‘The curious ways to observe weight in Water’: Thomas Harriot and His Experiments on Specific Gravity

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Abstract

This paper explores the experiments of the English mathematician Thomas Harriot (1560-1621) on specific gravity in the years 1600-1605, as recorded in a series of manuscript notes in British Library Add. MS 6788. It examines the programme of reading undertaken by Harriot before (or during) these experiments (including works by Jean Bodin, Giovanni Battista della Porta, Gerard de Malynes, Gaston du Clo, and Juan Bautista Villalpando), and describes a series of experiments conducted by him which compared the weight of a wide variety of substances in air and water. Harriot’s work is compared to that of his contemporary Marino Ghetaldi (1568-1626) in *Promotus Archimedis* (1603), and the work of both mathematicians can be positioned in the context of sixteenth-century mathematical responses to the famous problem posed by Hiero, King of Syracuse to Archimedes (as related by Vitruvius). Harriot’s use of proportional mathematics (especially the “rule of alligation”) in his experimental work and his application of this technique to problems in the alloying of metal and chymical analysis is examined in detail.

Keywords

specific gravity – experiment – alligation – Thomas Harriot – chemical analysis

Introduction

In 1598, the Elizabethan poet George Chapman published a translation from Homer's *Iliad* entitled *Achilles Shield*. The translation is preceded by a fulsome dedicatory poem "To my admired and soule-loued friend Mayster of all essentiall and true knowledge M. Hariots," that is, to the English mathematician Thomas Harriot (1560-1621).

> To you whose depth of soule measures the height,
> And all dimensions of all workes of weight,
> Reason being ground, structure and ornament,
> To all inuentions, graue and permanent,
> And your cleare eyes the Spheres where Reason moues;
> This Artizan, this God of rationall loues
> Blind *Homer*; in this shield, and in the rest
> Of his seuen bookes, which my hard hand hath drest,
> In rough integuments I send for censure,
> That my long time and labours deep extensure
> Spent to conduct him to our enuious light,
> In your allowance may receiue some right
> To their endeuours and take vertuous hearte
> From your applause, crownd with their owne desert.[1]

[1] George Chapman, *Achilles Shield. Translated as the other seuen Bookes of Homer, out of his eighteenth booke of Iliades. By George Chapman. Gent.* (London, 1598), lines 1-14, sig. D verso.

Chapman sends his Homer translation to Thomas Harriot (1560-1621) for "censure," not just because he was a noted scholar of Greek whilst an undergraduate at Oxford, but also because of Harriot's expertise in mathematics and natural philosophy.[2] Harriot, Chapman says, was a man who had made "demonstratiue veritie" his "great obiect."[3] While poetry delights the vulgar with "sweet passions" it can also reveal the obscure truths of philosophy. According to Chapman, Homer offers us an excellent example of poetry's philosophical depth. He has chosen Harriot to be a "competent and partles [i.e., impartial] iudge" of Homer's merits in this regard, because his "serious eyes" will be able to discern the merits of Homer's "Muse." It is possible that he might have seen Harriot as an appropriate judge of the cosmographical passages in Homer's description of the shield's engravings.[4] It is particularly striking, however, that Chapman begins his praise of Harriot's rational achievements with an allusion to "workes of weight." Whilst this phrase might be seen merely as a synonym for "serious work" (witness the reference to "inuentions graue"

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[2] For Harriot's expertise in Greek, see Stephen Clucas, "Mathematics and Humanism in Elizabethan England," *Journal de la Renaissance*, 4 (2006), 303-318, 309. On Harriot and his mathematical and natural philosophical work, see John W. Shirley, *Thomas Harriot: A Biography* (Oxford, 1983); Robert Fox, ed., *Thomas Harriot: An Elizabethan Man of Science* (Aldershot, 2000); idem, ed., *Thomas Harriot and his World: Mathematics, Exploration, and Natural Philosophy in Early Modern England* (Farnham, 2012); and Matthias Schemmel, *The English Galileo: Thomas Harriot's Work on Motion as an Example of Preclassical Mechanics*, 2 vols. (Dordrecht, 2008).

[3] Chapman, *Achilles Shield*, sig. D2 verso lines 56-57. Chapman also sought to align himself with Harriot's patron Henry Percy, ninth Earl of Northumberland (1564-1632), whom he described as "deepe searching *Northumberland*" in a dedicatory epistle to his philosophical poem *The Shadow of Night: Containing Two Poeticall Hymnes* (London, 1594), sig. Aij verso.

[4] Ibid. 6, "In it was earthes greene globes ...," etc.

two lines later) it also seems likely that Chapman was making a knowing allusion to his friend's interest in the nature of weight, or gravity. Harriot's work on specific gravities was not widely known in his own time, since – as has often been noted – he frequently neglected to publish his findings. Harriot's learning was – as Chapman says – "farre from plodding gaine./Or thirst of glorie [...]."[5]

This refusal to commit his work to print was nonetheless a cause for concern amongst Harriot's friends. In a letter to Harriot written by Sir William Lower in February 1610, Harriot was upbraided for his negligence in failing to publish his scientific discoveries. Both Harriot and Lower had been reading Kepler "diligentlie," and Lower agrees with his friend that the theory is established "soundlie" and that it "overthrowes the circular Astronomie." But, he continues,

> Do you not here startle to see every day some of your inventions taken from you; for I remember long since you told me as much, that the motions of the planets were not perfect circles. So you taught me the curious ways to observe weight in Water, and within a while after Ghetaldi comes out with it in print, a little before Vieta prevented you of the garland of the greate Invention of Algebra. Al these were your deues and many others that I could mention; and yet too great reservednesse has rob'd you of these glories, but although the inventions be greate, the first and last I meane, yet when I survei your storehouse, I see they are the smallest things and such as in comparison of manie others are of smal or no value.[6]

[5] Ibid., sig. D2 verso, lines 57-58.

[6] Sir William Lower to Thomas Harriot, 6 February 1610, BL Add. MS 6789, fols. 427-428. On the friendship and correspondence of Harriot and Lower, see Shirley, *Thomas Harriot*, 391-393, 398-401, 404-406 and Paul M.

While Lower emphasises the “first and last” inventions (elliptical orbits and algebra), I want to dwell a little further on Harriot’s “curious ways to observe weight in water.” In British Library Additional MS 6788, we find a series of documented experiments on specific gravities which Harriot carried out between 1601 and 1605.[7] The book which Lower refers to as having “robd” Harriot of his discovery is Marino Ghetaldi’s short treatise, *Promotus Archimedis, seu de varijs corporum generibus gravitate et magnitudine comparatis*, published in Rome in 1603, which – as its subtitle indicates – dealt with “various kinds of bodies compared in terms of their weight and magnitude.”[8] Like Harriot, Ghetaldi used the

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Hunneyball, *Sir William Lower and the Harriot Circle*, Thomas Harriot Seminar Occasional Papers (Durham, 2002).

