A TEST OF DIFFERENTIAL GPS CORRECTION METHODS AT FORT HUACHUCA, ARIZONA

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By
JOSHUA G. SWANSON

Dr. C. Mark Cowell, Thesis Supervisor

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The undersigned, appointed by the Dean of the Graduate School, have examined the thesis entitled

A TEST OF DIFFERENTIAL GPS CORRECTION METHODS
AT FORT HUACHUCA, ARIZONA

Presented by Joshua G. Swanson

a candidate for the degree of Master of Arts in Geography

and hereby certify that in their opinion it is worthy of acceptance.

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Professor C. Mark Cowell

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Professor Cuizhen Wang

____
Professor David Vaught

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Joshua G. Swanson

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ABSTRACT

High accuracy GPS using inexpensive field equipment is increasingly made possible through use of reference data provided by the Continuously Operating Reference Station (CORS) network. There are currently three CORS within 100km of Fort Huachuca, Arizona, but use of CORS data in differential correction has previously proven unreliable. The effectiveness of base data acquired through use of a second field unit as an on-site base station was compared with the use of CORS. The accuracy of data differentially corrected using base data acquired from an on-site base station showed marked improvement over the use of CORS base data. Accuracy of locally corrected points improved by 75cm and 95cm in two study areas as compared to uncorrected data, while accuracy actually degraded by 28cm and 1cm in these areas when differentially correcting using the nearest CORS. Sub-meter accuracy was attained in over 90% of local base corrected Differential GPS (DGPS) points.

This project explores differences in horizons at rover and base as one possible explanation for the limited utility of CORS base data at Fort Huachuca. The 'Sky Islands' of southeastern Arizona present widely varying terrain conditions over relatively short distances, and blockage of the sky due to horizon differences is one variable condition at the collection sites. Upon testing, however, variability in horizon did not prove to be the

primary cause of limitied utility of DGPS using CORS at Fort Huachuca. Thus, site conditions limiting the utility of CORS in the Sky Islands, and perhaps other areas, remain to be identified.

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CHAPTER 1
Introduction: GPS and Accuracy Enhancement

Global Positioning System (GPS) receivers are used to triangulate a two or three dimensional location on or above the surface of the earth by measuring the distance from a number of satellites, or space vehicles (SVs) to the receiver. The receiver determines distance from at least three SVs by measuring the time it takes for radio waves to travel from each of the SVs. A stream of pseudorandom code is continuously sent from each SV in two radio frequencies, and accurate clocks in the SVs and the receiver enable the receiver to determine both the time the code was sent and the time it was received. The time it takes to receive the code from each available SV, coupled with knowing the speed with which the radio waves travel, enables the receiver to calculate distance to each SV (speed*time=distance). Coupling the necessary triangulation distance data with knowledge of the exact locations of the SVs enables determination of the receiver's location (Thompson 1998).

The United States Government authorized Navstar GPS (Navigation System with Time and Ranging-Global Positioning System), now simply known as "GPS," in 1973, which incorporates a minimum of 24 SVs by design, but currently contains an additional seven. The SVs circumnavigate the Earth roughly twice per day in six orbits and continuously transmit radio waves in two, or sometimes three, frequencies towards the surface of the planet. The system is managed by the Space and Missile Systems Center (SMC), Air Force Space Command, Los Angeles Air Force Base, California, and operated by by the 50th Space Wing's (Air Force Space Command) 2nd Space Operations

Squadron, Schriever Air Force Base, Colorado (http://www.losangeles.af.mil/library/factsheets/factsheet.asp?id=5325 (last accessed 19 January 2009)).

GPS hardware currently includes the 31 SVs, six monitor stations, and four ground antennae. The ground stations and antennae support the system by monitoring signals transmitted by the SVs, and sending information back to them to correct for any error in clock or location accuracy and precision. SVs scheduled for launch in the future will be upgraded for improved operation and for better interoperability with Europe's system, called Galileo (http://www.losangeles.af.mil/library/factsheets/factsheet.asp?id=5325 (last accessed 19 January 2009)).

Uses and Limitations of GPS

Personal and commercial navigation are widely used applications of GPS. A myriad of relatively low cost receivers are available to assist boaters, hikers, bikers, and motorists know where they have been, where they are, and to help them arrive where they want to go. The transportation and aeronautical industries also benefit from the technology, through navigation and tracking ability. Scientists, utility companies, surveyors, and others collect horizontal and vertical position measurements of on and above ground features. GPS receivers attached to tractors enable farmers to variably and precisely apply fertilizer on their fields. Despite these many uses, GPS was originally developed by the military for military applications. In fact, until May 2000, the military intentionally scrambled the GPS signal to limit the accuracy achieved by non-military users (selective availability, or SA), while only military users were granted access to the unscrambled code (Adrados et al. 2002).

