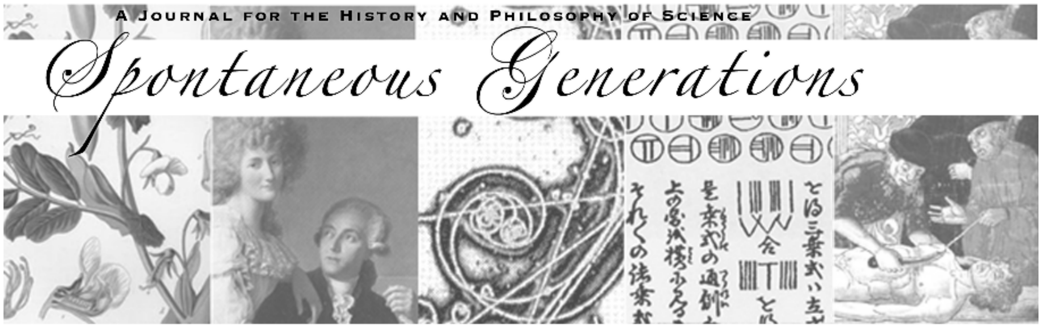

On Adaptive Optics: The Historical Constitution of Architectures for Expert Perception in Astronomy

Author(s): Ian Lowrie

Source: *Spontaneous Generations: A Journal for the History and Philosophy of Science*, Vol. 6, No. 1 (2012) 203-224.

Published by: The University of Toronto
DOI: 10.4245/sponge.v6i1.16133

EDITORIAL OFFICES

Institute for the History and Philosophy of Science and Technology
Room 316 Victoria College, 91 Charles Street West
Toronto, Ontario, Canada M5S 1K7
hapsat.society@utoronto.ca

Published online at jps.library.utoronto.ca/index.php/SpontaneousGenerations
ISSN 1913 0465

PEER-REVIEWED

On Adaptive Optics:

The Historical Constitution of Architectures for Expert Perception in Astronomy*

Ian Lowrie†

This article charts the development of the modern astronomical observational system. I am interested most acutely in the digitization of this system in general, and in the introduction of adaptive optics in particular. I argue that these features have been critical in establishing the modern observatory as a factory for scientific data, rather than as a center of calculation in its own right. Throughout, the theoretical focus is on the nature of technological evolution in the observational system, understood as inextricably bound up with both the system-internal drive to surpass the limits imposed upon the distributed cognition of the researcher and the boundary at which empirical objects resolve themselves into technical objects. In short, this article explores the historically constituted character of expert astronomical perception, arguing that it is impossible to understand without constant reference to its material substrate.

Over the last century or so, something happened to the observatory. What was initially the center of astronomical calculation has rapidly become a manufactory for observational data, which are then processed and analyzed elsewhere, farther down the data pipeline. The observatory is no longer a contingent enclosure housing congeries of astronomical inscription devices and stores of data, to be assembled and reconfigured at will and as needed by the astronomers in residence. Instead, the contemporary observatory is a thoroughly integrated, if modular, material assemblage; a critical component of the "externalized retina" of the academic astronomer, who generally resides and works elsewhere (Lynch 1985). This paper seeks to chart this historical shift, paying particular attention to the role played therein by the introduction of digital technologies in general and adaptive optics in particular. Nevertheless, this shift is far from a unique or total rupture with the historical trajectory of observational astronomy, broadly conceived. For this reason, in advancing my argument, I begin with a rudimentary outline of the earliest configuration

---

* Received 23 February 2012. Accepted 7 August 2012.

† Ian Lowrie is currently a doctoral student in the sociocultural anthropology program at Rice University, with regional focus on the United States and Russia. His research interests include the human engagement with space, the interactions between religious and scientific systems, and the development, circulation, and politicization of models of intelligence.

of what we might call the modern astronomical observational system, in the sixteenth century, before moving through a succession of modulations in its configuration and use, culminating in my discussion of adaptive optics. Throughout, the focus is as much on delineating the parallels between the core epistemological and diagnostic processes at the heart of the observational system at different historical moments as it is on marking the revolutionary changes brought about in the professional practice of astronomers by the introduction of new components to their externalized retinae. While the mode of this essay is historical, its aims are theoretical. I am not a historian, however, and rely heavily upon those who are in order to advance my argument. In describing this history of epistemic things, my goal is to present a view of scientific development which takes seriously both the actuality of the objects of science and the broader social context in which these objects of necessity present themselves. In so doing, I hope to demonstrate the insufficiency of both an enthusiastically constructivist version of Latourian ontology as well as of a thoroughly positivist understanding of knowledge production.

Perhaps the most taken-up of Latour's claims has been the realization that facts are manufactured: we now know that the business of science is to produce inscriptions, traces, or records of objects and events in the world in such a way that they are capable of articulating with others so produced. This is an essentially contingent process, predicated upon a host of concrete mechanisms, developed over a historically particular trajectory; upon modes of seeing, thinking, producing, and knowing that could havebeen quite different. However, I ask in this essay, does this contingency necessarily have the epistemological consequence of radical constructivism for which some contemporary readers of Latour would argue? Facts are manufactured, but so are shoes, and shoes are certainly an "objective" way to keep one's feet dry—despite their historical contingency.

Thus, I argue, *pace* Latour, that scientific systems are best understood as "arrangements that allow us to produce, in a regular manner, unprecedented events" (Rheinberger 1997, 23). Of course, these systems are established and made coherent only by virtue of a field of written intelligibility, which Rheinberger calls a "graphematic space," wherein standardized inscriptions, capable of being articulated with other inscriptions, are produced and circulate. However, this is most often in the service of a positive feedback mechanism, whereby newly produced inscriptions are tested against others for validity, and ultimately reincorporated back into the system itself in the form of either new instruments or new technical knowledge. As Rheinberger (1997, 27) has it, the more the scientist learns to handle an observational system, "the more it plays out its own intrinsic capacities. In a certain sense, it becomes independent of the researcher's own wishes just because he or she has shaped it with all possible skill." The scientific system, then, is here conceived of as as a collection of technical, or well-described and previously encountered, and epistemic, or relatively unknown and novel, objects. This system is constantly overcoming itself in ways that require justification and elaboration if it is to maintain its forward momentum, and hence its very existence. In its wake, it leaves a trail of facts and machines, or "technical objects" in Rheinberger's terms, as the scientists with which it is imbricated search after ever further and more obscure "epistemic things." I suggest that scientific systems must be analyzed on their own terms, rather than as either derivative of social processes or as neutral-universal conduits for the encounter between people and their world. I return to the implications of this refocusing for the social study of science and technology in my conclusion.