[7] See British Library Additional MS 6788, fols. 166r.-178v and 229r-231r. On these experiments, see Shirley, *Thomas Harriot*, 264-265; Stephen Clucas, “Thomas Harriot and the Field of Knowledge in the English Renaissance,” in Fox, *Thomas Harriot: An Elizabethan Man of Science*, 93-136 (122-123) and Schemmel, *The English Galileo*, vol. 1, 138-139.

[8] Marino Ghetaldi, *Promotus Archimedis seu de varijs corporum generibus gravitate et magnitudine comparatis* (Rome, 1603). Ghetaldi’s work is only seventy-two pages in length. It comprises a series of theorems, propositions and problems relating to the gravities of solid and liquid bodies (1-31, and 54-66), interrupted by a series of tables results relating to the relative gravities of different bodies, and the relationship between the weights and the diameters of metallic spheres (32-51) and a brief excursus on Archimedes (51-4). The book ends with “A table for finding the quality of gold, from the weight which it has in air and water” (*Tabula ad inueniendam qualitatem Auri, ex grauitate quam habet in aere & aqua*) (67-72). Harriot also copied out a table from *In tractatu de ponderibus et mensuris* (1603) by Juan Bautista Villalpando (1552-1608), which details the proportions in weight of cubes made of different metals; see Add. MS 6788, fol. 109r. On Ghetaldi’s *Promotus Archimedis*, see Pier Daniele Napolitani, “La geometrizzazione della realta’ fisica: Il peso specifico in Ghetaldi e in Galileo,” *Bollettino di Storia delle Scienze Matematiche*, 8 (1988), 139-247, and Domenico Bertoloni Meli,

Archimedean method of weighing in air and water, and he too employed the accurate Troy weight measurement system, and converted his weights into grains for greater precision.[9] Also like Harriot, Ghetaldi tabulated his results, and investigated the ponderation of a wide range of substances including both precious metals, and more everyday substances such as oil, wax, wine and honey.[10] I will give further consideration to Harriot and Ghetaldi's approaches to the question of weight in the second section below. Firstly, however, I will consider the research undertaken by Harriot prior to (or alongside) his experimental investigations.

1 Reading for Weight

"The Role of Numerical Tables in Galileo and Mersenne," *Perspectives on Science*, 12 (2004), 164-190, at 165-170.

[9] Ghetaldi describes his experimental set-up at the end of Problema I, Propositio VIII (*Promotus*, 10), in a paragraph entitled "The manner in which solid bodies may be weighed in water" (*Quomodo ponderanda sint corpora solida in aqua*): "The body that one intends to weigh is hung by a horse hair from one balance, and the weight is placed in the other balance, and the hanging body is lowered into the water, so that it is hanging freely in the water, and neither the balance to which the body is attached, nor the other balance which contains the weights touches the water, and so the body one intends to weigh as if it were being weighed in the air." (*Corpus quod ponderandum proponitur seta equina ex altera libra lance appendatur, in altera lance ponantur pondera, & corpus appensam demittatur in aquam, ita vt in aqua libere pendeat, neque lancem, cui appensum est corpus, neque aliam in qua sunt pondera aqua contingat, & ita ponderetur propositum corpus, ac si in aere penderet.)* Harriot does not describe his experimental procedure, although we do have a diagram illustrating it, which looks remarkably similar to Ghetaldi's description; see Add. MS 6788, fol. 231r (Fig. 3). On Ghetaldi's experimental set-up, see Domenico Bertoloni Meli, *Thinking with Objects: The Transformation of Mechanics in the Seventeenth Century* (Baltimore, MD, 2006), 45.

[10] See footnote 8 for details of the tables.

Just as Francis Bacon argued that it was important to collect information on the natural philosophy of the ancient and modern philosophers,[11] and in particular, to gather information on mechanical arts whose experiments would "lead more directly to practice,"[12] so Harriot often began his experimental investigations by reading all the available literature that he could find on the topic, with a particular focus on those works which had a practical orientation, and critically comparing their results.[13] This is certainly the case with his work on specific gravities. Amongst his papers on this subject we find a few pages relating to Harriot's research into the existing literature. We find, for example, a table "Concerning the weights of metals" (*De ponderibus metallorum*) which, as his note at the head of the page tells us, was extracted from "Baptista in magia, pag. 631," that is to say, from the 1591 Frankfurt edition of Giovanni Battista della Porta's *Magiae naturalis libri viginiti*, printed by Andreas Wechel.[14] The original passage appears in the ninth chapter of Book 18, which deals with the allaying of gold with silver. Harriot tabulates information

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[11] Francis Bacon, *Advancement of Learning*, ed. Michael Kiernan (Oxford, 2000), 92: "I wish some collection to be made painfully and vnderstandingly *de Antiquis Philosophijs*, out of all the possible light which remaineth to vs of them … Neither doe I exclude opinions of latter times to bee likewise represented in this Kalender of Sects of Philosophie."

[12] Francis Bacon, *Parasceve ad historiam naturalem et experimentalem*, sec. 5, in Graham Rees and Maria Wakely, eds., *The Instauratio magna Part II: Novum Organum and Associated Texts* (Oxford, 2004), 463; cf. Bacon, *Advancement of Learning*, 65: "the vse of HISTORIE MECHANICAL, is of all others the most … fundamentall towards Naturall Philosophie … such [natural philosophy] shall bee operatiue to the endowment and benefit of Man's life."

[13] Johannes Kepler, too, assembled – and tabulated – data on specific gravity from a wide range of sources in his *Außzug auß der Uralten MesseKunst Archimedis* (1616); see Cesare Pastorino's essay in this special issue.

[14] Add. MS 6788, fol. 230r. Giovanni Battista della Porta, *Magiae naturalis libri viginti* (Frankfurt, 1591), 631-632.

which della Porta relates in continuous prose on various kinds of metals and various kinds of gold coins circulating in sixteenth-century Italy. As Harriot's table makes clear, della Porta's technique is essentially the Archimedean technique of comparing the weights of metals in air and in water (a story which was circulated widely in the Renaissance through the famous "Eureka" narrative recorded by Vitruvius).[15] Della Porta explains to his readers the usefulness of this method. It can be used to calculate how much gold is present in various alloys, such as in coins or gilded vases. "Which speculation," della Porta says, "is not only useful for bankers or moneylenders, but also for chymists, who have experience in the examination of metals, in the fixing of silver, and their other operations."[16]

The interest of chymists in these kinds of experiments is corroborated on the same page of Harriot's manuscript, by the appearance of "The Experiments of Gaston DuClo or Claveus in his Apologia Chrysopoeia, page 43" ["Experimenta Gastonis Dulconis siue Clauei, in Apologia Chrysopoeiae, pag. 43"] (see Fig. 1).[17] The *Apologia Chrysopoeiae* of Gaston DuClo (1532-1592) was a defence of the alchemical art against the polemical attacks of Thomas Erastus, and theorized that metals contained generative seeds (*Argyrogonia* for silver, *Chrysogonia* for gold), which could be used by the alchemist to "grow" metals in the laboratory.[18]

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[15] Porta re-tells the story at the beginning of XVIII.8, ibid., 629-630.