Though SA was removed in 2000, several natural factors still exist which introduce errors to GPS measurements. Atmospheric effects may slow or speed the radio waves, terrain features or vegetation may be present to block visibility of SVs, and the SVs may not be in optimal positions relative to the horizon, to name a few (Straka and Gregorwich 1996). 'Multipath' is an error inducing phenomenon where a receiver may receive a secondary signal that bounces off a terrain or man made object near the receiver (Morgan-Owen and Johnston 1995, 15). Several methods have been devised to remove some of the introduced errors involving what is known as 'differential correction' (eg Dussault et al. 2001, Martinez et al. 2000).

Differential Correction and CORS

Differential GPS (DGPS) involves the use of two GPS receivers working in conjunction with one another. One GPS unit, known as a ‘base station,’ is located on a point with known coordinates to record offset of calculated positions from the true location, while a nearby second unit, known as a ‘rover,’ is used to collect field data. It is assumed that the errors experienced by both receivers will be similar because the signals received by each travel through a very similar slice of atmosphere. The error offset information from the base station is then used to ‘correct’ the data collected by the rover (Morgan-Owen and Johnston 1995). Correction can be performed in real-time through direct communication between the base station and rover using FM radio waves, known as Real Time Kinematic (RTK) differential correction. Post-processing is another method, which uses a computer to differentially correct the rover data after collection on a PC, and does not require that a transmitter be connected to the base station.

A network of 'Continually Operating Reference Stations' (CORS) is a large collection of base stations administered by the National Geodetic Survey (NGS). CORS continually collect base data, which is available by RTK radio link from some stations, and also for download from the internet for post-processing. As of August 2008, there were 1497 CORS worldwide, the majority of which reside in the United States. Land managers routinely use CORS data for DGPS correction, a standard practice due to their availability and ease of use.

Purpose of This Study

This study examines the feasibility and potential benefit of an alternative to CORS: using a temporary, locally operated base station to enhance the accuracy of GPS data collection in the Sky Islands of southeastern Arizona (Figure 1). Questions as to the performance of DGPS measurements using CORS in this environment while collecting data at Fort Huachuca arose, although the CORS used are within what is generally regarded as an acceptable distance between rover and base. One hypothesizes that the highly variable topography and influence of horizon in the region may contribute to a degradation of usefulness of DGPS base data based on terrain association of the base station vs. the rover.

Fort Huachuca and the surrounding area offer a unique landscape for electronic testing due to the nature of the topography. The Fort is home of the United States Army's Electronic Proving Ground. To facilitate equipment testing, thousands of benchmarks have been installed and verified to centimeter level accuracy by land surveyors over the

