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ORBITAL OPERATIONS STUDY
Technical Report No. 2

PROPOSED NAUTICAL UNITS OF LENGTH AND TIME

John C. Bellamy April 1965

This is the second of a series of technical reports of an Orbital Operations Study by the Natural Resources Research Institute sponsored largely by Grant No. NsG 658 of the National Aeronautics and Space Administration. It proposes the use of some new "nautical" units of length and time which were conceived during this study of the data acquisition, conversion and utilization problems of orbital operations. It is planned that this report be widely distributed and published elsewhere in order to bring the basic concepts involved to the critical attention of all who could profit by their adoption for operational use. Supplementary reports illustrating specific operational potentialities of these units are also soon to be published under the (tentative) titles: The Extent of Gravispheres; Values of Nautical Constants; A Nautical Definition of Altitude.

PROPOSED NAUTICAL UNITS OF LENGTH AND TIME

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PROPOSED NAUTICAL UNITS OF LENGTH AND TIME

John C. Bellamy

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1. Purpose

The purpose here is to define some units of length and time which might well be adopted as standards for coordinating the space-time positions of occurrences throughout, especially, the Earth-centered region of the universe.

The need for and potential utility of these units have been derived in an Orbital Operations Study with and for the National Aeronautics and Space Administration. Its purpose, as outlined in its Plan of Study,[1] is to help establish more productively effective ways of controlling "orbital operations", defined to be "the activities of utilizing satellites in free-fall orbits around, especially, the planet Earth". The effectiveness of such control can be measured largely by the extent, quality and utility of the scientific, engineering and operational data that the orbital operations produce. The utility of such data can be measured, in turn, by how well they serve to coordinate the space-time positions of occurrences throughout the regions in which satellites operate and which they observe. The units of length and time proposed here offer a means of making these coordinating operations much more conveniently and usefully productive.

More specifically, this Orbital Operations Study is concerned with better ways of portraying the information contained in vast amounts of quantitative data. Inherent to this problem is the selection of characteristically appropriate units with which to formulate the quantitative values to be portrayed. It is especially important that appropriate space-time coordinate systems and associated units of length and time be found, defined and used. Otherwise the basic goal of "portraying clear numerical pictures" of the occurrences of interest has been found to verge upon the impossible.

2. Kinds of Units

It is useful for this purpose to recognize three general classes of units. The first, which can be called "primary standard units of measure", is that class of basic units in terms of which all other units are defined as particular numerical multiples. Currently it includes the orange-red spectral line of Krypton 86 for length, the International Prototype Kilogram for mass, and the tropical year of 1900, January, 0 days, 12 hours for time.

The second class of units can be called "characteristic units" in the sense that they are defined to be characteristic of some particular natural occurrence. For example, the length of the International Prototype Meter was originally established so that as nearly 10,000,000 meters as practicable would be contained in a meridianal quadrant of the Earth's surface. Similarly the mass of the International Protoptype Kilogram was established so that it is as nearly equivalent as practicable to the mass of 1,000 cubic centimeters of water. The period of a second was selected so that as nearly 86,400 seconds as practicable would be contained in each solar day. These characteristics have been maintained in current definitions by selecting 1,650,763.73 as the defining number of Krypton 86 wave lengths in a meter, and by selecting 31,556,925.974 7 as the defining number of ephemeris seconds in the 1900.0 tropical year.

The third class of units can be called "customary units". They are units with which many people are accustomed, or whose use maintains a continuity of knowledge and data derived from and associated with well established custom. Such "customary units" thus include "characteristic units" such as the meter and kilogram which by now have become customary for many people and purposes. In particular, the metric units of the International System of Units[2] fall into the class of "customary units" in comparison with the newly proposed "characteristic units" of concern here.

In basic principle the units proposed here are defined as particular, appropriately selected, numerical multiples of the primary standard units of measure. It is frequently more convenient, however, to define them as being convenient numerical multiples of some other, previously defined, units. In such cases their basic definitions are understood to be the complete (or non-rounded) numerical products of however many such defining numbers might be required to express them explicitly in terms of primary standard units of measure.

3. Circumferential Units of Length

For example, the international nautical mile is now defined to be that characteristic unit of length which contains exactly 1,852 meters. This definition implies that, in basic principle, the nautical mile is defined to contain exactly 1,852 times 1,650,763.73 or exactly 3,057,214,427.96 wave lengths of the primary standard Krypton 86 spectral line. The characteristic feature of the nautical mile is that it is as typically representative as practicable of the length of one minute of great-circle arc anywhere on the Earth's surface. The nautical mile is also a customary unit of length since it has long been used, and is increasingly being used, as the primary unit of length in operations such as nautical and aeronautical navigation.

