Scientific observation is determined by the human sensory system, which generally relies on instruments that serve as mediators between the world and the senses. Instruments came in the shape of Heron’s Dioptra, Levi Ben Gerson’s Cross-staff, Egnatio Danti’s Torquetto Astronomico, Tycho’s Quadrant, Galileo’s Geometric Military Compass, or Kepler’s Ecliptic Instrument. At the beginning of the seventeenth century, however, it was unclear how an instrument such as the telescope could be employed to acquire new information and expand knowledge about the world.

To exploit the telescope as a device for astronomical observations Galileo had to:

1. establish that telescopic images are not optical defects, imperfections in the eye of the observer, or illusions caused by lenses;
2. develop procedures for systematically handling errors that may occur during observation and measurement and methods of processing data.

Galileo made it clear that in order to measure and interpret natural phenomena accurately, a suitable method and instrument would need to be developed. It is intriguing, therefore, to regard the Galilean telescope in this light and to discover the linkage established by Galileo among theory, method, and instrument—the telescope. Although the telescope was not invented through science, it is instructive to see how Galileo used optics to employ a theory-laden

An earlier version of this paper was read at the fifth biennial History of Astronomy Workshop, University of Notre Dame July 5–8, 2001. I would like to thank the participants of this meeting for their advice. I would like to thank two anonymous referees for their thoughtful comments. In particular I express my gratitude to Giora Hon for his help and encouragement.
instrument for bridging the gulf between picture and scientific language, between
drawing and reporting physical facts, and between merely sketching the world and actually describing it.

Introduction

In a letter, from 1611, addressed to the Jesuit mathematician Blancanus, Galileo wrote: “How then do we know that the moon is mountainous? We know it, not simply by the senses, but by copying and combining up discourse with observation and sensory appearances.” R. Feldhay argued that “Galileo’s usage of the word discourse (discorso) is intriguing. Galileo emphasized the interdependence between observation and scientific language. In Galileo’s texts, the term discorso acquired the meaning of rational (linguistic) practice. Facts are not known by simply being observed . . . Observation is always mediated by arguments” (Feldhay 1995, pp. 119–120). As such, Feldhay suggested three categories of practice through which Galileo’s scientific discourse can be analyzed. The first is concerned with the constitution of the scientific object. The second relates to the construction of boundaries by which Galileo attempted to differentiate his discourse from other systems of knowledge in the same cultural field, especially the mixed mathematics practiced by his Jesuit interlocutors. The third, by which Galileo’s discourse was differentiated, involves techniques of establishing the speaker authority, in this case the authority of a philosophical astronomer (Ibid., p. 121). Feldhay’s contention is that “science is basically a discourse. This does not mean that science is only a discourse. Science has its own strategies for treating natural objects, within a well-defined discursive space, and by certain authorized speakers” (Ibid.). To meet these criteria, Galileo must have been more than just better at observation and mathematical reasoning than his colleagues.1

Astronomical instruments and the advent of the telescope

Detecting a phenomenon is a problem of getting a signal in a sea of noise. It is also a problem of identifying a relatively stable and invariant pattern of some simplicity and generality with recurrent features, which is not just

1. The scientific instrument, in this case the telescope, will constitute a primary element in my discussion. Without engaging, at this stage, in a discussion of whether Galileo was an apriorist or an empiricist, clearly the telescopes he constructed were not abstract objects. People, even professionals, think that Galileo fumbled along in the development of the telescope because he did not provide us with a text, like Kepler’s Dioptrice, that spells out its theory. As argued elsewhere (Zik 1999; Zik 2002), I suggest to “read” the telescope as a text and to show that its development and application cannot evolve without a theory. Since I am “reading” an instrument (not in the sense of taking measurements but spelling out its theory and understanding), there is no escape but to use modern terminology and self-aware anachronism.
an artifact of the particular detection techniques we employ or local environment in which we operate (Woodward 1989, pp. 396–397). As reflected through the long traditions of astronomy as a mixed mathematical science (dealing with celestial phenomena by mathematical methods of investigation), observation was a crucial factor in the constitution of a scientific object. Scientific observation is determined by the human sensory system, which generally relies on instruments that serve as mediators between the world and the senses. Astronomical instruments of greater or lesser sophistication constituted an integral part of the practice of the science of astronomy. These instruments were essentially based upon three pillars:

1. The visual ray in its transformation into the line of sight, which enables one to describe objects in space geometrically.
2. Geometrical formulations (lines, arcs, triangles) which were used to define the relation between the object and the observer.

2. For a background discussion on the distinction between data and phenomena and the implication of these aspects on issues concerning explanation, testing, and theory-structure, see Woodward et al. (1988, pp. 303–352). The distinction between mere observation and theory-laden observation is an ongoing source of controversy in the philosophy of science. The boundaries of this epistemological debate about the objectivity of science may be marked as follows: On the one hand, direct observational data are described by an ‘observational sentence’, which refers to certain observable properties and relations of a given object. It enables one to formulate an ‘empirical criterion of meaning’ by which observation data are neutral and free from influences of the observer’s conceptual system. On the other hand, difficulties deriving from the cognitive limitations of the human sensory system introduce the need for correcting errors of perception. Thus, observation practice and its outcomes in the form of ‘observational sentences’, by themselves, are theory-laden operations which are certainly far from neutral.


4. At that time a phenomenon was considered as a celestial behavior or appearance that was immediately obvious to the causal observer. An observation was a piece of empirical knowledge that could only be created through the use of instruments and calculatory techniques available to the expert astronomers (Dear 1995, pp. 49, 54, 97–100).