I. From Brahe to Hale

In this paper, I bypass the admittedly fundamental *theoretical* contributions of Copernicus and Kepler to the heliocentric model of the solar system, and to the gradual erosion of the primarily theological understanding of astronomy *qua* project of revealing the mathematical perfection of the Heavens. Instead, as I am concerned with charting the development of the astronomical phenomenotechnique (Latour and Woolgar 1986), I might begin with Galileo; he was, after all, the first to adapt refracting telescopes to the use of sky-gazing (circa 1609). Indeed, this choice would make a certain sense: after all, the telescope stands in for astronomy as such in many cases. However, this metonymic conflation of observer with the technical means of observation is entirely too much a result of hindsight. It grants unwarranted predominance and an undue sense of inevitability to the mode of assemblagecharacteristic of modern astronomy, preventing us from understanding the historical particularity and contingency of this mode.

Instead, if we want to study science in the making, to analyze "warm and unstable" rather than "cold [and] stable" processes and objects (Latour 1987, 21), I suggest that we ought to look for the emergence of the observational complex as a scientific *system*, with a coherence above and beyond its merely material substrate. Following Rheinberger, this investigation looks to the "*system* as a point of orientation for the historian in the overly complex happenings of the modern empirical sciences" (1997, 19, italics original). This system is not a fixed constellation, but rather one which is always already superseding itself in ways that demand its evolution; it is both a "dynamic body of knowledge" and a "network of practices structured by laboratories, instruments, and experimental arrangements." In short, it "is a reasoning machinery in its own right" (Rheinberger 1997, 20). Its coherence can be analytically guaranteed only by a careful charting of its movements and mutations.

I suggest that we ought, then, look to Tycho Brahe (1546-1601) rather than Galileo as the genitor of the modern observational complex. Brahe was among the first to reorient the scientific study of the heavens away from mathematical speculation, conceived as the manipulation of perfect, geometric *res cogitans* and turning to observation only for confirmation or denial of posited first principles, to observation of *res extensa* as the only possible basis for eventual mathematization and formalization of laws and models. Brahe's observational system did not partake of refraction- or reflection-magnifying optics, but that is not to say that he was simply standing in a field looking at the stars. Rather, Brahe leveraged his aristocratic position to convince the Danish government to fund an elaborate purpose-built observatory on his island estate of Hven. This observatory contained an array of inscription devices—cutting-edge technology designed to aid the human eye in translating unmagnified observations of the sky into rigorous and precise measurements (see Høg 2010). His initial system was simple and ingenious: a rectangular hole was cut high into a wall, allowing the observation of the movements of the stars across a fixed plane over the course of the night. In the center of the room, a large mural sextant was placed across the floor, running up the wall opposite the observing slit. With this simple inscription device, Brahe was able to record the locations on the celestial sphere of some one thousand stars on the orders of minutes of arc (sixtieths of degrees) using an azimuth-altitude coordinate system that he himself had devised. Using the king's largesse, he eventually upgraded this rudimentary observational set-up to include a framed sextant: a slit-and-plate device allowed the observer to isolate one star in an aperture specifically calibrated to display a sextant reading, and could be moved to point at stars on any point in the visible celestial sphere, thereby improving accuracy to under one arc-minute (Høg 2010, 226).

Of course, the totality of modern astronomy is not contained within the germ of Brahe's work. What makes Brahe more-or-less foundational, however, was his creation of a novel observational *and representational* strategy. It was this observational assemblage—sextant, slit-and-plate, and Azimuth-Altitude system—that allowed Brahe to "bring celestial bodies billions of tons heavy and hundreds of thousands of miles away to the size of a point on a piece of paper" (Latour 1987, 227). This process allowed astronomy for the first time to make of the visual "a regular avenue through space," and to create "optical consistency" that would allow observations to be excised from the conditions and locations of their production (Latour 1985, 6). In order to come to analytic grips with this sort of representation, the historian or anthropologist of science and technology must attempt to "wrest the idea of *representation* from an individualistic cognitive foundation, and to replace a preoccupation with images on the retina ... with a focus on the 'externalized retina' of graphic and instrumental fields upon which the scientific image is impressed and circulated" (Lynch 1988, 202).

That said, in the seventeenth century, the telescope—although not the Galilean version—quickly became the dominant instrument by which astronomical observations were conducted. This was not only because of its ability to magnify objects in the sky and thereby increase the angular resolution of the images thus formed, but also because of its greater light-collecting power than the unaided human eye, which allowed observers to catalog and record the positions of many more than the one thousand stars so treated by Brahe. The Galilean telescope, with its concave eye-piece, was quickly surpassed by the Keplerian, which used a convex optical focus (Høg 2010). Galileo's telescope gathered about four times as much light as the unaided human eye, but could only magnify by a factor of twenty or so. This was enough for Galileo, famously, to see the mountains on the moon, the striations on Jupiter, and to resolve several blurry stellar objects into the clusters of stars which we now know them to be, "but not enough to reach much deeper into the solar system and reveal other satellites or surface features on the planets" (Van Helden 2010, 7). Ultimately, "by 1611 the potential of the Galilean telescope for discovery had been exhausted" (Van Helden 2010, 7). It would take the Keplerian model, which utilized a system of convex lenses to significantly improve the resolution, field of view, and magnification available, to expand upon Galileo's voluminous contributions to astronomical knowledge. Convex lenses also had the important benefit of enhancing the consistency and stability of the image as resolved by the human eye as it tracked across the visual field of the instrument (Van Helden 2010). This greatly improved the accord between observations made by physiologically different individuals.

The Keplerian improvement, however, allowed for not just better visualization on the human retina, but the production of better inscriptions. Convex-lens technology allowed augmentations to human sight and estimation to be placed within the telescope's optical system; predominant among these was the filar micrometer. Placed at the common focus between a convex eye-piece and the front lens of the telescope, the micrometer was used to produce ever more accurate measures of the angular size and separation of celestial objects. The wire micrometer was essentially a cross-hair of wires, with an additional, moveable wire parallel to one of those comprising the cross-hair; the observer would place one star at the center of the cross-hair, rotate the instrument until another star was bisected by the single wire, and then move one of the double wires to bisect the second star again at right angles. The measurements on the wires' frame were calibrated to the specific angular size of the field of magnified vision particular to the telescope to which they were attached. This allowed a simple trigonometric calculation to reveal the true angular separation of stars, which might appear to be a single point on the night sky to the unaided observer, or the accurate size of planets and other satellites.