The nautical mile is also typically representative of the newly conceived characteristic units being proposed here. They as well as the meter and kilogram all share the common purpose of providing for convenient coordination of the values of two or more associated things. In the case of the kilogram, it has been defined so that the mass of any amount of water, when expressed numerically in kilograms, will be as nearly equal as practicable to the volume of that amount of water expressed in either liters or thousands of cubic centimeters. In the case of the nautical mile and the meter, they have both been defined to provide for as near numerical equivalence as practicable between angular and linear measures of horizontal distances between any and all points on the surface of the Earth.

The conceptual difference between the nautical mile and the meter is thus only that they are to be used with different angular units. When the degree-minute-second system of angular measure is used to evaluate latitudes and longitudes, then the use of the nautical mile provides for the desired near numerical equivalence of angular and linear distances. If, on the other hand, latitudes and longitudes were to be evaluated with the decimal (or 100 grad per quadrant) units of angular measure, then the desired near numerical equivalence would be provided by using the meter as the unit for evaluating horizontal distances.

Evidently the choice of sexagesimally units of length and angle is advantageous for many purposes. Especially, their similiarity to the hour-minute-second unit of time provides for a highly desirable near-numerical-equivalence of values of all three of time and angular and linear distances on the surface of the Earth. It thereby also provides for the use of exceptionally convenient and useful units of angular and linear velocities and accelerations, of which the explicit unit of velocity called the knot is an outstanding example.

Greater use of this way of intercoordinating values of angles, lengths, times, velocities and accelerations can be achieved by defining and using a more complete, sexagesimally related, set of units of length. Toward this end, the "nautical foot, chain and span", defined to be 1/6000, 1/60 and 60 times the length of a nautical mile, have recently been proposed.[3,4] Their utility stems from the fact that they are typically representative of the length of one centisecond, one second and one degree, respectively, of great-circle arcs anywhere on the surface of the Earth.

One of several advantageous characteristics[3,4] of these particular nautical units of length is that two of them are virtually customary units. The length of one nautical foot or chain fortuitously differs from the length of the now customary foot or engineer's 100 foot chain by only about 1 part in 80, or by only about one and one quarter percent. Consequently those who are now accustomed to thinking in terms of feet and chains can as readily think in terms of nautical feet and chains. For example, they could readily utilize a "nautical yard" whenever it might be advantageous to do so without having to define it formally. It is quite self-evident from its name that a nautical yard is equal to 3 nautical feet, or that exactly 2,000 nautical yards are contained in a nautical mile, or that a nautical yard is exactly equal to 1,852/2,000 or 0.926 meters.

Evidently the choice of the names "nautical foot" and "nautical chain" was apt since those names, of themselves, can lead to the use of units such as a "nautical pace or fathom", a "nautical yard" or even a "nautical inch" insofar as it might be desirable to do so for some particular purpose. In contrast, the name "nautical span" neither conveys a concept of its size nor infers what other related units might be. Consequently it is suggested here that the name "nautical deg" could better be used to identify that 60 nautical mile unit of length which is typically characteristic of the length of one degree of arc on the Earth's surface. Units of length called the "nautical quad" and "nautical circ" could then be used insofar as it might be useful to do so. It would be virtually self-evident that they refer to units of length which contain exactly 90 and 360 nautical degs, and which are typically characteristic of the length of quadrants and circumferences of the Earth's surface.

4. Radial Unit of Length

In this respect, the entire biosphere in which we and our supporting flora and fauna live is all at very nearly the same distance from the center of the Earth. Consequently the task of coordinating positions has heretofore been concerned primarily with horizontal positions, and it is greatly simplified by defining and using the preceding kinds of characteristic subdivisions of the Earth's horizontal circumference. It has also been of more academic than operational importance how far from the center of the Earth the thin-shell biosphere happens to be, or what explicit radial distance happens to be associated with these nautical subdivisions of the Earth's circumference.

Now that we have started to explore, travel and live outside this thin-shell biosphere, however, the vertical or radial dimension has been added to the operational problem of coordinating positions. This has in turn engendered a need to define and utilize units of length which are characteristic of radial rather than circumferential distances. For example, it is very conveniently important to be able to utilize whichever of the nautical mile or the nautical deg might better serve a particular purpose, even though the conversion factor between them is the relatively simple number sixty. In comparison, sixty is a much simpler conversion factor than those which involve the incommensurable ratio of π between circumferential and radial measures of length.

