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A General Guide to Global Positioning Systems (GPS)— Understanding Operational Factors for Agricultural Applications in Arizona

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Introduction

Farm mechanization at the turn of the 20th century was one of the main factors that paved the way for the modernization of production agriculture in Arizona. This process replaced draft animals with mechanical sources of power to create highly productive farming systems. Early in this process, we benefited from the outstanding gains in productivity. After the introduction of the diesel engine, our main strategy to increase productivity has been to use larger, more powerful machines. Some argue that, without an alternative source of energy, we have reached a limit in the response of farming systems to the use of mechanical inputs. A new paradigm in modern agriculture has appeared, one in which higher levels of information are incorporated into the management of production inputs in order to create more efficient farming systems. The new frontier of agricultural production in the semi-desert is rich in information technology. We are experiencing exciting times in technology use, and technological innovation is taking place at a fast pace in Arizona. This bulletin will cover important topics in the operation, limitations, types, and current status of this technology.

GPS in Agriculture

Global Positioning Systems (GPS) are a relatively new technology when it comes to applications in agriculture. GPS was developed by the U.S. Department of Defense in the 1980's under the name NAVSTAR (Navigation System for Timing and Ranging). Initially the U.S. government made available to the public GPS signals of intentionally degraded quality. The induced error, known as "selective availability," was removed in May 2000. Since then we have seen an explosion of applications, including tractor guidance, variable rate dispensing of chemical inputs, in-field monitoring of crop yield, and many others. Agricultural GPS technologies have been developing at a fast rate and they are made available all across the United States through the networks of farm equipment dealers. This commercial channel has provided a robust mechanism for the dissemination of GPS technology. As these technologies keep evolving, the private sector will intensify its product development and provide growers with solutions that have increased accuracy and affordability. This publication is focused on the basic concepts of GPS as they apply to agricultural production. The companion article "From GPS to GNSS – Enhanced functionality of GPS-integrated systems in agricultural machines" provides a detailed review and analysis of the newest developments in this area with a focus on functionality and efficiency.

How Does GPS Work?

GPS receivers are electronic devices that provide positioning information using a global network of orbiting satellites and ground stations. Positioning is based on the mathematical principle of trilateration, requiring the precise timing of radio signals transmitted from orbiting satellites to GPS receivers on the ground. To solve for position, a GPS receiver must link communication with at least four satellites and calculate its distance from them. These distances (or ranges) are obtained by measuring precisely the time-of-flight of each signal and multiplying it by the speed of light. These distances are actually known as pseudo-ranges to reflect the error in these computations. Due to the iterative nature of trilateration algorithms, the accuracy of the position information will depend primarily on the number of satellites communicating with the GPS receiver.

The basic framework of satellite-receiver communication was improved significantly when the concept of "differential correction" was introduced. This concept relies on the addition of a correction station installed at a point of known position. Differential correction compares the true position of the correction station and the calculated position according to the direct satellite-receiver links. This differential correction information is constantly broadcast to receivers in the area which will use it to improve the accuracy of their positioning computations. Receivers capable of collecting correction data are classified as DGPS receivers where the letter D denotes differential-correction. With very few exceptions, most agricultural applications of GPS rely on differential correction of some kind.

Now that we have set up this basic framework of GPS operation, let's analyze the larger scope by separating the three parts of a GPS system. The *space* segment refers to the

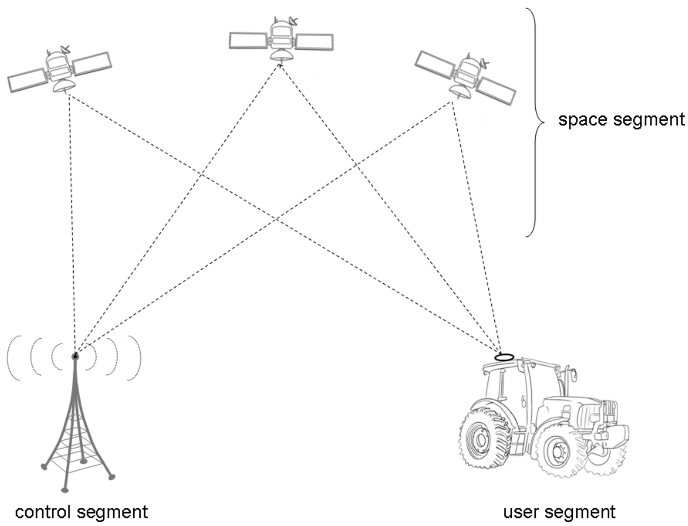

Figure 1. Diagram of GPS space, control, and user segments in agricultural applications.

