NAVIGATION METHODS OF EUSEBIO FRANCISCO KINO, S. J.

by

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ONE of our treasured legacies from the Jesuit mission era is the beautiful and famous map "Passo por Tierra a la California," drawn in 1707 by Eusebio Francisco Kino, S. J., known to history as "The Apostle to the Pimas": maker of Christians and builder of missions. So accurate is this map that it did not become completely obsolete until 1912, when Lumholtz' map "Papaguería" was published.[1]

As might be expected, the Kino map was widely circulated and widely plagiarized during the early eighteenth century, so that many versions, many of them not credited to the original author, are now extant. Checking of this map against the best available today shows that all major features of Papaguería are shown in their correct interrelations to a rational scale ("Leguas Castellanas"), that the latitudes are all correct to less than a degree of arc, and that the longitudes are

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[1] Karl Kumholtz, *New Trails in Mexico* (New York: Scribner's, 1912).

all in reasonable proportion. And, as will be shown later, Kino had no way of making rigorous longitude determinations.

Field checking of the may amply demonstrates its practical utility. Almost any reasonably intelligent person using this map — and, in a few instances the descriptions from Kino's notes,[2] or the substantially parallel Manje notes[3] — can recover any site shown on the map, usually within a few hundred feet. This was actually done by the late Herbert E. Bolton in retracing hundreds of miles of Kino's trails; and the present writer has had equal success in the lavas and sand dunes around Pinacate, where Professor Bolton did not go.

Interestingly, although the "Passo por Tierra" is Kino's most famous map, it is not his only competent cartographic effort. Eight Kino maps, still extant, are listed by Bolton;[4] and it seems possible, from internal evidence in Kino's writings, that his total map output may have been as high as twenty. Checking of the known Kino maps, and consideration of the possible additional output not available to us today, both indicate that Kino's title "Royal Cosmographer," granted him in preparation for the Atondo expedition to Baja, California, was not an empty one.[5]

From the viewpoint of our present overspecialized culture — in which a student usually learns "more and more about less and less" until, on finally attaining the doctorate, he reputedly knows "everything about nothing" — it is somewhat surprising to find that a man extensively trained in theology, as was Father Kino, was also an expert in cartography as well as several other fields from architecture to astronomy. Such multiple competences, however, are not uncommon, and apparently never were. Leonardo da Vinci, known to us as an artist, was also a competent inventor and engineer; Sir Isaac Newton, discoverer of the Laws of Gravitation and Motion and one of the developers of

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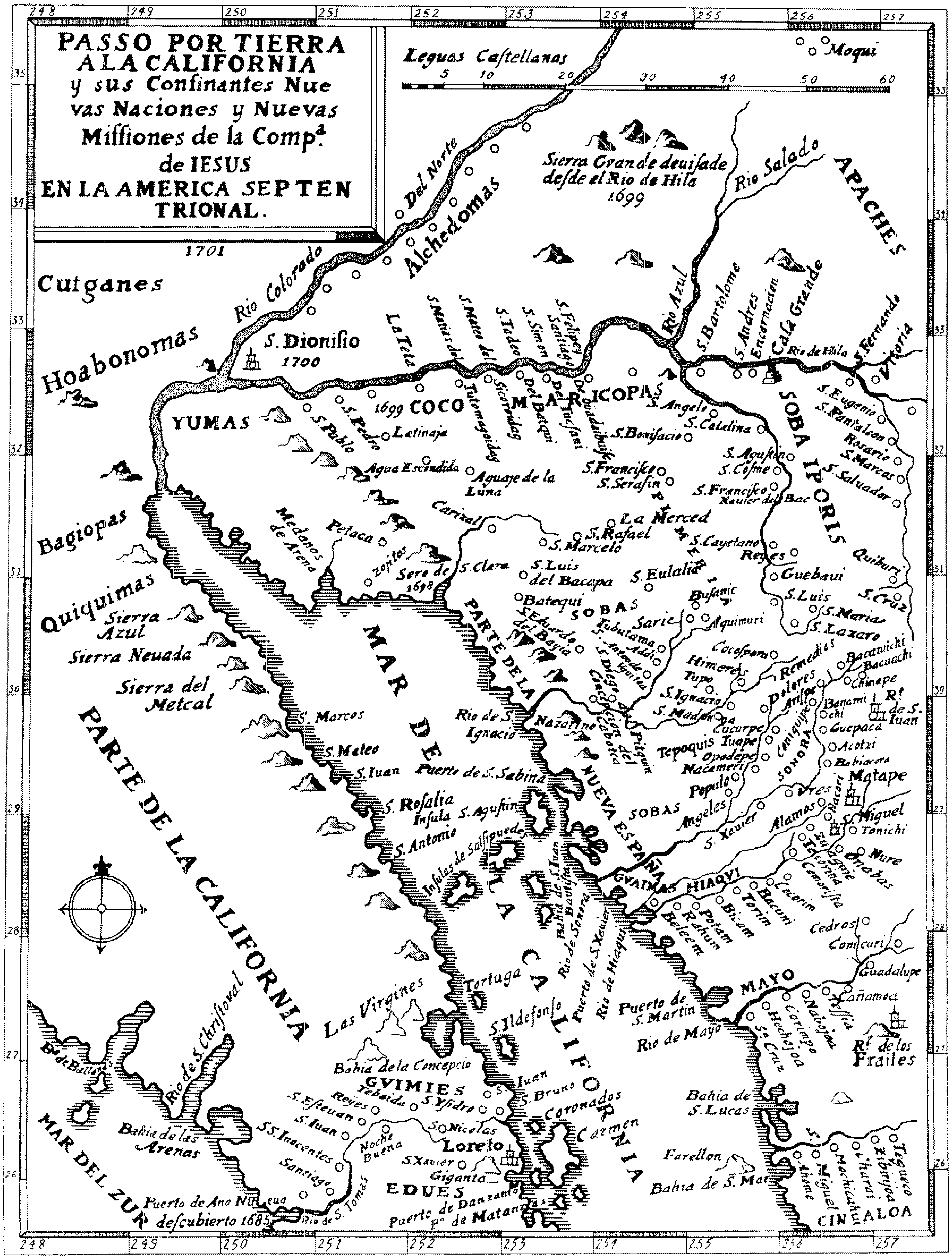
[2] See H. E. Bolton, *Kino's Historical Memoir of Pimeria Alta* (Cleveland: Arthur H. Clark Company, 1919), *passim;* Bolton, *Rim of Christendom: A Biography of Eusebio Francisco Kino, Pacific Coast Pioneer* (New York: Macmillan, 1936); Ernest J. Burrus, *Kino Reports to Headquarters* (Rome: Inst. Hist. S. J., 1954).

