Modern Terrestrial Reference Systems (Part 1)

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Surveyors, GIS/LIS professionals, engineers, cartographers, and others who work in North America face the challenge of dealing with at least three different 3D terrestrial reference systems. For many legal activities, these people express positional coordinates in the reference system known as the North American Datum of 1983 (NAD 83). Alternatively, they often favor using the World Geodetic System of 1984 (WGS 84) for various practical positioning activities involving the Global Positioning System (GPS), or they find the International Terrestrial Reference System (ITRS) more suitable for achieving superior positional accuracy. While these three reference systems differ from one another only slightly in concept, they differ significantly in how they have been realized, where the realization of a particular reference system is called a “reference frame”. A particular reference frame is usually established by designating positions and velocities for several identifiable points. To date there have been several realizations of each of these three reference systems, as institutions have systematically revised positions and velocities from time to time to keep pace with how evolving technology has improved positioning accuracy. Here, we review the evolution of these reference frames, and we discuss transforming positions between different reference frames. Finally, we address some practical considerations for accurate positioning and discuss plans for a new NAD 83 realization.

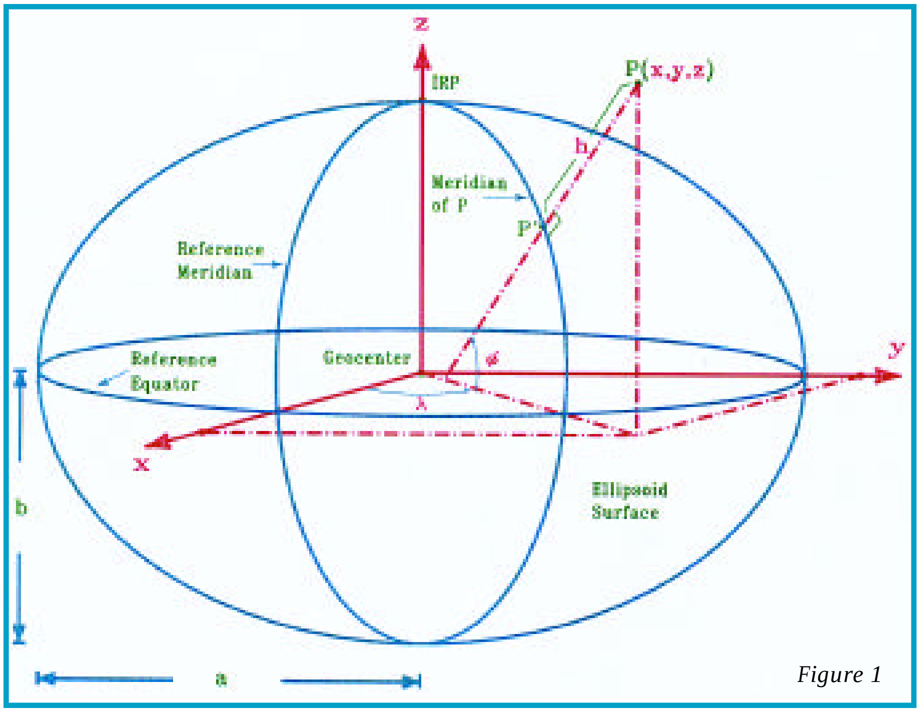

Figure 1

Defining a Reference System

The modern approach to defining a 3D terrestrial reference system may be divided into four steps. The first step links the axes of a 3D cartesian coordinate system to a configuration of physically measurable locations on or within the earth. As a result, the location and orientation of the three coordinate axes are defined. The second step relates the concept of distance to physically measurable quantities whereby a unit of length is introduced. The third step introduces an auxiliary geometric surface that approximates the size and shape of the earth. Finally, the fourth step addresses the question of how Earth’s gravity field contributes to the notion of position, and especially that of height. We shall be concerned here with only the first three steps, thus focusing on the geometric aspects involved in defining a reference system.

