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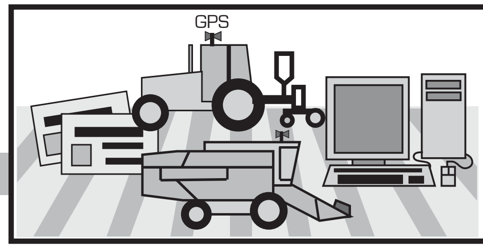

Precision Farming

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Precision Farming Tools: Global Positioning System (GPS)

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Precision Farming. Modern agricultural management practices are changing from assuming homogenous fields to attempting to address field variability by dividing the field into smaller zones and managing these zones separately. Precision farming can be defined as the gathering of information dealing with spatial and temporal variation within a field and then using that information to manage inputs and practices (*Precision Farming: A Comprehensive Approach*, Virginia Cooperative Extension (VCE) publication 442-500). Precision farming is made possible by linking computers, on-the-go sensors, Global Positioning Systems (GPS), and other devices. This publication discusses GPS principles and the technology that makes it possible.

Global Positioning System (GPS). GPS is widely available in the agricultural community and its potential is growing. Farm uses include mapping yields (GPS + combine yield monitor), variable rate planting (GPS + variable-rate planter drive), variable rate lime and fertilizer application (GPS + variable-rate spreader drive), variable rate pesticide application (GPS + variable-rate applicator), field mapping for records and insurance purposes (GPS + mapping software) and parallel swathing (GPS + navigation tool). Terms associated with GPS are listed in the Glossary.

GPS Design

The U.S. Department of Defense's (DOD) GPS is a navigational system made up of 24 satellites. GPS uses satellites and computers to determine positions anywhere on Earth 24 hours a day. The orbital patterns and spacing of the GPS satellites (their constellation) provide nine to 12 satellites above the horizon at any point on the Earth. This allows every point of the Earth's surface to have a unique address.

There are essentially three parts that make up GPS: the space segment, user segment, and control segment. The space segment is based on the constellation of 24 active and 3 spare satellites orbiting the Earth. The control segment is a system of five monitoring stations located around the world, with the master control facility located at Falcon Air Force Base in Colorado. The user segment, which is the fastest growing segment, is made up of

GPS Cool Facts

- First GPS satellite was launched in 1978.
- Current system is composed of second-generation GPS satellites, called Block II.
- First Block II satellite was launched in 1989.
- Defense Department declared GPS fully operational in 1995.
- When the system was first introduced, miscalculations (called SA – Selective Availability) were programmed into GPS transmissions to limit the accuracy of non-military GPS receivers. This operation was cancelled in May 2000.
- There are 24 GPS satellites in orbit at this moment.
- The 24 satellites cost an estimated $12 billion to build and launch.
- Each satellite weighs about 1,735 pounds.
- Satellites are orbiting about 12,500 miles above the Earth.
- Satellites take 12 hours to orbit the Earth once.
- The Russians have a system identical to the U.S. system called GLONASS.

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GPS receivers and the user community. GPS receivers convert the satellites' signals into position, velocity, and time. This information is used for navigation, positioning, time dissemination, and research.

Location and Space Segment

Using triangulation to determine precise location is the basic idea behind the GPS system. Based on the intersection of a group of satellites' signals, triangulation or satellite ranging is used to calculate a location on earth by measuring the distance from each of several satellites in space. The satellites act as reference points in space. Knowing the distances from the satellites to a point on the Earth's surface allows a position to be accurately determined.

Four satellite measurements are needed to determine exact position in three-dimensional space. In order for triangulation to work, a receiver measures the amount of time a radio wave takes to travel from a satellite to the receiver. Both the satellite and receiver generate a set of digital codes called pseudo-random codes at exactly the same time. The pseudo-random code repeats itself every millisecond and is carried on radio waves. Each satellite transmits two carrier signals. Thus, the difference between the satellite's code and receiver's pseudo-random code will give the distance between the two.

