3.8 Systems of Coordinates for Field Applications

GPS receivers provide the real-time position of the on-vehicle antenna in *geodetic coordinates*; namely, *latitude* (λ), *longitude* (ϕ), and *altitude* (h). The *World Geodetic System 1984* (WGS 84), developed by the US Department of Defense, defines an *ellipsoid of revolution* that models the shape of the Earth, upon which the geodetic coordinates are defined. The WGS 84 also defines the *geoid*, another surface that models the mean sea level as the reference of altitudes. According to the schematic representation of Figure 3.17, *latitude* is the angle measured in the meridian plane containing point P between the normal N_o (line perpendicular to the surface of the ellipsoid at P) and the equatorial plane of the ellipsoid, considered positive north from the equator; *longitude* is the angle measured in the equatorial plane between the prime meridian (statistically determined mean Greenwich meridian [2]) and the projection of the point of interest P on the equatorial plane, measured positive east from the reference meridian; while *altitude* (or *height*) is the normal distance between the surface of the ellipsoid and P. Note that the geodetic altitude has no physical correspondence as it is referenced to the ellipsoid, which is a mathematical model. This difficulty is overcome by defining the geoid as an idealized representation of the mean sea level. The most accurate geoid model currently available is the WGS 84 geoid. The circles that connect all points of the ellipsoid with constant

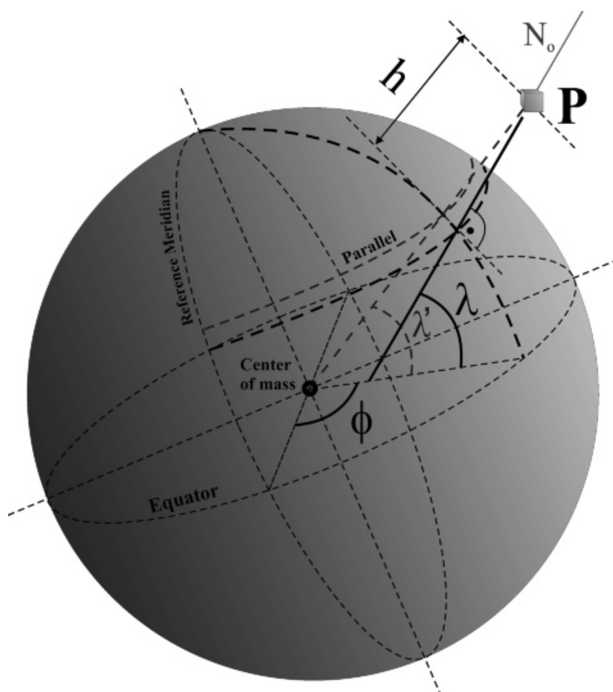

Figure 3.17 Definition of geodetic coordinates

latitude are called *parallels*, and the ellipses that connect all points with the same longitude are called *meridians*. Note that in Figure 3.17 latitude can be defined according to the center of mass of the ellipsoid (*geocentric latitude* λ') or referred to the perpendicular line to the ellipsoid at P (*geodetic latitude* λ), which does not cross the center of the Earth as the ellipsoid is slightly flattened at the poles.

Apart from facilitating geodetic coordinates, the WGS 84 also defines a Cartesian coordinate system that is fixed to the Earth and has its origin at the center of mass of the Earth. This system is called the *Earth-centered Earth-fixed* (ECEF) coordinate system, and provides an alternative way to locate a point on the Earth's surface with the conventional three Cartesian coordinates X, Y, and Z. The Z-axis coincides with the Earth's axis of rotation and therefore crosses the Earth's poles. In reality, the axis of rotation is not fixed; it wanders around, following a circular path, moving several meters a year in what is called polar motion. A change in the position of the poles alters the definition of latitude and longitude, as this means that the equatorial plane is not fixed either. Nevertheless, these slight variations do not have a strong influence on the results for the applications pursued by intelligent vehicles operating in the field. In any case, given that the Z-axis of the ECEF frame needs to be defined unambiguously, geodesists have estimated the average position of the Earth's pole of rotation, which is called the conventional terrestrial pole (CTP) and crosses the Z-axis by definition. The X-axis is defined by the intersection of the equatorial plane (0° latitude) with the prime meridian (0° longitude). The Y-axis is also contained in the equatorial plane and completes the right-handed coordinate system. Figure 3.18 represents the ECEF coordinate system.

