Essay on the Geography of Plants

ALEXANDER VON HUMBOLDT AND AIMÉ BONPLAND

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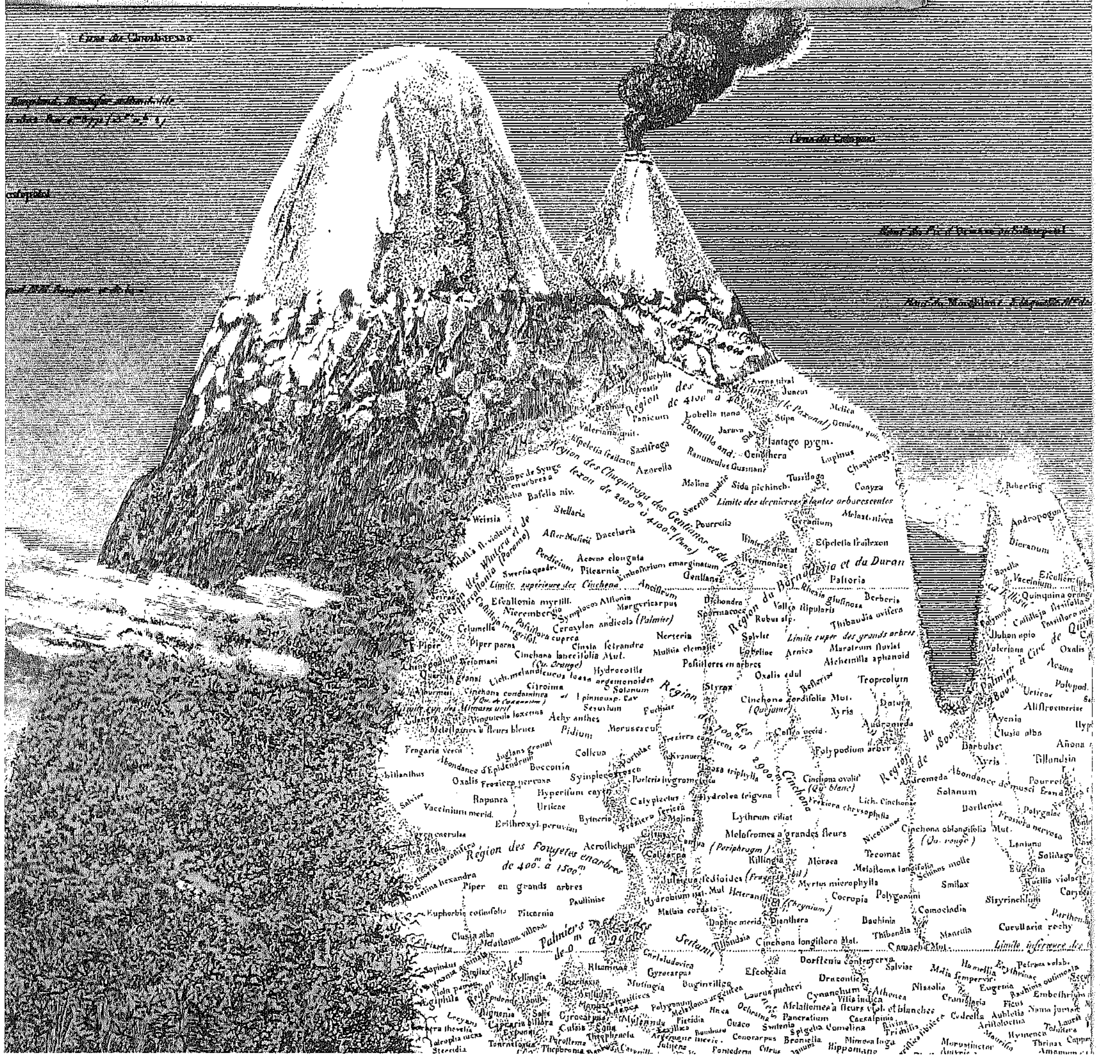

