermi, another European émigré, to work to determine if, and then to demonstrate, the ability to create and to control a sustainable chain-reaction. At this point, the physical theory, the material science, the engineering design and manufacture, the mathematics and computer science were way behind the experimental results. To make this 'gadget', the project would have to get very much

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[86] JPL-CalTech2022a

[87] Wilson2022

[88] JPL-CalTech2022b

bigger.[89] A Brookings Inst. study reports the cost of the Manhattan project through 1945, in constant 1996 dollars, at \$20B.[90]

I do not ignore, but I shall not here rehash the ethical issue engendered; nevertheless, post-WWII, the Truman administration re-directed at least part of the resources of the 'Manhattan Engineer District' to the Atomic Energy Commission for peaceful uses of atomic energy. One legacy of this era is the US National Laboratories as center of leading-edge science: Fermilab, Brookhaven, Los Alamos, Oak Ridge, and others. Another legacy, while not bricks and mortar, is the history of a successfully managed, large, public project on a military mission that yielded generally useful new knowledge and institutions dedicated to further research.

7.1.3 Rad Lab, 1940 - 1945

In 1940, during the Blitz, the Tizard Mission delivered a British top secret device to the US. It was a one of only a dozen 'cavity magnetrons' recently developed at the Univ of Birmingham, and small enough to hold in one hand. The device was passed to MIT with the mission to create a compact radar system. MIT started the Radiation Laboratory (Rad Lab), allocated a couple floors of a wing of a building, hired / assigned a few and scientists / engineers / physicists / mathematicians and (according to Buderi) changed the world. The radar system, the mission, was a huge success: improved coastal radar allowed longer lead time before enemy attack, enabled night-fighter aircraft to better locate the enemy, enabled bombers to see targets through thick clouds, enabled attack aircraft to see enemy submarine periscopes. More than that, to create the radar system, the Rad Lab had to greatly extend our understanding of electromagnetic radiation, electronic circuits and various manufacturing processes. Resulting spin-offs include radio telescopes, the first long-distance navigation system, advances in electronic components and computer memory, pre-cursors of the transistor, and (for heaven's sake) the microwave oven. Also, a generation of electrical (electronics) engineers were trained from textbooks on radiation and circuits written by alumni of the Rad Lab.[91]

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[89] Gosling2010

[90] Schwartz1998

[91] Buderi1996

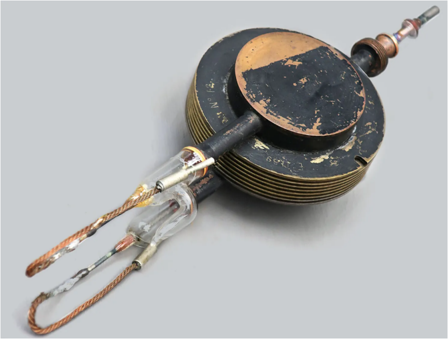

Figure 17: An original 'cavity magnetron'

7.1.4 Jefferies and AMOS

Jefferies and his colleagues were part of the 'big science' AMOS project. We do not have information about the larger project. But clearly, it existed. The larger AF project conceived, designed, commissioned construction and installation of the observatory, computer center and communication link; as well as the software project to analyze the data and communicate the results. Nor do we have information about the military SSA products of the AMOS system. As a teaser, see Fig 13 for a reconstructed image of a satellite from data taken in full daylight. And the legacy of AMOS includes the successful efforts of Jefferies to expand the institutional capabilities at the Univ of New Mexico and Univ of Hawaii.

7.2 Scientific Knowledge Making (by Social Means?)

Bruno Latour is a French philosopher, sociologist, man of letters. He is prolific and writes on many topics. One of his abiding topics is the process of scientific knowledge making. Two aspects of his work are of interest for this paper; they are: a) the socio-political decisions that drive knowledge making, and 2) the ephemeral networks that come together, create knowledge and then disperse. In 2002, in an amusing article, 'The Science Wars', Latour makes his case that knowledge is a social construct driven by political values and subsequent budget allocations.[92] In this paper, we have just looked at exemplar government projects derived from military necessity that drove immediate as well as long lasting knowledge making.