In this discussion of the evolution of the telescope, what is essential to take away is not *what* the new developments allowed one to see, but *how* they allowed what was seen to be rendered mobile, immutable, and combinable (Latour 1987). To put it in Latourian terms, the telescope was one, albeit critical, component of a distributed network of rendering the sky and the objects that populate it ever more closely at hand. The transformation of the inscriptions created by telescopes in the field into the hardened facts that would propel the evolution of astronomy as a discipline (and brought into focus the epistemic objects which required ever larger and more precise telescopic inscription devices) occurred not at the telescope, but in the observatory. From its inauguration until at least the turn of the nineteenth century, the observatory as space was not the privileged locus of actual *observation*, or at least not *only* that. The telescopes used by and at an observatory were by both nature and design moveable. Moreover, several substantial innovations in telescopic systems occurred *outside* the context of the observatory proper (Bennet 2010, *passim*). Rather, the *unique* purview of the observatory, what separated it from the field astronomy of amateurs like John Goodricke, was its situation as the *center* which collated and combined the immutable mobiles produced by observations the world over into new patterns, searching for new epistemic objects (cf. Latour 1987, 215-57 *passim*). As astronomy began to shift from a popular pass-time of the so-called "gentleman-amateurs" of the eighteenth century to the professionals of the later nineteenth, the observatory was the point of articulation whereby properly packaged inscriptions were placed within an emergent field of scientific knowledge production. The observatory might not have even had the best telescope, or even a mounted telescope at all; but it *did* have all the books, charts, and communiques from observatories in other countries by which the observations of those who did might be combined to form the models and other *n*-th level inscriptions which would render them intelligible (Golay 2001, 14; cf. Latour 1987, 232-47).

II. The Age of Big Telescopes

This particular configuration of the observatory as (primarily) the site of articulation and remobilization of the work done by gentleman-amateurs in the field would not last beyond the introduction of the "Big Telescope" as the astronomical instrument *par excellence*. However, neither the transition to professionals and big telescopes, nor the emergence of the contemporary relationship between the two, was natural or inevitable. There was considerable contestation over the propriety of these unwieldy instruments, which needed a whole class of skilled technicians, not merely an interested gentry, for both their installation and operation. Unsurprisingly, "those most vocal against the large telescope were amateurs, who had enjoyed a long tradition ... of making substantial contributions to the science. This was the end of the era of the grand amateur, protesting the rise of the professional class" (DeVorkin 2010, 71). Indeed, the story of the emergence of astronomers as a professionalized body of experts fits well within another narrative common to historical studies of the emergence of the science—that of the political-economic changes that destabilized the constitution of the gentleman as the proper producer of scientific knowledge (Livingstone 2003, Shapin 1988).

For whatever reason, however, towards the end of the nineteenth century, observatories were becoming the hegemonic locus of astronomical *observation*, not just collation, and observation was becoming the defining feature of astronomy's professional portfolio—the phenomenotechnique by which it claimed a unique place among the sciences. Unsurprisingly, this shift towards conducting observation exclusively within the observatory by highly trained and professionalized observers was accompanied by a shift from the small, moveable telescope in the Gallilean-Keplerian tradition to ever larger and more complex optical systems. One such system, identified by most analysts as a watershed moment in the history of the modern observatory, was the 60-inch Hale telescope at Mount Wilson Observatory, which went online in 1908, followed soon by its 100-inch cousin, the Hooker Telescope (notably used by Edwin Hubble to measure the redshift of distant galaxies). What made these telescopes qualitatively, rather than merely quantitatively, different from their smaller antecedents was that they were the first to be thoroughly *integrated* into the design of the observatories in which they were housed, rather than merely *built* within them; they utilized optical and steering systems which were "far too heavy and dynamically fragile to be sitting on a moving telescope in a drafty dome" in order to achieve their dominant status among contemporary astronomers (DeVorkin 2010, 64).

With the dawn of the "age of the big telescopes" (DeVorkin 2010) at the end of the nineteenth century, however, we don't immediately leave behind telescope *qua* "beautiful and cantankerous instrument," requiring not merely professional training and expertise, but also "high artistry" to operate (Whiteford in McCray 2010, 78). Despite the integrated design and the beginnings of mechanization of the steering and focusing systems of these telescopes, their use remained an intimate, physical engagement on the part of even the most highly trained astronomers and astrophysicists. As late as 1948, when the Hooker telescope was surpassed by the George Hale 200-inch at Palomar as the largest in the world, "many of the observation runs ... were carried out at the telescope's prime focus station. There, researchers sat in the cramped 'observing cage' and rode with the telescope all night long while collecting data." (McCray 2010, 79). A certain amount of practical finesse and familiarity with the given instrument was required in order to produce good science images. One consequence of the cantankerousness of these instruments was that astronomers remained more-or-less indissolubly associated with "their" observatories. The idea of simply "dropping in" to use a telescope for a few nights was so impractical as to be unthinkable; one would have wasted the entire visit merely learning the tricks required to get the telescope to perform its role as inscription device properly. Over the past fifty years, "astronomers' relationship with telescopes has changed profoundly." Their interactions have "become more productive, yet more impersonal and remote ... efficiency, improved performance, comfort, and access to more data are goals that the scientific community has chosen to pursue" (McCray 2010, 78).

III. The Organization and Evolution of Astronomical Observation Since World War Two

The sociological and procedural environment of astronomy today bears little resemblance to that of the early twentieth century, much less to the age of the gentleman-amateur (although I argue it nevertheless retains much of the epistemological core outlined above in the discussion of Brahe's observational practice). While some observatories remain under the control of an astronomer every bit as cantankerous as his instrument, these are the minority; no one would think to build a telescope that could not be used by a visiting scholar with little to no specific preparation beyond the elaboration of a research plan. This shift has been characterized as one from an "exclusive and rarefied" group of astronomers in firm control of their own observatories, endowed by wealthy families or grants from lens- and optic-manufacturing companies interested in promoting the excellence of their products, to a thoroughly professional group of university- rather than observatory-based astronomers engaging government- and foundation-funded observatories for limited, goal-based research (Roy and Mountain 2006, 12). No longer is the observatory the center of calculation, trafficking in immutable mobiles created elsewhere, or only incidentally in-house; instead, the centers of calculation are professors' cramped offices at their home institutions, with the observatory having become a highly complex and integrated manufacture of science data.