[3] See Juan M. Manje, *Unknown Arizona and Sonora, 1693–1701,* trans. and ed. Harry J. Karns (Tucson: Arizona Silhouettes, 1954).

[4] *Rim of Christendom,* pp. 606–610.

[5] *Ibid.,* p. 75.



DRAWN 1701 BY EUSEBIO FRANCISCO KINO, S. J.

TRACED 1948 BY R. L. IVES

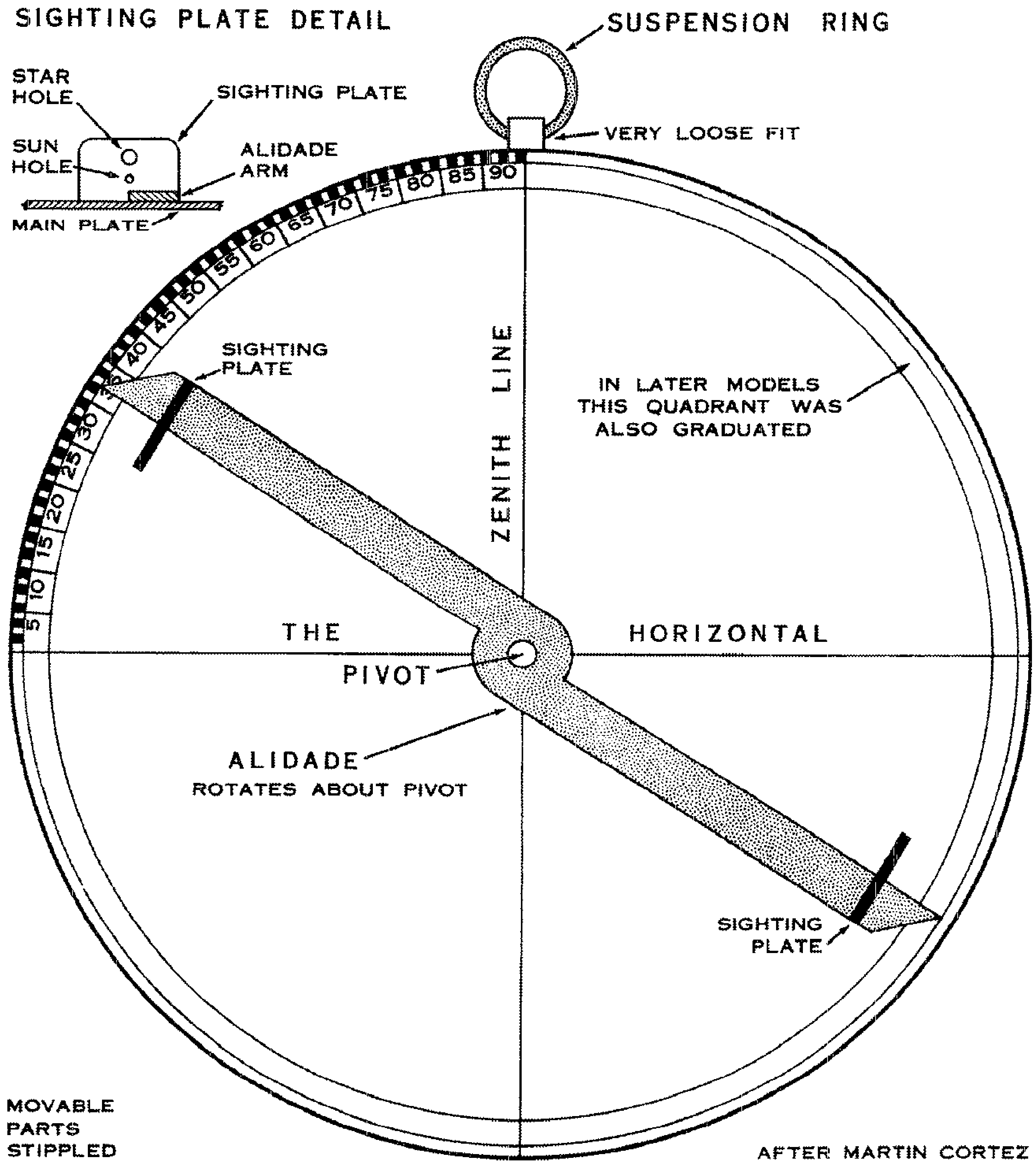


Fig. 1 Summary diagram of a mariner's astrolabe, or shipman's quadrant, based on diagrams and descriptions by Martin Cortes (ca. 1551).