The second concept we take from Latour is best spelled out in his 2005 book *'Reassembling the Social'*. A wide-ranging work about 'actor-network-theory' (ANT). Such networks

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[92] Latour2002

include the (perhaps ephemeral) associations of individual scientists that assist, compete with, constrain, correct, encourage, inspire, extend their work.[93] Throughout this paper we have identified the many colleagues and institutions associated with the work of Jefferies.

As a freshman in chemistry class, our professor was asked the goal of his research; he answered: ‘truth’. Again, the motto on the Harvard Univ crest is one word: ‘veritas’, again ‘truth’. The clear, predominate desiderata of the vast majority of scientific knowledge making is ‘truth’; that is, knowledge of reality not twisted by political, ideological or commercial interests. It is equally clear that if one traces the network of associations for a lot of our knowledge, one sees direct links to some political decision and subsequent allocation of resources. In the end, however, it is worth remembering that from the beginning of US space activity, then President Eisenhower steadfastly maintained that US space activity would include scientific purposes.

8 CODA–Institution Building

So far, we have examined the work of a particular GSU professor, Jefferies, and his network of colleagues and institutions. To recap, Jefferies took the idea of blind deconvolution and, with his network, developed it into a powerful and adaptable tool for scientific knowledge making and an efficient and effective applied technology for an important national security mission. We have located this work in the very long tradition of astronomical image making and in the more recent context of big science projects funded by government for military necessities. In addition to scientific knowledge making and applied technology development, we noted that an important legacy of big, government funded, science project can be the building of institutions that outlive the original project, but carry-on related work. To wit: JPL and the Department of Energy National Laboratories.

We have seen that Jefferies helped extend the capabilities of the Univ of New Mexico and created the Institute for Astronomy at the Univ of Hawaii. Most recently, along with his scientific and technology research, Jefferies has devoted effort toward institution building at GSU. Here are two instances; the first proposed, selected and in-the-process of being implemented; the second in the proposal stage. The first is the GSU Imaging Innovation Hub (IIH). The second is for a National Institute for Space Domain Awareness (NISDA) to be led by GSU.

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[93] Latour2005

The GSU IIH was selected as one of three new research clusters as part of the ambitious Next Generation Program. The Next Generation Program is an effort through strategic faculty hiring to build strength around core and innovative research and scholarship, to interdisciplinary research topics, investigating pressing issues facing our society and the world. The Next Generation Program continues the success of the university's Second Century Initiative, which has raised the level of external research funding, quality of research and scholarship, and the university's reputation for innovative research and scholarship in areas critical to solving problems of the 21st century.[94]

For the GSU IIH proposal, Jefferies brought together faculty from Physics & Astronomy, Computer Science, Psychology, Neuroscience, Chemistry and Mathematics & Statistics; all of whom were engaged in digital imagery for basic, applied and clinical scientific research. These research activities address a wide range of topics of national significance including; molecular/nano-particle imaging, remote sensing for biophysics and space sciences, digital pathology for virtual tumor micro-environment reconstruction, and brain imaging through magnetic resonance imaging (MRI) and other tools. The resulting proposal stipulated that the majority of these research areas involve imaging that deals with similar challenges related to incomplete data, spatial resolution (sharpness/clarity of the image), contrast between bright and faint elements, fusion of diverse types of imaging information, and the large volumes of image data that need to be analyzed. Additionally, image analyses in these research areas share many common threads: mathematics and statistics, machine learning, and artificial intelligence. These are all areas of strength for GSU.

