19. User Equivalent Range Errors

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"UERE" is the umbrella term for all of the error sources below, which are presented in descending order of their contributions to the total error budget.

1. **Satellite clock**: GPS receivers calculate their distances from satellites as a function of the difference in time between when a signal is transmitted by a satellite and when it is received on the ground. The atomic clocks on board NAVSTAR satellites are extremely accurate. They do tend to stray up to one millisecond of standard GPS time (which is calibrated to, but not identical to, Coordinated Universal Time). The monitoring stations that make up the GPS "Control Segment" calculate the amount of clock drift associated with each satellite. GPS receivers that are able to make use of the clock correction data that accompanies GPS signals can reduce clock error significantly.
2. **Upper atmosphere (ionosphere)**: Space is nearly a vacuum, but the atmosphere isn't. GPS signals are delayed and deflected as they pass through the ionosphere, the outermost layers of the atmosphere that extend from approximately 50 to 1,000 km above the Earth's surface. Signals transmitted by satellites close to the horizon take a longer route through the ionosphere than signals from satellites overhead, and are thus subject to greater interference. The ionosphere's density varies by latitude, by season, and by the time of day, in response to the Sun's ultraviolet radiation, solar storms and maximums, and the stratification of the ionosphere itself. The GPS Control Segment is able to model ionospheric biases, however. Monitoring stations transmit corrections to the NAVSTAR satellites, which then broadcast the corrections along with the GPS signal. Such corrections eliminate only about three-quarters of the bias, however, leaving the ionosphere the second largest contributor to the GPS error budget.
3. **Receiver clock**: GPS receivers are equipped with quartz crystal clocks that are less stable than the atomic clocks used in NAVSTAR satellites. Receiver clock error can be eliminated, however, by comparing times of arrival of signals from two satellites (whose transmission times are known exactly).
4. **Satellite orbit**: GPS receivers calculate coordinates relative to the known locations of satellites in space. Knowing where satellites are at any given moment involves knowing the shapes of their orbits as well as their velocities. The gravitational attractions of the Earth, Sun, and Moon all complicate the shapes of satellite orbits. The GPS Control Segment monitors satellite locations at all times, calculates orbit eccentricities, and compiles these deviations in documents called ephemerides. An ephemeris is compiled for each satellite and broadcast with the satellite signal. GPS receivers that are able to process ephemerides can compensate for some orbital errors.
5. **Lower atmosphere**: (troposphere, tropopause, and stratosphere) The three lower layers of atmosphere encapsulate the Earth from the surface to an altitude of about 50 km. The lower atmosphere delays GPS signals, adding slightly to the calculated distances between satellites and receivers. Signals from satellites close to the horizon are delayed the most since they pass through more atmosphere than signals from satellites overhead.

6. **Multipath**: Ideally, GPS signals travel from satellites through the atmosphere directly to GPS receivers. In reality, GPS receivers must discriminate between signals received directly from satellites and other signals that have been reflected from surrounding objects, such as buildings, trees, and even the ground. Some, but not all, reflected signals are identified automatically and rejected. Antennas are designed to minimize interference from signals reflected from below, but signals reflected from above are more difficult to eliminate. One technique for minimizing multipath errors is to track only those satellites that are at least 15° above the horizon, a threshold called the "mask angle."

Douglas Welsh (personal communication, Winter 2001), an Oil and Gas Inspector Supervisor with Pennsylvania's Department of Environmental Protection, wrote about the challenges associated with GPS positioning in our neck of the woods: "...in many parts of Pennsylvania the horizon is the limiting factor. In a city with tall buildings and the deep valleys of some parts of Pennsylvania, it is hard to find a time of day when the constellation will have four satellites in view for any amount of time. In the forests with tall hardwoods, multipath is so prevalent that I would doubt the accuracy of any spot unless a reading was taken multiple times." Van Sickle (2005) points out, however, that GPS modernization efforts and the GNSS may well ameliorate such gaps.

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