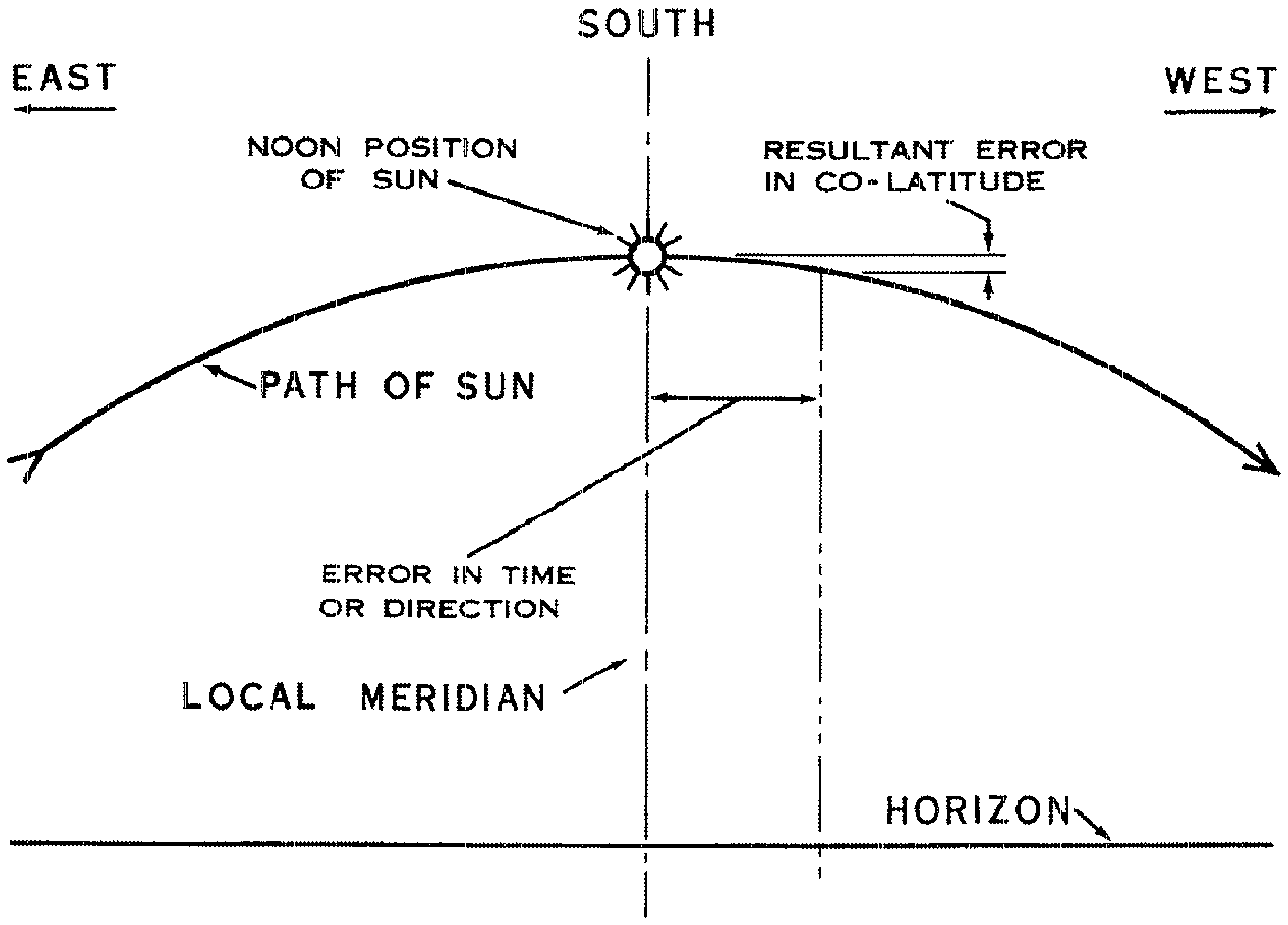


Fig. 2. Errors in meridian altitude sights.

the Calculus, was better known in his lifetime as a theological researcher; William Henry Jackson, pioneer photographer of the American West, was also a painter of respectable attainments and author of a number of meritorious historical papers.