Since accurate time is important to the system, each satellite carries four atomic clocks. Only one clock on each satellite is used while the other three are backups. An atomic clock gets its name from using the oscillations of either cesium or rubiduim atoms as the "timing regulator." These clocks give the most stable and accurate measurement of time. However, even though they are very accurate, atomic clocks are not perfect and slight inaccuracies can occur. These inaccuracies can result in errors in position measurements. Receiver clocks do not have to be as accurate because trigonometry can correct receiver-clock errors.

In addition to having accurate time, the location of each satellite is needed in order for GPS to work. The satellites are placed high above the Earth (about 12,500 miles) so their orbits are very predictable. However, the DOD's monitoring stations measure minor variations in orbits called ephemeris errors and the data are transmitted back to the satellites. Other satellites and receivers adjust for any errors read from this data message giving the exact orbital location and condition of each satellite.

Receivers and User Segments

In the user segment there are two classes of receivers, military and civilian (standard). The civilian receiver can read the L1 frequency. Military or authorized users with cryptographic equipment, keys, and specially equipped receivers can read the L2 as well as the L1 frequency. The combination of the two frequencies greatly increases the accuracy.

Most receivers available are continuous receivers and they can monitor four or more satellites simultaneously, depending on the number of channels available. Continuous receivers are more expensive and require more power, but they can give instantaneous position and velocity. There is also less possibility of error because the receiver can receive several pseudo-random codes at the same time. The user has to determine what level of accuracy for location and velocity is needed for the available budget. With more channels, the receiver can gain additional accuracy but the cost is higher for the unit.

Management or Control Segment

The ultimate accuracy of the system is determined by the sum of several types of errors (see "What causes error in GPS readings?" below). The DOD can realign and reposition the orbits of the satellites for increased accuracy.

The system was designed with an operational mode called "selective availability" (SA) which the DOD can use to purposefully degrade the accuracy of the system. SA was designed to prevent hostile forces from having the tactical advantage of GPS positioning. When SA is activated, the signal gives the largest source of error. Currently, SA is turned off and DOD does not intend to use SA again. To ensure that potential adversaries do not use GPS, the military is dedicated to developing and deploying regional denial capabilities in lieu of global degradation through SA.

GPS Signals and Corrections

What causes errors in GPS readings? There are several things associated with the GPS system that can cause errors in GPS position information. The most common GPS errors are shown in Table 1.

The contributor of each source of error may vary depending on atmospheric and equipment conditions. With all these types of errors, it would appear that the system could not be all that accurate. However, with the use of mathematics and modeling, some of the errors can be eliminated or reduced. The receiver does

Table 1. Common errors associated with GPS signals.

Error	Explanation
Clock	GPS satellites carry very accurate atomic clocks to generate timing signals. GPS receivers must also have a clock to compare the timing signals received from the satellites to internally generated timing signals. For cost reasons, most GPS receiver clocks are not as accurate as satellite clocks, nor are they tightly synchronized with satellite clocks. Though only three satellite signals are absolutely necessary for triangulation calculations, a fourth satellite signal is necessary to synchronize the receiver clock with the satellite clocks.
Ephemeris	Satellite orbits can vary slightly over time and require periodic adjustment by system maintainers. Since the orbits vary, errors can exist in the satellite ephemeris (location) data used in triangulation calculations.
Dilution of Precision (DOP)	The configuration of the satellites in view to a receiver at any given time can affect the accuracy of position determination. For instance, if all of the visible satellites happen to be bunched close together, the triangulated position will be less accurate than if those same satellites were evenly distributed around the visible sky (Figures 1 and 2). The Dilution of Precision (DOP) is quantified from the satellite configuration. Many GPS receivers will display values for Horizontal DOP (quality of latitude and longitude data), Vertical DOP (quality of elevation data), Position DOP (quality of three-dimensional measurement), or Time DOP (quality of time determination). Lower values for DOPs indicate better satellite configurations. In general, DOPs less than four will give good position determinations.
Atmosphere	When radio waves from GPS satellites enter the Earth's atmosphere, their paths can be bent or refracted. This bending will actually change the length of the path the radio signal takes to get to the receiver. This change in length will cause an error in distance determination. Atmospheric effects are usually greater on satellites low on the horizon since the radio waves enter the atmosphere at more of an angle. Some GPS receivers allow the user to ignore or mask satellites below a set angle above the horizon.
Multipath	Multipath errors are similar to atmospheric errors but are often more severe. Multipath means that the same radio signal is received several times through different paths. For instance, a radio wave could leave a satellite and travel directly to the receiver, but it also bounces off a building and arrives at the receiver at a later time (Figure 3). Multipath can confuse position calculations and cause significant errors. The most common causes of multipath errors in agricultural settings are buildings, ponds, and lakes.