The task of selecting an appropriate characteristic unit of length for radial distances is not, however, difficult once the need for it is recognized. Clearly the length of the nautical circ divided by 2π (or about 3,437.746···nautical miles) is typically characteristic of distances from the center of the Earth to its surface. The desired radial unit of length can thus well be defined with a convenient, definite number, counterpart of this incommensurable number. Specifically, it is recommended that it be defined to be exactly 3,437.75 nautical miles. This choice provides, among other things, the convenience of being exactly equivalent to a whole number (6,366,713) of meters, a whole hundreds number (6,875,500) of nautical yards, and a whole hundreds number (20,626,500) of nautical feet.

This radial unit of length might appropriately be called either the "nautical radius" or the "nautical rad." The latter name has been derived much as the names "circ, quad and deg" in terms of their characteristic associations and is recommended here. In the expected event that these several nautical units of length find wide acceptance and use, the adjective "nautical" is likely to be dropped in their everyday use. In that event the single word "radius" would be entirely unsuitable. In addition, the many other closely related uses of the word "radius" tends to make the term "nautical radius" connote more some kind of physical constant to be measured than a unit of length with which to measure. This later connotation is clearly associated with names such as mile, foot and meter and could well soon become associated with the name "rad".

The full name "nautical rad" seems to be especially appropriate. It is, for example, typically representative of any one of the semi-diameters of the Earth which astronauts might observe in the future in order to determine their distances from the Earth. Its representativeness for such purposes is indicated by the lengths of the semi-major and semi-minor axes of the International Reference Ellipsoid of the Earth. These standard equatorial and polar radii are currently defined to be 6,378,388 and 6,356,912 meters or, equivalently, 1.001 834 and 0.998 461 or 1-0.001 539 nautical rads.

The definitions of these proposed nautical units of length are summaried in Table I. This table also contains rounded values of equivalent numbers of meters, statute feet and statute miles to provide for conversions to and from data expressed in terms of these currently customary units of length.

5. Nautical Units of Time

A somewhat similar need to identify and define a new unit of time has arisen in conjunction with our freeing ourselves from the thin-shell biosphere. This need first become evident in the development of aeronautical celestial navigation, in which it has been found that the needs for frequent and rapid star fixes can well be served with clocks which keep sidereal rather than mean solar time. It is also now quite evident[5] that celestial techniques of navigation are likely to become an inherent if not indispensable part of astronautics, or hence that the convenience of time-keeping with the sidereal kind of time might become virtually an astronautical necessity. In addition, the orbital parameters basic to all Earth-centered astronautics are inherently associated more closely with the period of rotation of the Earth with respect to the fixed stars than with either the sidereal or mean solar kinds of time.

This need to define a new unit of time has, in basic effect, been engendered by the recent adoption[6] of the ephemeris second as the primary standard unit of time. Previously the period of rotation of the Earth with respect to the fixed stars was the primary standard measure of time, and both the sidereal and mean solar units of time were defined numerically in terms of that period. Now that the primary standard measure of time is the tropical year of 1900, however, none of the mean solar day, the mean sidereal day nor the period of rotation are now "units" in the strict, numerically defined, sense of the word. Rather they have now become "physical constants" whose periods are now subject to continual observational determination.

Significantly, the ephemeris second has been defined to be a characteristic counterpart of the now variable mean solar second. But no such characteristic counterpart has yet been defined for either the sidereal day or the period of rotation of the earth. To remedy this lack, the "nautical" units of time defined in Table II are proposed to serve as numerically and invariably defined units which are as usefully characteristic as practicable of the period of rotation of the Earth with respect to both the equinox and the fixed stars.

These nautical units of time can conveniently be thought of as being ideal units of time associated with an ideal planet in much the same way that an ideal gas is utilized as an easily conceived gas whose states are readily computable. That ideal planet is conceived as being precessionless so that there is no need to distinguish between either its tropical and sidereal years or its sidereal day and period of rotation. This ideal planet is also conceived to have periods of revolution and rotation such that the ratio of the length of its year to its solar day is exactly equal to the conveniently round 365.25 ratio between the Julian year and ephemeris day. In that case exactly one more, or exactly 366.25, of that ideal planet's sidereal days and rotational periods (or, in short, of its nautical days) is contained in its year.