The majority of the applications developed for off-road vehicles do not require the coverage of large surfaces in a short period of time with the same vehicle; rather,

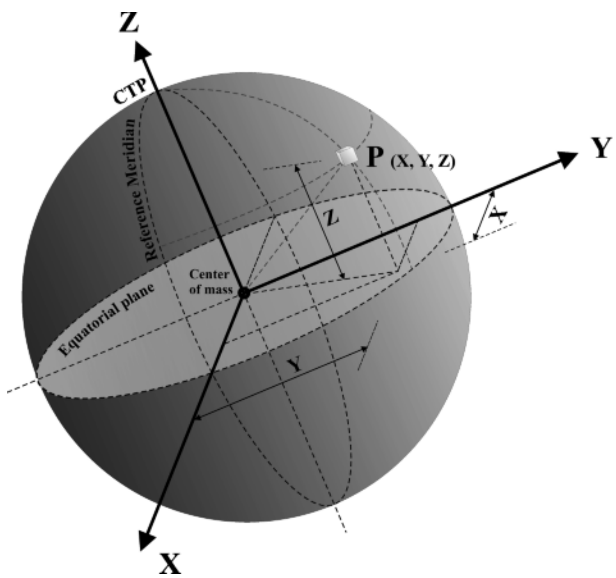

Figure 3.18 Definition of ECEF coordinates

given that off-road equipment cannot travel at high speeds, these machines tend to remain within areas of limited size. In these circumstances, the curvature of the Earth has a negligible effect, and fields can be considered flat. Both geodetic and ECEF coordinates are defined in such a general manner that figures and calculations are cumbersome, and origins are quite abstract, as nobody has seen the center of mass of the Earth. It would be much more practical to define a local system of coordinates where the origin is close to the operating field. Furthermore, modest changes in the position of the vehicle would result in very tiny changes in latitude, longitude, X or Y. However, a local origin and more intuitive coordinates such as east or north would simplify the practical realization of GNSS-based tasks. This need has been fulfilled by the development of the *local tangent plane* (LTP) system of coordinates. The local tangent plane coordinates, also known as NED coordinates, are north (N), east (E), and down (D). These coordinates are measured along three orthogonal axes in a Cartesian configuration generated by fitting a tangent plane to the surface of the Earth at an arbitrary point selected by the user and set as the LTP origin. A simplified sketch of the local tangent plane coordinate system is depicted in Figure 3.19. Notice that the scale of the plane has been greatly exaggerated to illustrate the definitions of the axes; the tangent plane should be small enough to be able to disregard the Earth's curvature.

For practical field applications we would definitely use the LTP, but the GPS receiver typically provides geodetic coordinates through the NMEA code. In other words, the receiver acquires the latitude, longitude, and altitude of the vehicle's position, but it would be much more helpful to know the NED coordinates for a real-time locally based operation. It is therefore necessary to *transform geodetic coordinates to LTP coordinates*, and this can be carried out using the ECEF coordinates, as detailed in the following paragraphs. The first step in the transformation process is to