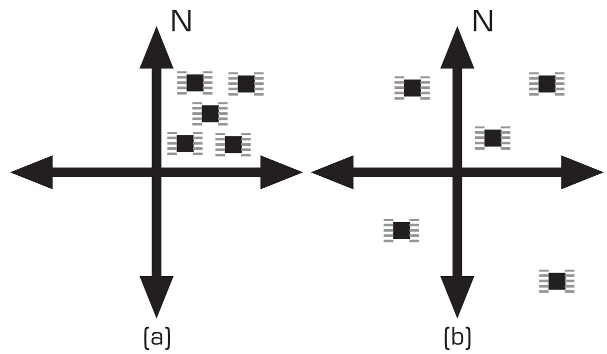


Figure 1. Satellite configuration that has a) poor DOP and b) good DOP

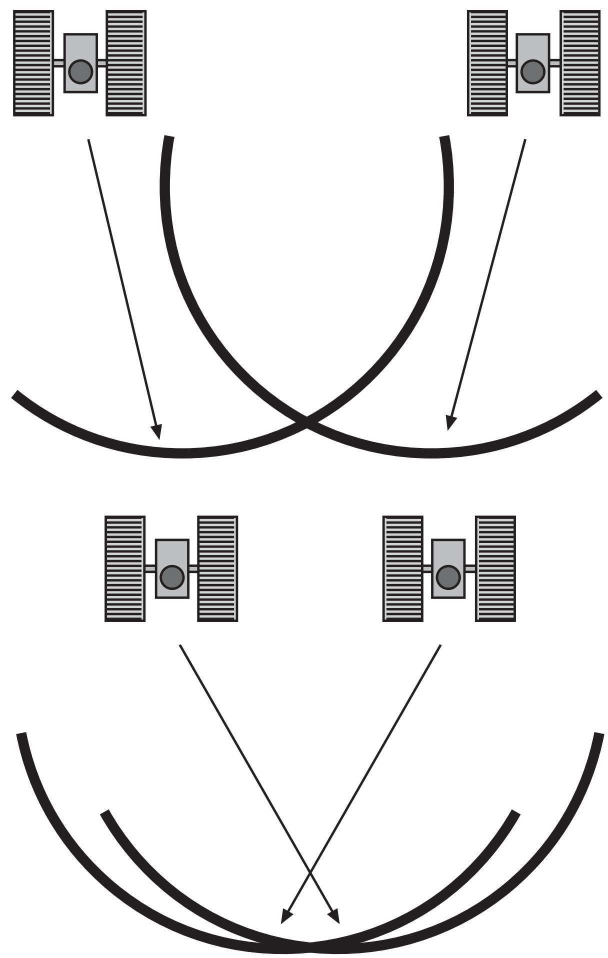


Figure 2: Geometric Dilution of Precision is an error caused by the angle between satellites. The closer the satellites are the more room for error at the intersection of the signals.