Because of the great breadth and depth of Jesuit training, and of careful personnel selection, we should expect to find a large number of multiple-talented men in that famous order, and such has been the case for more than four centuries. An outstanding early example was Athanasius Kircher, whose published works include a pioneer attempt to decipher the Egyptian heiroglyphics, a very good early work on geology[6] and a description (perhaps the first) of the now-familiar projection lantern. Today we find that Jesuits are substantial contributors to most fields of learning, a current example being Father Daniel J. Linehan who, during a recent tour of duty in Antarctica with primary duties as a geophysicist, was also expert in getting radio signals through the Aurora Australis and reputedly was able to fix "anything from a troubled conscience to a malfunctioning radar."

Modern science is indebted to the Sonoran Jesuits for many gems of scientific observation, among which are Juan Nentvig's [supposedly] description of the geodes of Oputo,[7] Cristobal de Cañas' [supposedly] summary of Indian ceremonial dances,[8] and Pfefferkorn's lucid description of the habits and attributes of the *zorillo.*[9] Kino's own "quest of the blue shells,"[10] which was collateral to his field explorations, was actually a competent ecological investigation, and probably the first American use of "tracers." From direct evidence, largely collected by Bolton, we learn that he also had specific training and associations qualifying him for advanced cartographic work.

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[6] *Mundus Subterraneus* (Amsterdam, 1665).

[7] "*Rudo Ensayo,*" trans. and ed. Eusebio Guiteras, *Records of the American Catholic Historical Society of Philadelphia,* v. 5 (1894), pp. 214–215. Cf. R. L. Ives, "The Geodes of Oputo," *Rocks and Minerals,* v. 23 (1948), pp. 387–391; Ignaz Pfefferkorn, *Description of Sonora,* trans. and ed. Theodore E. Treutlein (U. of New Mexico Press, 1949), p. 82.

[8] "The Sonoran Census of 1730," trans. and ed. Ronald L. Ives, *Records of the American Catholic Historical Society of Philadelphia,* v. 59 (1948), pp. 319–339.

[9] *Description of Sonora,* pp. 115–116. Cf. the substantially parallel account in *Rudo Ensayo.*

[10] Considered in Bolton, *Kino's Historical Memoir of Pimeria Alta,* v. 1, pp. 46, 55, 195, 230, 231, 234, 237, 241, 259, 272, 310, 317, 322, 342, 352; v. 2, pp. 87, 170, 174, 185, *passim.* (Similar coverage is given in *Rim of Christendom.*)

The ample records summarized by Bolton show that Kino studied at the famous Jesuit colleges of Trent, Hala, Freiburg, Ingolstadt, Munchen, and Oettigen.[11] These were the Yales, Harvards and Caltechs of seventeenth-century Europe. While at Ingolstadt he studied under Fathers Adam Aigenler and Henry Scherer, both outstanding geographers of their time and authors of important works. While still a student Kino was invited to become a professor of mathematics under the patronage of the Duke of Bavaria. Kino's mathematical studies were undertaken because of the great prestige of mathematics in China, where he hoped to go as a missionary. Because of this same missionary desire, Kino did not accept the proffered professorship in Bavaria. From other sources we know that Kino was familiar with at least parts of Giovanni Battista Riccioli's *Tables;*[12] and at least one member of the Kino party which visited Sierra de Santa Clara in 1701 was sufficiently familiar with the writings of Athanasius Kircher to reason correctly from them. This led to the first North American identification of the extinct volcano Pinacate before the usually-credited discoverers of extinct volcanoes (Desmarest and Guettard) were born.[13]

Academically, then, Father Kino was certainly well prepared for a career as a cartographer. Practically, and prior to his coming to the New World, Kino demonstrated that his knowledge was not just rote memorization of lectures and textbooks. On his voyage from Genoa to Cádiz, he assisted the captain of his ship in the taking of latitudes. Later, while in Spain awaiting passage to America, Kino and his companions constructed a number of compasses and sundials. During his stay in Cádiz Kino observed the famous comet of 1680, giving specific figures on its trajectory and rate of travel. These, plotted on a star map, agree closely with other records of the same comet, indicating clearly

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[11] See Bolton, *Rim of Christendom*, pp. 32–38.

[12] *Georgraphia et Hydrographia Reformata* (Bologne, 1661; Venice, 1672); *Astronomia Reformata* (Bologne, 1669). Father Riccioli, an astronomer of great competence, reportedly was assigned the task of writing an omnidemolitive study of Copernicus' *De Revolutionibus Orbium Coelestium*, then regarded as false and heretical. This study (resulting in the publication, ultimately, of the *Astronomia Reformata*), led Riccioli to the persuasion that the Copernican system (heliocentric) was far superior to the ancient and then accepted Ptolemaic system (geocentric). Largely as a result of Riccioli's studies, the Copernican system became universally accepted.

[13] See Ives, "The Discovery of Pinacate Volcano," *Scientific Monthly*, v. 54 (1942), pp. 230–238.

that Kino's knowledge of astronomical observation was sound and practical. His later description of the comet, published in Mexico in 1681,[14] is a curious mixture of sound science and contemporary beliefs in signs and portents. It is thus clear that, on arrival in Mexico, Father Kino not only had adequate training in the art and science of cosmography, but also had demonstrated his ability to apply that training to the solution of actual problems.