[16] Ibid., 629: "[Q]uae speculatio non solum trapezitis, sed chymistis etiam vtilis, quum examina metallorum experant, in fixionis argenti, aliisve eorum operationibus."

[17] Add. MS 6788, fol. 230r.

[18] Gaston DuClo, *Apologia Chrysopoiae et Argyropoeiae, adversus Thomam Erastum* (Ursel, 1602), 54. On DuClo, see Lawrence Principe, "Diversity in Alchemy: The Case of Gaston 'Claveus' DuClo, a Scholastic Mercurialist Chrysopoeian," in Allen G. Debus and Michael Walton, eds., *Reading the Book of Nature: The*

The "experiments" which Harriot refers to concern the comparison of weights of drawn wire of equal length and thickness (that is "drawn through the same hole"; "et eodem foramine tracta") by the wire-maker or goldsmith ("aurifaber").[19] It was artisanal knowledge of just this kind that Bacon believed would energize natural philosophy, albeit he saw arts which relied on "dextrous use of hand or instrument" as less fruitful than those which involved changing or preparing natural bodies.[20] DuClo and Harriot, however, include artisanal knowledge as part of a wider investigation of natural phenomena, in the way that Bacon envisaged.

Harriot also notes that "in another experiment" ("alio experimento") DuClo discovers that gold is heavier than mercury (*argentum vivum* or quicksilver) in a proportion of 7 to 6. DuClo doesn't give details of this experiment (he simply says that he had "learnt it by experience" – "experientia didici"), although prior to this he gives a very detailed experiment involving cinnabar (or mercury sulphide) which is known to artisans ("haec norunt artifices") who sublimate mercury from it. DuClo, however, is led by these artisanal reflections to reflect on the inferior weight of mercury as opposed to gold, in relation to an alchemical authority. "Geber says that mercury is heavier than gold," writes DuClo (in a

Other Side of the Scientific Revolution (Kirksville, MO, 1998), 169-185. Harriot himself was conducting alchemical experiments in 1599-1600; see Clucas, "Harriot and the Field of Knowledge," 123-126.

[19] Add. MS 6788, fol. 230r; cf. DuClo, *Apologia*, 43. Lazarus Ercker's experiments involving the weighing of gold and silver wire as discussed in Cesare Pastorino's essay in this special issue.

[20] Bacon, *Parasceve*, sec. 5, in Rees and Wakely, *Instauratio magna*, 463.

passage which Harriot copies into his manuscript), "although perhaps he understood by this mercury purged of phlegm etc."[21]

Another text which Harriot consults is Jean Bodin's treatise on the embasing (i.e., alloying) of metals, the *Discours ... sur le Rehaussement et Diminution des monnoyes tant d'or que d'argent* (1578), which was also included in the third chapter of book VI of his *De la République* (1576).[22] Harriot, however, refers to it as his "discourse on enhaunsing and embasing of monyes," and it is clear that he possessed the work in its free-standing form, as the misprinted numbers he corrects are from the *Discours* rather than from *De la République*. As Harriot notes "The nombers as they are in Bodin by examination we find some false printed, such as are aboue cancelled. The nombers of the author we take to be as followeth" (see Fig. 2).[23]

The "false printed" numbers correspond exactly to the Vincent edition. The proportions given in Bodin are attributed to the French mathematician François de Foix Candale (1512-1594), and Harriot inscribes Bodin's praises of the mathematician at the head of the folio. De Foix, Bodin says, is "the great Archimedes of our age, who was the first to

[21] DuClo, *Apologia*, 48: "Geber, ipsum profiteatur auro esse grauius, sed fortisan de argento vivo purgato & paululum ab humiditate nimia arte vindicatio intellexit"; cf. Harriot, Add. MS 6788, fol. 230r: "Geber dicit [mercurius] esse auro fortasse intelligit de purgato a flegmate etc."

[22] Jean Bodin, *Discours ... sur le Rehaussement et Diminution des monnoyes tant d'or que d'argent Jean Bodin* (Paris, 1578), sig. xij recto-xiij verso. I have not been able to consult the first edition, but cf. Jean Bodin, *Les six livres de la République* (Paris, 1580) VI.3, 651-652 which has a figure for silver of 998 (*neuf cents nonante & huict),* which differs from the *Discours*. The 1593 reprint also repeats this figure for silver.

[23] Add. MS 6788, fol. 229r.

discover the true proportions of metals in weight and volume."[24] If Sir William Lower thought that it was Ghetaldi who had pipped Harriot to the post, Harriot himself was aware of a number of other competitors. On the same page Harriot also includes a short table of figures attributed to "Lazarus Erker" (see Fig. 2). This is almost certainly a reference to Lazarus Ercker's treatise on ores and assaying, the *Beschreibung Allerfürnemsten Mineralischen Ertzt und Bergwerksarten*, first published in Prague in 1573.[25] On another folio Harriot cites a contemporary English treatise criticising Bodin's discourse by Gerard de Malynes, who styles himself a "Merchant." Harriot includes a list of weights extracted from Malynes' book *Englands View*, noting only that the figures on page 185 are taken out of the 1593 edition of Bodin, "Errors & all."[26]

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[24] Jean Bodin, *Discours .... sur le Rehaussement et Diminution tant d'or que d'argent* (Lyon, 1593), 75v-76r; cf. Harriot, Add. MS 6788, fol. 229r: "The Experiments of François M. de Foix. Le grande Archimede de nostre aage [*sic*] et qui se premier a descouuert la vraye proportion des metaux en poids et en volume as Bodin writeth in <his> discourse of enhaunsing and embasing of monyes." Harriot was not sure whether the Foix mentioned by Bodin was the "Flussas" he knew as the editor of Euclid's *Elements* ("quaere whether the man be Flussas"); see *Euclidis Megarensis mathematici clarissimi elementa geometrica … authore Francisco Flussate Candalla* (Paris, 1566).

[25] See Anneliese Grünhaldt Sisco and Cyril Stanley Smith, *Lazarus Erker's Treatise on Ores and Assaying, translated from the German edition of 1580* (Chicago, IL, 1951). It seems likely that Harriot may have come to know this work through his work on mineral assaying with the Czech metallurgist Joachim Gans on the Roanoke voyage of 1585.