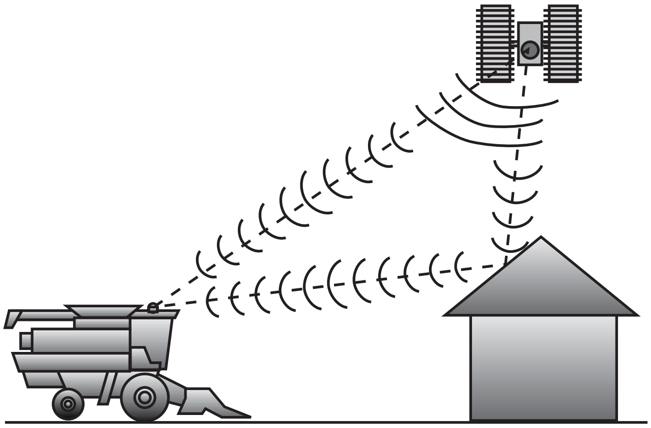


Figure 3. Multipath signal error.

the mathematics calculations and error corrections. Thus, error effect can be reduced depending on the capabilities of the receiver.

How do we increase GPS accuracy? In agricultural applications, the most common way to counteract GPS errors is by using Differential GPS or DGPS. In a DGPS system, a GPS receiver is placed at an accurately known location (Figure 4). This base station receiver will calculate the error between its actual location and the location computed from the GPS signals. The error information is communicated to the rover receiver being used in the field, which is then able to correct the position information it computes from the GPS signals. Most differential corrections are provided by the U.S. Coast Guard (USCG), WAAS (the FAA's Wide Area Augmentation System), or by subscription to a private radio carrier or satellite link.

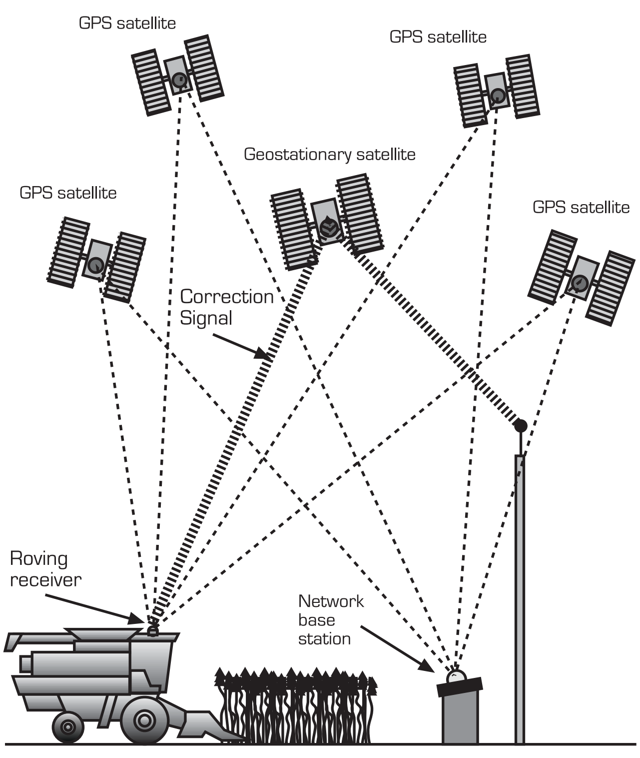


Figure 4. Differential GPS Systems.

The idea behind differential positioning is to correct bias errors at one location with measured bias errors at a known position. A reference receiver, or base station, computes corrections for each satellite signal. Because individual pseudo-ranges must be corrected prior to the formation of a navigation solution, DGPS implementations require software in the reference receiver that can track all satellites in view and form individual pseudo-range corrections for each. These corrections are passed to the remote (or rover) receiver. This remote receiver must be capable of applying these individual pseudo-range corrections to each satellite used in the navigation solution. Applying a simple position correction from the reference receiver to the remote receiver has limited effect at useful ranges. This is because both receivers would have to be using the same set of satellites in their navigation solutions and have identical GDOP (Geometric Dilution of Position) terms (not possible at different locations) to be identically affected by bias errors.