constellation of U.S. GPS satellites orbiting the earth. Many satellites have been launched but 32 remain operational (PRN-132) and only 24 are required at a given time to secure full operation. The *control* segment is composed of 11 ground stations around the world that track and update the precise position of every satellite in the U.S. constellation. A central control unit is located at Schriever Air Force Base in Colorado. The third part is the *user* segment which refers to the actual GPS receivers used by the civilian and military communities. Figure 1 presents a diagram with a view of the GPS space, control, and user segments that provide the functional platform of satellite-based communications in agricultural applications. In the next sections we will analyze the contribution of additional ground stations such as the US Coast Guard Beacons that broadcast correction data to enhance the operational and functional characteristics of GPS receivers used in agriculture.

As can be expected in agricultural applications, we abide by the rules for civilian use. For civilians, two satellite signals of relatively low power (20-50 Watt) are available, starting with the L1 signal (1575.42 MHz) broadcast by all GPS satellites, and the L2C signal (1227.6 MHz) released in September 2005 which is currently available in 6 satellites. Dual-frequency receivers are capable of receiving these two signals simultaneously, resulting in increased accuracy. The Federal Aviation Administration (FAA) has proposed an upgrade to three civilian-use signals (L1C, L2C and L5 (1176.45 MHz)), which may be available for initial operational capability by 2012 and for full operational capability by approximately 2015. Updated information on the current status and modernization of GPS can be found on FAA's page: **http://www.navcen.uscg.gov/?pageName=GPSSOI**

Expected Error in GPS Signals

GPS receivers are always subject to receive satellite signals with a certain amount of error. The main sources of error are: *ionospheric and tropospheric signal delays*, which cause signal slowing due to changes in atmospheric conditions; poor *satellite geometry* that occurs when the satellites are tightly grouped or in a line with respect to the GPS receiver on earth; *orbital errors*, also known as ephemeris errors, that result from inaccuracies of the satellite's reported location. These sources of error occur in the space segment and therefore they are out of our control. On the ground, nearby objects such as trees and buildings can cause *signal multipath*; the bouncing of satellite signals off of surrounding objects increases signal travel time between the GPS receiver and satellites resulting in an inaccurate position measurement.

At the user level, we have limited options to GPS signal quality control, but the best approach is to avoid using GPS during times of substandard signal transmission. One way to achieve this is by monitoring the GPS receiver status in what is called *Dilution of Precision (DOP)*. In particular, the horizontal component of DOP, called HDOP, which is constantly reported by most receivers, should be monitored. A HDOP of 2.0 or less is acceptable. Planning ahead according to the GPS forecast of future days is an excellent approach when we need the best GPS signal quality. For this purpose, Trimble offers free GPS planning software (available online at **http://trimble.com/planningsoftware.shtml**). Figure 2 displays a screenshot of this software with the predicted number of satellites that will be visible by GPS receivers in the area of Maricopa AZ on 8/10/11. This information was generated 24 hrs in advance. Notice that from 14:00 to 16:00 the number of satellites was expected to change from 6 to 11, a very typical situation in Central Arizona.

Accuracy and Precision of GPS Positioning Data

The previous section described the signal error in the space segment, which refers to the quality of data arriving at the GPS receiver. Now let's focus on the quality of the data produced by the receiver. Before going deeper it is important to define two terms used to this regard. *Accuracy* indicates proximity of measurement results to the true value. *Precision* refers to the repeatability or reproducibility of the measurement. Accuracy and precision are terms commonly misused interchangeably to refer to the same concept; however, this is incorrect. What is important from the stand point of GPS use is to realize that our objectives are a) to make positioning measurements with the least amount of unexplained variation (i.e. accuracy) and b) to insure that these measurements remain unchanged as time goes by (i.e. precision). These concepts are very important because the quality of a GPS receiver is commonly described as pass-to-pass accuracy. GPS receivers graded with low numerical values of pass-to-pass accuracy indicates greater certainty in calculating the true position, therefore higher quality. In a GPS receiver, the accuracy and precision depend on the combination of hardware, firmware, and correction service.