[26] Add. MS 6788, fol. 230r; cf. Gerard de Malynes, *Englands View, in the vnmasking of two paradoxes: with a replication vnto the answer of Maister Iohn Bodine. By Gerrard de Malynes, Merchant* (London,1603), 185. Malynes does not mention that he has taken the figures from Bodin, but simply says they were "exactly found by the last triall made there of" (ibid, 184-185). It is interesting to note that Francis Bacon's interest in hydrostatic experiments was also informed by the work of Foix de Candale, Bodin and Malynes; see Cesare

After these brief, but suggestive, notes about Harriot's reading programme, we find a list of substances which appear to be a list prepared with his own experiments in mind. Not only does it contain the metals which had been the main ones treated by the authors he consulted, but also "a Marble stone," "diamonds," "Crystall" and "glasse." Harriot's interest, then, went beyond the "fructiferous" activities of metal assaying and the goldsmith's shop, towards a "luciferous" interest in weight more generally.[27] This can be seen even by a casual look at the wide range of substances he tested, which included "white morter," whetstone ("Cos cinera"), a "square amber," two pieces of glass he had been using for refraction experiments,[28] "cockle stone," "white flinte" and a "shoing horne,"[29] and even (presumably after a visit to Sir Walter Raleigh in the Tower where he had been imprisoned after his involvement with the Bye Plot), "Toure ashes calcined" and "stalkes of Tobacco," both "calcined" and "lesse calcined."[30] Harriot used his connections with those involved in practical activities such as Raleigh's half-brother Sir Adrian Gilbert (whose mines produced samples of metallic ores and even a "round loadstone"), "Su[sse]x bottle glasse blewish

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Pastorino, "Weighing Experience: Experimental Histories and Francis Bacon's Quantitative Program," *Early Science and Medicine* 16 (2011), 542-570 (557-562). There is also considerable overlap between Harriot's sources and those of Kepler in his *MesseKunst*, including – in addition to the three aforementioned authors – Lazarus Ercker and Juan Bautista Villalpando. This may partly be due to the fact that the two men had corresponded on this issue prior to the publication of Kepler's work; see Cesare Pastorino's essay in this special issue.

[27] For the distinction between "fructiferous" and "luciferous" experiments, see Francis Bacon *Novum Organum*, sec. 99, in Rees and Wakely, *Instauratio magna*, 156-159.

[28] Add. MS 6788, fol. 237r (30 September-9 December 1604).

[29] Ibid., fol. 237v (20 October 1604).

[30] Ibid., fol. 242r, headed "June 28 1605. S[ir][W[alter?]."

changeable," which may have come from local glassworks close to his patron's Sussex estates, and "molten brasse" from a "fire shovel" which sounds as if it may have come from a workshop.[31] All of these substances were subjected to the same Archimedean regime: first they were weighed in air, then they were weighed in water, the differences noted, and their specific gravity derived from dividing the weight in air by the difference between their weights in air and water (see Fig. 3).[32]

This can be seen clearly from two examples of experiments which Harriot did on 9 December 1604, using a piece of "square amber" and "two peeces of ... magnets." Harriot used the Troy weight measuring system used by goldsmiths and jewellers to weigh precious metals and gemstones. First, he weighs the amber in air, converting the figure into grains (167); he then finds its weight in water (11.1), then he finds the difference between the weights in air and water (155.9); then, dividing the weight in air by the difference, we get 1.071.[33] As Harriot takes the density of water to be 1000 rather than 1, the specific gravity of amber is 1071. Things get a little more complicated when the substance you are measuring is porous, and in other experiments (dated 20 October 1604), Harriot offers the weights of substances such as copper ore in a dry and a wet weight form, which gives him upper and lower gravities for the substance in question. Harriot notes some problems which he encounters with this approach, as in the case of marcasite, which he only has in "very small peeces" and therefore cannot provide a reliable range of gravities. In the same day's experiments he notes of one batch of copper ore that "it seemeth it soked no water."[34] Four

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[31] Ibid., fol. 241v (28-30 October 1604).

[32] See Schemmel, *The English Galileo*, 139.

[33] Schemmel, ibid., expresses this procedure in the following formula: $\frac{Wair}{Wair - W\,water}$.

[34] Add. MS 6788, fol. 237v.

days later, when he is investigating the weights of various kinds of stones he notes that when he tested a piece of "Hard sand or soft sand stone" that he performed the process twice and that they were "(throgh) wet."[35] In the case of "Rigate firestone" (a kind of sandstone or greensand used in the construction of furnaces), he gives figures for stones that have been soaked "an houre after" and "12 houres after." Finally, to make sure that the stone is genuinely soaked through he says "I cut the stone presently in the midle & it was wet throughly."[36] Harriot ran into problems with the nature of his samples on 28 November 1604 when he was weighing 24 diamonds and 67 rubies in air and water (see Fig. 4).

Having fumbled the delicate operation of getting 67 rubies weighed in water, five of them fell into the water, and one (as he notes) was "quite lost." More importantly, the five rubies did not feature in his recorded weights – "therefore try agayne" he notes. Thus, when he records his result he notes that the figures are not strictly accurate but "by coniecture," and he allows a compensatory five grains to allow for the discrepancy. Harriot was not averse to repeating experiments, and we find, for example, that he repeated his experiments on hard and soft kinds of calamine stone (a form of zinc oxide used in the production of brass) on two separate days, obtaining slightly different results each time.[37] These calculations of specific gravities and Harriot's scrupulosity as an experimenter are impressive in their own right, but they were only the beginning of a more ambitious

[35] Add. MS 6788, fol. 238v.

[36] See Clucas, "Field of Knowledge," 123.

[37] Cf. Add. MS 6788, fol. 238v (24 October 1604) and fol. 239v (28 October 1604).

mathematical approach to specific gravities which Harriot's friend saw as similar to that of Ghetaldi in the *Archimedes Promotus*.[38]

2 Emulating Archimedes

What exactly were the "curious ways" that Harriot taught Sir William Lower, and in what way are they similar to Ghetaldi's work on the subject? It was certainly a little more than the experimental procedure of weighing bodies in air and water. As the main title suggests, Ghetaldi was offering his own work as an advance on that of Archimedes (*Promotus* = "advancement" or "enlargement"), and he makes his claim explicitly in relation to the *locus classicus* of Archimedes' insight into the nature of specific gravity – the tale of Hiero's crown in Vitruvius' *De Architectura*, IX.9-12.[39] In a section headed "The manner in which Archimedes discovered the mixture of silver in gold" (*Quomodo Archimedis argenti mixtionem deprehendit in auro*), Ghetaldi retells the Vitruvian narrative. "Thus far, Vitruvius," he adds. "It was certainly a wonderful invention of Archimedes," he continues,

> but his method of finding the measure of water which corresponds to a certain weight of gold, or silver, or of the crown, requires a greater diligence than that which can be applied by men, for it is impossible, having removed the crown, or the gold or the

[38] It should be noted – although a full exploration is beyond the scope of this paper – that Harriot exhibited a similar scrupulosity in his experiments on optical refraction and falling bodies, and in the conduct of his astronomical observations. I would particularly emphasise Harriot's habit of rigorously comparing calculated values with experimental results.