The potential utility of these ideally simplified units of time is illustrated by nautical-day evaluations of the observed lengths of mean sidereal days and periods of rotation of the Earth. As indicated in Table II, they are only about 6 and 4 parts per hundred million smaller and larger, respectively, than the nautical day, and these very small differences are only about 6 and 4 times larger than the temporal variability of the Earth's period of rotation. Consequently the length of the nautical day can well be used as "the" length of either or both of these periods for most practical purposes. For purposes in which distinctions are important, the nautical day can also well serve as a standard value to which only very small corrections need be applied to obtain precise values of either of these periods.

The definition of the nautical units of time in terms of the Julian year is quite appropriate since the Julian year is one of the primary standard units of time. As summarized at the bottom of Table II, for example, the primary standard measure of time is now the geometric mean longitude of the Sun. Hence the primary standard unit of time measure can well be considered to be the Julian century with which the variable T in Newcomb's time-defining equation is evaluated. Parenthetically, Newcomb's equation for values of T might well be called "Newcomb's Law" now that all measures of time are physically and legally defined with it.

In addition, Julian years and centuries are the basic ordinal or entry variable of ephemerides.[6] Consequently a nautical calendar, which would contain exactly one more day per Julian year than the ephemeris-time calendar, could usefully and readily be formulated. It would provide, among other things, a convenient way of entering ephemerides in terms of the indications of whatever nautical time-keepers might be found to be useful.

The name "nautical" for these new units of time also seems to be quite appropriate. Alternate names such as "inertial" or "stellar" units of time could reflect one, but not both, of their dual characteristics. On the other hand, "nautical" reflects both of these characteristics since it is in astronautical operations that they both are likely to be utilized most frequently. In addition, these "nautical" units of time are closely related to the nautical units of length through their close mutual association with the Earth's mean sea level surface. The size of that surface is represented by the size of the nautical units of length, and its nearly ellipsoidal shape is directly related to its period of rotation or, most characteristically, to the "nautical" units of time.

6. Space-Time Coordinates

In summary, the nautical units of length and time have been defined so that:

- The several circumferential units of length provide as near numerical equivalences as practicable between angular and linear measures of distance on the surface of the Earth;

- The nautical rad is characteristically representative of the nominal radial distance of those circumferential units of length from the center of the Earth; and
- The nautical units of time are characteristically representative of the speed of rotation of those nominally Earth-bound units of length with respect to the equinox, the stars and, especially, the orbital planes of earth-satellites.

The potential utility of these characteristics are illustrated by the following discussion of ways in which the space-time positions of things are coordinated on and among a wide variety of topographic, weather, aeronautical and astronautical charts.

For example, occurrences of and on the surface of the Earth's lithosphere are coordinated primarily by the horizontal latitude and longitude coordinates with which features of the land are positioned on topographic and aeronautical charts. The space-time positioning of things such as aircraft is then greatly facilitated by utilizing the nautical mile and knot to evaluate and coordinate their distances and velocities of travel with respect to latitudes and longitudes and, thereby, with respect to the features of the land.

Similarly, occurrences of and in the Earth's atmosphere are coordinated[7,8] by positioning characteristic features of the atmosphere with respect to the latitude and longitude coordinates of upper air "weather" charts for several different barometric levels of the atmosphere. Again the use of the nautical mile and knot greatly facilitates the coordination of horizontal distances and velocities of air movement with respect to the ground, and hence of aircraft movements with respect to features of both the ground and the atmosphere.

By analogy, occurrences in and of the space outside the Earth's aeronautical atmosphere are soon likely to be coordinated by routinely charting its characteristic features much as the features of the land and atmosphere are now charted. In this case, however, two quite different kinds of angular coordinates of horizontal positions are involved and will frequently need to be intercoordinated. In one, coordinates such as latitude and longitude are attached to or remain at rest with respect to the solid Earth. These coordinates provide for conveniently positioning natural features of the Earth's ionsphere, Van Allen belts, etc. On the other hand, coordinates such as declination and sidereal hour angle remain virtually at rest with respect to the stars and the orbital planes of satellites. The intercoordination of space-time positions could evidently be greatly facilitated by utilizing the characteristic period of rotation of these two kinds of horizontal coordinate systems with respect to each other (or, in short, the nautical units of time) as the unit of time in both systems.

In comparison with operations within the biosphere or even the relatively thin-shell atmosphere, orbital operations inherently involve much wider ranges of radial or vertical positions. Consequently the charting of occurrences outside the atmosphere will undoubtedly involve many more vertical cross-sections than has heretofore been necessary, and the radial geometric distance from the center of the Earth is one of the primary coordinates to be charted on such cross-sections. The frequent contemporary use of number of "Earth radii" attests well to the appropriateness of the rigorously defined nautical rad as an appropriate unit of length for this purpose.