GPS receivers are built to achieve different accuracy levels depending on their internal components, communication protocols, and available capabilities in firmware. Accuracy is perhaps the single most important factor, so we should review the manufacturer's claims on accuracy. Trimble

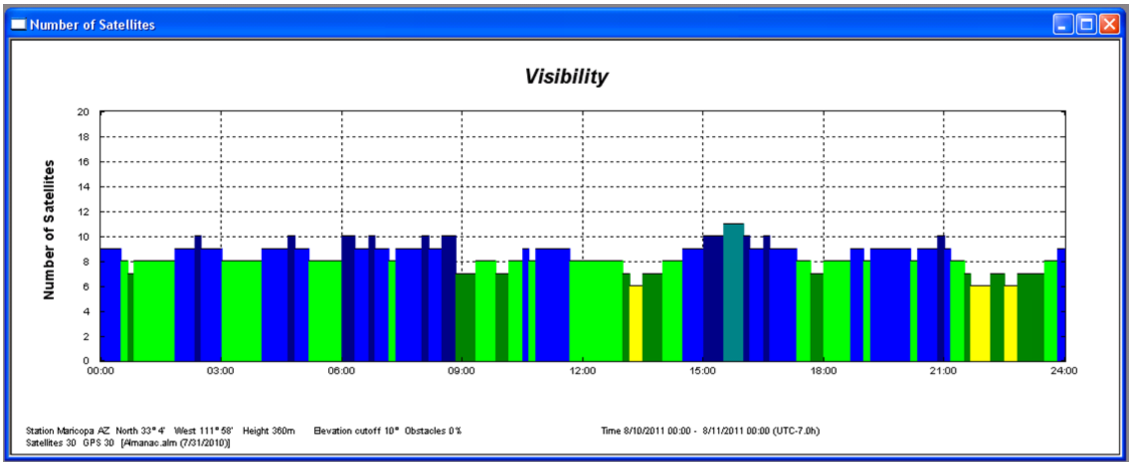

Figure 2. Predicted number of satellites visible in the Maricopa AZ area on August 10, 2011. Data generated with Trimble Planning Software v. 2.90.

provides definitions on two forms of accuracy with particular application to agriculture: "Pass-to-Pass accuracy measures the relative accuracy over a 15 minute interval, usually thought of as guess row error when driving rows, or skip/overlap from one pass to the next when driving swaths; and Year-to-Year accuracy is the measure of repeatable accuracy that you can drive the same rows a day, week, month, or year later". These definitions are simple and current. Most receivers are graded based on these values which are reported in informational brochures.

A deeper analysis of the reported values of accuracy needs some level of statistical definition by using the 95th percentile (95 percent of the data is better than the specification). For instance, a receiver graded for accuracy of 4 inches pass-to-pass, means that 95% of the time the receiver will provide positioning information on vehicle skip or overlap of less than 4 inches. The same is true for year-to-year accuracy; the reported value of accuracy is expected to hold at least 95% of the time. More rigorous descriptions of GPS accuracy are based on terms such as CEP (Circular Error Probable), which determines the radius of a circle that contains 50% of positioning calculations from a stationary receiver. This circle is centered on the true position. A similar concept of accuracy is expressed by the Root Mean Squared (RMS or dRMS) which is a statistical measure of the magnitude of variation in position data. Accuracy levels can be reported as 1, 2, or 3 RMS, that correspond to 68, 95, or 99.7% of the data points falling within the distance of the true position respectively. Keep in mind that the cost of a receiver is proportional to its accuracy level. It is worth making a careful assessment of accuracy needs before purchasing a system.