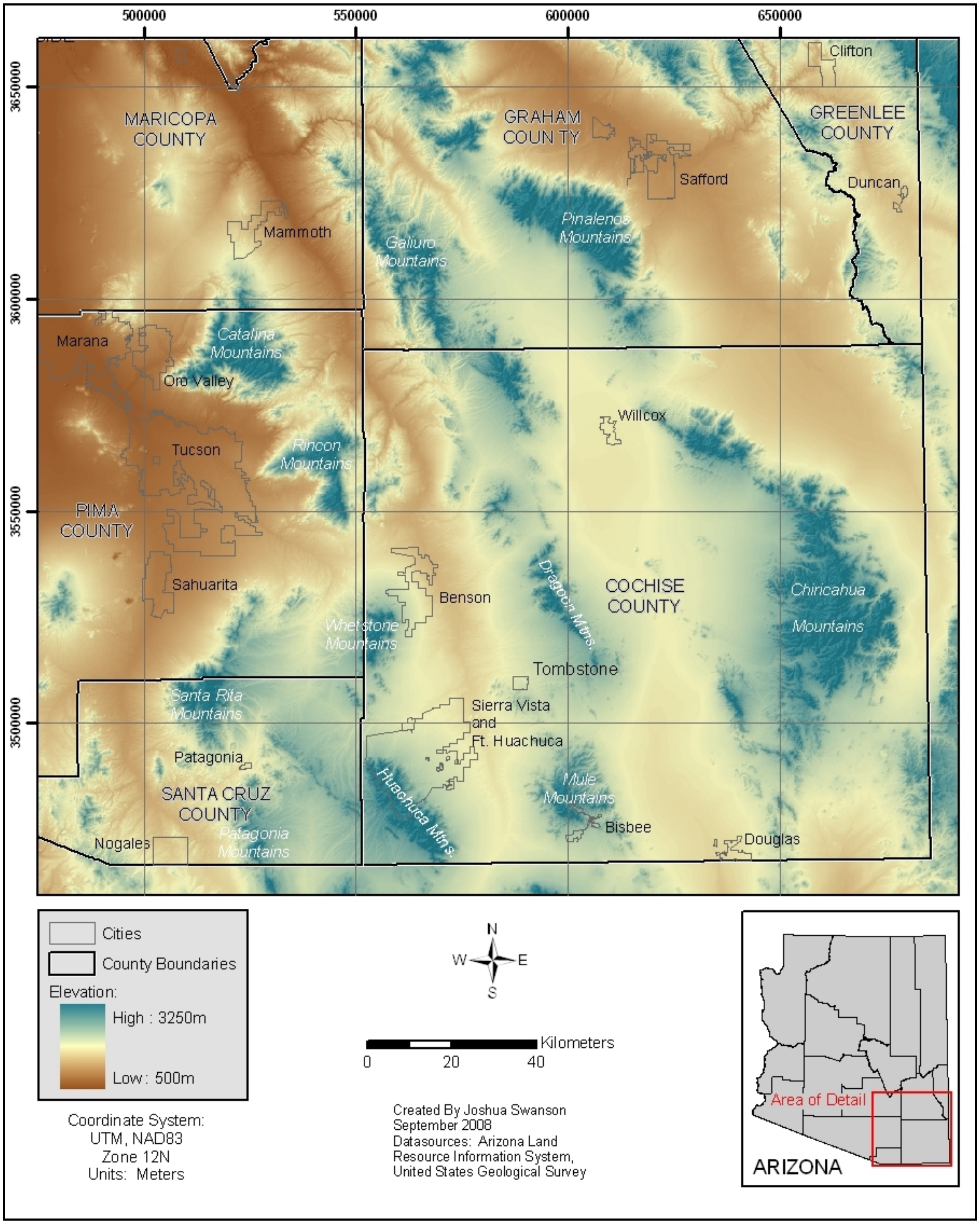


Figure 1.1. The 'Sky Islands' of southeastern Arizona occur primarily in Cochise, Graham, Pima, and Santa Cruz Counties. Several mountain ranges have peaks reaching over 9,000' above mean sea level, with valleys of desert and grassland separating the ranges.

past decades. These benchmarks are called "ASA Points" and provide a unique resource for testing the accuracy of GPS positions and for use as locations on which to collect GPS base data. In April of 2008, permission was granted to use a handful of ASA points to test the accuracy of GPS data and for use in collecting base GPS data.

The maximum horizontal error generally experienced using mapping grade GPS data collection devices, as used in this study, is within 5m. Accuracy at this level is more than adequate for many GPS applications, such as navigation. Sub-meter or better accuracy is desirable when performing field work where measuring the relationship between points, for example. The desire for high accuracy at Fort Huachuca initially grew out of a project that required the delineation of surface danger zones (SDZs) for small arms projectiles. This area is considered hazardous when a weapon is discharged, and is a broad area that is calculated using the coordinates of one or more firing positions and target locations (see Department of the Army Pamphlet 385-63). Sub-meter accuracy may also be desired when measuring the movement of a stream bank over time, or plotting the location where an archaeological artifact was discovered, for example.

The single frequency units used in this study are widely used by land managers in the area. A need for accurate GPS readings using commonly available equipment coupled with the inconsistent accuracy results when using CORS base data drove the desire to test the accuracy enhancement potential of using base data collected on site. This technique was once more common, but has been largely replaced by using CORS base data.

Research Questions

A case study was performed to answer three questions: 1) What post-processing technique provides the best horizontal locational accuracy improvement, and by how much, to L1 GPS measurements in two different environments at Fort Huachuca? 2) Is it possible to reliably attain sub-meter accuracy with commonly used L1 field GPS units? And 3) Assuming differential correction using CORS demonstrates inconsistent or marginal results, or a degradation in horizontal accuracy as it has in the past, can this be attributed to the varying visibility of the sky due to horizon differences at the base station vs. rover locations?