Occurrences throughout several horizontal surfaces of near-Earth space will undoubtedly also be charted routinely in the near future. Many of these horizontal surfaces are likely to be those surfaces which are traversed by observational satellites which have been emplaced in as nearly circular orbits as practicable. The horizontal positions of conditions observed by such satellites could well be charted with respect to some latitude and longitude kind of angular coordinates. A single map projection could then serve as a basic chart for all such surfaces.

In that case, however, the choice of units with which to identify the particular surface being charted becomes critically important, and the number of nautical rads from the center of the Earth could well serve this purpose. That number of nautical rads would be the scale factor of the chart in relation to the scale factor of the most familiar of all such charts, namely charts of the Earth's mean sea level surface. The intercoordination of angular and linear distances on the charted surface could then also be readily accomplished in terms of length units such as "chart degs, miles or chains". The ratio of each of them to the nautical deg, mile and chain would be equal to the number of nautical rads in the nominal chart radius. Also, the ratios of the lengths of radial and circumferential units listed in Table I are the ratios of the lengths of any such "chart radius" to corresponding "chart degs, miles, chains, etc."

The choice of surfaces to be so observed and charted depends in large part upon how easily they can be coordinated with other surfaces. It would thus be desirable for this purpose to establish the orbits of observational or surveying satellites at conveniently round numbers of nautical rads from the center of the Earth. Alternatively, and for some purposes much more advantageously, their orbits could be selected so that the observational satellites would revolve around the Earth an integral number of times during each rotation of the Earth.

Or, more generally, vertical positions in orbital space can best be coordinated for some purposes geometrically and for others chronometrically, and the need to intercoordinate values of such geometric and chronometric vertical coordinates is becoming an increasingly important operational task. As an initial step toward facilitating this task, Kepler's Law

$$a^3 n^2 = GE\ (1+m/E) \qquad (6.1)$$

has been used to compute the values listed in Table III of orbital mean distances, a, for round values of orbital periods, $p = 1/n$, and frequencies, n, and vice versa. For these calculations, the ratio m/E of a satellite's mass to the Earth's mass has been neglected with respect to unity, and the Earth's gravitational constant GE has been assumed to have the recently determined[9] value of

$$GE = 398{,}603\ (\text{kilometers})^3\ (\text{radians/ephemeris second})^2 \qquad (6.2)$$

or, equivalently, of

$$GE = 290.461\ (\text{nautical rads})^3\ (\text{revolutions/nautical day})^2 \qquad (6.3)$$

Of the orbits listed in Table III, the one with a frequency of 6 revolutions per nautical day (or with a period of 4 nautical hours) would be especially convenient for space-surveying satellites from a coordinate-transformation point of view. Since no two such satellites would be in exactly the same orbit, the chart for the surface that they would be surveying could better be drawn for a typical rather than any "actual' surface and period. Consequently a "four hour period chart" could also be considered to be "2 nautical rad" chart on which the length of "chart degs, miles and chains" would each be equal to 2 nautical degs, miles and chains, respectively. In this regard, the listed distance of 2.006 nautical rads for this period is itself a "typical" approximation since it has been computed from Kepler's Law without corrections for pertubations by the Sun, the Moon or the distribution of mass within the Earth.

The one per nautical day orbit is especially worthy of attention. If this orbit were also equatorial the satellite would remain stationary with respect to the Earth and there would be no need to transform between orbital and fixed-to-the-Earth coordinates. Since such satellites encounter space-conditions at only one point in Earth-bound coordinate systems, however, they are not very useful for surveying the spatial distributions of occurrences in space. Rather such stationary satellites are evidently much more useful for purposes such as relaying communications and observing the weather. The nominal radial distance of this exceptionally important class of satellites might well be considered for most purposes as being the conveniently round radius of 6.625 or 6 5/8 nautical rads. The difference between this value and the Kepler-Law value of 6.62261 nautical rads is well within the effects of pertubations or the accuracy of emplacing satellites in orbit.

Significantly, this task of interrelating geometric and chronometric coordinates of vertical position in orbital space is analogous to that of interrelating geometric and barometric coordinates of vertical position in the the atmosphere, and to that of interrelating linear and angular coordinates of horizontal position. It is evidently advantageous in each case to select coordinates and units of length and time which will provide the kind of near numerical equivalence between linear and angular distances that is provided by the nautical units of length. As recently pointed out,[3,4] a similar near numerical equivalence could well be achieved by adopting the nautical foot for evaluations of geometric elevations and barometric altitudes in the atmosphere. By analogy, Table III seems likely to be the forerunner of tables of a "standard gravisphere" with which similarly related geometric and chronometric radial coordinates could well be defined.