5. In the first book of *Perspectiva*, Witelo defined sixteen geometrical formulations upon which he developed his optical arguments. Unguru listed those definitions as: “pole, convex, and concave line or surface, perpendicular line to a convex or concave surface, intersecting circles, great and small circles of a sphere, equal spheres, parallel spheres or circles, tangent spheres, intersecting spheres, tangent plane surface to a sphere, denomination of a ratio, and compound ratio” (Unguru 1987, p. 271).
3. Mathematical operations by which those relations were converted into physical measurements such as distance, height, and apparent angle.

Being designed and built in correspondence with abstract theoretical definitions, which were transformed into the technological realm according to formulations derived from geometry and arithmetic, these devices were regarded as the ‘mathematical instruments’ of the time. They came in the shape of Heron’s Dioptra, Levi Ben Gerson’s Cross-staff, Egnatio Danti’s Torquyetto Astronomico (Danti 1578, p. 223), Tycho’s Quadrant, Galileo’s Geometric Military Compass, or Kepler’s Ecliptic Instrument. The restricted capabilities of these instruments due to errors resulting from flaws in design, manufacturing techniques, and incorrect usage limited the potential for obtaining accurate astronomical knowledge.

---

6. In his Conversation Kepler described a projection device he used in order to “Admit the light of the moon through an aperture to a sheet of paper mounted on a rod. The aperture will be fitted with a crystal lens curving spherically from a circular edge. The paper will be adjusted to the focus of the rays. In this way, with a rod 12 feet long, a perfect image of the body of the moon will be obtained the size of a large silver coin. I explained the device in Proposition 23 on page 196 of my book [Paralipomena] and on page 211. But a simpler form was suggested by Della Porta in the first article of Chapter VI [In Natural Magick book 17], where he introduced a lens, whereas I dealt with an entire sphere” (Rosen 1965, p. 23). Della Porta’s suggestions were quite elaborated. The passage Kepler had referred to can be read in Della Porta (1658, pp. 363–365).

7. By the adaptation of diagonal scales to the limb of his astronomical instruments, Tycho could read small fractions of a degree without enlarging the physical dimensions of the instrument beyond the handling of a single observer; he thus produced a compact and stable instrument. Tycho’s improved sights installed in his sextants and quadrants made it
Theory, method and instrument—the Telescope

In Paralipomena Kepler argued that:

All practicing astronomers complain that it is with difficulty that they [images of heavenly bodies] are measured. This is partly because the bodies have a very narrow apparent size, and partly because they constrict the eye with their exceptional light, so as to prevent their fulfilling their function in seeing (Donahue 2000, p. 16).

Galileo too was aware that the angles formed by the rays issuing from the rim points of a heavenly body are extremely acute, "as if these angles were absolutely imperceptible and nonexistent" (Drake 1967, p. 286). Therefore, Galileo continued, to produce cogent observational results,

Astronomers and mathematicians have discovered infallible rules of geometry and arithmetic . . . Then if the rules depending upon geometry and arithmetic are correct, all the fallacies and errors that might arise in attempting to determine the altitude of new stars, or comets, or the like, would have to depend upon improper measurements . . . [Therefore], all the differences that are seen . . . depend not upon any defect in the rules of calculation, but upon errors made in determining those angles and distances by instrumental observations (Drake 1967, pp. 286–287).

Hence, instruments capable of measuring angles more accurately than ever before were needed, and Kepler and Galileo, like their colleagues, were trying to improve their equipment. It is not surprising, therefore, to read Kepler’s response to the employment of the telescope, as described by Galileo in Sidereus Nuncius:

Now so far as its use is concerned, you have certainly discovered an ingenious method of ascertaining to what extent objects are magnified by your instrument, and how individual minutes and

possible to eliminate alignment errors, which he claimed were as large as one-eighth of a degree (7.5 arc minutes) on the instruments of Copernicus (Chapman 1996, II: pp. 133–135, III: pp. 70–76). Kepler argued in Astronomia Nova that instruments of the time could err by three minutes as a result of improper construction and positioning (Donahue 1992, p. 201). Chapman concluded that by the end of the sixteenth century, the artisan’s skills actually determined the qualities of the graduation scales and the sights of the instruments. However, the mean accuracy of the best-constructed instruments, due to the difficulties at the operational level, was around 1 arc minute (Chapman 1996, II: p. 134). Note that 1 arc minute will comprise the height of 29 cm at a distance of 1000 m. As we shall see later, by 1612, with the micrometer, Galileo made a leap in improving the mean accuracy of his measurements to 10 arc seconds (4.8 cm at 1000 m).
fractions of minutes can be discerned in the heavens (Rosen 1965, p. 21).

In his careful reading of Sidereus Nuncius, Kepler did not avoid the link established by Galileo between the theory behind the telescope and the instrument’s usage (Rosen 1965, p. 15). Addressing the way Galileo used the telescope with the investigation of natural phenomena, Kepler wrote:

What you say, then, is correct and in full accord with mathematics. In your discussion of the spots first noticed by you in the bright region of the moon, you show in thorough optical analysis of the illumination that they are hollow or sunken cavities in the body of the moon (Rosen 1965, p. 24). 8

Having understood that “sorting out differences about data, evidence, observation, may require more than simply gesturing at observational objects” (Hanson 1965, p. 19), Kepler continued:

For you have established most firmly by brilliant observation in full accord with the laws of optics that many peaks tower above the body of the moon, throughout the bright region, especially in the lower portion. Like the loftiest mountains on our earth, they are the first to enjoy the light of the sun as it rises for the moon, and are thereby revealed to you when you make use of your telescope (Rosen 1965, p. 25). 9

The recognition of Galileo’s discoveries in telescopic astronomy carried further implications. The use of instruments is not transparent, but usually involves the issue of ‘authority’ and depends on audiences. 10 The establishing of real material objects indicating true celestial appearances does not follow automatically from mere observations. A detailed description of the mode of observation, the material means available, the correct way of using the instrument and the method of minimizing possible errors in the process are an integral part of this practice. It is essential to substantiate the new ‘facts’ in full accord with mathematics, and thorough optical analysis in full accord with the laws of optics (Drake 1957, pp. 29, 44–45; Rosen 1965, pp. 21, 24, 25; Caspar et al. 1937, Vol. 4: 296).