Instruments Utilized in Developing the *Tableau physique*

Stephen T. Jackson

Humboldt's *Essay* and his other writings contain an array of quantitative measurements—of spatial coordinates (latitude, longitude, altitude) as well as physical and chemical phenomena. The need for spatial precision was not as obvious in Humboldt's time as it is in ours. Modern science relies heavily on precise measurement of innumerable phenomena. Such precision for physical, chemical, and biological properties, however, was not universally accepted in the late eighteenth and early nineteenth centuries. Humboldt's obsession with precision and measurement followed a late eighteenth-century tradition of Lavoisier and other French scientists, which was still considered controversial. Lavoisier and his followers postulated that precise measurement of subtle variations in physical and chemical systems would reveal fundamentally important properties and principles. Others, particularly in England and Germany, viewed such variations as noise and precision a waste of time and resources.[1] In retrospect, Lavoisier and Humboldt were correct in principle, and sometimes in practice (e.g., Humboldt's geomagnetic measurements). However, many of Humboldt's instruments (e.g., the eudiometers) were not up to the task of detecting subtle variations; Humboldt's exacting efforts during his voyages often yielded meaningless numbers.

Humboldt took a large and diverse collection of instruments on his voyage to the Americas, with which he obtained many of the measurements used to compile the *Tableau physique*. He devotes several pages of the first chapter of the *Personal Narrative* to a detailed enumeration of his physical and astronomical instruments and their sources.[2] These instruments were state-of-the-art for his time, constructed of wood, glass, brass, and mercury, all packed in wooden cases. Humboldt, Bonpland, and their helpers hauled this arsenal for thousands of miles across Venezuela, the

1 This controversy is discussed in detail in Michael Dettelbach's 1999 essay, "The Face of Nature: Precise Measurement, Mapping, and Sensibility in the Work of Alexander von Humboldt."

2. Pages 34–40 in volume 1 of the translation by Helen Maria Williams (7 vols., 1814–29). The section describing the expedition's instruments was omitted from the translations by Thomasina Ross (1851) and Jason Wilson (1995).

Orinoco drainage, the Andes, and much of Mexico. This essay briefly discusses the instruments Humboldt used to obtain measurements for the *Tableau*, based on the "Physical Tableau" text itself, descriptions in the *Personal Narrative*,[3] and the general state of the art for physical measurement at the beginning of the nineteenth century.

Latitude, Longitude, and Elevation. Measurement of latitude using a sextant was straightforward at the time of Humboldt's voyage. Latitude determination was based on measurement of the angle of elevation of some celestial object (typically the midday sun) above the horizon. Humboldt had two sextants. The first was a high-performance Ramsden instrument with a ten-inch radius and high-magnification telescopes.[4] The second was a portable "snuff-box" sextant with a two-inch radius and weaker telescopes. Humboldt described this latter instrument as being especially convenient for making measurements on horseback or in a small boat.

Longitudinal determinations were routinely made using a chronometer, a high-precision portable clock that kept the time for a reference location (Paris in Humboldt's case). Longitude was calculated from the difference between local time and the time at the reference point. However, Humboldt frequently made more precise measurements astronomically by determining the local timing of astronomical events, particularly occultation of the moons of Jupiter. The event would be perceived as simultaneous across the globe, and tables of predicted times for specific reference points ("ephemeredes") could be used to determine longitude. This technique was proposed by Galileo in 1610 and perfected in the following century by Cassini and Rømer.[5] Humboldt also timed lunar eclipses and measured lunar distances (between the moon and the sun or certain stars) to estimate longitude (again using prescribed tables and formulas).

3. This essay does not include the many other instruments Humboldt took on the voyage, which included a microscope, surveying chains, a balance, a rain-gauge, various magnetometers, dipping-needles, and other geomagnetic equipment, evaporating pans, plant presses, dissecting tools, a small chemical laboratory (with glassware, reagents, etc.), galvanic equipment, and "a great number of small tools necessary for travelers to repair such instruments as might be deranged from the frequent falls of the beasts of burden."

4. Jesse Ramsden (1735–1800) was a prominent London instrument-maker. Ramsden had a reputation for designing and manufacturing high-precision instruments of various kinds. Among other things, he developed the Ramsden theodolite, a 200-pound monster of a surveying instrument. His theodolites were used in the late eighteenth-century Ordnance Survey of Britain, which served the basis for British maps until the mid-twentieth century. Humboldt carried Ramsden barometers, thermometers, and other instruments.