I would like to suggest that two main components comprise the mechanism whereby the material bases of the astronomical phenomenotechnique have been updated to accommodate the project of scientific star-gazing to the contemporary milieu of highly audited Big Science: an ever-increasing mechanization and integration of the telescope with the observatory, on the one hand, and increasing digitization of the inner workings of the entire assemblage on the other. In earlier observatories, as discussed above, the telescope was essentially a moveable instrument, standing merely in a relationship of contingency to the building which housed it. During the early years of the age of big telescopes, this relationship was becoming more indissoluble for both technical and organizational reasons: technical, because telescopes were simply becoming too large and complicated to move from the site of their installation; organizational, as the agents of astronomical investigations were becoming increasingly professionalized. Further technological innovations, however, have rendered the telescope and the mechanical and architectural system in which it is embedded synonymous. Even during the first half of the twentieth century, "large telescopes were understood by engineers as a system of separate parts—mirror, truss, dome .... Their design was largely done independently" (McCray 2010, 83). As the epistemic objects under investigation by astronomers became ever more distant, small, faint, and complicated, however, the delicacy of the instruments required for their felicitous inscription increased. New advances in optics required careful calibration to the surrounding atmospheric conditions as well as insulation from vibrations. This, in turn, required the co-ordinated construction of telescope, dome, and truss. Additionally, the control of such delicate equipment could not be trusted to the hand of even an experienced practitioner, at least unmediated by hardware controls. The guidance and drive systems used to both point the telescope initially and to keep it on target while it resolved the science image soon became thoroughly automated.

One critical component of this mechanization was the introduction of digital computing technology into the work-flow of the observatory; perhaps most obviously, and certainly initially, in the guidance and tracking of science objects, computers "provide the interface between the observer and the instrument" (Shortridge 2001, 164). They also increasingly control the interactions between the components which make up a given observing instrument (Shortridge 2001, 164). The digitization of recording media, made possible by the advent not just of computing technology but also of electronic detection hardware, has revolutionized the way that the data produced by telescopes are analyzed. Initial forays into electronic (rather than photographic) detectors, such as the photomultiplier tube, were useful, but far from general-purpose. "In a photomultiplier," for example,

> the initial photon strikes a photocathode, releases an electron, which is then amplified by passage down a cascade of intermediate electrodes, and something like 10-20 percent of the incident photons cause the release of a photoelectron. The great advantages of such a device are its quantum efficiency, its linear response, and the multiplication of the signal within the tube, without which it would have been exceedingly difficult to measure charge or current. But a photomultiplier provides a measure only of the total light incident on its photocathode. Each object must be measured separately. (Smith and Tatarewicz 1985: 1222-23)

This means that while the photomultiplier was extremely useful for applications such as measuring the flux of an individual star, it could not easily take over the multiplex role of photographic imaging. The Charge Coupled Device (CCD), on the other hand, emerged as a highly versatile detector during the planning for the Hubble Space Telescope. As Smith and Tatarewicz note, the CCD won out over a number of competing designs not simply because of its technical suitability for the task at hand, but because of a felicitous "alliance of astronomers, planetary scientists, engineers, and industry made possible by the investment by industry in the devices for a range of possible commercial and military applications, as well as more directed funding by NASA" (1985, 1222). This coalition was successful because of the greater flexibility in application of CCD imaging compared to alternatives, and, I would argue, on the ability of CCD *qua* digital detector to articulate with other, then-digitizing military, industrial, and scientific systems. Moreover, it was a primary motivating factor for the eventual ubiquity of CCD detectors in astronomical systems.

In essence, the CCD is "an array of electrodes on an insulating base on the surface of a thin wafer of semiconducting silicon" (Smith and Tatarewicz 1985, 1226). The CCD can be conceptualized as a system of electron potential wells, arranged into a grid as pixels, each of which records the impact of individual photons. At the end of an exposure period these pixels are emptied out and tallied, producing a digital file showing quantitatively the distribution of light falling through the telescope that can be translated into an image, contour, or other type of output in software packages such as Image Reduction and Analysis Facility (IRAF). The advantages of the CCD approach to imaging and spectroscopy are multiform. The human eye can detect at best 1% of the light falling onto it, along a limited range of wavelengths; photomultiplier tubes allow the recording of about 20% in a slightly wider band of wavelengths, but contemporary CCDs can achieve around 95% quantum efficiency across most wavelengths of interest to astronomers (Janesick and Blouke 1987, 241). Moreover, unlike point-source photomultipliers, CCDs produce a two-dimensional image akin to a digital photograph. However, it is not possible just to snap a picture with a CCD; the electronics are highly sensitive to cosmic rays, temperature differentials across the grid, statistical noise resulting from the vagaries of quantum mechanics, and fixed-pattern noise from microscopic irregularities resultant from the manufacturing process. Without image processing, because of the signal-to-noise ratio in the raw image, much of what is produced by CCDs would otherwise be useless.

This is where image-processing packages like IRAF come to the fore as the primary postdetection tool of modern astronomy. Even leaving aside their powerful analytic algorithms, imaging software is essential in translating CCD data into useable images. To make a science image readable, one must also, using the same observational system, take several calibrating images; dark images, or exposures the length of the science image exposure taken with the lens caps on to record the noise created by thermal variation across the CCD; flat-field images created by short exposures aimed at a uniformly lit surface to account for fixed and statistical noise aberrations due to differences in photoelectric sensitivity in specific pixels; and bias images created by zero-second "exposures" to record the read-out noise due to manufacturing error in the CCD. Several of each type of image is taken, averaged together, and either subtracted from or divided into the science images before they are in turn averaged and normalized. This only begins to describe the effort that goes into making useable images out of CCD data; there are a host of imaging packages in IRAF that serve no other function than to massage or calibrate the data into revealing what the investigator hopes to find. However, the fabrication of data is generally prevented by statistical calculations determining the propagation of error across images; the error margin for any science feature created whole-cloth through image manipulation would be enough to render it obviously such. Neither this clean-up work nor the sophisticated analytical work of which IRAF is also capable is conducted on-site at the observatory; this would be a colossal waste of time and thus of money. Rather, observatories are primed to produce data in mobile form—raw digital read-outs of the counts produced on the CCD that the observers may use in their home institutions to produce useable science images.

The outcome of this mechanization and digitization, this lengthening of the network connecting the astronomer to the stars—which once consisted of merely an eyeball-telescope-sky circuit—has been, predictably, a complete refashioning of the observatory as such. As I have posited above, the observatory housing today's large telescopes is no longer a center of calculation in its own right, but rather exists primarily, and in many cases exclusively, as:

> the most visible part of a much bigger astronomical data-collecting network ... linked in real-time to engineers and astronomers by high-speed data networks [and] fiber optic cables ... This shift has entailed a re-casting of the telescope by astronomers and science managers as a factory of scientific data and scientists as customers who order up astronomical data that is delivered to them electronically while they monitor the process through internet links. (McCray 2010, 84)

Unsurprisingly, these factories of scientific data are being run as such, not like classical observatories. The operating costs of a modern large telescope are staggering, and "it is hard to imagine that any foundation or agency called upon to spend about \$4-\$5/second on a night of observing will not expect every second to be accounted for and used productively" (Roy and Mountain 2006, 29). This, at least in part, has been responsible for the introduction of telescope operators and queue scheduling.