CHAPTER 2
Background: Global Navigation Satellite Systems, Error Sources, and Error Reduction Methods

GPS is of growing use to foresters, wildlife biologists, and other field researchers, and is increasingly being relied upon in lieu of traditional field measurement methods (Johnson and Barton 2004). Reflecting this shift, much research has recently focused on the accuracy potential of commonly used GPS equipment under various field conditions (e.g. D'Eon et al 2002, Di Orio et al 2003). A variety of sources introduce error into GPS measurements, and research has also focused on negating the individual sources of error (e.g. Kijewski-Correa and Kochly 2007). Frequently these techniques are complex and not field expedient, however. Therefore, field researchers often rely on the relatively simple and effective technique of differential correction to improve accuracy of GPS measurements (e.g. Squarzoni et al 2005). This project examines the possibility of enhancing this technique under field conditions where normal DGPS techniques prove unreliable.

GPS Satellite Systems

The number of Global Navigation Satellite Systems (GNSSs) is currently increasing. The oldest and currently only independently usable GNSS is GPS, operated by the United States Government since the late 1970s. GLONASS (Globaluaya Navigatsionnaya Sputnikovaya Sistema), operated by Russia, is the second system to be launched, but is not yet fully and independently operational. Both were developed nationally for military applications, and their signals are currently also available for civilian use (Lechner and Baumann 2000). Galileo is a GNSS currently being launched by the European Space Agency (ESA). Galileo is set apart in that it is being developed with civilian/commercial use in mind. While GPS and GLONASS signals can be degraded or restricted for defense or security purposes, the civilian user should have unfettered access to Galileo regardless of circumstance (Clery 2005).

GLONASS is scheduled to have a full complement of 24 SVs occupying three orbits sometime in 2009. The first generation GLONASS SV was single civilian band capable, but the newer "GLONASS-M" model is dual band capable, and was launched beginning in 2005. The third generation "GLONASS-K" will be three band capable, and is scheduled for launch beginning in 2009. The Russians are also developing a full complement of ground stations and antennae to keep GLONASS operating effectively (Sergey et al. 2007).

Galileo as a standalone system is currently scheduled for debut by 2013, and will contain 30 SVs in three orbits (European Space Agency). O'Keefe et al. (2006) used simulation modelling to predict the accuracy potential of Galileo and combined use of Galileo and GPS. The model shows that much better satellite geometry will be normally achievable when receiving from both systems than with either system alone. The simulation predicts a reduction in maximum horizontal position error from 60m using either GPS or Galileo alone to only 10m using the combined constellation. The technical aspect of integrating Galileo with GPS is not particularly daunting, especially since the first band frequencies will likely be the same (O'Keefe et al. 2006). However, political obstacles to integration remain formidable (see Blanchard 2003).

Tripling the number of available SVs for use by individual receivers in the future could soon open up many new opportunities for research. There are currently receivers available in the US that can access the GLONASS frequencies. However, GLONASS capable receivers are not yet widely used, and the ones used in this study exclusively use the GPS frequencies. The focus of this study is on the use of the GPS constellation, and the terms 'SV,' 'satellite,' 'ground station,' etc. will heretofore refer exclusively to NAVSTAR GPS hardware.

The six orbits of the GPS constellation are spaced equally around the globe, 60° apart, inclined at 54.7° (Lechner and Baumann 2000, Sergey et al. 2007). The geometry should provide line of sight to between five and eight SVs at any given time and point on the planet. SVs orbit the Earth every 11 hours 58 minutes. SVs acquire data on their orbital position (ephemeris) and corrections to their clocks through periodic communication with the ground stations. The NAVSTAR satellites broadcast on two frequencies: L1 (1575.42 MHz) and L2 (1227.70 MHz). The Course Acquisition Code (C/A Code) is available on the L1 frequency, and under SA, was the only code available to civilian users. The Precise Code (P Code) is broadcast on both L1 and L2, and is now available to all users (Lechner and Baumann 2000). A third frequency (L5) will be added to a new generation of SVs, which will be launched beginning in 2009 (http://www.losangeles.af.mil/library/factsheets/factsheet.asp?id=5325 (last accessed 19 January 2009)).

Measuring the Accuracy of GPS

The distance between a coordinate recorded by a GPS receiver and the actual coordinate of the location is easily measurable when the actual coordinate is known.