[39] See Vitruvius, *On Architecture*, ed. and trans. Frank Granger (Cambridge, MA, 1934), vol. 2, 203-207. On the importance of Archimedes' crown problem, see Bertoloni Meli, "Numerical Tables in Galileo and Gassendi," 165-168.

silver to know exactly [*ad unguem*] if the same amount of the water flows back, as flowed out of the vessel.[40]

The amounts of water can only be approximated, and "conjecture cannot be accepted as truth" (*coniectura pro veritate non accipitur*). This kind of failing, he says, "induces a sensible error" (*huiusmodi defectus errorem inducit sensibilem*).[41] To discover exactly (*exacte*) how much silver is mixed with the gold, he says, can only be accomplished by the method of weighing bodies in air and water that he outlines in proposition 8.[42] Using this method, he says, it doesn't matter how large or small the body is, and you don't have to have masses of silver and gold equal to each other and the crown; all that is required are some small pieces, even if they are of different sizes.[43] Many people have written about Archimedes' method for discerning the weight of silver in Hiero's crown from the weights of the three bodies, and various methods have been devised by them; but they are tedious and difficult to use, says Ghetaldi, and the various authors haven't been able to come up with a

[40] Ghetaldi, *Promotus Archimedis*, 52: "Hactenus Vitruvius. Mirum certe Archimedis fuit inuentum, ipsius tamen modus ad inueniendam illam aquae mensuram, quae ad certum pondus auri, vel argenti, vel coronae responderet, maiori diligentia indiget, quam quae ab hominibus adhiberi potest, impossibile enim [scire] est, exempta corona, vel aurea massa, vel argentea, tantum aquae refundere, quantum è vase effluxerat ad vnguem [...]."

[41] Ibid., 53.

[42] Ibid, 53 (for the method outlined in proposition 8, see footnote 9 above).

[43] Ibid, 53-4: "siue sit corpus illud paruum, siue magnum nihil interest, & praeterea facillima est operatio, nec adinueniendae sunt auri, & argenti massae aeque graues, ac corona, sed quaelibet particulae, grauitate quacunque, etiam differentes inter se, sufficiunt."

"fixed and stable rule of operation" (*operationis ... praeceptum firmum ac stabile*).[44] Ghetaldi's answer – and it is, as we shall see, not unlike Harriot's "curious way" – is to use geometrical proportions: "But I, by means of proportional reasoning alone, or the rule of three (as it is popularly called) obtain the same briefly and without difficulty, and I demonstrate it with geometrical proportion."[45] He then presents a problem, the solution to which will answer Hiero's question (Problema IX, Propositio XVIII: "To discern the portion of a metal mixed with another metal, by reasoning of weight"), and gives two worked examples.[46] The problem and solution are stated as follows:

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[44] Ibid., 54 "De ratione autem, qua Archimedis, cognitis grauitatibus trium corporum ex aqua, magnitudine aequalium, coronae scilicet vnum, alterum massae aureae, tertium argenteae, potuerit furtum aurificis in regia corona deprehendere, atque argentum, quod erat in ea permixtum ab auro discernere, plurimi scripserunt, modos etiam ad id faciendum excogitarunt varios, longa tamen methodo, atque difficili vsi sunt, & quod maximam confusionem, & obscuritatem parit, nullum operationis tradunt praeceptum firmum, ac stabile."

[45] Ibid., 54: "ego autem vnica tantum proportionis ratiocinatione, seu regula trium (vt vulgo dicitur) breuiter, & expedite idem consequor, eamque geometrica ratione demonstro."

[46] Ibid., 54-56: "*Portionem metalli, alteri metallo mistam, ponderis raticinatione discernere*. Quoniam de Hieronis corona facta est mentio, sit ea B, eiusque grauitas EK, & oporteat argentum, quod sit in ea permixtum, ab auro discernere, hoc est oporteat inuenire quanta erit portio argenti & quanta auri. Intelligantur duo corpora A, D, vnum aureum, alterum argenteum aeque grauia atque corona, deinde trium corporum ex aqua, magnitudine aequalium, aureo scilicet corpori vnum, alterum coronae, tertium corpori argenteo, inueniantur grauitates, id autem poterit fieri facillime [...]. Sit igitur primi corporis aquei aequalis aureo A, inuenta grauitas G, secundi vero aequalis coronae B, grauitas F, & tertij aequalis corpori argenteo D, grauitas H, & fiat vt differentia inter G, & H, ad EK, ita differentia inter G & F, ad aliam grauitatem, quae sit K. Dico K, grauitatem esse portionis argenti, quod est in corona, E vero grauitatem auri."

> Since the crown of Hiero has been mentioned, let it be B, and its weight EK, and it is required to discern the silver which is in it from the gold, that is to find how large the portion of gold is, and how much the portion of silver is. Let there understood to be two bodies A and D, one gold, and the other silver, of equal weight and equal in weight to the crown. Then find the weights of the three bodies of equal magnitude ... out of water, it will be possible to do this very easily. [...] Let therefore the weight of the first watery body equal to the gold A be found to be G, and the second weight equal to the crown B be found to be F, and the third weight equal to the silver D be H, and let it be done so that the differences between G & H to EK are the same as the differences between G & F to the other weight, which is K. I say K is the weight of the portion of silver, which is in the crown, and E is the weight of gold.[47]

He then goes on to state what one does in the case of adding a third or fourth term to the proportion, and supplies two worked examples. The following theorem (Theorem X, Propositio XIX), Ghetaldi says, demonstrates that this mode of reasoning is "rightly constructed" (*recte esse institutam*).[48]

As Ghetaldi intimates, he was not the first mathematical critic of Archimedes' solution to the problem of Hiero's crown, and he was not the first to turn to the rules of proportion for more exact answers. Gemma Frisius, in his *Arithmeticae practicae methodus facilis* (1552), also addresses Archimedes' solution to Hiero's problem as related by Vitruvius. "However, Vitruvius did not adjoin Archimedes' demonstration [*praxin Vitruuius non*

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[47] Ibid., 54-55.

[48] Ibid., 56. Theorem X is detailed in 55-59.

adiungit],” he notes, and so he has devised his own.[49] Like Ghetaldi, Frisius solves the problem using the rules of proportions, in this case the “rule of the false” (*regula falsi*), and gives a worked example of how to solve the problem assuming the weight of the crown and the two other masses to be five pounds.[50] After this, he adds the following:

> It should be noted in passing that it wasn’t necessary for Archimedes, or anyone else who might wish to perform an experiment of this matter, to make masses of gold or silver of the same weight as the crown or whatever other things are to be examined, but any notable part of the weight of silver or gold would have sufficed. This and an infinite number of other examples may be performed by means of the rule of the false, all of which would require infinite labour and intolerable tedium to calculate.[51]

In a section devoted to the rule of alligation (*regula alligationis*), after providing a number of worked examples of the application of the rule to a range of practical problems, Frisius observes that there are “almost infinite” (*infiniti fere*) uses of the technique, and he

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[49] Gemma Frisius, *Arithmeticae practicae methodus facilis, per Gemmam Frisium medicum ac mathematicum, iam recens ab ipso auctore emendata, & multis in locis insigniter aucta* (Antwerp, 1552), 41r.

[50] Frisius explains the rule of the false at ibid., 33v.