Astronomers no longer guide the best telescopes themselves. Nor, increasingly, are they allowed to interact with the software which guides the automated tracking systems; instead, they interact with telescope operators, employed by the observatory and specifically trained to efficiently and reliably produce the images requested by the visiting astronomers (Robson 2001, 125). In a funding climate where efficiency is the top concern in terms of both research output and outlay and where a telescope that is so expensive to operate that "if a staff member's work can save two nights" for other research, then "their salary is already accounted for," it is not surprising that astronomers are not allowed to operate the telescopes themselves (McCray 2010, 85). Instead, often, "the astronomer's role [is] solely to command the sequence of observations, undertake online analysis to determine the scientific progress, and make decisions accordingly" (Robson 2001, 125). By "online analysis," Robson means the real-time monitoring of the quality of images being produced by the telescope (2001, 125).

The concern that one's carefully planned and enormously expensive observing program might come to naught is the primary reason that "observing modes for ground-based telescopes have become a hot topic over the past decade" (Robson 2001, 121). As Robson (2001, 122) explains;

> The traditional mode of observing for ground-based astronomers … is to travel to the telescope on scheduled dates to undertake their allocated observing program. Unfortunately, the best-laid plans are often thwarted due to the vagaries of … the weather. This sometimes results in the scientifically highest-ranked programmes failing to be completed … resulting in a major loss of science benefit to the scientists, the telescope and the funding agency.

The solution to this problem, more satisfying to the science managers and funding agencies than to the astronomers themselves, has been to implement so-called "queue scheduling." In simplest terms, the weather common to a given location is divided into a fixed number of categories, and the observing programs for a fixed period of some months are ranked against both one another and the weather categories, and algorithmically assigned to be conducted on a given night, on the fly. The problems with this are immediately obvious; most universities would not take kindly to being told that they were expected to pay for their astronomy faculty to traipse off to Hawaii for a six-month period, where they might conduct only two weeks of observation, scattered across the entire "vacation." The accommodating strategy has been a combination of remote observing (telecommuting, essentially) and mixed queue scheduling, wherein astronomers are granted a guaranteed shot at observing at least a few nights during a shorter period of just weeks, and promised to have the rest of their observations conducted remotely over the next few months.

As McCray points out, "in many ways, observatories' emphasis on flexibility, adaptation, and streamlined efficiency [resembles] Japanese 'just in time' manufacturing practices admired by American and European business leaders in the 1980s" (2010, 85). Of course, the question of efficiency raises the difficulty of how to quantify this nebulous value. The answer, however unsatisfying it may be to astronomers, is a simple calculation of dollars spent on capital and upkeep for a given observatory per favorable citation of a paper produced based upon observation conducted at that observatory. Admittedly, this has not rendered high-outlay programs of investigation, such as those requiring space-based platforms, from still receiving funding:

> During the period surveyed [1991-8] space telescopes such as ASCA, CGRO, COBE and ROSAT had impacts 4 times greater than those of typical ground-based 4-m optical telescopes. The capital costs were 15-30 times greater than those of a typical 4-m. HST [Hubble Space Telescope] has an impact 15 times higher than a 4-m telescope, but cost 100 times as much (200-300 times as much, if the cost of servicing missions is included). (Benn 2002, 86-87)

However, these platforms require special justification beyond a boiler-plate "to advance the cause of scientific understanding of the universe;" ASCA, CGRO, COBE and ROSAT were all launched "to solve a specific scientific problem which can't be tackled from the ground," and as such, "may have a short-lived community of citers," allowing them to argue that traditional citation-impact metrics are not a fair measure of their efficiency (Benn 2002, 87). Similarly, projects like the European Southern Observatory's Very Large Telescope (VLT) and the HST itself can only justify their massive budgets as part of national or regional scientific boosterism. For ground-based telescopes, the guiding rule of thumb is that citational impact *is* statistically, and thus *ought* be for any new telescopes, "approximately proportional to collecting area, for mirror diameter between 2 and 10m" (Benn 2002, 89). It is into this funding climate that adaptive optics, which promise to minimize or even negate the effect of the earth's atmosphere on telescopic vision, have insinuated themselves.

IV. Adaptive Optics

Astronomers have been aware of the limitations that the Earth's atmosphere imposed upon their ability to resolve images clearly at least since Newton's work on turbulence and refraction in the seventeenth century (Hardy 1998). However, using contemporary technology, there was little that Newton's coevals could do to improve the resolution of their optics. This was, in fact, one of the reasons for the debates between the gentlemen-amateurs and the professionalizing scientific astronomers of the nineteenth century over whether bigger telescopes were, in fact, better than their more mobile counterparts (DeVorkin 2010). This argument was ultimately won by the scientists and their larger telescopes, not on the basis of the *clearer* images produced by their work, but rather due to the ability of telescopes with larger light-collecting areas to see fainter objects, which became important as the amount of novel celestial phenomena within the reach of the amateur's optical systems dwindled. Just as Galileo had, these scientists faced the exhaustion of potential targets for observation as their observational systems began to brush up against the limits imposed by atmospheric conditions. Babcock (1953) first proposed a method to compensate for the distortions in the light passing through our atmosphere: his entirely theoretical contribution was brought about by musing on the then-emergent automatic telescope guidance systems discussed above, which focused, not so much on resolving the distorted star image itself better, but rather on keeping it fixed in the center of the photographic plate better than a human operator might (Hardy 1998, 5-7). These systems were designed to correct *human* error; Babcock wanted to correct *natural* error.