With the instrument, the method of observation, and observational data

10. For a discussion on the meaning of scientific authority, how the truth of observational data was validated and presented to the public at that time, see Van Helden et al. (1994a, pp. 1–6); Van Helden (1994b, pp. 9–29); Smith R. W. (1997, pp. 49–56).
at hand, the particular techniques of representing and interpreting the results could be obtained.

Galileo’s authority was established not because once experiment was introduced into the practice of science as an appropriate scientific method, technologies rushed into science in the form of instruments. Galileo’s practices encapsulated different kinds of knowledge into an integrated instrument, which mediated the interaction between science and technology. The telescope presented a complex field of knowledge in which various theories and practices met. The telescope also acted as a ‘buffer zone’ (ideal reality) located somewhere between what is called today laboratory effects and technological artifact. Kepler himself evinced this kind of awareness in *Paralipomena* when considering mathematical order, logical simplicity, and the concept of error as regulative guidelines for scientific investigation and instrument construction (Rosen 1965, pp. 11, 13; Hon 1987, pp. 581–584, 589–591).

11. These aspects are well illustrated through the modifications that Galileo introduced into his manufacturing procedures and telescopes (as well as other instruments) which were derived from analyzing the various ‘impediments’ involved. By modifying and testing the optical system, a solution was found for all the problems defined by Galileo (Zik 1999, pp. 34, 42, 45–47, 60–67; Zik 2002).

12. In this respect Koyré did not “believe in the explanation of the birth and development of modern science by the human mind turning away from theory to praxis” (Koyré 1956, p. 12). While addressing Crombie’s argument regarding the roots of modern science which, according to Crombie, is “fundamentally and essentially in its methodological and philosophical inspiration, a medieval invention” (Ibid., p. 2), Koyré wrote: “Crombie’s own history of medieval optics seems to me to confirm my contention of the far-reaching independence, at least up to the development of scientific technology—a quite recent phenomenon of practical and theoretical achievement. It is possible, of course, although extremely improbable that the unknown genius who invented eyeglasses was led by theoretical considerations; it is certain, on the other hand, that this discovery did not have any effect upon the development of optical theory; whereas the latter, despite the boasts of Roger Bacon, did not give birth to optical technology and the construction of optical instruments. In the seventeenth century, on the other hand, the invention of the telescope was followed by a new optics and a new praxis” (Ibid., pp. 12–13). According to Koyré, modern sciences derived from a radical change of philosophical paradigms. As such, the Aristotelian view of nature, bound to sense perception and to everyday life concepts was replaced by a mathematical one in the tradition of Plato (Lefèvre 2000, pp. 281–284). Or, as N. Jardine put it, Koyré’s central tenets concern the priority of theory over experiment and observation, of intuition over method, of Plato over Aristotle, in the endless striving of the sciences towards truth (Jardine 2000, p. 365). But, “with the accelerating turnover of historiographical fads and fashions in the history of sciences” (Jardine 2000, p. 373), a new optics and a new praxis in the realm of astronomical instruments could not appear unless a new system of thought has been developed. Theory, observation, observational error, practical needs (in the shape of certain devices), intuition, ‘wrapped’ in a well-defined method regarded as prototypes of experimental arrangements, were taken to the test bench from which modern science emerged.
At the beginning of the seventeenth century, however, it was unclear how an instrument such as the telescope could be employed to acquire new information and expand knowledge about the world. To exploit the telescope as a device for astronomical observations, Galileo had to:

1. establish that telescopic images are not optical defects, imperfections in the eye of the observer, or illusions caused by lenses; 13
2. develop procedures for systematically handling errors that may occur during observation and measurement and methods of processing data.

In this respect, Galileo wrote:

In order to determine the magnifying power of an instrument, trace on paper the contour of two circles or two squares of which one is four hundred times as large as the other . . . Then, with both these figures attached to the same wall, observe them simultaneously from a distance, looking at the smaller one through the telescope and at the larger one with the other eye unaided . . . The two figures will appear to be of the same size if the instrument magnifies objects in the desired proportion (Drake 1957, p. 30).

This paragraph is very interesting for what is omitted. Galileo, while looking through the telescope, does not describe several things that surely could not have escaped his observation. Looking at the same target that Galileo describes, the same way he did, we see that the geometrical shapes do overlap. Moreover, it is easily observed that some lens combinations highly distort and blur the image compared with that observed with the unaided eye, while others have better qualities. Similarly, Galileo could easily see that the whole process was dependent on proper placing and alignment of the lenses on an optical axis, since any deviation from that axis would increase the image blurring and colored patches. Aperture stops of various diameters and shapes could also be systematically fitted to the objective lens to reduce the effects of the accidental rays. 14