From internal evidence in his own writings and from the diaries and reports of his field companions, we can state with certainty that Father Kino's navigation instruments consisted of a compass – which was probably equipped with a gnomon, so that it could also be used as a sundial – and a telescope and an astrolabe. His navigation handbook was Adam Aigenler's *Tabula Geographic-Horologa Universalis,*[15] which included selected portions of Riccioli's *Tables.*[16] This work, specifically mentioned in Kino's diary,[17] antedated both Bowditch and Weems.[18] Careful checking of Aigenler's Latin text shows that the accuracy of his method was superior to the best instruments available in his time, and consequently that many of the deficiencies of seventeenth-century cartography and navigation were due to instrumental inadequacies rather than to lack of technique.

We have no full description of Kino's compass, but we do know that he made one or more instruments which were combinations of compass and portable sundial; and from this we can assume with some confidence that his field instrument was such a combination. As the design of the mariner's compass was fairly well standardized before 1550 and has not changed greatly since that date, the compass used by Kino probably differed little from those available today – and the method of use in 1700 was almost identical to the most modern methods.

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[14] *Exposicion Astronomica de el Cometa Que el Año 1680. . . .*

[15] (Ingolstadii [Ostermayri], 1668).

[16] Tables of latitude and longitude from Book 9 of Riccioli's *Geographiae Reformatae* are appended to Aigenler's *Tabula Geographico-Horologa Universalis.* Incidentally, Aigenler credits his source fully – an uncommon practice at that time.

[17] See Bolton, *Kino's Historical Memoir of Pimería Alta,* p. 330.

[18] Nathaniel Bowditch, *Practical Navigator* (Salem, 1801); P. V .H. Weems, *Air Navigation* (New York: McGraw-Hill, 1938). Bowditch's manual is still current, after innumerable reprintings and a few revisions. Current editions, titled *The American Practical Navigator,* are available from the Government Printing Office, Washington 25, D.C.

Although it was known before Kino's time that the magnetic compass did not everywhere indicate true north, we have no direct evidence that he made corrections for local magnetic variation, which is now about 12 degrees East in most of Papaguería. As Kino's maps and observations do not contain the errors which would occur if compensation were not made for such variation, we can assume either that this variation was substantially zero in 1700 – which is improbable – or that he corrected for it, at least approximately. This correction is rather easily made for a small area, such as Papaguería, by the standard and well known method of comparing magnetic north, as indicated by a magnetic compass, with true north, as determined by a sight on Polaris.[19] The observed difference is then applied to all magnetic bearings taken thereafter, giving a reasonably valid true north anywhere in the area for a few years after the observation is made. Because magnetic variation is not fixed – due in part to migration of the magnetic poles – local corrections become obsolete in a relatively short time.

Kino set down no detailed description of his telescope, but, as this instrument first became generally known to Europeans about 1609, it was still, in Kino's time, an "advanced" scientific instrument. Although Galileo in 1610 made telescopes having magnifications up to 33, it seems probable that Kino's telescope, which was portable, had a magnification not greatly exceeding 10, an objective not over 2 inches in diameter, and a resolution not better than perhaps 3 seconds of arc. Numerous refracting telescopes, made for use at sea after about 1650, had these characteristics. A better telescope, having a greater magnification, larger objective, and better resolution, was surely available by 1685; but just as surely Kino did not have one. Such a telescope would have been portable only with difficulty, usable only if mounted on a tripod, and usable then only for a few minutes to a few hours a day because of atmospheric turbulence which interferes even with naked-eye observations in the Sonoran Desert.

All of the latitudes specifically recorded in Kino's works were measured by use of an astrolabe, an instrument completely unfamiliar to most twentieth-century readers. In its basic form, the astrolabe is an open-sight pendulum clinometer. As commonly made, the instru-

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[19] Noted by Kircher, *Magnes Siue, De Arte Magnetica* (Colonia Agrippina, 1643). Cf. Frederic H. Lahee, *Field Geology* (New York: McGraw-Hill, 1941), pp. 422–423, 493–495.

ment performed additional functions, serving as a star-finder, a nocturnal clock, or even as a crude form of circular slide rule.

The origin of the astrolabe is lost in the mists of antiquity. Some historians cite excellent evidence to show that it originated in India, some time before the Christian era. Others cite equally good evidence to show that the instrument was developed by Babylonian astrologers, possibly as long ago as 2,000 B.C. Certainly the calibrations on the instruments surviving today show Bablylonian influence, as the circle is divided into 360 degrees, a Babylonian, and not a Hindu, division. The instrument was early adapted by Arab astrologers, who brought it to Spain, perhaps as early as 800 A.D. Knowledge of the astrolabe was officially brought to the Christian world by Gerbert (The Necromancer) of Aquitaine, who studied under the Moorish scholars in Córdova from 967-970, learning not only the use of the astrolabe, but also the decimal system, Arabic numerals, and the "black arts" of algebra and trigonometry.[20] On returning to the Christian world Gerbert taught extensively for twelve years, then advanced rapidly, becoming Abbot of Bobbio (983), Archbishop of Rheims (991), Archbishop of Ravenna (998), and Pope Sylvester II (999-1003). His astrolabe, still extant, has been described in detail by Robert T. Gunther.[21]