7. Conclusion

The preceding discussion indicates some of the potential advantages of using characteristic units such as the nautical units of length and time. As an extreme but not now unrealistic example, colonists on Mars would obviously find it prohibitively inconvenient to run their clocks on Earthly ephemeris time. Rather, units of time which are characteristic of the periods of rotation and revolution of Mars will undoubtedly be defined for use in such colonies even before they become colonized.

The obvious advantages of such characteristic units are, however, counterbalanced by some just as obvious disadvantages. The most apparent disadvantages are (1) the difficulty of gaining acceptance of new, unfamiliar, units even by those who would profit most by their use, and (2) increased needs, after their adoption, to convert among data expressed in terms of different units. This second disadvantage seems especially serious in view of the large number of sexagesimally related units of length which might well be used for different purposes, and which would be different in each of the several operational regions around other planets.

This unit-conversion problem is evidently of primary importance to those general kinds of science whose purpose it is to interrelate all kinds of physical phenomena, whether they be of sub-nuclear or extra-galactic scale. It is of little importance for this purpose whether the units to be used are characteristic of any particular one of the multitude of kinds and scales of phenomena involved. Rather it is of much greater importance that but a single set of units become customary for evaluating them all so that they can be interrelated with as few and as convenient data-unit conversions as possible. The International System of Units[2] is well suited for this purpose since it is already the customary system of units for most scientific work. It is a useful but not critical bonus in this regard that its units of time and mass are also characteristic of the solar day and the density of water.

But then this is only one kind of data conversion problem of primary importance for but one general kind of purpose. Aeronautical and astronautical operations, for example, are specifically concerned with only one particular kind and scale of phenomena, and hence the ease of comparison with other kinds and scales of phenomena are of little direct importance to their basic purposes. Rather it is of primary importance for their purposes that characteristic units be used which will simplify as much as possible their continual day-by-day or even minute-by-minute data conversions among different kinds of coordinates as discussed above.

Similarly, the unit-conversion problem is of more importance to the general purposes of science than for the specific purposes of some of its specialized branches. For example, a basic purpose of sciences such as geodesy, geology, oceanography and meteorology (and a similar not-yet-named Earth-centered space science) is to map and predict the distribution of natural occurrences throughout their specific regions of interest. They, like aeronautical and astronautical operations, are thus primarily concerned with the ease of their day-by-day needs to convert among the several coordinate system which are characteristic of their specific regions of interest. Consequently, as illustrated by the basic geodetic intent of the definition of the meter, their day-by-day data conversion problems can much better be served by units characteristic of their region than by whatever other units might previously have been customary for their own or other scientific purposes.

Indeed, the establishment of new characteristic units for specific purposes can well be considered to be an important ultimate purpose of standardizing upon the International System of Units for general scientific work. Insofar as that standardization helps to gain knowledge of the characteristics of specific things or regions, so also does it help to establish those units with which those specific things and regions can be most concisely and usefully characterized. This process is well illustrated by the way in which the metric units of length were themselves necessarily derived from measurements of the size of the Earth with some other, then customary, units of length. This process is apparently one of the most effective ways of summarizing and utilizing hard-won scientific knowledge, both operationally and in subsequent searches for more specific knowledge.

In other words, no one set or system of units can possibly best serve all of the multitude of human purposes. Rather, successes gained in a continual search for units which can better serve specific purposes are in large measure milestones of progress. This is obviously true of (1) the original definition of the metric system of units, of (2) the subsequent definition of the primary standard measures of length and time in terms of the Krypton 86 wave length and of the mean astronomical longitude of the Sun, and of (3) whatever primary standards of measure will be found in the future to better serve the particular purpose of numerically defining and interrelating the multitude of units needed to serve many other specific purposes. Hopefully the adoption of the nautical units of length and time proposed here will prove to be a milestone of progress in air and orbital operations.

It is thus concluded that these nautical units of length and time should be tried in the court-of-use in aeronautical, astronautical, meteorological and Earth-centered space survey operations. There is good reason to think that their combination of basic metric-system rationale and near English-system sizes might well be the key to the units problem which is currently blocking[3,4] the mutually dependent progress of meteorological and aeronautical operations. Early operational use-trials are especially important since they could well forestall the development of a similar units problem between the astronautical and space-survey aspects of orbital operations.