For the first step, most scientists involved in defining modern reference systems agree that the origin of the 3D cartesian system should be located at Earth’s center of mass (geocenter); also that the cartesian system’s z-axis should pass through the conventional definition of the North Pole, or more precisely, the International Reference Pole (IRP) as defined by the International Earth Rotation Service (IERS), an international organization established in 1988 and headquartered in Paris, France. The x-axis should go through the point of zero longitude located on the plane of the conventional equator, which is also defined by the IERS. The meridian going through this point is located very close to the meridian of Greenwich although the two are not coincident. The y-axis forms a right-handed coordinate frame with the x- and z-axes. Indeed, each of the three reference systems—NAD 83, WGS 84, and ITRS—has been accordingly defined in concept. They differ, however, as we shall soon discuss, in their realizations; that is, in how the location and orientation of their respective cartesian axes have been physically materialized as well as their respective concepts of distance. Unfortunately, what initially appears to be a simple geometric procedure is complicated by Earth’s dynamic behavior. For example, Earth’s center of mass is moving relative to Earth’s surface. Also, there are variations of Earth’s rotation rate as well as motions of Earth’s rotation axis both with respect to space (precession and nutation) and to Earth’s surface (polar motion). Moreover, points on the earth’s crust are moving relative to one another as a result of plate tectonics, earthquakes, volcanic/magmatic activity, postglacial rebound, people’s extraction of underground fluids, solid Earth tides, ocean loading, and several other geophysical phenomena. Modern terrestrial reference systems, hence, need to account for these motions. One option is to relate the cartesian axes to the locations of selected points measured at a particular instant of time (epoch). This alternative is generally used when dealing with the motion of the earth's rotational axis and with the motions associated with plate tectonics. Other types of motion (for example, subsidence) are accounted for by fixing the cartesian axes to some temporal average of the locations for selected points. As we shall see, a fundamental difference among the various reference frames involves how they address the motion associated with plate tectonics.

For the second step, scientists concerned with defining up-to-date terrestrial reference systems agree that the unit of length, the meter or "metre", corresponds to the length of path traveled by light in a vacuum during a time interval of exactly 1/299,792,458 seconds. This solves the problem of relating the concept of distance to a physically measurable quantity in theory, but not in realization. Each of the various reference frames associated with NAD 83, WGS 84, and ITRS relies on a distinct set of measurements that were performed using one or more of several widely different types of instruments and techniques, among the most representative: GPS, electro-optical distance measuring instrumentation, Doppler satellite positioning, very long baseline interferometry (VLBI), and satellite laser ranging (SLR). While each measurement type had been calibrated to fit the definition of a meter as best as possible, the observations, nevertheless, contain uncertainties. Consequently, the "scale" of any particular reference frame is somewhat less than perfect. In particular, when old classical terrestrial frames are compared with modern "space-age" frames, scale errors at the part-per-million (ppm) level may often be detected. Because of recent technological advances in the measurement of time and, consequently, distance, scale differences between modern frames are now approaching the part-per-billion (ppb) level.

For the third step, the earth's surface is approximated in size and shape by the geometric surface that is formed by rotating an ellipse about its smaller axis (Figure 1). The generated surface is termed an "ellipsoid of revolution" or simply ellipsoid. The ellipsoid's geometric center should be located at the origin of the 3D cartesian system, and its axis of radial symmetry (semi-minor axis) should coincide with the cartesian z-axis of the selected terrestrial reference frame. The size and shape of the rotated ellipse may be completely specified using two parameters: the length of its semi-major axis, usually denoted a, which approximates the distance from the geocenter to a point on the equator (approximately 6,378 km); and the length of the semi-minor axis, denoted b, which approximates the distance from the geocenter to the North Pole. The value of b is about 0.3% shorter than a. The fact that a is longer than b is a consequence of the force imparted by Earth's rotation causing our home planet to bulge outward around its equator. Often, instead of b, the ellipsoid's flattening, $f = (a - b)/a$, is used.

Different ellipsoids have been adopted for the different reference systems. NAD 83 uses the same ellipsoid as the Geodetic Reference System of 1980 which was adopted by the International Association of Geodesy. WGS 84 uses an ellipsoid adopted by the National Imagery and Mapping Agency (NIMA, formerly the Defense Mapping Agency), and ITRS uses an ellipsoid adopted by the IERS. Corresponding values of a and f are presented in the table below.

Given values for a and b (or f), people can convert 3D cartesian coordinates—x, y, z— into the curvilinear coordinates—latitude, longitude, and ellipsoidal height—and vice versa. These curvilinear coordinates embody a certain intuitive appeal in specifying locations on and near the earth's surface, as they relate to our innate sense of the horizontal and vertical dimensions.

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Reference System	Semi-major axis, m	Flattening, unitless
NAD 83	6,378,137.0	1/298.257222101
WGS 84	6,378,137.0	1/298.257223563
ITRS	6,378,136.49	1/298.25645