Differential Correction for GPS Receivers

So far we have mentioned that GPS receivers need differential correction to be accurate enough for agricultural applications. The accuracy of a GPS receiver by itself can be on the order of tens of feet, but DGPS receivers with differential correction can achieve lower than 40 inches of pass-to-pass accuracy. Newer DGPS receivers typically achieve 13 inches of pass-to-pass accuracy. This section deals with different options and services available for real-time correction. We have omitted post-processing as this is very rarely implemented in production agriculture. Following is a brief review of these services:

1. The U.S. Coast Guard (USCG) and Army Corps of Engineers have established a network of ground-based radio beacons that constantly broadcast differential corrections to GPS receivers. One main advantage of radio beacon DGPS is that the corrections are free to anyone with the appropriate equipment. The network includes approximately 100 beacon stations to cover the entire United States from coast to coast. In spite of being a dense network, in Arizona there is only one beacon station located in Flagstaff AZ (35°13′10.8″N, 111°49′3.6″W) transmitting at a frequency of 319 kHz with a nominal range of 280 miles. The long-range signals of this beacon serve Central Arizona with strong signals that penetrate into valleys and urban settings and travel around obstacles. Figure 3 shows the areas in Arizona covered with the USGC radio beacons. Note that beacon stations in Tucson, AZ and Kanab, UT remain in the planning stage at the present time.
2. Wide Area Augmentation Service (WAAS) was first developed for civil aviation. It is a very popular source of differential correction in the U.S., also available free of charge to civilian users with appropriate DGPS receivers. In the control segment, WAAS uses a network of 38 base stations on the ground to monitor the GPS satellites. These networks send signals up to geostationary satellites, which broadcast the signals back to the end-user DGPS receivers on Earth. Before December 2010, the space segment of WAAS consisted of two commercial satellites, PRN-135 (in the Western US at 133° W) and PRN-138 (in the Central US at 107° W). When PRN-135 went off-line, a new satellite (PRN-133 in the Eastern US at 98° W) became available for WAAS corrections. DGPS receivers needed firmware updates to communicate with this new satellite. The concept of 'wide area' is based on calculating corrections at each

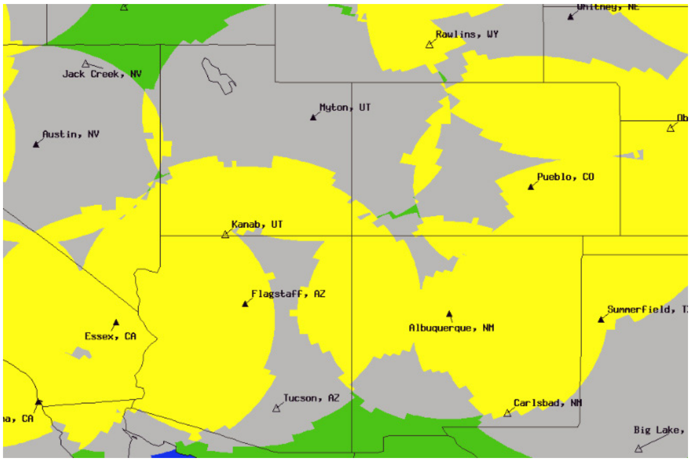

Figure 3. US Coastguard Radio Beacon stations providing differential correction service in Arizona. Yellow indicate areas covered by more than one station; gray areas are covered with one station; green areas have no coverage.

base station applicable to the area surrounding each site, and determine corrections for very large areas by using all base station data together. WAAS performance is constantly monitored and it is generally accepted that the coverage all across the U.S. has very high quality. Airports in Southern Arizona experience slightly smaller WAAS coverage, but effects are minor for agricultural applications of GPS.