Differential corrections may be used in real-time or later, with post-processing techniques. Real-time corrections can be transmitted by radio link (FM) or satellite signal. Corrections can be recorded for post processing. A number of public and private agencies record DGPS corrections for distribution by electronic means.

The United States Coast Guard (USCG) has established base stations along major navigable bodies of water (e.g., the Ohio River and the Great Lakes). The differential correction information is broadcast from radio towers at these locations. The major advantage of the USCG corrections is that there is no subscription fee for signal usage. One disadvantage is that coverage is limited to areas near established base stations (typically a 100- to 150-mile radius). Also, signal strength decreases, and the correction information itself becomes less accurate with increasing distance from the base station receiver. Norfolk station is probably the closest base station for Virginia residences.

The Wide Area Augmentation System (WAAS) is an FAA-funded project to improve the overall accuracy and integrity of the GPS signal for flying aircraft in instrument meteorological conditions, primarily during the approach to the landing phase of flight. It is a space-based system that broadcasts integrity information and correction data as determined by ground reference stations. WAAS consists of approximately 25 ground reference stations positioned across the United

States that monitor GPS satellite data. Two master stations, located on either coast, collect data from the reference stations and create a GPS correction message. At this time the system is still in the development stage with a goal of providing reliable signals with an accuracy of 21 to 22 feet both horizontally and vertically more than 95 percent of the time. Tests have shown the actual accuracy to be on the order of less than 7 feet. The corrected differential message is then broadcast through one of two geostationary satellites, or satellites with a fixed position over the equator. The information is compatible with the basic GPS signal structure, which means any WAAS-enabled GPS receiver can read the signal (http://gps.faa.gov/Programs/WAAS/waas.htm).

Even though the USCG Beacon and WAAS systems are free-to-public receivers (if they are equipped with the proper antennas), they have limitations. Most of these systems are limited by reliability and repeatability. These systems are free and they provide no guarantees or customer support. Users of the USCG Beacon have good reception within 100 miles of the beacon but greater distances could be subject to interference from electrical activity (thunder storms, etc.). The WAAS system is still under development and can be off-line without notice but the signal is widely available and for short-term "pass-to-pass" are very repeatable. However, WAAS's long-term repeatability is less consistent than the USCG Beacon. Thus, year-to-year variability of a location will likely be larger with the WAAS, followed by the USCG Beacon, and the least variable should be with subscription-based satellite correction.

Commercial satellite providers are another common source for DGPS signals. These organizations have established GPS base stations at various locations in their geographic region of interest. Error correction information obtained from these stations is sent to a communication satellite (separate from the GPS satellites) and broadcast to the user. These satellite-based corrections tend to have a more widespread coverage than the tower-based broadcasts (FM links), and system accuracy is not greatly affected by the user's distance from the base station receivers. Most of these service providers require a subscription fee for use, which is typically less than $800 per year.

An improvement over the standard DGPS is Kinematic DGPS or Real Time Kinematic (RTK) GPS. An RTK system counts the number of wavelengths of the carrier frequency radio signal between the satellite and receiver, thereby achieving accuracies of less than one foot. These systems are expensive ($15,000 to $60,000), and require users to set up and maintain their own base stations; therefore, they are not commonly used in agricultural applications except for topographic map generation, tractor guidance, and accurate placement of crop beds and drip tubing.

Some earlier generation DGPS receivers required separate antennas for GPS signals and differential correction signals. Most modern receivers combine all antennas into one integrated unit.

How do GPS manufacturers report accuracy? GPS users should be aware that manufacturers use one of several methods to report the accuracy of a GPS receiver. Though manufacturers rarely intend to deceive, an uneducated user can easily be misled. For example, a single GPS unit could have equivalent accuracy specifications of "1-ft CEP," "1.2-ft RMS," or "2.4-ft 2DRMS." Definitions for RMS, 2DRMS, and CEP are found in the Glossary.