[51] Ibid., 41r: “Hic obiter notandum, non opus fuisse Archimedi, neque cuiquam alteri, quod velit huius rei periculum facere, conficere vel auri vel argenti massas eiusdem ponderis cum corona vel quauis alia re examinanda, sed suffecerit quaeuis pars notabilis ponderis auri vel argenti. Haec atque infinita alia exempla licet per regulam falsi perficere, quae omnia recensere infiniti esset laboris, ac intollerabilis nauseae.”

says, “what we have set out in [problems concerning] liquids and spices will come out the same in the mixture of metals, and there is no difference in the operation.”[52]

In 1552, the English mathematician Robert Recorde (1512-1558), in the second, enlarged edition of his elementary treatise on arithmetic *The Ground of Artes* (first published in 1543), added a “second part touchyng fractions,” which dealt with the rules of proportion – the “Golden rule” (or “rule of three”), the “rule of Fellowship,” the “rule of Alligation,” and the “rule of Falsehode” (or false position).[53] At the end of the latter he appended his own solution to the problem of Hiero’s crown, which – like Frisius – he solves using the rule of false position.[54] At the end of this example, he alludes to a work on the mixture of metals (which he never published), which would define the specific gravities of the two metals in order to make it easier to assay mixtures:

> if you knewe the exacte proportion between gold and syluer and water bothe in ther waight and in their quantities, then coulde you easily fynde out the mixtures of them.

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[52] Ibid., 32v: “Quod in liquidis & aromatibus proposuimus, idem in metallis miscendis euenit, verùm operationis nulla est diuersitas. Quod in liquidis & aromatibus proposuimus, idem in metallis miscendis eueationis nulla est diuersitas.”

[53] Robert Recorde, *The ground of artes teachyng the worke and practise of arithmetike, bothe in whole numbres and fractions after a more easyer and exacter sorte than any lyke hath hytherto been sette forth: with diuers new additions as by the table doeth partely appeere* (London, 1552), sig. Liii recto-[Zix] recto. On Recorde’s account of proportion, see Alvan Bregman, “Alligation Alternate and the Composition of Medicines: Arithmetic and Medicine in Early Modern England,” *Medical History*, 49:3 (2005), 299-320.

[54] Recorde, *The grounde of artes*, sig. Zv verso-[Zix] recto.

> Which thinge I haue reserued for an other woorke that intreateth suche matters specially.[55]

The mathematician and natural philosopher John Dee (1527-1609) also promoted the use of the rules of proportion in practical problems, in the section on arithmetic in his *Mathematicall Praeface*, in Henry Billingsley's English translation of Euclid's *Elements* (1570). Merchants of all kinds, Dee says, are witness to the "frute receiued by Arithmetike":

> How could they forbeare the vse and helpe of the Rule, called the Golden Rule? Simple and Compounde: both forward and backward? [...] The Rule of Alligation, in how sundry cases, doth it conclude for them, such precise verities, as neither by naturall witt, nor other experience, they, were hable, els, to know?[56]

But then application of the rules of proportion go beyond the needs of merchants, says Dee. The "Rule of False positions," he says is "ample & wonderfull,"

> especially as it is now, by two excellent Mathematiciens (of my familier acquayntance in their life time) enlarged? I meane *Gemma Frisius*, and *Simon Iacob*. [...] [W]ho can Imagine the Myriades of sundry Cases, and particular examples, in Act and earnest,

[55] Ibid., sig. [Zvii] verso.

[56] John Dee, *Mathematicall Praeface*, in *The Elements of Geometrie of ... Euclide ... now first translated into the Englishe toung, by H. Billingsley* (London, 1570), sig. *ij verso-*iij recto.

> continually wrought, tried and concluded by the forenamed Rules [i.e. the *regula trium*, the *regula alligationis* and the *regula falsi*], onely?[57]

Not only are these tools useful to the "Mintmaster, and Goldsmith, in their Mixture of Metals," but physicians "will gladly confesse them selues, much beholding to the Science of *Arithmetike*," particularly in the "Art of Graduation, and compounde Medicines."[58]

In 1561 Dee had edited a posthumous reprint of Recorde's *The grounde of artes*, where Recorde – who was a practising physician – noted that alligation "hath great use in composition of medicines, and also in myxtures of mettales." [59] In a short passage added by Dee to the section on alligation, he indicated the enormous potential of this technique in other applications. "Truth it is, that this consideration [of the rule of alligation] may fall in practise as well politike, as philosophical, and sundry waies in them be applied."[60] Given the breadth of its of applications, it is small wonder then, when Harriot turned to the problem of specific gravities, that he – like Ghetaldi and Frisius and Recorde – brought the powerful tool of proportional mathematics to bear on it.

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[57] Ibid., sig. *iij recto. The German mathematician Simon Jacob (1510-1564) was the author of an influential and frequently reprinted treatise on arithmetic, *Ein newes und sehr nützliches gerechnetes Rechenbuch*, first published in 1555.

[58] Dee, *Mathematicall Praeface*, sig. *iij recto. On the use of the rule of alligation in medicine, see Bregman, "Alligation Alternate."

[59] Robert Recorde, *The grounde of artes: teaching the worke and practise of arithmetike, both in whole numbres and fractions, after a more easyer and exacter sorte then any like hath hitherto been sette forth: made by M. Robert Recorde doctor of physik, and now of late ouerseen & augmented with new & necessarie additions*, (London, 1561), sig. Y1 recto-Y1 verso. See Bregman, "Alligation Alternate," 303-307.

[60] Recorde, *The grounde of artes* (1561), sig. Z1 verso.

3 Harriot's Experiments and the "Rule of Alligation"

As we shall see, in Harriot's hands, the rules of proportion became a versatile tool for questions concerning mixtures of bodies with different specific gravities. As an example, let us take an "experiment" which Harriot performed some time in or shortly after 1604, concerning the proportion of salt and water in saline mixtures (see Fig. 5).[61]

The "experiment" begins practically: Harriot weighs a glass measuring vessel full of "Syon water" (that is, the water available to him at his home in the grounds of Syon House in Isleworth). The water weighs a little over 14 troy ounces. Using a table which gives the number of grains in a troy ounce and its fractions, he arrives at the figure 7098 grains (**A**). He then mixes a saline solution containing 840 grains of "comon salt not dried" (**x**) and 6840 grains of water (**y**), giving a total of 7680 grains (**B**). The experiment then shifts to calculation: first, he presents the known proportion between the "roome" (volume) of water and salt (which he calculates by subtracting the weight of a measureful of water (**A**) from the weight of water in his saline solution (**y**). This gives him the first term of his proportion, 258 (**C**), the second term being the weight of the salt (**x**), 840, which ratio he

[61] Add MS 6788, fol. 166r. The record of the experiment is undated, but there is a reference to a work published in 1604 on the same page: "Halichimia Tholdus 1604. 8° in duch." This seems to refer to a German ("duch") translation of Hessian salt-maker Johannes Thölde's work on the chymistry of salts, *Haliographia* which had been published in Latin in 1603. I have not been able to locate a 1604 edition of Thölde's work with this title in either Latin or German. On Thölde, see Hans-Henning Walter, ed., *Johann Thölde: um 1565 - um 1614: Alchemist, Salinist, Schriftsteller und Bergbeamter: Tagung vom 26. bis 28. Mai 2010 in Bad Frankenhausen am Kyffhäuser*(Freiberg, 2011), and John Ferguson, *Bibliotheca Chemica*, q.v. "Thölde, Johann." On the *Haligraphia* specifically, see Katrin Cura, "Die chemisch-technologisches Literatur und Thöldes Haligraphia – Einfluss und Auswirkung" in Walter, *Johann Thölde*, 82-202.