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Table I

NAUTICAL UNITS OF LENGTH

{Numbers in braces are the exponents, n, of exponential factors, 10^n}

1 Nautical Foot = 1/6,000 nautical miles = 308 2/3 millimeters
= 3.086 667{-1} or {9.489 4897-10} or 1/3.239 741{ 0} meters
= 1.012 686{ 0} or {0.005 4748 } or 1/9.874 730{-1} statute feet
= 1.917 966{-4} or {6.282 8408-10} or 1/5.213 857{ 3} statute miles

1 Nautical Yard = 1/2,000 nautical miles = 920 millimeters
= 9.26 {-1} or {9.966 6110-10} or 1/1.079 914{ 0} meters
= 3.038 058{ 0} or {0.482 5961-10} or 1/3.291 577{-1} statute feet
= 5.753 897{-4} or {6.759 9621-10} or 1/1.737 952{ 3} statute miles

1 Nautical Chain = 1/60 nautical miles = 308 2/3 decimeters
= 3.086 667{ 1} or {1.498 4897 } or 1/3.239 741{-2} meters
= 1.012 686{ 2} or {2.005 4748 } or 1/9.874 730{-3} statute feet
= 1.917 969{-2} or {8.282 8408-10} or 1/5.213 857{ 1} statute miles

1 Nautical Mile = 1,852 meters
= 1.852 { 3} or {3.267 6410 } or 1/5.399 568{-4} meters
= 6.076 115{ 3} or {3.783 6260 } or 1/1.645 788{-4} statute feet
= 1.150 779{ 0} or {0.060 9921 } or 1/8.689 762{-1} statute miles

1 Nautical Deg = 60 nautical miles = 111,120 meters
= 1.111 2 { 5} or {5.045 7922 } or 1/8.999 280{-6} meters
= 3.645 669{ 5} or {5.561 7772 } or 1/2.742 981{-6} statute feet
= 6.904 677{ 1} or {1.839 1433 } or 1/1.448 294{-2} statute miles

1 Nautical Quad = 5,400 nautical miles = 10,000,800 meters
= 1.000 08 { 7} or {7.000 0347 } or 1/9.999 200{-8} meters
= 3.281 102{ 7} or {7.516 0198 } or 1/3.047 756{-8} statute feet
= 6.214 209{ 3} or {3.793 3858 } or 1/1.609 215{-4} statute miles

1 Nautical Circ = 21,600 nautical miles = 40,003,200 meters
= 4.000 32 { 7} or {7.602 0948 } or 1/2.499 800{-8} meters
= 1.312 441{ 8} or {8.118 0797 } or 1/7.619 390{-9} statute feet
= 2.485 684{ 4} or {4.395 4458 } or 1/4.023 038{-5} statute miles

1 Nautical Rad = 3,437.75 nautical miles = 6,366,713 meters
= 6.366 713{ 6} or {6.803 9153 } or 1/1.570 699{-7} meters
= 2.088 817{ 7} or {7.319 9003 } or 1/4.787 400{-8} statute feet
= 3.956 092{ 3} or {3.597 2664 } or 1/2.527 747{-4} statute miles

= 2.062 65 { 7} or {7.314 4256 } or 1/4.848 132{-8} nautical feet
= 6.875 5 { 6} or {6.837 3043 } or 1/1.454 440{-7} nautical yards
= 2.062 5 { 5} or {5.314 4256 } or 1/4.848 132{-6} nautical chains

= 3.437 75 { 3} or {3.536 2743 } or 1/2.908 879{-4} nautical miles

= 5.729 583{ 1} or {1.758 1229 } or 1/1.745 328{-2} nautical degs
= 6.366 204{-1} or {9.803 8805-10} or 1/1.570 795{ 0} nautical quads
= 1.591 550{-1} or {9.201 8203-10} or 1/6.283 183{ 0} nautical circs

where 1 meter = 1,650,763.73 Kr86 Wave Lengths
1 statute foot = 0.3048 meters
1 statute mile = 5,280 statute feet = 1,609.344 meters

Table II

NAUTICAL UNITS OF TIME

{Numbers in braces are the exponents, n, of exponential factors, 10^n}

1 Nautical Day = 1/366.25 Julian Years = 365.25/366.25 ephemeris days
= 1-0.002 730 375 426 621 ... ephemeris days
= 1/1.002 737 850 787 132 ... ephemeris days
= 86,164.10 or {4.935 3264 } or 1/1.160 576 {-5} ephemeris seconds

1 Nautical Hour = 1/24 nautical days = 365.25/366.25 ephemeris hours
= 3,590.171 or {3.555 1151 } or 1/2.785 383 {-4} ephemeris seconds