When a recorded point is made up of more than one position, there are two measures of accuracy. It is possible to measure both the distance between the recorded point and the actual point, or between each recorded position and the actual point. In the latter case, each position is treated as if it is an individual point collection.

Circular error of probability (CEP) is frequently used in studies on GPS accuracy, and applies when multiple positions are collected. CEPs are typically given at the 50 percent and 95 percent thresholds. Ten-meter accuracy at 50 percent CEP would indicate that of all GPS positions collected at a particular location, 50 percent of them fell within 10m of the true horizontal location (Thompson 1998). In this paper, this value will be expressed as 10m(50%). See Figure 2.1 for additional explanation.

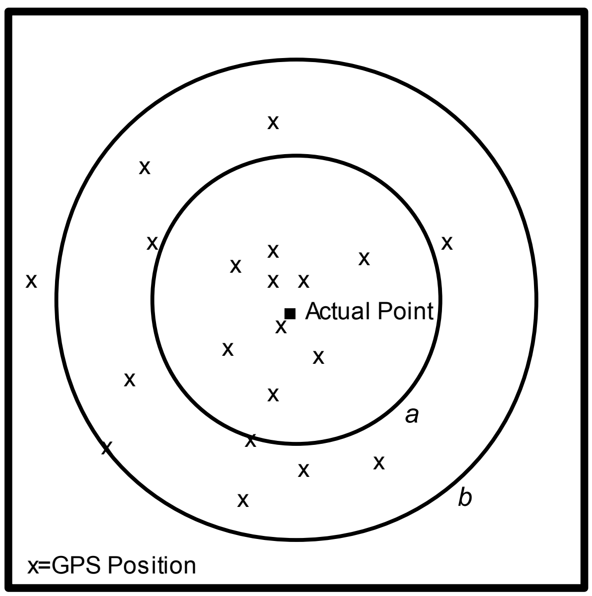


Figure 2.1. A theoretical graphic showing 20 positions collected on one point with a known location. The radius that 10 (50%) positions fall within (circle *a*) would be the 50 percent CEP value, expressed as *a*(50%). 19 (95 percent) of the positions fall within circle *b*, so that radius value is expressed as *b*(95%).

Sources of GPS Error

Two general types of errors are important concerns for GPS data accuracy: those that result from satellite based sources, and those that result from environmental (atmosphere or terrain based) sources. With the removal of Selective Availability, the main satellite based sources of error are clock drift and ephemeris error, which are problems on board the individual SVs, and poor positional dilution of precision (PDOP), which is a problem involving the position and geometry of SVs above the horizon relative to the receiver location. Ground and atmosphere based sources of error include varying density of the atmosphere between SV and receiver, multipath, and foliage based attenuation of the signals.

Satellite-based Error

<u>Selective Availability</u>

Selective Availability was the primary source of error until it was removed in 2000. With SA turned on, GPS users were only able to receive the C/A Code on the L1 frequency, while military users could receive the P Code on both L1 and L2 (Lechner and Baumann 2000). Users saw immediate and dramatic accuracy improvements with the removal of SA. Adrados et al. (2002) recorded reduction of mean positioning error before and after SA removal using using wildlife monitoring GPS collars. Non-differential collars recorded a mean error reduction from 78m with SA to 11.9m, while with differential collars a reduction from 11.3m to 5.2m was achieved. That differential correction continued to provide benefit after the removal of SA demonstrated that effects of other sources of error could also be reduced by DGPS.

Satellite Ephemeris and Clock Error

While the intentionally introduced error of SA has been removed, other unintentional satellite based errors are still present. For a receiver to accurately triangulate its position, the SVs from which it receives data must accurately broadcast their clock time and position (ephemeris). Clock and ephemeris errors on board the SV will result in positioning error being recorded by the GPS receiver, as the receiver is misinformed of the distance between itself and the SV and/or the time that the signal was sent. Six monitor stations are used by the Air Force to measure these errors, and four ground antennae transmit corrected ephemeris and clock data to the SVs using the S-band (http://www.losangeles.af.mil/library/factsheets/factsheet.asp?id=5325 (last accessed 19 January 2009)).