- A GPS receiver reporting "1.2-ft RMS accuracy" means that positions indicated by a GPS receiver claims to be within 1.2 feet of the actual position about 68 percent of the time. The other 32 percent of the time, positions may not be within 1.2 feet of the actual location.
- A GPS receiver specification that claims "2.4-ft 2DRMS accuracy," wil give the actual position within 2.4 feet of the indicated position 95 percent of the time (Figure 5).
- A "1-ft CEP" GPS receiver will be within 1 foot of the actual position 50 percent of the time where Circular Error Probable (CEP) is based on a 50 percent confidence level.

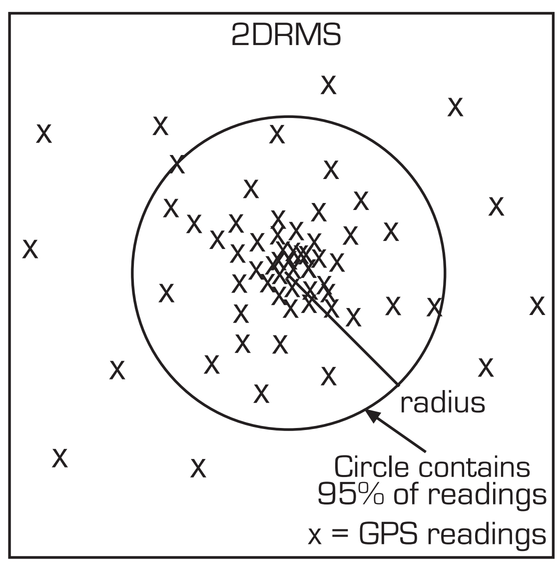
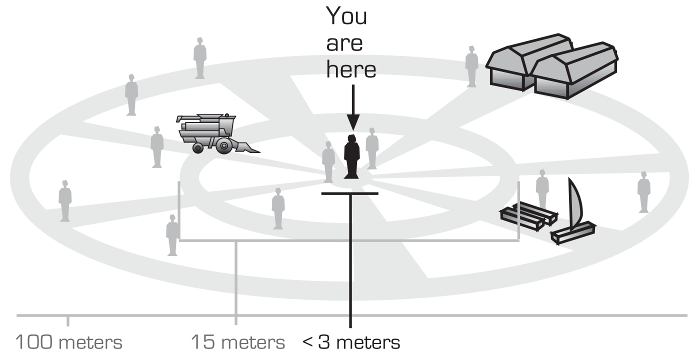


Figure 5. Accuracy of GPS for 2DRMS or twice distance root mean square. A horizontal distance representing the radius of a circle within which the true value is within at least 95 percent of the time.

Table 2. Accuracy of GPS and DGPS and relative costs.

45 ft (15 m)	Typical GPS position accuracy without SA. ($100-$700)
7-15 ft (3-5 m)	Typical differential GPS (DGPS) position accuracy. ($300-$2,000)
<7 ft (< 3 m)	Typical WAAS position accuracy. ($2,000 to $6,000)
0.03-0.3ft (0.01-0.1 m)	Real-time kinematic RKS ($15,000 to $60,000)



This reporting information is particularly important when comparing GPS receivers. A 2DRMS accuracy specification is twice as big as the RMS specification for the same unit. The RMS specification is about 1.2 times the CEP accuracy. Therefore, a unit with "5-ft 2DRMS accuracy" is actually more accurate than a unit with "3-ft RMS accuracy" since "3-ft RMS" is equal to "6-ft 2DRMS."

When comparing the accuracy of GPS units, make sure that the accuracies are specified in the same terms (CEP, RMS or 2DRMS). Another important observation about RMS, 2DRMS, and CEP accuracy specifications is that they are usually based on horizontal (latitude and longitude) position only. Vertical (elevation) data from GPS units are generally less accurate than horizontal data. In fact, a GPS receiver with a "3-ft RMS" horizontal accuracy may only have "10-15 ft RMS" elevation accuracy.