By the latter part of the sixteenth century, the astrolabe was shorn of its astrological attrributes, and became a utilitarian scientific instrument. Some of the finest astrolabes ever built are the work of Humphrey Cole (*ca.* 1575), who reputedly made all of Sir Francis Drake's navigation instruments. Many of these instruments, as well as a variety of others of Spanish and Portuguese manufacture, are preserved, many of them in working condition, in a group of British museums.[22] With them, in many cases, are the detailed instruments for their use, and descriptions of just how they were made. A typical mariner's astrolabe, also known as a shipman's quadrant, is illustrated in the summary dia-

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[20] See Horace K. Mann, *The Lives of the Popes in the Early Middle Ages* (London, 1910), v. 5, pp. 91–120.

[21] *Astrolabes of the World* (Oxford U. Press, 1932), v. 1, pp. 230–231; illustrated in Plate LII(2). This instrument, dated A.D. 990, is in the Galileo Tribuna, at Florence, Italy.

[22] Especially the National Maritime Museum, Greenwich; the Science Museum, South Kensington, London; the British Museum, London; the Museum of the History of Science, Oxford; the University of St. Andrews, Fife, Scotland; and Albert Institute, Dundee, Scotland.

gram comprising Fig. 1. This is based on a diagram by Martin Cortez, which, with accompanying descriptions, gives all necessary data for the construction and use of the astrolabe. Geoffrey Chaucer, better known for his *Canterbury Tales*, also wrote a description of the Astrolabe and its use.[23]

Essentially, the mariner's astrolabe consists of a main plate, with a suspension ring loosely mounted at the top. When hung by the ring, the zenith line was vertical, and the horizontal line, at right angles, horizontal. Pivoted at the intersection of the zenith and the horizontal was an alidade, which contained a sighting plate at each end. One or more quadrants of the main plate were divided into degrees, usually numbered with zero at the horizontal, and ninety at the zenith (as in Fig. 1). The sighting plates contained two holes, one, the star hole, "as bigge as may conteyne a great pinne," and the other, the sun hole, "so subtile and small as a fyne sowyng needle." These were aligned so that a line of sight through them was parallel to the line between the two pointers of the alidade.

Because the suspension ring, even when fitted very loosely, had some friction, early mariners recommended suspending the astrolabe "by a thread or lyne." (This difficulty was, of course, less with astrolabes having chain suspension.) In order to measure the angular elevation of any celestial object except the sun above the horizon, the astrolabe was suspended (by string or chain) so that it hung vertically, much like a plumb bob; the alidade was rotated about its pivot until the star could be seen through the "greate holes;" and the angle of elevation was then read at the pointer of the alidade adjacent to the graduated quadrant. (The angle indicated in Fig. 1 is 32°.)

To obtain higher accuracy, a few astronomers, and a very few mariners, rotated the alidade 180 degrees, and repeated the observation. The two values so obtained were then averaged, in an effort (sometimes successful) to secure a more accurate value. Similarly, when two quadrants of the astrolabe were graduated, a few careful workers repeated their measurements, using first one quadrant, and

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[23] *A Treatise on the Astrolabe* (1391). This was many times reprinted, after its first printing in London by Wm. Thynne in 1532. An excellent modern version is contained in Volume Five of R. T. Gunther's *Early Science in Oxford* (Oxford U. Press, 1929).

then the other, in the belief that the average value would be more accurate than any single value. Although these refined methods are mathematically sound, they were not very much used, as they involved the complicated processes of addition and division, which were difficult for mariners who had trouble counting above ten without taking off their sea-boots.

Measurement of the angular elevation of the sun, or, as it was more commonly stated, its altitude, was performed in a different manner, as the sun cannot be directly viewed many times without permanent ocular damage. A method of doing this, dated 1545, follows:

> To take the altitude of the Sunne, hange up the Astrolabe by the rynge: and set the Aluidada against the Sunne. And rayse it or put it downe in the quarter that is graduate, untyll the beames of the Sunne enter in by the lyttle hole of the tablet or raysed plate, and precysely by the other lyttle hole of the other tablet. Then looke uppon the lyne of consydence. And howe manye degrees it sheweth in the quarter that is graduate (beginnynge fro the horizontall lyne) so many degrees of height hath the Sunne....[24]

Although these instructions are approximately 400 years old, they are still valid today, and would apply quite well to the use of a modern pendulum clinometer or bubble sextant. In a modern handbook, we would modernize the spelling a bit, substituting our modern "madde consystencie" for the archaic forms.

The latitude of any point on the earth's surface is defined as the angular distance of that point from the equator. By modern convention, the latitude of the equator is zero, that of the poles is 90 degrees, the arithmetical sign of latitudes north of the equator is positive (+), and that of points south of the equator is negative (—). Although Kino used these conventions, they were not universally accepted until the beginning of the nineteenth century, so that some old maps list latitudes as measured from "el polo del Norte," or "el polo Boreal." We now call such designations co-latitudes, and the change from co-latitude to latitude is made by substracting the co-latitude from 90 degrees.