Scientists have also worked independently to attempt to reduce the influence of clock error. Han et al. (2000) developed a technique that uses precise orbit data from the International GPS Service (IGS) to estimate clock error on board the SVs. The error data was then fed into a complex algorithm developed by the authors to increase accuracy in absolute positioning. Clock error was estimated every 30 seconds, and interpolated down to 1 second intervals. Recorded positions averaged <18cm offset (SD <2cm) from their surveyed, absolute positions at the 30 second intervals. Offset averaging <40 cm distant from short range DGPS positions (300m from base station) were observed using the 1 second interpolations. The Han et al. study demonstrates that very high accuracy is achievable by minimizing satellite based error sources in areas with minimal ground based error potential. The means, however, are not field expedient.

PDOP: Position Dilution of Precision

PDOP (Figure 2.2) is a factor of Horizontal dilution of precision (HDOP) and Vertical dilution of precision(VDOP). PDOP refers to the geometry of visible SVs with relationship to the horizon. With wide angles between SVs, PDOP values will be low, while PDOP values will be high when SVs are clustered in the sky, and angles between them are thus reduced. Assuming only four satellites are visible, the best position for the SVs to be in is one directly above, and three evenly spaced around, and slightly above, the horizon (Straka and Gregorwich 1996).

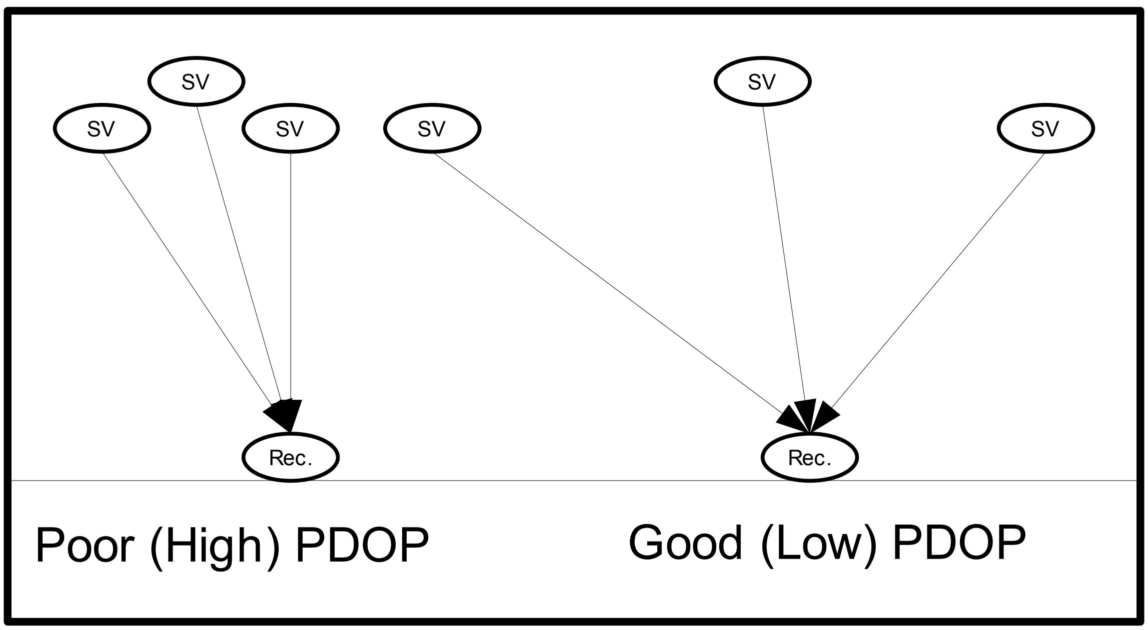


Figure 2.2. Poor PDOP results from SVs being relatively clustered in the sky, and angles between them being low. Good PDOP results when SVs are evenly spaced in the portion of the sky above the horizon.

Dussault et al. (2001) established that a linear relationship exists between HDOP and both horizontal and vertical accuracy of 3D GPS measurements, the effect of which is less dramatic, but still present, when using differential correction. At HDOP=30, GPS collars normally used to track the movements of moose recorded DGPS locations 15m(50%) from their true positions , while non-differential collars measured an accuracy of 160m(50%). At HDOP<5, the values were reduced to approximately 10m(50%) with DGPS and <50m(50%) without. The relationship of DGPS measurements between error offset and HDOP at 95 percent CEP is somewhat more dramatic, with an offset of approximately 45m(95%) at HDOP=30, and 15m(95%) at HDOP<5.