13. The need for a perfect telescope which would show all objects bright, distinct, and free from any obscurity was announced in Sidereus Nuncius (Galileo 1610, p. 7). In Letter On Sunspots Galileo argued that before determining something about the true nature of the sunspots it was essential to establish that the spots were not telescopic illusions or optical defects (Drake 1957, p. 91). “E prima, che esso siano cose reali, e non semplici apparecche o illusioni dell’occhio o de i cristalli” (Favaro 1890–1909, Vol. V: 95).
14. A simulation of a bright star image, as seen through Galileo’s x14 telescope (see Figure 2), gives us a visual demonstration of how the diaphragm that Galileo used to improve the resolution of his telescopes worked. The left figure shows the image seen while stopping down the aperture to 26 mm, just like Galileo did. Without a diaphragm, as
The ability to evaluate image degradation provided Galileo with empirical criteria for evaluating the lens quality. Galileo analyzed the telescope in geometrical and arithmetical terms:

Let ABCD be the tube and E the eye of the observer. When there are no glasses in the tube, the rays proceed to the object FG along the straight lines ECF and EDG, but with the glasses put in they proceed along the refracted lines ECH and EDI. They are indeed squeezed together and where before, free, they were directed to the object FG, now they only grasp the part HI. Then, having found the ratio of the distance EH to the line HI, the size of the angle subtended at the eye by the object HI is found from the table of sines (Van Helden 1989, pp. 38–39).

Clearly, by using an observational target for testing the telescope, with and without lenses in the tube, Galileo was able to trace precisely the path of light rays along the instrument. That way, he learned how the introduced lenses affected the magnification and field angle of the telescope and was able to calculate them accurately (Zik 1999, pp. 46–51, 64).

From the very beginning of his telescope enterprise, Galileo considered the telescope not only an instrument capable of revealing enemy ships and the mysteries of the heavens, but also a measuring and experimental device.15 Galileo’s first direct reference to a kind of micrometrical scale at-

15. In *Two new Sciences* Galileo wrote, “The inconclusiveness of these and like observations caused me once to think of some way in which we could determine without error
tached to the telescope as a measuring device was made on January 31, 1612 (Drake et al. 1980, pp. 52–54). However, Galileo’s account in *Sidereus Nuncius* clearly shows that he was aware of the telescope’s capacity as a measuring device at the very beginning of his telescopic enterprise (Van Helden 1989, pp. 38–39; Zik 1999, pp. 52–53). A telescope with a cross hair micrometer requires a real image that is produced by a Keplerian telescope. Nevertheless, Galileo was able to think of and to devise a micrometric instrument that worked reasonably well with his telescope (Drake et al. 1980, p. 54). 16 Galileo attached a movable grid to the telescope tube in such a way that one eye looked through the telescope and the other through the grid (figure 4). That is, if one looked with the unaided eye at the grid attached to the telescope, the image of Jupiter and its satellites, as seen through the telescope is optically superimposed by the image of the grid. Moving and rotating the grid back and forth along the tube made it possible to adjust the disk of Jupiter exactly between and in the center of the grid lines. Then, by rotating the grid until the central horizontal line crossed through Jupiter’s satellites, and the intervals between any vertical lines matched the radius of Jupiter, Galileo was able to take readings with great accuracy (Drake et al. 1980, pp. 52, 54).

**Figure 4**

whether illumination (that is, the expansion of light) is really instantaneous.” Discussing how to perform the experiment to prove his assertion he suggested, “We could make use of the telescope, focusing one for each observer at the places where the lights were to be put into use at night. Lights easy to cover and uncover are not very large, and hence are hardly visible to the naked eye at such distance, but by the aid of telescopes previously fixed and focused they could be comfortably seen” (Drake 1974, p. 50).

16. Galileo himself did not give any details of his micrometric device. It was mentioned by his disciple Borelli who described a kind of ruled grid (Shea 1996, pp. 518–520). Relying on various comments of Galileo and by comparing many of his mea-
The known magnifying power of the telescope, the exact intervals between the vertical and horizontal rulings on the grid, and its distance from the eye made it possible first to measure and then to calculate the magnitudes of celestial bodies with the precision of a few arc seconds. For example, “on the assumption that the spacing between the grid rulings was two millimeters, the radius of the magnified disk of Jupiter would be two millimeters. From these measurements and a table of sines Galileo could have calculated that an angle of 0.115 degree was subtended at the eye by the radius of Jupiter. Dividing 0.115 degree by the magnifying power of the telescope (×18), yields an apparent radius of 23 arc seconds” (Drake et al. 1980, p. 54). From my discussion, it is clear how Galileo made his assumption about the reliability of procedure for acquiring and analyzing observational data.

Physical science is not just a systematic exposure of the senses to the world. It is also a way of thinking and a way of forming conceptions about the world. Galileo’s discoveries of Jupiter and its satellites as presented in Sidereus Nuncius, and his investigations of the periods of the satellites and their orbital radii, can teach us about how he sought to minimize errors. Jupiter being more frequent and a better subject for precise timing than lunar eclipses, Galileo thought of a good way of approximating longitudes, especially at sea, by using Jupiter as a celestial clock with the positions of its satellites as pointers (Swerdlow et al. 1999, Vol 1: 424).

Drake emphasized that physical science is inextricably linked with calculations. Galileo’s practice and his calculations “were often the source, not just the product, of his opinions in scientific matters. Galileo’s calculations were based on observations, and that is how he came to characterize science as that in which no appeal was necessary beyond sensate experience and necessary demonstrations” (Swerdlow et al. 1999, Vol. 1: 420–421).

17. To get those results Drake must also have assumed that the distance of the grid from the eye is about 1000 mm. It is also important to note that Jupiter’s angular diameter at mean opposition distance is about 46.9 arc seconds. In January 1612 Galileo reported Jupiter’s diameter to be about 41.5 arc seconds, and four months later, when the earth and Jupiter were farther apart, he measured it as 39.25 arc seconds. Drake concluded that modern calculations of the diameter on the two days Galileo cited reveal a similar ratio of visual reduction. This similarity strengthens confidence in Galileo’s measurements and the reconstruction of his scientific practice as suggested by Drake (Drake et al. 1980, p. 54).