The proposal asserted that the network of imaging-expert scientists of a GSU IIH will develop new synergistic approaches for acquiring, processing, and characterizing image data from microscopic to macroscopic scales, unlike any other imaging groups. To then make these advanced imaging technologies internationally available to other groups, they will leverage cloud-based technology to build fully automated imaging pipelines: from the acquisition of the image data to their full analysis. This will ensure the far-reaching impact of GSU's imaging research across a wide range of disciplines.[95]

Finally, Jefferies is proposing a National Institute for Space Domain Awareness (NISDA) to be led by GSU. NISDA clearly leverages AMOS, but goes beyond it by bringing in an additional suite of resources to bare and an expanded vision. The space domain is near-earth orbit plus the

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[94] GSU2022

[95] Jefferies2019

Lagrange-points where military, commercial and civilian satellite assets operate. Awareness means identifying what's up there, their condition, who owns them, what capabilities they have and where they are going. These assets provide essential navigation, communication, IT, network and surveillance services. The risks to these assets include collision (accidental and deliberate) and adverse effects of extreme space weather. Such risks could compromise national security and cripple economic activity.

The mission of NISDA would be to contribute to the achievement of a comprehensive SDA competency that will allow the U.S. to monitor the health of our own on-orbit assets. This will require developing the next generation of sensors for SDA, building a complete tool kit for the forensic analysis of SDA data acquired from different space missions, ground-based observations, and laboratory experiments, and advancing methods for extracting information from all sources of SDA data. The institute will foster multidisciplinary research through research teams, workshops, working groups, forums, and individual visiting scientists. The critical component of each of these avenues is that the interactions will extend over extended periods and will engage researchers from each sub-field. This approach to an institute of advanced study is based on the highly successful model used by the Institute for Space Sciences in Switzerland for over twenty years. Use of the approach for a new Institute for SDA studies could, therefore, be executed both rapidly and with a high degree of confidence for its future success.[96]

The proposal suggests GSU is uniquely situated lead NISDA. GSU offers the IIH and its broad and deep imaging research capability and the CHARA observatory, a unique high-angular resolution telescope system located in California, but operated by GSU. GSU has association with several observatories in the U. S. Jefferies has associations with observatories in New Mexico and Arizona. He has another research interest in Solar science and association with an Antarctic observatory. Additionally, the proposal suggests Atlanta offers important support to such a national institute. Atlanta hosts three R1 research universities within a few miles of each other: GSU, Georgia Tech and Emory. These universities already cooperate in many areas, and would provide excellent opportunity for multi- and interdisciplinary graduate training appropriate to the needs of NISDA. Atlanta has an international airport and an extensive hospitality/convention infrastructure to accommodate visiting scientists and symposia, large and small. The proposal envisions the GSU NISDA as the central hub of a network of other institutions across the U. S. Already other institutions with significant expertise in

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[96] Jefferies2022

areas relevant to SDA have indicated interest in NISDA, including Univ of Georgia, Colorado (Boulder), Arizona, Hawaii and Minnesota.

Of course, these institutions are in their infancy. Their endurance not assured. But their very existence reminds us what can result when highly creative people are supported / engaged in big science projects.

8.1 Final Comments

So, one question remains: how to sustain / encourage creative knowledge making? First, let's distinguish creative knowledge making from 'normal science' (in the sense of Kuhn). For 'creative' knowledge making, let's use the term 'breakthrough' knowledge making. As an example, at the turn of the 20th century some of the doyens of physics were saying physics was done. All that remained was to estimate parameters more precisely. More precision was predictable, the quantum breakthrough was not even imagined; though only some twenty-odd years off.[97]

So, where does truly creative breakthrough knowledge making come from? The ancient Greeks tells us such breakthroughs are divinely inspired. (That is a redundant statement!) The muses whispered to mortals. There were nine sisters, each had her own domain, music, dance, etc. Astronomers had their own, Urania.[98]

Now, consider the job of the large research universities: teaching, research and service. And how do they evaluate themselves and their peers? For teaching; students enrolled, students graduated, graduates employed and starting salaries, (and perhaps) alumni contributions. For research, publications and external funding attracted. For service, external contracts delivered. Next, there are prizes awarded to individual faculty. Add to these the public rankings by various agencies, largely based on qualitative criteria. What can be said of this list of metrics? Do they capture creative breakthroughs? Do they even capture the pre-conditions for breakthroughs? Perhaps the prizes may. The rest are fairly soft.