Environmental Sources of Error

Atmospheric Effects on Radio Waves

Atmospheric effects are considered the largest post-SA sources of GPS error (Kintner and Ledvina 2005). Radio waves travel at different speeds in a vacuum than in an atmosphere. GPS signals must travel through both the troposphere and the ionosphere; it is the later in which the most significant error can be introduced (Morgan-Owen and Johnston 1995). The thickness and density of atmosphere traveled through vary when waves travel from SV to receiver. Increased sharpness of the angle at which the signal must pass through the ionosphere at can worsen the effect; signals of SVs closer to the horizon must traverse a longer path through the atmosphere. Small scale ionospheric disturbances can variably influence GPS measurements over short distances for short periods of time (Warnant et al 2007).

Dual band receivers, still relatively uncommon and expensive on the civilian market, can measure the ionosphere by comparing the amount of time it takes for each band (L1 and L2) to receive their respective signals. The two frequencies are affected differently by the Total Electron Content (TEC) of the portion of the ionosphere passed through, and the delay difference can be used to calculate the TEC. Kintner and Ledvina (2005) state that TEC in the ionosphere can lead to horizontal positioning errors of between 5m and 40m in raw single band GPS measurements. The error is reduced to around 1m with the aid of either the L2 band or differential correction. The authors demonstrated in an experimental collection both that SVs closer to the horizon pass through areas of higher TEC, and that periodic spikes in TEC due to ionospheric "bubbles" can impact measurements from SVs further from the horizon.

<u>Multipath</u>

In multipath (Figure 2.3), a signal from an SV may be received more than once by the receiver, or only secondary, indirect signals received. The signal may literally take two or more paths to the receiver, by bouncing off terrain features or man made structures. Multipath tends to occur in areas with high topographic variability, such as in canyons, or near large buildings (urban canyons). The effect of multipath is locally induced, and can vary over short distances (Morgan-Owen and Johnston 1995, Straka and Gregorwich 1996).

Multipath is the only source of error that cannot be dramatically reduced by using DGPS or dual band receivers (Kintner and Ledvina 2005). Manufacturers have produced multipath resistant antennae, but the multipath removal capability is dependent on the secondary signal arriving from a low angle. Therefore, these are not 100 percent reliable in areas of extremely high topographic variability or in urban canyons. Receivers are also being programmed with algorithms that can detect secondary signals, but these are not yet widely available or reliable. Although complex techniques have recently been

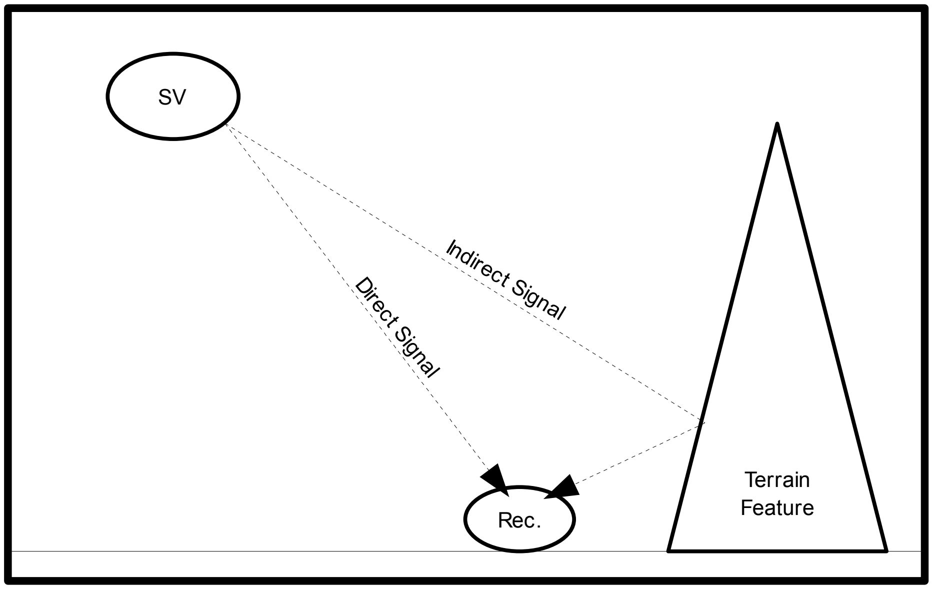


Figure 2.3. Multipath error occurs when a radio signal sent by a transmitter on board an SV is received indirectly by a GPS receiver. A direct signal may or may not be received first; the indirect signal is received later than it should be, and causes the receiver to compute that the SV is more distant than it actually is.

developed to remove multipath signatures (e.g. Kijewski-Correa and Kochly 2007), multipath appears to remain a source of error that is not reliably correctable, detectable, or eliminatable by the standard GPS equipment user.