5. The history of methods for determining longitude is discussed for a general readership in Dava Sobel's *Longitude*.

Humboldt carried two chronometers. His primary one was by "Lewis Berthoud, No. 27,"[6] which had formerly "belonged to the celebrated Borda."[7] Berthoud's chronometer No. 9 is apparently the instrument that Humboldt took on his voyage.[8] Humboldt also carried a "demi-chronometer by Seyffert, serving for ascertaining the longitude at short distances."[9] He probably used this smaller, durable instrument during overland journeys when the Berthoud chronometer was likely packed and stowed for protection.

Humboldt's astronomical collection included a high-quality, three-foot achromatic telescope "by Dollond."[10] He also carried a smaller telescope which he could attach to tree trunks in the field.

Site-specific elevations were determined mainly by air-pressure estimates. Humboldt had two Ramsden barometers. Humboldt also measured the boiling-point of

6. Pierre Louis Berthoud (1754–1813) was France's leading maker of clocks and chronometers in the late eighteenth century.

7. *Personal Narrative*, vol. 1, p. 34, Williams translation. Jean-Charles de Borda (1733–99) was a prominent French physicist and military engineer who pioneered a number of navigational and cartographic methods, including the repeating-circle. Borda commanded a French warship during the American Revolution and was taken prisoner off Barbados following a severe battle with a superior British force. Borda's repeating-circle was the primary contender against Ramsden's theodolite in a classic English-French competition over which nation could build the more precise surveying instrument. The repeating-circle was far more portable than Ramsden's theodolite and easily its match in precision and accuracy.

8. Berthoud kept excruciatingly detailed records of his individual instruments, including their designs, repairs, and provenances. These have been summarized in a beautiful monograph by Jean-Claude Sabrier, *Longitude at Sea in the Time of Louis Berthoud and Henri Motel* (1993). Berthoud's No. 27 was made in 1793 for the Chevalier de Fleurieu. No. 26 was made in 1796 for the Chevalier de Borda, and was the first precision timekeeper made according to the Revolutionary decimal system. There are no records of either chronometer passing into Humboldt's hands. No. 26 was later owned by Alexis Bouvard (1767–1843), Director of the Paris Observatory. Berthoud's No. 9 was his first pocket marine watch, made in 1786 for Chastenet de Puységur. No. 9 was extensively tested by a committee at the Royal Observatory, leading to Berthoud's being awarded a lucrative prize for its design and accuracy. No. 9 was repaired by Berthoud and sold to Alexander von Humboldt in October 1798. In a December 1798 letter from Marseilles, Humboldt reported to Berthoud on its performance and closed by asking that "if you see our respected M. Borda express to him my gratitude for the happy advice that he gave me to acquire this superb chronometer." (All information from Sabrier; Humboldt quotation from 101–102.) The source of the discrepancy between Humboldt's *Personal Narrative* and Berthoud's records is not clear.

9. Johann Heinrich Seyffert (1751–1818) was a self-taught Dresden watchmaker.

10. Peter Dolland (1730–1820) was a London telescope-maker (and brother-in-law of Jesse Ramsden). Thomas Jefferson also purchased telescopes from Dolland.

water at various locations using "an apparatus by Paul,"[11] but he apparently did not use this as a means of elevational estimation.

Elevations of distant points were estimated using standard triangulation techniques, which were also applied to determining latitudes and longitudes in some cases. He had a variety of instruments for these purposes, including a repeating-circle by Le Noir[12] (used to calculate the angular or zenithal distance between objects in any plane), a theodolite by Hurter[13] (for measuring horizontal and vertical angles), a plane level, a quadrant, a graphometer (a simple form of theodolite), and a "lunette d'épreuve," which he used to measure small angles for distant points and to determine the progress of eclipses. Of these, the repeating circle, an instrument invented in the late eighteenth century by Borda, was the most precise. A pair of small telescopes mounted separately on independently rotating, concentric brass rings allowed the user to obtain a series of angular measurements from the same point with minimal error. Errors were further reduced by averaging the individual measurements within a series. Surveying techniques did not change appreciably for more than 150 years after Humboldt's voyage, although field instruments were made increasingly portable and compact.

Temperature. Humboldt's interest in temperature is obvious; he recorded thousands of temperature measurements during his travels. He carried a variety of thermometers of various sizes and scales, including a "thermometrical lead" for measuring water temperature at depth from a ship.