19. On Galileo’s ‘giovilabio’ (of 1612), a calculating device for computation of the periods and distances of the satellites of Jupiter, see Bedini (1967, pp. 279, 280–283).
These insights were also shown in a letter Galileo sent to Giuliano De’ Medici, the Tuscan Ambassador at Prague, on June 23, 1612:

Kepler will, I think, be pleased to learn how I have finally discovered the periods of the Medicean stars, and have constructed exact tables, so that I can calculate their past and future constitutions without an error of a single second.20

In the postscript to *Letters On Sunspots* Galileo suggests this to his readers:

Finally I put to you for consideration by your discreet judgement that you should not wonder if what I propound shall be not exactly comparable with the experience and observations to be made by you and others, because there are many ways to err. One, almost inescapable, is some mistake in calculation; besides that, the smallness of these planets [Jupiter satellites] and their being observed with telescope, which so greatly enlarges every object seen, means that even an error of one second of arc in the meetings and separations of these stars is made more apparent and noticeable than an error a thousand times as great in the aspects of other [naked eye] stars. Most important of all, the newness of this and the shortness of time [of their study to date], and the possibilities of other differences and anomalies in movement of these stars beyond those thus far observed by me, will excuse me among those who understand this art [of astronomical prediction] (Swerdlow et al. 1999, Vol. 1: 426–427).21

In fact, Galileo used different terms for miscalculation and wrong use of the telescope. This means that he was aware of the different nature of these errors, which attests to his profound understanding of the interrelations

21. “Voglio finalmente mettere in considerazione al discretissimo suo giudizio che non voglia prender meraviglia, anzi che faccia mie scuse, se quanto gli propongo non riscontrasse così puntualmente con le esperienze e osservazioni da farsi da lei o da altri, perché molte sono le occasioni dell’errare. Una, e quasi inevitabile, è l’inavvertenza del calcolo; oltre a questo, la piccolezza di questi pianeti e l’osservarvi col telescopio, che tanto e tanto aggrandisce ogni oggetto veduto, fa che circa i congressi e le distanze di tali stelle l’error solo di un minuto secondo si fa più apparente e notabile che altro fallo mille volte maggiore ne gli aspetti dell’altrre stelle; ma, quello che più importa, la novità della cosa e la brevità del tempo e il poter esser ne’ movimenti di esse stelle altre diversità ed anomalie, oltre alle osservate da me sin qui, appresso gli intendenti dell’arte doveranno rendermi scusato; ed il non avere ancora gran numero di uomini in molti migliaje d’anni perfettamente rivestiti e i periodi ed esplicate tutte le diversità dell’altrre stelle vaganti, ben farà scusabile e favorabile la causa di un solo ch’in due o tre anni non avesse puntualmente spiegato il piccol sistema Giovanale, che, come fabrica del sommo Artefice, creder si deve che non manchi di quegli artifizi, che per la loro grandezza incomparano di lungo intervallo l’intelletto umano” (Favaro 1890–1909, Vol. V: 248–249).
between science and instrument/technology. Note that observational errors are associated with either the external or internal condition of the observed object, and those that pertain to a particular method of observation. G. E. R. Lloyd introduced this classification to analyze how the concept of observational error was acknowledged in later Greek science (Lloyd 1982, pp. 133–134, 159–164). Despite his familiarity with the effects arising from atmospheric conditions, and his discussion of the effects of refraction in his *Optics*, Ptolemy did not make systematic corrections to accommodate this obstacle in reference to astronomical instruments in *Syntaxis* (Lloyd 1982, pp. 136–137; Hon 1989, pp. 144–145). But practicing Greek astronomers knew that the faulty construction or positioning of instruments could introduce sources of error, a notion well known throughout the sixteenth and in the early seventeenth centuries. In this respect, Hon proposes that “Kepler’s novel understanding of the problem of experimental error took into consideration not only errors that pertain to observation, but also errors that may arise in the theoretical background” (Hon 1987, pp. 589–591; Hon 1989, p. 150). This is evident through the theoretical assumption Kepler made about instruments he built and the actual employment of those instruments as well as the interpretation of the data they yielded (Donahue 1992, pp. 198–201, 207–211, 494, 644–645; Donahue 2000, pp. 13–16, 347–353, 355–356, 362–372). But this was true only for naked-eye astronomical observations. As shown in *Conversation*, Kepler could not devise the procedure for coping with the limits imposed by the eyes, which “would not permit greater precision, nor would the effect of refraction, which alters the position of the stars with reference to the horizon.” Therefore, Kepler was convinced that the “pinnacle in astronomical observation had been reached.”

Galileo’s attitude to the problem of experimental error becomes clearer as he went beyond the discrepancies between calculation and observation to types of errors that pertain to observation and optical instruments. Galileo made it explicitly clear that the reliability of the telescope was not enough for obtaining observational data. To understand, explain, and appropriately record observations:

23. Ptolemy’s instruments were the four-cubit rod dioptra, the equinoctial armillary, the meridional armillary, the quadrant, and the astrolabe.
24. “Valde me contendisse, ventum esse ad summum, nec relictum esse quicumque humanae industrie, cum nec oculi maiorem ferant subtillitatem, nec refractionum negotium, siderum loca respectu horizontis statum moveant” (Caspar et al. 1937, IV: 295; Rosen 1965, p. 21).
25. Scheiner, too, was concerned with the possibility that the sunspots were caused by some defect in the eye, a fault in the lenses, or a disturbance in the atmosphere. Therefore, he used eight different telescopes and several observers to verify the reliability of the instrument (Favaro 1890–1909, Vol. V: 26).
tional data it was essential to know how the image of an object was quantitatively determined through the telescope. As shown earlier, Galileo knew how to measure the exact magnifying power of the telescopes he used. Having tested and modified each one of them by using a “resolution” target, Galileo was able to define precisely the relations between the observed object and its image. In principle, these procedures could have provided Galileo with the exact error factor introduced by the telescope he used. By controlling the performance and knowing the limits of the telescope, Galileo could make the appropriate corrections needed for the constitution of a scientific object.