Using Handheld GPS Receivers for Precision Farming

Agricultural DGPS receivers for yield mapping and lightbar navigation typically cost from $2,000 to $6,000. By contrast, consumer GPS receivers, originally developed for recreational uses (such as fishing, hiking, and auto trips) are much more affordable because they are mass-produced for a wider market. Currently, a handheld GPS receiver costs from $200 to $400 and can provide a positioning accuracy better than 20 feet. Some of the handheld GPS receivers with free differential correction signals from WAAS are more accurate, less than 7 feet. The accuracy of a handheld receiver is sufficient to make rough maps and to mark obstacles, varieties, or even pest infestations. Many handheld receivers store these features internally for future reference and/or offer the ability to download stored data to a computer for further analysis.

Locating or mapping potential yield-limiting factors can be done throughout the year with these inexpensive units. Examples are:

- Wet spots: Map those boundaries for future tile drainage decisions or for future crop scouting activities.
- Patches of perennial weeds: Map the boundaries for future site-specific herbicide applications (spot spraying). Annotate those mapped boundaries with ratings of the severity of the weed problem so that you can prioritize your spraying schedule.
- Drain tile blowouts or sinkholes: Map those spots to return and fix them in dry conditions or to help avoid them with the tractor and planter during field operations.
- Areas for future site-specific insect-pest monitoring such as areas where black cutworm (BCW) larvae would be feeding on corn that will eventually be growing in those fields.
- Points where machinery failed, malfunctioned, or operation was delayed.
- Areas of hybrid trials and field experiments.

DGPS, a Tool for Precision Farming

DGPS is having a great impact on navigation in the agricultural industry; it gives a producer the ability to know a specific location. Depending on the receiver used, this location can be found instantaneously.

By knowing location, farmers can look at the field as a group of small zones and determine if the field is uniform or not (break the field up into smaller fields or grids). Computers and geographical information systems (GIS) enable producers to record location and other information. For example, a yield monitor used with GPS allows a farmer to record yield for every location in the field. With this information practices that may improve efficiency and increase profitability can be considered.

GPS receivers are rapidly becoming inexpensive enough that most producers can afford considering their use at some level of management.

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Glossary of GPS/DGPS terms

2DRMS - Twice-distance Root Mean Square, a horizontal measure of accuracy representing the radius of a circle within which the true value lies at least 95 percent of the time.

Anywhere fix - The ability of a receiver to start position calculations without being given an approximate location and approximate time.

Bandwidth - The range of frequencies in a signal.

C/A code - The standard (Coarse/Acquisition) GPS code. A sequence of 1023 pseudo-random, binary, biphase modulations on the GPS carrier at a chip rate of 1.023 Mhz. Also known as the "civilian code."

Carrier - A signal that can be varied from a known reference by modulation.

Carrier frequency - The frequency of the unmodulated fundamental output of a radio transmitter.

Carrier phase GPS - GPS measurements based on the L1 or L2 carrier signal.

Channel - A channel of a GPS receiver consisting of the circuitry necessary to receive the signal from single GPS satellite.

Circular error probable (CEP) - A statistical measure of the horizontal precision. The CEP value is defined as a circle of a specified radius that encloses 50 percent of the data points. Thus, half the data points are within a 2D CEP circle and half are outside the circle.

Clock bias - The difference between the clock's indicated time and true universal time.

Code phase GPS - GPS measurements based on the pseudo-random code (C/A or P) as opposed to the carrier of that code.

Cold start - The power-on sequence where the GPS receiver downloads almanac data before establishing a position fix.

Control segment - A world-wide network of GPS monitor and control stations that ensure the accuracy of satellite positions and their clocks.

Datum - A math model, which depicts a part of the surface of the earth. Latitude and longitude lines on a paper map are referenced to a specific map datum. The map datum selected on a GPS receiver needs to match the datum listed on the corresponding paper map in order for the position readings to match. WGS-84 (World Geodetic System, 1984) is the primary map datum used by GPS. Geodetic Datum is a math model representing the size and shape of the earth (or a portion of it). Universal Transverse Mercator (UTM) is a nearly worldwide coordinate projection system using north and east distance measurements from reference point(s). UTM is the primary coordinate system used on U.S. Geological Survey topographic maps.