Stars appear to twinkle because of the impact of atmospheric turbulence on their light. One might conceptualize the light emitted by a star as expanding in an ever-greater emission sphere; over the many light-years between the star and our optical systems, this sphere has expanded to the point where, even to our most sensitive space-based instruments, the light waves are indistinguishable from a flat plane. These incoming, successive, flat waves, however, are degraded and bent, as "turbulence in the Earth's atmosphere produces inhomogeneities ... which affect the image quality of ground-based telescopes" (Roddier 1999, 3). Because these inhomogeneities are neither spatially nor temporally consistent, the waves hitting a given optical system are neither flat *nor* statically disrupted; each successive wave is scrambled in a different pattern from the wave before, preventing a "set it and forget it" approach to image correction. These disruptions, particularly when studying particularly faint or distant stars, make considerable noise on the photographic plate or CCD used to image them. Babcock's novel suggestion contained the same three essential components characteristic of modern adaptive optical systems:

> a wave-front corrector, a wave-front sensor, and a control system. They operate in a closed feedback loop. The wave-front corrector first compensates for the distortions of the incoming wave fronts. Then part of the light is diverted towards the wave-front sensor to estimate the residual aberrations which remain to be compensated. The control system uses the wave-front sensor signals to update the control signals applied to the wave-front corrector. As the incoming wave-front evolves, these operations are repeated indefinitely. (Roddier 1999, 25)

Unfortunately, when he proposed it, Babcock's plan was not feasible for technological reasons: even if an optical system capable of changing shape rapidly and accurately were to have been built by sheer force of will and post-war American technological ingenuity, the computing speed needed to calculate the necessary correction to the wave-front in real time remained unthinkable for at least the next two decades. As mentioned above, the early computers used in astronomy were primarily for postdetection image processing and "clean-up" (Roddier 1999). By the 1970s, however, there was a felicitous conjuncture of a precipitous increase in available computing power and a pressing strategic need for adaptive optics, which John Hardy found himself in an excellent position to take advantage of:

> In 1972, the Advanced Research Projects Agency (ARPA), whose mission was to develop new technology for the U.S. Department of Defense, was wrestling with the problem of identifying newly launched Soviet satellites.... At that time, the only method of space object surveillance from the ground was to obtain short exposure images of the space objects ... and then to process the somewhat fuzzy images digitally to bring up the desired detail. This post-detection processing technique did not give useful results [because of] image degradation produced by atmospheric turbulence. (Hardy 1998, 16)

Itek, the military contractor where Hardy worked in the early seventies, sponsored Hardy's proposal to ARPA in November 1972, where he suggested that they might solve this problem by developing an adaptive optics system (see Hardy 1998 16-24). ARPA began funding Hardy's work at Itek, and within two years, Hardy and his colleagues had produced the first adaptive optics system capable of sharpening images in real time (Roddier 1999). The technical accomplishment that this represented must be emphasized; while deformable mirror technology had already been substantially improved from 1950s levels, largely due to military research on IR laser transmission (Hardy 1998), digital computing technology was still incapable of keeping up with the necessity of performing some 1,000-odd wave-front adjustment calculations per second. Hardy's solution was remarkable: he built an analog computer from scratch, in which "electric currents representing the wavefront slopes were added in a two-dimensional resistor network having the same configuration as the subapertures in the wavefront detector" (Hardy 1998, 18). It is hard to overstate how ingenious this solution was. As part of the system's feedback loop, it merely converted the wave into another form and convoluted it with an ideal wave, inverted it, and relayed the corrected wave to the mirror actuators in the form of electrical impulses, the magnitude of which at any point along the wave indicated the amount of correction to be applied to the corresponding segment of the mirror.

In any event, Hardy's system worked, and worked well; the Department of Defense was able to use his system at Itek, as well as a later system installed at the Air-Force Maui Optical Site (AMOS) on Haleakala, to produce stunningly clear images of Soviet satellites. The system at AMOS remained the largest AO system well into the nineties. Although I have not been able to corroborate this elsewhere in the literature, according to Roddier, "by the end of the 1970s, AO systems were widely developed by industry for defense applications" (1999, 3). That said, there is a record of substantial defense research into the improvement of adaptive optic systems through the 1980s, primarily focusing on the use of laser beacons to create a light source bright enough to calibrate the wave-fronts in real time while tracking or imaging objects in a field of the sky devoid of bright stars. This application is clearly of great strategic utility, but also scientific; in "1991, after the political changes in Russia, the U.S. National Science Foundation … convinced government authorities of the importance of the technique to astronomy, and obtained its declassification" (Roddier 1999, 5). As is wont to happen, deprived of large defense grants, the Laser Guide Star concept was slow to make a material appearance within astronomy, in 1995 (Léna 2010, 325).

The technical literature is in agreement that even after forty-odd years of development, adaptive optics is still firmly on the side of science in the making. Nevertheless, the efficiency literature produced by astronomers and science managers anticipates its prominence on the basis of the leaps in performance which even rudimentary AO systems provide to already established telescopes. Léna's quantitative survey of telescope performance finds that in addition to the well-established correlation between collecting area and citational impact described by Benn (2002), the inclusion of more recent data demands the incorporation of the relative sophistication of the adaptive optics used at a telescope into the model predicting citation impact. His statistical survey indicates that "the progress in performances is related primarily to the number … of actuators of the active mirrors, which has increased from 10 to 10^3 [since 1982], but also to the loop correction frequency and the sensitivity of the wavefront sensors" (Léna 2010, 323). For his part, Hardy seems to view the ever-increasing sophistication and soundness of adaptive optics systems as a given. He argues that astronomers hired as consultants for future adaptive optics projects ought keep in mind the fact that "the practical utility of adaptive optics depends greatly on the presence of a convenient and user-friendly interface with the telescope operator" (1998, 76). In keeping with the general trend outlined here towards ever greater automaticity in observational systems, his urging for those engaged in building the next generation of AO systems is to "minimize the need for operator inputs by making the system autonomous" (1998, 76). It is here that I will end my biography of astronomical things, however roughly sketched, and move into a more analytic mode; with adaptive optics just at the threshold of thorough black-boxing (Latour 1987), right at the point of their collapse from the epistemic regime into the technical (Rheinberger 1997).

V. Conclusions

The discussion above has centered on chronicling the genesis and unfolding of the astronomical sciences proper, the emergence of astronomers as a professional class distinct from other star-gazers, and the development of the observational systems by which they produce novel articulations of the real. I have attempted to demonstrate how "within these complex, tinkered, and hybrid settings of emergence, change, and obsolescence" that are experimental—or, in this case, observational—systems, "scientific objects continually make their appearance and eventually recede into technical, preparative subroutines of an ongoing ... manipulation" (Rheinberger 1997, 21). I would like now to return more explicitly to the concerns with which I initially framed my discussion in order to draw out more thoroughly the implications of this study for our understandings of the role and nature of human cognition and perception in the assembly and evolution of scientific systems.