Galileo’s intentions, however, were much more decisive. In *Sidereus Nuncius* Galileo argued that the laws of optics were applicable to the moon as well as to the earth (Drake 1957, pp. 42–45). On the moon, when looked at through the telescope,

There is a similar sight on earth about sunrise, when we behold the valleys not yet flooded with light though the mountains surrounding them are already ablaze with glowing splendor on the side opposite the sun (Drake 1957, p. 32).

By the same reasoning, optics and geometry remove all doubts with respect to Jupiter and its satellites as being like a small solar system. Later, in *Letters On Sunspots*, Galileo argues that observational data, of comets, new stars, and sunspots, become evidence when they have been interpreted mathematically. By applying the laws of optics and a geometrical model as a sort of calculus—a method for analyzing, explaining and demonstrating (*modi necessari*)—Galileo wanted his audience to realize that only one realm of physical laws determine the appearances of natural phenomena (Favaro 1890–1909, Vol. V: 139–140; Pitt 1987, pp. 106–111).

Let us consider another example of how Galileo introduced the telescope into his scientific inquiry. Galileo stated that the fundamentals of the telescope were derived from the science called optics. This very same


27. On the first day of *Dialogue* Galileo also argued that the moon is similar to the earth. It is spherical, dark, and opaque because it reflects the light of the sun. The moon is dense and solid, and has an uneven surface. The moon’s prominences and cavities, as shown by the telescope, resemble the mountains on earth. The earth and the moon illuminate each other reciprocally and eclipse one another. In refuting Simplicio’s arguments, Galileo did an experiment with a mirror he hung on a wall illuminated by the sun. By changing the place of the mirror on the wall, and evaluating the reflection patterns of flat and convex mirrors on the opposite wall, Galileo was able to demonstrate that the moon surface is not smooth like a mirror (Drake 1967, pp. 67–84).
science also enabled him to describe and analyze the nature of the sunspots. In the third Letter On Sunspots, dated December 1, 1612, Galileo referred to Scheiner’s argument that Jupiter had five moons which appeared and vanished just like sunspots, so the spots were nothing but stars wandering around the sun. Galileo commented:

The conjectures that led you to believe it was a planet were founded on various fallacies and observations, which were often wrong. First, your diagrams omit some stars, which were then very substantial. Second, the distances of the stars from Jupiter are almost all wrong, I suppose, because of lack of a suitable method and instrument for measuring them. Third, there are gross errors in their arrangements and confusion in identifying them because the satellites changed places from one evening to the next without that being recognized (Favaro 1890–1909, Vol. V: 227).

Galileo implies that a scientific investigation is actually conducted in an environment where the obtained data reflect the sum total of many different causal factors. Data regarding natural phenomena under investigation should be reliable evidence for the phenomenon in question, so the scientist must control the idiosyncratic features of the instruments he employs and the particular background situation. Since phenomena are detected through the gathering of data, it is highly important to observe the apparent travel of sunspots day by day, over time long enough to substantiate an adequate database (Favaro 1890–1909, Vol. V: 107, 116, 145–182).

28. My discussion is mainly concerned with the reconstruction of Galileo’s epistemology regarding the telescope and its capacity as a scientific instrument. For the most recent discussion on the development of visual language of astronomy and the use of pictorial evidence as shown through Galileo’s and Scheiner’s sunspots episode, see Van Helden (1996, pp. 358–396). For further reading on Galileo and sunspots see Drake (1970, pp. 177–199); Shea (1970); Smith A. M. (1985); Baumgartner (1987); Kemp (1990, pp. 93–95); Hutchison (1990); Machamer (1995); Topper (1999). On the nature of visual imagery and understanding of the epistemology of scientific illustration see, Topper (1996).

29. "e le congettture dalle quali e’ si lasciò sollevare a stimarla errante, ebbero per lor fondamento varie fallacie; conciosia cosa che le sue osservazioni, primieramente, sono errate bene spesso, come io veggo da’ suoi disegni, perché lasciano qualche stella che in quelle ore fu copitusa; secondariamente, gli’interstizii tra di loro e rispetto a Giove sono errati quasi tutti, per mancamento, com’io credo, di modo e di strumento da potergli misurarre; trezo, vi sono grandi errori nella permutazione delle stelle, scambiandole il più delle volte l’una dall’altra e confondendo le superiori con l’inferiori, senza riconoscerle di essa in essa; le quali cose gli sono stante causa dell’inganno."

30. Galileo wrote that he observed the spots for about eighteen months, but in fact he observed them in uninterrupted sequence for over a month. He also argued that in order to perceive the difference between Jupiter’s satellites periodic returns and the movement of the spots, one must observe them systematically in a well-planned procedure (Drake 1957,
sunspots are movable (figure 5). They appear on the extreme edge of the sun, advanced gradually on a disk, moving from west to east, reach the opposite edge, and disappear, showing themselves again on the other edge in fifteen days (Drake 1957, pp. 91, 95, 111; Drake 1967, p. 55).