Differential GPS (DGPS) - A technique to improve GPS accuracy that uses pseudorange errors measured at a known location to improve the measurements made by other GPS receivers within the same general geographic area.

Differential positioning - Accurate measurement of the relative positions of two receivers tracking the same GPS signals.

Dilution of precision - The multiplicative factor that modifies ranging error. It is caused solely by the geometry between the user and his set of satellites. Known as DOP or GDOP.

Dithering - The introduction of digital noise. This is the process the DOD uses to add inaccuracy to GPS signals to induce Selective Availability.

Ephemeris - The predictions of current satellite position that are transmitted to the user in the data message.

Geometric dilution of recision (GDOP) - See Dilution of precision.

Georeferenced - Associating some piece of information (yield, pH, soil nitrogen, etc.) with field position in two dimension space, latitude and longitude (Lat, Long).

Ionosphere - The band of charged particles 80 to 120 miles above the earth's surface. Ionospheric refraction is the change in the propagation speed of a signal as it passes through the ionosphere.

L-band - The group of radio frequencies extending from 1000 MHz to 2000 MHz. The GPS carrier frequencies (1227.6 MHz and 1575.42 MHz) are in the L band.

LAAS - Stands for Local Area Augmentation System. The implementation of ground-based DGPS to support aircraft landings in a local area (20 mile range).

Latitude (Lat) - A north/south measurement of position perpendicular to the earth's polar axis.

Longitude (Long) - An east/west measurement of position in relation to the Prime Meridian, an imaginary circle that passes through the north and south poles.

Meter - A metric measure of length equal to 3.28 feet.

Multipath error - Error caused by the interference of a signal that has reached the receiver antenna by two or more different paths. Usually caused by one path being bounced or reflected.

Multi-channel receiver - A GPS receiver that can simultaneously track more than one satellite signal.

Multiplexing channel - A channel of a GPS receiver that can be sequenced through a number of satellite signals.

P-code - The Precise code. A very long sequence of pseudorandom binary, biphase modulations on the GPS carrier at a chip rate of 10.23 MHz, which repeats about every 267 days. Each one-week segment of this code is unique to one GPS satellite and is reset each week.

Precise Positioning Service (PPS) - The most accurate dynamic positioning possible with standard GPS, based on the dual frequency P-code and no SA.

Pseudo random code - A signal with random noise-like properties. It is a very complicated but repeating pattern of 1's and 0's.

Pseudorange - A distance measurement based on the correlation of a satellite transmitted code and the local receiver's reference code that has not been corrected for errors in synchronization between the transmitter's clock and the receiver's clock.

Real time kinematic (RTK) - The DGPS procedure whereby carrier phase corrections are transmitted in real time from a reference station to the user's roving receiver.

Remote sensing - A sensor that measures the characteristics of a field (soil or plant) without having contact with the characteristic being sensed (includes aerial photographs, satellite imaging, and other non-intrusive sensing methods).

Root mean square (RMS) - A one-dimensional measure of accuracy representing the limits (plus or minus) within which the true value lies 68 percent of the time.

Satellite constellation - The arrangement in space of a set of satellites.

Selective Availability (SA) - A policy adopted by the Department of Defense to introduce some intentional clock noise into the GPS satellite signals thereby degrading their accuracy for civilian users. This policy was discontinued as of May 1, 2000, and now SA is turned off.

Standard positioning service (SPS) - The normal civilian positioning accuracy obtained by using the single frequency hC/A code.

Static positioning - Location determination when the receiver's antenna is presumed to be stationary on the earth. This allows the use of various averaging techniques that improve accuracy by factors of over 1,000.

Triangulation - A method of determining the location of an unknown point, as in GPS navigation, by using the laws of plane trigonometry.

WAAS - A differential correction system that stands for the "Wide Area Augmentation System."