Hygrometry (Humidity). Hygrometry, the measurement of the moisture content of ambient air, was in a relatively primitive state in Humboldt's time. All available measures were based on the tendency of certain materials (wood, hair, catgut, bone, ivory, plant

11. Probably Théodore-Marc Paul (1760–1832), a prominent Geneva instrument-maker. Humboldt lists other Paul instruments (hygrometers, thermometers, magnetometer, cyanometer). It is possible some of these were made by Paul's father, Jacques Paul (1733–96), who made many instruments for Saussure and Deluc.

12. Etienne Lenoir (1744–1822), a skilled Parisian instrument-maker, built the repeating-circles designed by Borda, including those used in the great French meridional survey of Méchain and Delambre. In 1799, Lenoir crafted the archetypal meter-stick, the precisely machined platinum bar that served as the metric standard. Humboldt had other Lenoir instruments with him, including a dipping needle and a variation compass.

13. Humboldt's theodolite was built by Johann Heinrich Hurter (1734–99), a Swiss-born artist and instrument-maker who spent much of his later career in London. Hurter was a popular and well-known portrait artist and miniaturist; many of his enamels and miniatures can be seen in museums in England and elsewhere in Europe. He was also a skilled metal-worker, preparing gilt frames for his enamels and miniatures. These skills undoubtedly prepared him for his parallel career as a maker of scientific instruments after 1780.

fibers) to swell and shrink as they respectively absorbed or lost moisture to the atmosphere. Most could not be related directly to estimates of moisture content or relative humidity. Humboldt used a formula developed by Jean d'Aubuisson de Voisins (1762 [1769?]–1841), another of Werner's students) to estimate vapor content of the air from his hygrometric measurements.

Humboldt carried two hygrometers, both crafted by Paul in Geneva. The Saussure hygrometer used a human hair of approximately 12 inches length, fixed at one end with the other end suspended over a small cylinder and counterweighted with approximately 200 mg. The cylinder rotates upon an axis with a scaled dial attached. Contraction and lengthening of the hair under dry and wet conditions, respectively, rotates the cylinder and, accordingly, the dial. The scale runs from 0 (absolutely dry) to 100 (saturated). The relationship between the Saussure scale and modern relative humidity is logarithmic, and so the device is most accurate at moderate to high humidities.[14]

The other is described as a whalebone hygrometer of Deluc. This could refer to one of two Deluc designs. Deluc's earlier (1773) hygrometer used a thin cylinder of whalebone or ivory, filled with mercury, and fitted with a scaled glass thermometer-like tube. Under moist conditions, water absorption by the ivory would expand the diameter of the cylinder and the mercury in the tube would drop; in dry air evaporative loss would contract the ivory, driving the mercury up the tube. Obviously, this hygrometer required corrections for ambient temperature. Deluc's second (1791) design was similar to the hair hygrometer, except it used a very thin strip of whalebone instead of hair. Unlike Deluc's first design, it recorded lengthening and shortening of the whalebone rather than lateral expansion and contraction. It seems likely that Humboldt took this second, more portable Deluc instrument on his voyage.

Deluc and Saussure quarreled over the relative merits of their designs. Humboldt discussed his experience with the two hygrometers in the *Personal Narrative* (vol. 6, pp. 786–88, Williams trans.) with characteristic diplomacy. The Saussure instrument performed well under a variety of circumstances and served as the standard for Humboldt's measurements. He noted, however, that the Saussure instrument was unsuited for use in windy conditions. The Deluc hygrometer was especially sensitive to fine variations in humid conditions, but response-time was so slow in dry climates that Humboldt was "often uncertain whether we have not ceased our observations before the instrument has ceased its movement."

Electrometry. In modern usage, electrometry consists of measuring electrical charge or potential, and electroscopy consists of determining the existence of charge. Humboldt had two "electrometers," but one was actually an electroscope. The Ben-

14. Saussure's hair hygrometer was still in widespread use in the first half of the twentieth century, and was used in early aviation. F. J. W. Whipple's 1921 essay discusses the physical basis for Saussure's hygrometer and its relationship with relative humidity.

net electroscope, designed by Rev. Abraham Bennet in the 1780s, consisted of two leaves of gold foil, suspended from a conductor (usually brass) inside a glass jar. In the presence of strong static-electricity fields, the foil leaves repel each other. This device is essentially the same as the commercial or homemade electroscopes used in basic science-teaching.