Perhaps the earliest method of determining latitude was by measuring the angular elevation of the pole star, which gave an approximate latitude directly. This method was crudely satisfactory in high

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[24] From Martin Curtes, *The Arte of Nauigation* — "Translated out of Spanyshe into Englyshe by Richard Eden, 1561."

and middle latitudes, marginally useful in low north latitudes, and useless south of the equator, where Polaris could not be seen.

If we assume, as did the earliest navigators, that the pole star, Polaris, is always directly overhead at the north pole, and that it is infinitely distant, then it should be, and approximately is, on the horizon at the equator. At intermediate points on the earth's surface, the angular elevation of Polaris should be the latitude. As long as measurements were relatively crude, so that the elevation of Polaris was expressed in "fingers above the horizon," this method works well. Fifteenth-century navigators using it usually made landfall within a hundred leagues or so, north or south, of this desired destination.

Early astronomers, perhaps during the time of the Ptolemies, found that Polaris was not exactly over the pole, but revolved about the celestial pole (the infinite extension of the earth's axis), so that the elevation of Polaris was not always a true indicator of latitude. In 1000 A.D. Polaris was about 7 degrees from the celestial pole, this distance reducing to 3½ degrees by about 1500, 2 degrees in 1700, and about 55 minutes today. This change is due in large part to the precession of the equinoxes, which run a full cycle in about 26,000 years.

Early mariners were aware that something was amiss with their computations, but found that latitudes taken by the pole star method were consistent if the observations were made when the "Guardes" (such as the star *Kochab,* in *Ursa Minor*) were always in the same position. By the mid fifteenth century, this knowledge was organized into the "Rule of the North Star," so that substantially correct latitudes could be measured by Polaris observations at any time that Polaris was visible, and a number of ingenious mechanical devices were available to correct for the difference between the elevation of Polaris and that of the celestial pole.[25] With improved instruments and information, this method is still useful today,[26] particularly in "survival navigation."

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[25] See D. W. Waters, *The Art of Navigation in England in Elizabethan and Early Stuart Times* (Yale U. Press, 1958). Consult Waters' internal index under "Regiment of the North Star."

[26] See Ives, "Atemporal Polaris Correction," *Economic Geology,* v. 53 (1948), pp. 419–426; Ives, "Latitude Determination Without a Sextant," *School Science and Mathematics,* v. 48 (1948), pp. 441–445.

The other effective early method of determining latitude was by measuring the meridian altitude of the sun. This method depends for its operation on several fundamental relations in the solar system. The intersection of a plane through the earth's axis and any surface point is a north-south line, called the local meridian. When the sun is observed to be on the local meridian, it is local noon, and the sun is at its maximum elevation for that day.

Twice each year, at the equinoxes, which occur about March 22 and September 22, the noon sun is directly overhead at the equator and the elevation of the noon sun is the co-latitude of the point from which it is measured. At all other times, because the plane of the equator is inclined about 23½ degrees to the plane of the earth's orbit (the ecliptic), the noon sun is not directly overhead at the equator, and the observed meridian altitude is not the true co-latitude of the point of observation.

Because all major motions in the solar system are regular and systematic, the angular difference between the solar meridian altitude at any point and the co-latitude of that same point, known as the sun's *declination,* can be computed in advance for any day. These corrections were first systematized by the Jewish astronomer, Zacuto of Salamanca, about 1475. After simplification for navigational use by a commission under King John II of Portugal, these tabulated corrections, in various forms, and under various titles, became a permanent part of every navigator's armamentarium. Known in Elizabethan times as "The Regiment of the Sun," and included in Aigenler's *Tables,*[27] they today form an important part of the Nautical Almanacs published annually by all major maritime nations.

Measurement of the latitude by the meridian altitude method, on any clear day of known date, using an astrolabe (or equivalent instrument), and having available a table of solar declinations, is a relatively simple process. The angular altitude of the noon sun is measured with the astrolabe. To it is applied the declination correction for the date. The result is the co-latitude. Subtraction of this from 90° gives the latitude. If local noon is certainly known, or if true south is determined in advance of the observation, only a single "shot of the sun" is

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[27] *Tabula Geographic-Horologa Universalis,* p. 19.

required. If noon is not certainly known, or if the direction of true (not magnetic) south is uncertain, successive observations are taken, beginning shortly before noon, and continued until the solar elevation stops increasing. The time of maximum solar elevation is local noon, and the direction of maximum solar elevation is true south, in the northern hemisphere.

Most fortunately, this method of latitude determination is not only simple, but also insensitive to minor errors of time, direction, or date. At and near local noon, the angular elevation of the sun changes very slowly, as in Fig. 2, so that a small error in the timing or direction of the sun sight produces an even smaller error in the co-latitude measurement.