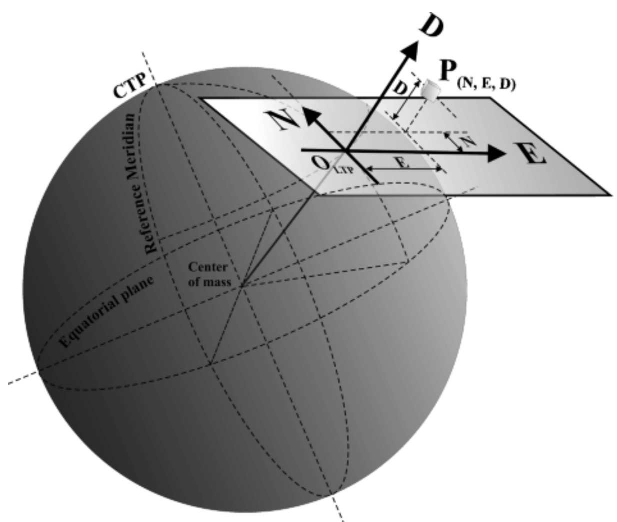

Figure 3.19 Definition of LTP coordinates

select an ellipsoid as a reference to model the shape of the Earth. The widespread use of GPS is turning WGS 84 from a global datum to an international datum, a *de facto* world standard [2] that provides excellent data that can be used to perform the transformation from geodetic coordinates to the local tangent plane. Equations 3.7–3.11 provide the fundamental parameters of WGS 84, revised in 1997. These parameters are the *semi-major axis* (a), the *semi-minor axis* (b), the *ellipsoid flatness* (f), the *eccentricity* (e), and the *length of the normal* (N_o).

$$a = 6\,378\,137.0 \text{ m} \tag{3.7}$$

$$b = a \cdot (1 - f) = 6\,356\,752.3 \text{ m} \tag{3.8}$$

$$f = \frac{a - b}{a} = 0.00335281 \tag{3.9}$$

$$e = \sqrt{f \cdot (2 - f)} = 0.0818 \tag{3.10}$$

$$N_o(\lambda) = \frac{a}{\sqrt{1 - e^2 \cdot \sin^2 \lambda}} \tag{3.11}$$

The length of the normal N_o, defined in Equation 3.11 and depicted in Figure 3.17 for point P, is the distance from the surface of the ellipsoid to its intersection with the axis of rotation Z. The relationship between the geodetic (λ, ϕ, h) and the ECEF (X, Y, Z) coordinates is given by Equations 3.12–3.14.

$$X = (N_o + h) \cdot \cos\lambda \cdot \cos\phi \tag{3.12}$$

$$Y = (N_o + h) \cdot \cos\lambda \cdot \sin\phi \tag{3.13}$$

$$Z = \left[N_o \cdot \left(1 - e^2\right) + h\right] \cdot \sin\lambda \tag{3.14}$$

The transformation from ECEF to LTP (N, E, D) coordinates requires the selection by the user of the origin of the coordinates on the tangent plane (X_0, Y_0, Z_0). Note that the origin belongs to the plane and is a point tangent to the surface of the Earth. The last step in the coordinate transformation leading to the LTP coordinates can be executed with Equation 3.15. Note that Equation 3.15 requires the coordinates of the arbitrary origin of the tangent plane in ECEF coordinates. Once a favorable point in the field has been chosen as the origin, its geodetic coordinates are easily established with a GPS receiver, but they need to be transformed into the ECEF frame with Equations 3.12–3.14 before they can be introduced into Equation 3.15.

$$\begin{bmatrix} N \\ E \\ D \end{bmatrix} = \begin{bmatrix} -\sin\lambda \cdot \cos\phi & -\sin\lambda \cdot \sin\phi & \cos\lambda \\ -\sin\phi & \cos\phi & 0 \\ -\cos\lambda \cdot \cos\phi & -\cos\lambda \cdot \sin\phi & -\sin\lambda \end{bmatrix} \cdot \begin{bmatrix} X - X_0 \\ Y - Y_0 \\ Z - Z_0 \end{bmatrix} \tag{3.15}$$

3.9 GPS in Precision Agriculture Operations

The birth of *precision agriculture* (also known as *precision farming*) and the advent of *GPS* are intimately related. It was the availability and the expansion of the latter