Saussure's electrometer was the first instrument that actually measured charge quantitatively. Saussure's instrument was similar to the Bennet device, with two exceptions. First, instead of metal foil, the device consisted of two balls of elder (*Sambucus*) pith suspended on strings inside a glass jar. Second, the glass was marked with a scale so the distance between the pith-balls could be measured. Saussure's instrument was originally an electroscope with an ordinal scale—distance between the balls is not linearly related to the intensity of the charge. The discovery of Coulomb's Law in 1784 led to direct estimation of electrical charge using the calibrated device.

Blueness of the Sky. The color of the sky was determined using a "cyanometer by Paul," a set of colored tiles ordered in a gradation from a deep, dark blue (1) to a very pallid, near-white hue (16). Cyanometry was based on a scale developed in the Alps by Saussure, and Humboldt's cyanometer was calibrated against de Saussure's standards.

Chemical Composition of the Atmosphere. Humboldt's primary concern was whether the "purity of air"—the oxygen content of the atmosphere—decreased with elevation above sea level. Several eudiometers had been designed in the late eighteenth century, starting with one by Joseph Priestley. All were based on volumetric displacement following oxygen absorption by chemical reaction or combustion. Humboldt took two eudiometers on his voyage. One, "of Fontana,"[15] used nitric oxide; the other "by Reboul" used phosphorus. Both were imprecise in practice, and Humboldt's measurements proved useless. Humboldt's *Tableau physique* and discussion were based on measurements in Europe (mountain and balloon ascents), using better instruments designed by Volta (e.g., his "electric pistol") and Gay-Lussac.

Gravity. Point-measurements of the strength of Earth's gravitational field were made in Humboldt's time using a standard pendulum. In the *Personal Narrative*, Humboldt lists an "invariable pendulum" made in Madrid among his instrument collection. However, he appears not to have used it in during his extended field excursions. He specifically mentions using his "inclination meter" in the "Physical Tableau," yielding an uncalibrated series of gravity estimates at various points in the Andes. It is not clear which of the instruments in the *Personal Narrative* he refers to; evidently one of his surveying instruments was doubling as a field-portable pendulum.

15. Abbé Felice Fontana (1730–1805), Florentine chemist and physicist.

Biographical Sketches

Stephen T. Jackson

More than ninety individuals are named in Humboldt's *Essay*. Most of these names will be obscure to all but the specialist or historian today, but they include some of the leading scientists and naturalists of the eighteenth and early nineteenth centuries. Many of these individuals were personal acquaintances or correspondents of Humboldt. Following are brief biographical notes for most of these individuals. I have omitted several, including his draftsmen (Schoenberger, Turpin), his instrument-makers (Bennet, Leslie, Paul), and peripheral figures (mainly cited as sources for barometric or other data). The draftsmen and some of the instrument-makers are briefly described in my accompanying essays on the *Tableau physique* and Humboldt's instrument collection. I have added six men who played important roles in Humboldt's botanical thinking (J. R. Forster, Goethe) or his voyage (Jefferson, Montúfar), or were important in Humboldt's subsequent scientific pursuits related to the *Essay* (Arago, Kunth). I have also added a sketch for Helen Maria Williams, who, as Humboldt's English translator in the years following his voyage, was his primary conduit to English-speaking readers.

François **Arago** (1786–1853)

François Arago was Humboldt's most intimate friend during his years in Paris. He was trained in Paris as a mathematician by Siméon Poisson, and in 1805 was selected to continue the meridional survey initiated by Delambre and Méchain. He was joined in this by Jean Baptiste Biot. The survey took him through Spain in the middle of the Peninsular War, where a Frenchman with instruments would naturally be under suspicion of spying. He was imprisoned, escaped, recaptured, and then released, only to be captured again in the Mediterranean and imprisoned in Algiers. He was eventually released and made his way back to Paris in 1809, his survey notebook intact. Arago was given an appointment at the Paris Observatory, which he held for the rest of his life. Arago conducted research on a variety of physical topics, including magnetism, sound, and meteorology, but his most important contributions were in the physics of light. He had strong liberal/republican political views, and in his political career