3. Correction through private companies. In the US there is a strong presence of privately owned solutions to differential correction such as OmniSTAR and John Deere StarFire. OmniSTAR provides differential correction signals to subscribing users through their systems of privately-owned satellites. To generate correction information, these systems use a network of permanent reference stations to track all visible GPS satellites and compute corrections every second. The corrections are sent to a network control center where these messages are formed into data packets for transmission up to the private satellite transponders. OmniSTAR-enabled GPS receivers are capable of decoding these packets of correction data from the satellite transponder. Correction data is further refined for atmospheric errors and optimized to the user's location through proprietary algorithms. The basic level of correction (VBS) is comparable to USCG radio beacon and WAAS. For dual-frequency receivers OmniSTAR offers two levels of higher accuracy for applications that require better than 8 inches (XP), and better than 4 inches (HP) pass-to-pass accuracy. Arizona and other states in the Western US are served with satellite MSV-W located at 101° W transmitting in the L-band at 1557.86 MHz frequency. Updated information can be found on-line at: **http://www.omnistar.com/**

The John Deere StarFire differential correction solution is computed internally by advanced GPS dual-frequency receivers in a private global tracking network. These receivers compare the phase of L1 and L2 satellite signals and estimate the effects of the ionosphere on the propagation time between the two. Correction signals are generated and transmitted via six Inmarsat satellite links directly to StarFire receivers. John Deere offers two levels of accuracy in differential correction for the StarFire 3000 GPS receiver: SF1 for 10 inches and SF2 for 4 inches of pass-to pass accuracy.

High-end Correction for GPS Receivers

Real-time kinematic (RTK) Positioning is the highest level of GPS accuracy currently available. In agriculture it is almost exclusively used in navigation solutions for machine guidance systems such as auto-steer. In these solutions, the RTK-enabled GPS receiver, called the 'rover', is installed on a tractor, sprayer or other self-propelled machine. A GPS-RTK network is also composed of a stationary GPS reference receiver, called a base station, and a radio link between the base station and the rover. The base station transmits a radio signal to the user's receiver which contains correction data, called carrier phase information, and is the basis for high accuracy positioning. In RTK positioning systems, the base station is retrofitted with a digital radio link to send correction data every second or even faster. The RTK-enabled rover GPS receiver then solves for a carrier-phase solution through sophisticated mathematical algorithms. This phase solution is accurate to about one half-inch in most cases. In RTK-GPS systems, the base station typically has to be within 10 to 20 miles of the rover because the base-rover radio link is of relatively low power (1.0 W or less). As expected in RF communications the signal strength of the RTK radio link will be affected by objects blocking the line-of-sight between the base station and the rover. In Arizona our flat topography is a factor that extends the coverage of these networks.

GPS Output for Positioning and Navigation Functions

This section provides a review of the nature and quality of GPS output. Once the GPS receiver has solved for position it sends this signal to the controller through one-way serial data communication using standard formats defined by the National Marine Electronics Association (NMEA). Agricultural GPS applications use NMEA Standard 0183 that defines electrical signal requirements, data transmission protocol and time, and specific sentence formats. Data strings contain information such as position, elevation, satellite signal quality, speed, bearing, etc. The most common NMEA strings used in agriculture are GGA and VRT but many other sentences are available in current receivers. Advanced users can check these strings by connecting the receiver to a serial port on a personal computer (PC) and use 8N1 settings (8 data bits, no parity and one stop bit) with 4800 baud in your hyper-terminal software. The latest version of NMEA 0183 Standard is v. 4.0. As it evolves, new versions will accommodate changes in GPS utilization.

The following section describes the GGA and VGT sentences of current NMEA-0183 strings as they would apply in a GPS-RTK application in Maricopa AZ with a vehicle moving at 5.5 mph in straight East to West direction at 2:15pm on August 30, 2011. A description of the fields in these sentences has been added to help understand the information conveyed in these formats. (Figure 4)

GPS Receivers Used in Agricultural Applications

In agriculture, the use of hand-held GPS receivers is limited to locating sampling points or other objects across the field. In spite of their small size and integrated antenna, some of these receivers can perform differential correction and can be quite accurate.

For machine applications of GPS there is a variety of receivers to choose from. Typically these receivers come in ruggedized metal enclosures with output port(s) to connect to the controller of the intended application. External antennas are connected through coaxial connectors. It is important to note that the antenna should match the receiver in signal process capabilities for the GPS to perform at full capacity. Consult with your GPS provider to select the right cable and antenna, as well as to obtain installation instructions, upgrades, service, etc.