The distance they travel and spread out increases as they reach the center and decreases as they approach the circumference. Sunspots are not permanent in shape and they appear thinner near the edge than close to the center. At one time they are in great numbers, and at another there are none. Some are formed under the eye of the observer, like storm clouds in our own atmosphere. Others are torn off in pieces, which group themselves in new configurations, or dissolve and disappear into the luminous background. Others of greater stability are brought round under our eye in the same general aspect by the rotation of the sun, but it is only rarely that they retain the same shape for several successive periods of rotation (Drake 1957, pp. 92, 95, 140; Drake 1967, pp. 54, 345).

Figure 5

The periodic return of the same spots show that the sun turns on its axis in 25.5 days (see figure 5).
Scheiner’s diagrams of the sunspots, as he told Welser, indeed were rough approximations based on observations he made with a telescope filtered with blue or green neutral glass placed before the objective lens (Favaro 1890–1909, Vol. V: 26–27, 219; Shea 1970, p. 499). Scheiner “looked directly at the sun at sunrise or sunset, observing the sunspots through clouds, and took peeps at the midday sun” (Favaro 1890–1909, Vol. V: 27). Galileo knew that sunspot images (l’immagine) projected through a pinhole camera (piccolo foro) were not depicted sharply on the screen and that direct observation damaged the eye. Moreover, by means of a pinhole camera or direct observation many of the spots were diminished by the strong illumination of the sun or distorted by refraction of the atmosphere near the horizon (Favaro 1890–1909, Vol. V: 137–138; Drake 1957, pp. 116–117; Drake 1967, p. 316). Galileo described in detail the method he used to draw sunspots with great accuracy (figure 7). The telescope was directed towards the sun, steadied, and focused on a sheet of paper placed about five or six palms (about 60 cm) away from the concave lens. A circular image of the sun would then fall onto the paper, with all the spots on it arranged and disclose, although inverted, in exactly the same proportions as on the sun. The farther the paper was moved away from the tube, the larger the image became, and the clearer the spots were depicted. To depict the sun accurately, Galileo drew a circle on a piece of paper. By varying the distance between the paper and the tube he was able to find the optimum distance between them to obtain the clearest image. The drawn circle also served as a control against tilting the paper towards the luminous cone of sunlight that emerged from the telescope, distorting the image. When the correct position of the paper was found, the spots could be marked on the paper in their respective shapes, sizes, and positions. However, the work had to be done by a skilled hand and to follow the movement of the sun. One might recognize the correct position by looking in the objective lens, where one might see a little luminous circle concentric with the lens when the tube was properly pointed toward the sun (Favaro 1890–1909, Vol. V: 136–137; Drake 1957, pp. 115–116; Van Helden 1996, pp. 375–376).

33. Scheiner’s figures indeed were inferior to those presented by Galileo and he was convinced that the spots evinced phases like the moon (Favaro 1890–1909, Vol. V: 30, 33, 47, 55, 63, 66). Scheiner was well aware of the limits set by the instruments he used for sunspot observations (Van Helden 1996, pp. 370–372).

34. Shea also pointed out that Scheiner was aware of the possible sources of error while observing through the telescope (Shea 1970, p. 499).

35. “The circle also serves to make all drawings the same size. This is important in planing a series of illustrations: the sun paints the spot on the paper, the hand traces the spots and the engraver traces the drawing” (an anonymous referee).
Observational facts become scientific evidence when they have been interpreted mathematically. Galileo realized that the image of the sun depicted on the paper was reversed. But since the spots were drawn on the side of the paper facing the sun, if the paper was turned upside down and the top spots were brought to the bottom, one had only to look through the transparency of the paper placed in front of a light source to see the spots precisely as if one were looking directly at the sun (Drake 1957, p. 116). The available data enabled Galileo to distinguish between what was immediately perceived and what had to be interpreted from the observational data:

The different densities [of sunspots] and degrees of darkness, their changes of shape, their collecting and separating are directly evident to our sight, without any need of reasoning, as a glance at the diagrams I am enclosing will show. But that the spots are contiguous to the surface of the sun, and are carried around by its rotation has to be deduced and concluded by reasoning from certain specific properties (certi particulari accidenti) which our observation yield (Favaro 1890–1909, Vol. V: 117).36

36. See also Shea (1970, p. 504).
Having obtained a suitable method and instrument for measuring these natural phenomena, and applying the characters of optics \((\textit{in virtù di perspettiva})^37\) to the foreshortening of the spots on a spherical surface, Galileo wrote:

For those who understand what is meant by foreshortening on a spherical surface, this is a clear argument that the sun is a globe, that the spots are close to the surface, and that as they are carried on the surface toward the center they always grow in breadth while preserving the same length (Favaro 1890–1909, Vol. V: 119).^38

Galileo made his argument clearer through a diagram based on the geometry of projection onto curved surface (figure 8). The sun is very distant. Therefore, the angle subtended to the eye by visual rays drawn to opposite edges of the sun’s disk is very small and for all practical purposes, without perceivable error, the rays may be considered as parallels.\(^39\) As shown, a unit of a given length \(\mu\) moves through points \(P, L, D,\) and \(B\) along the circumference of the sun towards point \(A\). According to the ratios of the intersections on the plane \(MA\) and the sun’s circumference \(PA\), intervals \(PL, LD,\) and \(DB\) will be seen diminished in size compared with \(RS, SO, OC,\) and \(CA\). When \(\mu\) reaches point \(A\) it vanishes (Favaro 1890–1909, Vol. V: 213–215).