Because the solar declination takes 182½ days to make its cyclic change of 47 degrees, average daily change in declination is only about 15½ minutes of arc. This means that "missing the date" by one day will produce an error of about 15 nautical miles in the north-south position. This will be somewhat more at the equinoxes, when the declination changes rapidly, and less at the solstices, when declination change is slow, but the error from this cause will never be as much as a day's walk, and hence usually the true position will be within "sight distance" of the supposed position, erroneously determined.

An astronomer or navigator will point out, correctly, that the usual tables of solar declination are correct only for a single meridian — that for which they were computed — so that an error in longitude determination will result in an erroneous declination correction, and hence in a wrong latitude computation. This is a pertinent objection, as we know that Kino's longitude determinations leave much to be desired.

Numerical evaluation of this error shows that if the longitude is "off" by fifteen degrees (about 900 miles at the equator), the declination error will be about 1/24 of the interdiurnal change, or approximately 34 seconds of arc. This averages out to about 3,400 feet — little more than the traditional "arquebus shot"!

In his memoirs, Father Kino clearly describes how he measured latitudes:

> At midday [March 3, 1702] we took the altitude of the sun with the astrolabe, and found it to be fifty-two degrees, which, adding to it the six and a half of south declination of that day, made fifty-eight degrees and a half.

> The complement to ninety degrees is thirty-one degrees and a half, and this was the . . . geographical latitude in which we found ourselves.[28]

This is a succinct description of the determination of latitude by the meridian altitude method. The declination for the day was obtained from Aigenler's handbook, which Kino brought with him "to the Indes and even to these now conversions." The important "Tabella Declinationum Solis ab Æquatore" is contained in this manual.[29]

From Kino's own writings, confirmed in large part by Manje's diaries,[30] we know that the latitudes shown on his maps were instrumentally determined, by the sound and practicable meridian altitude method. We also know that Kino's instrument was an astrolabe, and that he found his declination corrections in Aigenler's Tables, which are substantially correct.

A detailed study of the latitude errors in Kino's maps, reported elsewhere,[31] shows that Kino's astrolabe, which probably was not over 12 inches in diameter, had an index error of perhaps 11 minutes of arc around the 60-degree point. This small an index error indicates that it was a good instrument, well cared for. The mean deviation of all latitude observations attributed to Kino, which can be checked against modern geodetic observations, is 9.09 minutes of arc (read this "about 9 minutes," as the 0.09 given by the computations is probably without significance), which amounts to an error of only about 1/60th of an inch on a 12-inch astrolabe! Few skilled observers, either in 1700 or today, could consistently do as well!

The longitude of any point on earth is the angular distance, measured at the equator, between the meridian through that point and the index meridian. Today, by international agreement, we use the meridian of Greenwich, England, as the index (or prime) meridian, and describe longitude in angular degrees east or west of Greenwich. In Kino's time, there was less agreement among nations, but many Spanish maps used the meridian through the "Islands of Dogs" (Canary Islands) as the index, Tanarive (Tenerife) being on the usually-

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[28] Bolton, *Kino's Historical Memoir of Pimería Alta,* p. 341.

[29] Aigenler, *Tabula Geographico-Horologa Universalis,* p. 19.

[30] See Manje, *Unknown Arizona and Sonora.*

[31] Ives, "California no es Ysla . . .," *Records of the American Catholic Historical Society of Philadelphia,* v. 64 (1953), pp. 189–198.

chosen prime meridian. Use of an arbitrarily-chosen and mutually agreed-upon prime meridian is necessary because there is no convenient celestial indicator of the meridian of Greenwich (or any other meridian). This same "Heavenly fault" greatly complicates determination of longitude, particularly at sea, so that there was a lapse of almost 2,000 years between a clear understanding of the problem, and its consistent practical solution.

At some unknown time before the beginning of the Christian Era, Greek astrologers and navigators became aware that each difference in longitude was related to a difference in time, and were vaguely aware that if the time difference between two places could be learned, the longitude difference could also be determined. Although the Greek ideas seem quite rational (even though our information is largely based on copies of copies of copies of the original writings, some of them many times translated), the ancients probably could not make effective use of their knowledge, because they lacked effective time measuring devices. In 1522, Gemma Frisius of Louvain, a teacher of Gerald Mercator, clearly stated the longitude problem as follows:

> When the sun is directly overhead at any point on the earth's surface, it is [local] noon at that point, and at all points on the meridian running through it. At any position east of it, toward the sun's rising, it is already past noon; west of it, it is not yet noon. If the difference in time could be found, could not this be used to find the position of these places with reference to one where it was, say, already noon? As the earth in 24 hours rotates through 360°, in one hour it rotates through 15°, in one minute through 15′. Clearly position east and west could be found if time could be accurately measured.[32]

Frisius' pertinent words "If time could be accurately measured" explain why, even though sound methods of longitude determination were surely known to European navigators at least as early as 1522, consistent determinations of longitudes at sea were not possible until after 1761.

The portable timepieces of Frisius' time were accurate to about a quarter of an hour a day, when the temperature was reasonably constant, when the instrument was not jiggled around too much, and when the rest of the mechanism was working approximately right.

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[32] Explained fully in William Cunningham, *The Cosmographical Glasse* . . . (London, 1559).