In Rheinberger's view, the field of scientific endeavor, "which is irrevocably local and situated in space and time," is populated by "scientific objects and the technical conditions of coming into existence, ... differential reproduction of experimental systems, ... conjunctures of such systems, and graphematic representations" (1997, 21). The cognition embodied in these experimental systems is characterized by "a kind of movement oriented and reoriented by generating its own boundary conditions, within which reasoning displays itself as a dynamic interaction between material entities swept off by tracing" (Rheinberger 1997, 20). The distributed or situated cognition which acts as the motor driving the repetition and elaboration of the potentials of a given experimental system cannot engage with the real *qua* Nature, but must traffic in recombinations and articulations of what remain, in his view, essentially inscription devices and the limited concrescences of material signification which they produce. This is very different from Barad's monist suggestion that "apparatuses are not inscription devices," but rather are "dynamic reconfigurings of the world, specific agential practices/intra-actions/performances through which specific exclusionary boundaries are enacted" (formatting removed, 2003, 816). Following Rheinberger, and not Barad, I suggest that when astronomers point their telescope at a distant, epistemic object, one not yet *meaningful,* but merely *resistant*, they are not part of "a flow of agency through which 'part' of the world makes itself differentially intelligible to another 'part' of the world," although they may well be stabilizing and destabilizing "local causal structures, boundaries, and properties" (Barad 2003, 817). It seems to make both analytic and ontological sense to retain the distinction between apparatuses and phenomena, however much the two are imbricated, *particularly* when discussing observational rather than experimental systems. C*ontra* the "agential realist elaboration" of Barad's critique of the focus on representation rather than creation of phenomena in the scientific process, I suggest that it is a *fact* that the fuzzy blot on the CCD plate is *not* an "ontologically primitive relation" (Barad 2003, 815) between machine and galaxy cluster.

This is to say that what renders the image coherent is not its "vertical relation to a hidden referent" but rather its status as a highly overdetermined product of an inestimably dense "horizontal concatenation, both in time and space" of experimental, observational, and theoretical systems (Rheinberger 1997, 137). It is in this concatenation, and the mode of incorporating the as-yet-unknown into the very heart of its system, that the observational apparatus is most closely homologous to the experimental system. Admittedly, astronomers do not *create* the epistemic objects with which the technical things in their systems interact; they do, however, engage in the *exact* same kind of graphematic articulations of the real. These graphemes *are* in fact the real motor of their forward movement, not the unfolding of the universe as it comes to know itself. For the experimental system, "nature as such is not a referent … it is rather a danger," (Rheinberger 1997, 109) insofar as its impurity threatens the extraction of specific measurements of the epistemic object's *resistance*. In order to be able to interact with *other* graphematic articulations, "and, what is most important, not only [with] those from which they have originated," inscriptions must present themselves in the form of "durable and mobile purifications," capable of circulating and combining with other experimental systems' technical and epistemic objects alike (Rheinberger 1997, 105). It is this *latter* combinability that most clearly indicates the "reality" of the manufactured, graphematic purification: our scientists "do not read the book of nature, they do not depict reality. But they do not construct reality either. In configuring and reconfiguring epistemic things, scientists meet with resistance, resilience, recalcitrance, not anything goes" (1997, 225).

It is because "not anything goes" that astronomers strive after ever better observational and imaging systems. If their tracings are to interact felicitously with those produced by other observational systems, they must be at least as closely tied to the epistemic objects which are their object-cause; ideally, of course, they would be *more* closely tied. As Lynch points out, with the blissful honesty—all-too-often mistaken as naiveté—characteristic of the writings making up the early wave of what was to become an anthropological approach to science and technology studies, "artificial features of visual displays are sometimes blamed for illusions, misrepresentations or distortions, but in fields such as electron microscopy the artificial appearance of a specimen is what enables it to be observed and analyzed in the first place" (1985, 38). Perhaps it should not be regarded as epistemologically suspect to say that better instruments allow us to trace more of the world, and to trace that with great accuracy, if not exactitude.

My argument is not that we enter into an entirely new realm of the visual, as such, here; rather, it is that observational systems designed to create purified inscriptions of the very small, as the very large or very distant, must bring the invisible into the visible. It is the work of astronomy to render objects into pictures which measure, through their traces, the resistance posed by epistemic things. That we have taken these traces as reliable cannot be understood on the basis of some inherent quality in the image which would speak for itself; nor, however, is it *quite* that the astronomer *qua* professional is able to deploy his professional status and networks of allies in order to convince us. Instead, it can only be understood by virtue of the place of these images within a vast, elaborated, ever mutating and evolving concatenation of epistemic and technical objects; it has taken quite a lot of work to create optical systems that produce images "more real" than those impressed upon the human retina. It is true that "a profession carries with it an array of perceptual and cognitive operations that have far reaching impact [on] cognitive work ... but the parameters of that work have been established by the system that is organizing their perception" (Goodwin 1994, 609). This historically constituted architecture of perception does not reside in a subject, however "constructed" by its historical givenness. Rather, it is engendered by "a much larger organizational system," including such basics as established best-practices for the limits on postdetection image processing and error reduction, on the one hand, and "the use of appropriate artifacts" such as adaptive optics on the other (Goodwin, 1994, 609). These latter have only become part of the architecture of modern observational systems, and, as such, of modern astronomical perception, as they have moved from the position of an epistemic object, within a military experimental meta-system, to that of a technical object within the astronomical sciences.

As an anthropologist, I am interested in the analysis of both human subjectivities and their imbrication in sociocultural processes. As such, in order to describe this conjuncture as it plays out in the modern science of astronomy, I have turned to an investigation primarily of objects, both epistemic and technical. This has been at the risk, however, of rendering the subject itself apparently inconsequential. It is important to remember that the universe does not build telescopes by itself: all the "resistance" in the world cannot yet produce the self-surpassing of boundary conditions needed to turn epistemic objects into technical ones. That movement requires the genuine *interaction* of the subject with a wide variety of experimental, observational, and technical systems. I follow Suchman in suggesting that we observers of techno-science must "respecify sociomaterial agency from a capacity intrinsic to singular actors to an effect of practices that are multiply distributed and contingently enacted" (2007, 267). Indeed, her work on the situated cognition characteristic of human action as mediated through a technological ensemble dovetails quite thoroughly with Rheinberger's notion of the experimenter as only extimately related to his or her system. It is precisely this mode of cognition that *allows* for the creation of novelty through repetition, as ever-finer webs of traces are drawn around epistemic objects *by the experimental system as of its own accord*, fostering "a continuous generation of new phenomena, which need not have anything to do either with the preceding assumptions or with the presupposed goals" of the scientist (1997, 21). From the twinned observations that "we can take the interface not as an a priori or self-evident boundary between bodies and machines but as a relation enacted in particular settings and one, moreover, that shifts in time" (2007, 267) and that "the constitution of humans and artifacts does not occur in any single time and place, nor does it create fixed human-artifact relations as entities" (2007, 268), Suchman draws the conclusion that any sort of macro-scalar investigation of the contours of these relations is a hopeless endeavour. On the contrary, I argue that the self-same historical conditions that have given rise to the particular imbrication of human subjectivity, cognition, and perception with the machines making up adaptive optics systems have allowed both Suchman and me to analyze them as such.