Galileo represented his observational finding using the following geometrical model (figure 9, left).\(^40\) Galileo considered \(CE\) to be the diameter of the sun, and \(Z\) an observer placed at a distance \(GZ\) from the sun. Let \(G\)

---

38. See also Shea (1970, p. 504).
be the center of the sun and CDE a parallel to the circumference of the sun
where two spots, A placed at point H and B at point L (figure 9, right), are
observed. On observation of the spots, the following definitions are made:
CF is the distance observed between spot A and the circumference of the
sun. FI is the distance between spot A and B. The perpendiculares FH and
IL (to CE), cutting CDE at H and L respectively, are the actual positions of
the spots while F and I their apparent positions. Therefore, FI is the ap-
parent distance between the spots. When the spots move towards the center
of the sun, their apparent distance increases until the real distance HL is
seen equally distant from the center of the sun. Let the spots’ position be
changed so that spot B is now moved to T, and spot A to X (figure 9,
right), so the distance of spot B from E is the same as was the distance of
spot A from point C. In that case, SE is the apparent distance between B
and the sun’s circumference. SV is the distance between the two spots and
ST, VX are the perpendiculares to CE. Thus, the distance TX is equal to

Figure 9

Scheiner, being no less qualified in mathematics and astronomy than
Galileo, “considered it inconvenient to place spots, darker than any ever
seen on the moon and on the bright body of the sun . . . For if they were
on the sun, their motion would imply that the sun rotates” (Favaro
1890–1909, Vol. V: 26). Therefore, as shown in Figure 10, the spots must
be stars circling the sun and Scheiner took the occasional darkening of the
side of the spots nearest the rim of the sun as an evidence that they had
phases like the moon (Ibid., pp. 30–31, 50).41

What will happen if the spots are removed to an orbit distant from the sun by 1/20 of CE, circling the sun along arc MNO (figure 9, left)? Geometrically, the real distance between spots A and B is NO, which is less than HL. This fact contradicts Galileo’s previous analysis that the observed ratios should be equal. The same pertains when the spots are moved to a place where they are equally distant from the center and the distance between them is expected to be equal to NO. Galileo reported that according to his observations the distance is equal to HL and therefore, “the ratios implied by the hypothesis that the spots are not on the sun contradict the ratios that were in fact observed” (Shea 1970, p. 505). Having established these geometrical facts, Galileo argued, “if the motion took place on circles at even short distance from the sun, the space passed in equal times would appear to differ very little, the spots would not become narrower, and the distance between them would not change noticeably” (figure 11). In this way Galileo could show that the observed phenomena “are in agreement with the hypothesis that the sunspots are contiguous to the surface of the sun, and that they are carried around by it without any difficulty” (Favaro 1890–1909, Vol. V: 118). This also provided him with an argument against other hypotheses, which were false because of “obvious inconsistencies and contradictions” (Ibid.). Moreover, this insight also provided Galileo with the empirical and epistemological basis for taking the movement of sunspots as a model, which he used in the third day of the Dialogue, to demonstrate the Copernican theory (Drake 1967, pp. 345–355; Hutchison 1990; Smith A. M. 1985). Employing observation and mathematics in the practice of science, Galileo wrote with a certain irony: “Had this discovery been made several years ago, it would have saved Kepler the trouble of interpreting correctly the black spot he observed in 1607 upon the sun” (Drake 1957, pp. 117, 133; Rosen 1965, pp. 22, 97–98; Thoren 1973), which he similarly mistook for Mercury.

43. See also Shea (1970, p. 504).
Whenever one makes inferences about the existence of phenomena on the basis of data, one must make assumptions about various possible sources of error and about their control and detection. From that point of view, Galileo and Kepler also acknowledged the need for a comprehensive reappraisal of the interaction between science and instruments. The ecliptic instrument that Kepler introduced in *Paralipomena* and Galileo’s telescopic enterprise show us that they were concerned with the relationship between the instrument they used and its corresponding science. Departing from the prevailing Aristotelian schools, Galileo and Kepler took an immense step toward the mathematization of scientific inquiry. The mixed mathematical sciences spilled over into the realm of natural philosophy, carrying over practices that were needed for validating mathematical arguments and their relation to physics. By integrating the telescope as a new element into the practice of science, only Galileo proceeded further in determining the methods and setting the scientific agenda for years to come, illuminating the idea of an instrument placed between the naked eye and the object.

The new optical instrument equipped with lenses did introduce a whole new set of problems. Perplexing factors regarding the sense of sight, the nature of light, and how to interpret a visual picture as physical knowledge had to be resolved. As argued, only Galileo succeeded in developing procedures for data processing. He exploited the telescope: first as a device for military purposes and then as an astronomical scientific instrument. Galileo’s words in the *Assayer* that science should be dealt with “as a method of demonstration and human reasoning capable of pursuit by

---

44. Pitt emphasized the new basic feature that Galileo added to the practice of science—the interplay between instrument and theory (Pitt 1995, p. 9).
mankind” were not merely a rhetorical gesture (Drake 1960, p. 189; Pitt 1992, V, pp. 110–138). Being able to filter out the background noise, Galilean could extract signals that he determined as true phenomena and not artifacts of the device. He thought that these phenomena, sunspots for example, would be plausible candidates for a scientific inquiry: objects for prediction and explanation.

Galileo, Scheiner, and Kepler were among those who thought that the knowledge of nature should be expanded by combining the results of observational instruments and mathematical reasoning. Galileo, however, was the first scientist who established the linkage among theory, method, and instrument—the telescope. The laws of optics enabled Galileo to employ a theory-laden instrument to bridge the gulf between picture and scientific language, between drawing and reporting physical facts, and between merely sketching the world and actually describing it. In sum, I think that this historical evidence and the time frame strongly suggest that we should consider a much closer interaction between science and technology, at least with respect to optics and astronomy in the early seventeenth century.

References