When searching for GPS options and general information, it is important to consult with the farm machinery dealers in your area. Browsing online is a great way to review the latest information from manufacturers on operational issues such as firmware updates, service availability, etc. The following is a list of URL's for major GPS manufacturers that provide solutions for agricultural applications:

AutoFarm	**http://www.gpsfarm.com/**
Hemisphere-GPS	**http://www.hemispheregps.com/**
John Deere	**http://www.deere.com/en_US/ProductCatalog/FR/series/ams/displays_receivers/displays_receivers.html**
Leica Geosystems	**http://www.leica-geosystems.us/en/Agriculture_1707.htm**
Raven	**http://www.ravenprecision.com/**
Topcon	**http://www.topconpa.com/products/gps-receivers**
Trimble LTD	**http://www.trimble.com/agriculture/**

Key Points to Consider when Choosing the Right GPS Receiver

There are many benefits in using GPS technology and the potential to increase the productivity of your mechanized operations is great. Consider the following list of key points to make informed decisions as you implement this technology on your farm:

Figure 4. Description of fields.

$GPGGA,211500,3303.859,N,11158.189,W,4,08,1.9,360.16,M,-27.5,M,,*12

where:

GGA	Global Positioning System Fix Data
211500	Fix taken at 21:15:00 UTC (Coordinated Universal Time) -> 2:15pm
3303.859,N	Latitude 33 deg 03.859' N
11158.189,W	Longitude 111 deg 58.189' W
4	Fix quality for fixed RTK. Other possible values include: 0 = invalid;1 = GPS fix (SPS); 2 = DGPS fix; 3 = PPS fix; 5 = Float RTK
08	Number of satellites being tracked
1.9	Horizontal dilution of position
360.16,M	Altitude above mean sea level, in meters
-27.5,M	Height of geoid (mean sea level) above WGS84 ellipsoid, in meters
*12	Checksum (checksum is a fixed-size datum recorded to verify the integrity of the data transmitted).

$GPVTG,090.0,T,079.2,M,004.8,N,008.9,K*36

where:

VTG	Course Over Ground and Ground Speed
090.0,T	True track made good (degrees). Track relative to true North
079.2,M	Magnetic track made good (degrees). Relative to magnetic North
004.8,N	Ground speed, knots
008.9,K	Ground speed, kilometers per hour
*36	Checksum

1. Confirm that the GPS receiver has at least 12 channels. The number of channels determines how many satellites it can monitor simultaneously.
2. Choose an antenna that matches the technical specifications of the GPS receiver. In particular, check there is a match in satellite signals (L1 and L2C).
3. Make a careful assessment of the level(s) of accuracy you need. The cost of a GPS receiver will generally be determined by its accuracy.
4. Consider system portability. Your GPS receiver might provide positioning and navigation information to several machines.
5. Consider accuracy needs, signal availability, and cost of subscription when selecting which differential correction or RTK service to use.
6. Check the manufacturer's claims on accuracy, particularly pass-to-pass and year-to-year accuracy.
7. Verify the release date of the receiver's firmware version. Ask for instructions on how to update your receiver's operating system.
8. Make sure that the receiver output ports, cables, and communication protocols are compatible with existing hardware in your set of precision ag tools.

Related Publications

This article was written with particular focus on the case of Arizona. Other sources of complimentary information to the topic of GPS for agricultural use in the United States include the following list of extension bulletins:

1. Adamchuk, V.I. 2002. Untangling the GPS Data String. University of Nebraska Cooperative Extension. Publication EC 01-157.
2. Grisso, R., M. Alley, and G. Groover. 2009. Precision Farming Tools: GPS Navigation. Virginia Cooperative Extension. Virginia Tech. Publication 442-501.
3. Grisso, R., M. Alley, and C. Heatwole. 2003. Precision Farming Tools: Global Positioning System (GPS). Virginia Cooperative Extension. Virginia Tech. Publication 442-503.
4. Stombaugh, T. 2008. GPS Changes: How to be Prepared. Cooperative Extension Service. University of Kentucky. Publication AEN-95.
5. Stombaugh, T., D. McLaren, and B. Koostra. 2005. The Global Positioning System. Cooperative Extension Service. University of Kentucky. Publication AEN-88.

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