This paper has not been an attempt, however, to "bring the human out from behind the curtain ... without disenchantment" (Suchman 2007, 285). For the foreseeable future, human scientific cognition is inextricably bound to the material apparatus which constitutes its investigative system. If the "high artistry" of the era of big telescopes remains, it lies not in virtuoso discoveries made by "pointing the telescope at someplace new and hoping for a discovery based on serendipity and instinct" (McCray 2010, 84). Rather, it lies in the ability of the investigators to establish and maintain their system at the very limits of its coherence and dissolution, to regulate the proper admixture of technical and epistemic objects, and to perform the vital feedback functions that maintain its iterable connection to the broader world of scientific endeavor through the specifically human functions of collation, articulation, and circulation. To reintroduce an enlightenment Man into this vertiginous scene of our machines'—and they *are* ours—perpetual collapse into the future would be worse than banal political nostalgia; it would be to ensure that the social study of technology surrenders all claims to a place in this future.

Ian Lowrie
Department of Anthropology
Rice University
6100 Main MS-27,
Houston, TX 77005
USA
il4@rice.edu

REFERENCES

Babcock, Horace. 1953. The Possibility of Compensating Astronomical Seeing. *Publications of the Astronomical Society of the Pacific* 65(386):229.

Barad, Karen. 2003. Posthumanist Performativity: Toward an Understanding of How Matter Comes to Matter. *Signs: Journal of Women in Culture and Society* 28(3):801-831.

Benn, Chris. 2002. Scientific Impact of Large Telescopes. In *Organizations and Strategies in Astronomy III,* ed. André Heck, 85-94. London: Kluwer Academic Publishers.

Bennet, Jim. 2010. The Era of Newton, Herschel, and Lorde Rosse. In *400 Years of Astronomical Telescopes: A Review of History, Science and Technology,* eds. Bernhard Brandle, Remko Stuik, and Jeannette Katgert-Merkelijn, 31-40. N.p.: Springer Science+Business media.

DeVorkin, David. 2010. In the Grip of the Big Telescope Age. In *400 Years of Astronomical Telescopes: A Review of History, Science and Technology,* eds. Bernhard Brandle, Remko Stuik, and Jeannette Katgert-Merkelijn, 61-75. N.p.: Springer Science+Business media.

Goodwin, Charles. 1994. Professional Vision. *American Anthropologist* 96(3):606-633.

Golay, Marcel. 2001. Strategies for 21st-Century Astronomy. In *Organizations and Strategies in Astronomy II,* ed. André Heck, 9-28. London: Kluwer Academic Publishers.

Hardy, John. 1998. *Adaptive Optics for Astronomical Telescopes.* New York: Oxford University Press.

Høg, Erik. 2010. 400 Years of Astrometry: From Tycho Brahe to Hipparcos. In *400 Years of Astronomical Telescopes: A Review of History, Science and Technology,* eds. Bernhard Brandle, Remko Stuik, and Jeannette Katgert-Merkelijn, 223-238. N.p.: Springer Science+Business media.

Janesick, James, and Morley Blouke. 1987. Sky on a Chip: The Fabulous CCD. *Sky & Telescope* 74(3) (September): 238-242.

Latour, Bruno, and Steve Woolgar. 1986. *Laboratory Life: The Construction of Scientific Facts.* Princeton, NJ: Princeton University Press.

Latour, Bruno. 1985. Visualization and Cognition: Drawing Things Together. Knowledge and Society: Studies in the Sociology of Culture and Present 6: 1-40. citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.115.5725&rep=rep1&type=pdf

Latour, Bruno. 1987. *Science in Action: How to Follow Scientists and Engineers in Action.* Cambridge, MA: Harvard University Press.

Léna, Pierre. 2010. Adaptive Optics: A Breakthrough in Astronomy. In *400 Years of Astronomical Telescopes: A Review of History, Science and Technology,* eds. Bernhard Brandle, Remko Stuik, and Jeannette Katgert-Merkelijn, 317-330. N.p.: Springer Science+Business media.

Livingstone, David. 2003. *Putting Science in its Place: Geographies of Scientific Knowledge.* Chicago: University of Chicago Press.

Lynch, Michael. 1985. Discipline and the Material Form of Images: An Analysis of

Scientific Visibility. *Social Studies of Science* 15(3): 37-66.

Lynch, Michael. 1988. The Externalized Retina: Selection and Mathematization in the Visual Documentation of Objects in the Life Sciences. *Human Studies* 11(2-3): 201-234.

McCray, Patrick. 2010. 'Beautiful and Cantankerous Instruments': telescopes, technology, and Astronomy's Changing Practice. In *400 Years of Astronomical Telescopes: A Review of History, Science and Technology,* eds. Bernhard Brandle, Remko Stuik, and Jeannette Katgert-Merkelijn, 77-87. N.p.: Springer Science+Business media.

Rheinberger, Hans-Jorg. 1997. *Toward a History of Epistemic Things: Synthesizing Proteins in the Test Tube.* Stanford: Stanford University Press.

Robson, Ian. 2001. New Strategies in Ground-Based Observing. In *Organizations and Strategies in Astronomy II,* ed. André Heck, 121-138. London: Kluwer Academic Publishers.

Roddier, François. 1999. *Adaptive Optics in Astronomy.* Cambridge: Cambridge University Press.

Roy, Jean-Rene, and Matt Mountain. 2006. The Evolving Sociology of Ground-Based Optical and Infrared Astronomy at the Start of the 21st Century. In *Organizations and Strategies in Astronomy Volume 6,* ed. André Heck, 11-38. London: Kluwer Academic Publishers.

Shapin, Steven. 1988. The House of Experiment in Seventeenth-century England. *Isis* 79(3): 373-404.

Shortridge, Keith. 2001. Astronomical Software Strategies. In *Organizations and Strategies in Astronomy II,* ed. André Heck, 163-178. London: Kluwer Academic Publishers.

Smith, Robert, and Joseph Tatarewicz. 1985. Replacing a Technology: The Large Space Telescope and CCDs. *Proceedings of the IEEE* 73(7): 1221-1235.

Suchman, Lucy. 2007. *Human-Machine Reconfigurations*, 2nd ed. Cambridge: Cambridge University Press.

Van Helden, A. 2010. The Beginnings, from Lipperhey to Huygens and Cassini. In *400 Years of Astronomical Telescopes: A Review of History, Science and Technology,* eds. Bernhard Brandle, Remko Stuik, and Jeannette Katgert-Merkelijn, 1-14. N.p,: Springer Science+Business media.