simplifies to 43:140. Using the rule of three, he calculates the weight of salt that his glass measure (which contains 7098 grains of water) is able to hold, which is 23,109 (**D**); "so much my glasse must hold," he notes. He has thus established a measure of weight by volume. At this stage he decides to mix up a new solution using "pouder dried" salt (presumably so that the moisture of the salt will not skew his results). This new measure of "Syon salt water" weighs 8530 grains (**E**). Armed with his mixture of measured (**A** and **E**) and calculated (**D**) weights, Harriot uses the rule of alligation ("Then By the rule of Alligation") to calculate the ratios of water to salt, by weight, and by "roome" (volume). In the rule of alligation the proportions of substances of differing qualities in a mixture can be established by ordering the qualities (here weights), and their differences, and the sum of the differences is used as the first term of the rule of three. The second term in the proportion is the common quantity (the weight of a measure full of water, **A**). The sum of the differences in this calculation is 16,011 (the sum of the differences between the weight of the saline solution and the weights of salt and Syon water **[D-E]** and **[E-A]**). The third terms of the calculation are provided by the particular differences (**[D-E**] = 14,579 and **[E-A]** = 1432). In Table 1, I present the calculation Harriot made, using the notation for alligation used by Recorde (with the calculated values at the bottom right-hand side of each calculation).

Harriot rounds the second calculation up to 635. Using these values, he is able to establish the proportions of salt and water (by weight and volume) in his saline mixture, **E**. By weight, there are 6463 grains of water (**F**) to 2066 grains of salt (**G**, or **E-F**, *ut proxime*) and by volume 6463 (**F**) grains to 635 (**A-F**). There then follows another worked example, using a saline mixture weighing 8554 grains, in which he calculates salt and water to be mixed 2101½ grains to 6452½ by weight, and 645½ grains to 6452½ grains by volume. "It seemeth by experiment," Harriot concludes,

> that the weght of the salt to the water is as 1 to 3. & the roome as 1, to 10, measured. In the calculation following I will suppose the roome to be 1 to 10 exactely <& the weght as 1 to 3 exactely> & fro[m] that supposition I do set the reste to geue an occasion of further speculation & of an other experiment by molten salt to be made afterward.[62]

He then performs an alligation calculation in which the quantities chosen are (as he says), exact proportions (with none of the "rounding up" he allows himself in the calculations with experimentally derived quantities). Looking for the underlying mathematical structure, Harriot turns an approximate proportion, gained by subjecting measured weights to proportional rules, into a fixed proportion, but only (as he says) as a guide to further "speculation" and "experiment."

4 Specific Gravity and Harriot's Chymical Experiments

Although both John Shirley and Matthias Schemmel have suggested that Harriot's interest in specific gravities was intimately connected with his investigations into falling bodies, and both show that he made use of his knowledge of the different specific gravities in his experiments on this topic, the evidence suggests that Harriot's exploration of specific gravities seems to have been undertaken on a wider basis, and includes an interest in its use in the alloying of metals and chymical analysis.[63]

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[62] Add MS 6788, fol. 166r.

[63] See Shirley, *Thomas Harriot: A Biography*, 264-267; and Schemmel, *The English Galileo*, vol. 1, 137-151, esp. 137: "[Harriot] integrated the knowledge on the reduction of weights immersed in a medium into his

As we have already seen, Harriot's experimental programme involved a bewildering diversity of materials, and – like Ghetaldi – he seemed to have had a general interest in the relationship between weight, magnitude and substance. He addressed, for example, the question of "The proportion of Ise & Water" (see Fig. 6), and compared the weights of cubes containing ice both "swollen" and "iuste" (a difference of 249 grains), with the weights of the same cube filled with water and wax.[64] He also noted the "reciprocal proportion" (*ratio mutua*) of the weights of cubes and spheres of crystal, salt and water with known diameters.[65] Ghetaldi too, had been interested in the diameters of spheres and their relationship to weight, and produced tables of the weights of spheres of different sizes and metals.[66] Harriot's interests, however, went beyond the specific gravities of solid bodies, and extended to liquids, and – as we have already seen in the case of salt – solutions. This interest, as I will show, poses questions which are very different from those that he needed to answer in order to further his work on falling bodies.

On the 25 July 1604, which was, according to Harriot, a hot sunny day ("hot day, sonne shine"), he was pursuing his investigation of saline solutions, this time a mixture of water and "common white salt vndried" (see Fig. 7).

conception of the motion of fall as uniformly accelerated motion. He achieved this integration by identifying a falling body's degree of motion with the body's reduced weight in a medium."

[64] Add. MS 6788, fols. 75r-76v. The difference here would be between ice which has expanded beyond the limits of the volume of the measure in the process of freezing ("swollen"), and ice which has a surface exactly level with the upper rim of the measure ("iuste"). To attain the latter, Harriot may have trimmed off the excess volume of swollen ice.

[65] Add. 6788, fol. 167r.

[66] Ghetaldi, *Promotus Archimedis*, 32-51.

He dissolves a measure of salt weighing 1680 grains, in 6453 grains of "sion water." The "measure full of water & the salt, all dissolued not filtred" thus weighed 8133 grains. He calculates the weight of the measure of salt as 18,592 grains. Again using the rule of alligation, he establishes the proportion of salt and water in his solution by weight ($2354\frac{4}{10}$ to $6195\frac{6}{10}$) and by "roome," or volume ($898\frac{4}{10}$ to $6195\frac{6}{10}$). He extends his investigation to a "Measure full of salt water that had stood a twelue month in a vrinall with salt more then it could take by much."[67] The salt in this solution, Harriot specified, was "pouder dried salt of the last yeare" and not "vndried salt" as in other experiments. He also gives the weights of two measures of the solution, one that had been "Filtred <by> single paper," and another of the same solution "Filtred by double paper." The weights are almost identical (a mere 3 grains of difference), but clearly Harriot wanted to make sure. He compares this to a recent batch of salt solution which he has made, which "dissolved by boyling 3 houres" and allowed to cool for "two dayes." Harriot's measurements satisfy him that the weights are "All one with pouder dryed the yeare before, the cutting of the glasse allowed."[68] Presumably he had trimmed his uniform, glass measure which ensured that he had an equal "roome" (or volume) of the substances he was testing.

Harriot's laboratory was rich in supplies, and he visited it again on that same hot day to fetch saltpetre and copper sulphate ("vitrioll of copper"), that were stored there.[69] From these materials he prepared more solutions to test. The saltpetre solution, he notes, was "all dissolued" but "vnfiltred" with "some feces [i.e., undissolved salt or impurities] in the

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[67] Add. MS 6788, fol. 247v. NB, a "vrinall" was a glass vessel used to receive urine for a medical examination.

[68] Add. MS 6788, fol. 247v.