In the end, we do not know where breakthroughs come from. And we are not alone. The venture capitalists of Silicon Valley invest billions in incubators for start-up companies and are happy, apparently, when less that 1/10 of one percent of their start-ups become unicorns (achieve a market

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[97] Pemberton2019

[98] Williams2021

valuation over \$1B).[99]

Our subject, Jefferies has been part of a large project. He has participated in creative knowledge making. He has seen the power of having a place, a mission and a collection of talented colleagues.

There is a telling aphorism in a corner of the white board in his office: 'vision without resources is only hallucination'. So, the bet is: create institutions with big but focused missions, recruit / hire recognized talent and promising rookies, bring in outside funding, and let's see what we can do.

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[99] Griswold2018

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Glossary

’arXiv’ pronounced: ’archive’, an on-line pre-print site for scientific papers. 29

’de-convolution’ Inverse mathematical operation to convolution. 6

’seeing’ Astronomer’s term for the optical quality of the atmosphere at various places and times. 8

Adaptive Optics A technology to reduce for incoming wavefront aberrations by deforming the primary mirror. 12

ADMM A class of algorithms for solving constrained optimization problems. 31

ASPIRE The front-end GUI to AMOS PCID toolkit. 19

CAT scan A form of imaging known as cross-sectional imaging. 14

CG minimization An algorithm for the numerical solution of particular system of equations. 10

Charge Couple Device An electronic device that serves as detector/camera on telescopes. 4

convolution A mathematical operation on two functions that produces a third function. 6

D/r0 pronounced: ’D over r naught’, a measure of atmospheric turbulence. 23

diffraction Bending of a light wave due to passage through the aperture of an optical system. 12

Frozen flow hypothesis An assumption about atmospheric turbulence built into certain algorithms. 23

Laser guide star An artificial star, used by an ’AO’ system to improve ’seeing’. 14, 41

Pan–STARRS Panoramic Survey Telescope and Rapid Response System, on Haleakala, part of MSSC. 22

PCID The principal imaging processing algorithm toolkit of the AMOS system. 19

Phase diversity Imaging techniques that use two or more distorted views for wave front sensing. 20

Point spread function Describes the response of an imaging system to a point source of light. 6

Rad Lab The MIT Radiation Laboratory. 34

refraction The change in direction of light from passage between segments of air with diverse pressures, etc.. 8

resolution Ability of an imaging system to resolve details of the object being imaged. 1, 2, 12, 13, 18, 22, 24, 41

wave-front sensor A device for measuring the aberrations of an optical wavefront. 23

Acronyms

ADMM Alternating Direction Methods of Multipliers. 31

AFOSR Air Force Office of Scientific Research. 17

AFRL Air Force Research Laboratory. 16

AMOS Air Force Maui Optical Supercomputing Site. 15

AO Adaptive Optics. 12, 13

BD 'blind' deconvolution. 6

CAT Computerized Axial Tomography. 14

CCD Charge Coupled Device. 4, 6

CG Conjugate Gradient Minimization. 10

COSTAR Corrective Optics Space Telescope Axial Replacement. 5

DoD Department of Defense. 16

FFH Frozen Flow Hypothesis. 22, 23

FFT Fast Fourier Transform. 9

FT Fourier Transform. 6

GUI Graphical User Interface. 19, 22

HPC High-performance computing. 3

HST Hubble Space Telescope. 4, 5

IBD Iteative Blind Deconvolution. 10

ICBMs Intercontinental Ballistic Missiles. 16

IfA Institute for Astronomy, Univ of Hawaii, Maui. 18

IGY International Geo-physical Year. 15, 16

IIH Imaging Innovation Hub. 36–38

JPL Jet Propulsion Laboratory. 32, 33

LBT Large Binocular Telescope. 13

LGS Laser Guide Star. 14

NASA National Aeronautics and Space Administration. 5

PCID Physically Constrained Image Deconvolution. 17, 19

PD Phase Diversity. 20

PERT Partnership for Research Excellence and Transition. 17

PSF Point Spread Function. 6

SH Shack-Hartmann. 25, 41

SSA Space Situational Awareness. 16, 28

USAF U.S. Air Force. 16, 17

WFS Wavefront Sensor. 25, 41

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