1 Nautical Minute = 1/1,440 nautical days = 365.25/366.25 ephemeris minutes
= 59.836 18 or {1.776 9639 } or 1/1.671 230 {-2} ephemeris seconds

1 Nautical Second = 1/86,400 nautical days = 365.25/366.25 ephemeris seconds
= 0.997 269 6 or {9.998 8126-10} or 1/1.002 738 { 0} ephemeris seconds

1 Mean Solar Day	= 1.002 737 811 906	± 1	{-12}	periods of rotation
	= 1.002 737 909 265	+ 58.9	{-12}T_U	mean sidereal days
	= 1.000 000 00	± 1	{- 8}	ephemeris days
	= 1.002 737 85	± 1	{- 8}	nautical days
1 Mean Sidereal Day	= 0.997 269 566 414	- 58.6	{-12}T_U	mean solar days
	= 1 - 97093 {-12}	- 59	{-12}T	periods of rotation
	= 0.997 269 57	± 1	{- 8}	ephemeris days
	= 1.000 000 00	- (6±1)	{- 8}	nautical days
1 Period of Rotation	= 0.997 269 663 242	± 1	{-12}	mean solar days
	= 1 + 97093 {-12}	+ 59	{-12}T	mean sidereal days
	= 0.997 269 66	± 1	{- 8}	ephemeris days
	= 1.000 000 00	+ (4±1)	{- 8}	nautical days

where: T_U = Julian centuries after 1900.0 of Universal Time
T = Julian centuries after 1900.0 of Ephemeris Time
= 3,155,760,000 ephemeris seconds = 36,525 ephemeris days
= 3,164,400,000 nautical seconds = 36,625 nautical days
= argument of Newcomb's defining equation that

Geometric Mean Longitude of the Sun = 279°41'48".04 + 1296 02768".13T + 1".089T^2

corresponding to the definition that exactly
31,556,925.974 7 ephemeris second = Tropical Year of 1900 January 0d 12h.

(Source: Explanatory Supplement to the Astronomical Ephemeris
and the American Ephemeris and Nautical Almanac)

Table III

EARTH-CENTERED KEPLER ORBITS

$$\frac{\text{Nautical Rads of Mean Distance}}{(\text{Nautical Days per Revolution})^{2/3}} = 6.622\ 610 = \frac{1}{0.150\ 998} = 10^{0.821\ 0292}$$

$$\frac{\text{Nautical Days per Revolution}}{(\text{Nautical Rads of Mean Distance})^{3/2}} = 0.058\ 6754 = \frac{1}{17.042\ 9} = 10^{8.768\ 4562-10}$$

FREQUENCY Revs. per nautical day	PERIOD Nautical Units of time	MEAN DISTANCE Nautical rads
17		1.002
16	1^h30^m	1.043
15	1 36	1.089
14		1.140
13		1.198
12	2^h	1.263
11		1.339
10	2^h24^m	1.427
9	2^h40^m	1.531
8	3	1.656
7		1.810
6	4^h	2.006
5	4^h48^m	2.265
4	6	2.628
3	8	3.184
2	12	4.172
1	1^d	6.623
	2^d	10.51
	3	13.78
	4	16.69
	5	19.36
	6	21.87
	7^d	24.23
	14	38.47
	21	50.41
	28	61.07
	$2(28)= 56^d$	97
	3(28)= 84	127
	4(28)=112	154
	5(28)=140	179
	6(28)=168	202
	$*366^d06^h$	339

MEAN DISTANCE Nautical rads	PERIOD Nautical Units of time	FREQUENCY Revs. per nautical day
1.0	$1^h24^m30^s$	17.04
1.1	$1^h37^m29^s$	14.77
1.2	1 51 04	12.96
1.3	2 05 14	11.50
1.4	2 19 58	10.29
1.5	$2^h35^m13^s$	9.277
1.6	2 51 00	8.421
1.7	3 07 17	7.689
1.8	3 24 03	7.057
1.9	3 41 17	6.507
2.0	$3^h58^m59^s$	6.026
3	$7^h19^m02^s$	3.280
4	11 15 56	2.130
5	15 44 39	1.524
6	20 41 47	1.160
7	$1^d.087$	
8	1.328	
9	1.584	
10	1.855	
20	$5^d.248$	
30	9.641	
40	14.84	
50	20.74	
60	$27^d.27$	
70	34.36	
80	41.98	
90	50.10	
100	58.68	
200	166^d	
*235.060	211^d	

*Period and Distance of gravitational neutral point of the Sun and Earth