[69] Ibid., fol. 245v and fol. 246v (25 July 1604).

bottom."[70] So he adds figures for further measures: "saltpeeter water inriched the measure full. Not boyled." (8190 grains), "The measure full of the saltpeter water after it was shot ... after boyling & cooling two dayes" (also 8190 grains), and "The like but 4 dayes cooling & one in water" (8178 grains). The attention to such details shows a systematic attention to the nature of the experimental substances, seeking to ensure the purity and stability of his samples. Once again Harriot uses the rule of alligation to establish proportions by weight and volume for the solution. The same day he performed similar experiments with copper sulphate. As with the saltpetre, he gives the weights of the solutions in various states ("filtred not boyled," "after boyling & cooling two dayes" and "After the same manner agayne but cooled in a pot of cold water a day & night"). Looking over his notes later that year (in November) he also revisited the question of the weight of the Syon water: "I weyed the measure of water that had stood ¾ yeare in the bolts head & setled feces; being filtred it weyed the same ... 1604. Novemb[er] 4."[71] Harriot's noting of weight variation in his experimental procedures shows him to be as scrupulous in his practical handling of the substances as he is in his mathematical calculations (no doubt because the variations in weight had consequences for the accuracy of his calculated proportions).

Perhaps the most interesting of his chymical experiments with the alligation technique is his work on mercury sublimate (Mercuric Chloride), which Harriot worked on in March 1605. On 13 March that year, Harriot took 3443 grains of "Venice [mercury] sublimate <in pouder>" and added it to a measure of water weighing 5730 grains, and shook them together creating a solution that weighed 8188 grains (see Fig. 8).

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[70] Ibid., fol. 246v (25 July 1604).

[71] Add. MS 6788, fol. 245v (25 July 1604). A 'bolts head' is a globular flask with a long cylindrical neck, used in distillation.

Having already established by previous experiment that “the [mercury] sublimate is as 55 to 10 of water & quicke [silver] it is as 135 to 10,” Harriot notes that “The sublimate therefore is lighter by <the> vitrioll & salt with which it was sublimated. The which doth beare to water as 25 to 10, vt proximè.” The question provoked by these different ratios is: “In sublimate therefore it is required what proportion there is of [mercury] to salt, both in weyght & bulke. Which is answered thus.” What Harriot is doing here, I would suggest, is a relatively sophisticated form of chymical analysis – establishing the proportion of salt to mercury by weight and volume in the sublimate. To do this he uses the rule of alligation, inserting the known ratios between the various substances and water (135, 55 and 25), and calculating that the proportion between the two components (mercury and “salt vitrioll”) are as $18\frac{2}{11}$ to $36\frac{9}{11}$ or “a litle more then 2 to 1,” in weight, and 3 to 8, or “a little lesse then 1 to 3” in volume.

The investigation here is prompted by questions other than those driven by Harriot’s need to calculate the specific gravities for the purposes of his work on falling bodies. It is instead driven by a restless curiosity to understand the nature of mixed substances, enabled by the tool of proportional mathematics. Essentially Harriot is using alligation in the opposite way to which it was used by physicians. If the physician wanted to *compound* medicines, Harriot was seeking to *decompose* an existing substance.

He was also interested in the application of the rule of alligation to its more conventional metallurgical purpose – the alloying of metals in minting coins (a question also central to a number of the sources which Harriot had consulted whilst designing his own experimental programme). Between 18 and 25 September 1604, for example, Harriot weighed English coins (gold angels and silver shillings) in air and water, having calculated the specific gravities of “pure” silver and gold, and then calculated the difference in the mass of water equal to masses of gold, silver and quicksilver.[72] These monetary applications were later pursued by Harriot's mathematical colleague Walter Warner (1563-1643), together with Charles Thynne (1568-1652), when they were both in the employ of Sir Thomas Aylesbury (1576-1657), who became Master of the Mint in 1635.[73]

As so often happens in life, external events brought an untimely end to Harriot's investigations of specific gravity. The last dated series of experiments was on 28 June 1605.[74] In early November, after his patron's suspected involvement in the Gunpowder Plot, Harriot was imprisoned in the Gatehouse Prison in Westminster, and letters he sent requesting his release to Robert Cecil and the Privy Council were ignored until at least the end of the year.[75] He does not seem to have returned to the topic after his release.

Conclusion

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[72] Add. MS 6788, fols. 102r.-108r.

[73] See Walter Warner, "Ad praxim statica Elementa quædam accomoda," Northamptonshire Record Office, Isham Lamport MS 3422, I, fols. 1-8; see also British Library, Harley MS 6754, fols. 2-74. The debt of Warner's approach to that of Harriot can be seen in Isham Lamport MS 3422, I, fol. 9r, in the following theorem: "Yf a solid body of a hevier substance then water be severally waighed in the aire and also in the water, the excesse of the waight thereof in water, is in the waight of so much water as is equall in magnitude to the solid body so waighed. This may be assumed as demonstrated in the statik elements"; this is an English translation of the first theorem of the *Elementa*, ibid., fol. 1r. On Warner, Thynne and Aylesbury, see Noel Malcolm and Jacqueline A. Stedall, eds. *John Pell (1611-1685) and his Correspondence with Sir Charles Cavendish: the Mental World of an Early Modern Mathematician* (Oxford, 2005), 83.

[74] Add. MS 6788, fol. 242r.

[75] Shirley, *Thomas Harriot: A Biography*, 340-349.

If Matthias Schemmel was right to suggest that Harriot had Archimedes' work on floating bodies in mind as a way of understanding the behaviour of falling bodies (with the medium of air replacing that of water),[76] then his programme of research surrounding specific gravities had a particular significance for him, and might suggest that Harriot's experimental programme in the early 1600s provides further testimony of the importance of Archimedean mathematics in the development of natural philosophy in early modern Europe.[77] As Schemmel has noted, despite the fact that Harriot's work was unpublished and could not, therefore, have exerted any significant influence on the wider world of early modern natural philosophy, his work nonetheless provides a useful indicator of wider trends.[78] As we have seen, Harriot was not as original in his Archimedean approach to the topic of weight and volume as Sir William Lower might have assumed, and nor was Ghetaldi alone in pre-empting Harriot's work. A number of mathematicians in the second half of the sixteenth century responded to the provocation of Archimedes' solution to the problem of Hiero's crown, and all turned to proportional mathematics in order to resolve the question. While Jean Bodin might claim that François de Foix was the Archimedes of his age, many mathematicians tried their hand at solving the problem that Vitruvius had made so famous. What sets Harriot apart is not just that he integrated his findings on specific gravity into his investigation of falling bodies, but also that he saw the wealth of potential applications for the mixture of the experimental and calculatory techniques he employed, including the alloying of metals and chymical analysis.

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[76] Schemmel, *The English Galileo*, 141 and 149.

[77] On the significance of the Archimedean revival, see Domenico Bertoloni Meli, "Guidobaldo dal Monte and the Archimedean Revival," *Nuncius*, 7 (1992), 3-34.

[78] See Schemmel, *The English Galileo*, 1-6.

Acknowledgements

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