<u>Foliage and other 'Noise'</u>

Dense foliage between satellite and receiver can cause the loss of reception from some or all SVs above the horizon. This may be the most easily recognizable problem a casual GPS user encounters, as the effect can change dramatically over very short distances, or, in extreme cases, a GPS receiver will not work at all in a densely vegetated area. The effect of foliage based signal attenuation is virtually nonexistent in the lower elevations of the southeast Arizona environment where this study was conducted. The vegetation in oak woodland at medium elevations and pine forests of the higher elevations, however, can hinder accurate GPS data collection.

Foresters and wildlife managers frequently encounter this problem due to the nature of their working environment. DeCesare et al. (2005) tested the accuracy animal track segment measurements under a variety of vegetation canopy conditions, and found that increasing overestimation of track length correlates with higher canopy closure due to increased zig-zagging of lines caused by variable error between collected vertices. Measured tracks averaged 28 percent longer than the actual track length with canopy closure > 40 percent, while only 9 percent longer with closure < 10 percent. Similarly, the mean distance of individual collected vertices increased from the actual line location with an increase in canopy cover.

Unspecified Error Testing

The practical GPS user may concern themselves with error testing without understanding what specifically causes which portion of the error. Cain et al. (2005) examined the influence of topography on wildlife GPS telemetry collars in mountainous terrain in southern Arizona. Topographic conditions were measured by calculating "available sky" (AS), a measure of how much of the sky at $>10^{o}$ above the horizon is visible, at each test location. Mean positioning error was elevated in lower AS locations (13.46m where AS<33 percent, 5m where AS>66 percent). This type of study is less concerned with whether multipath, PDOP, or other causes are responsible for the error than understanding the overall accuracy impact of a variety of topographic conditions.

Improving the Accuracy of GPS

Differential Correction (DGPS)

Differential Correction was devised as a way to negate the accuracy robbing effect of Selective Availability. Under SA, non-differential GPS was limited to an accuracy of about 100m (95%). With differential correction, horizontal error could be reduced to about 1-5m. Assuming the base station could see the same satellite constellation, the effect of SA could be eliminated using DGPS. Other sources of error are still present that can be greatly diminished using DGPS include ionospheric and tropospheric delay, ephemeris, and DOP induced errors. Multipath and noise are errors that are highly dependent on specific location, and are not reduced by DGPS (Kintner and Ledvina 2005, Monteiro et al. 2005, Morgan-Owen and Johnston 1995).

Real time kinematic (RTK) and post-processing are the two methods that can be employed to differentially correct rover GPS data. RTK uses a separate FM radio transmission to send correction data real time from a base station to the rover. Many of the CORS send out RTK signals. Post-processing is done after data collection. Rover data and base data are loaded onto a computer hard drive, and the error offset calculations are performed using GPS software. RTK is virtually virtually instantaneous, and therefore is useful in navigation, while post-processing is only useful for data collection applications (Straka and Gregorwich 1996, 169).

Technically, DGPS is only 100 percent effective if the base station and rover occupy the same location, which is impossible and would defeat the purpose. Monteiro et al. (2005) measured an error increase with an increase in distance between the two receivers in a study along the coast of Portugal. The authors identified two types of error that can be corrected for using DGPS: spatial decorrelation errors (ephemeris and atmospheric), and lack of intervisibility of SVs between the base and rover receivers. Seven receivers were placed roughly 100km apart, and tuned to receive RTK correction data being broadcast from the receiver at one end of the array. According to the results, "the DGPS error (95 percent) is equal to 0.5m to 1m near the Reference Station, plus...0.2m for each 100km distance from the Reference Station" (pp. 218-219). Thus, a linear relationship exists between the rover-base distance and DGPS accuracy improvement in that type of environment.

This relationship suggests that it may be worthwhile to operate a base station on site, as close as possible to the area where rover data is to be collected. Martinez et al. (2000) tested such a technique using two commercial receivers communicating in RTK mode, but complicated the experiment through the use of complex satellite selection criteria. This ensured that both the base station and rover were receiving from the same set of 3, 4, or 5 satellites, but the experiment never involved the use of more than 5. The best accuracy using the technique was actually achieved when receiving from the same set of only three SVs when DOP values were low. This suggests that good satellite geometry is actually more beneficial than increasing reception from 3 to 5 SVs (which tends to increase DOP). Commercial base station corrections still provided the better absolute accuracy than the 3 SV/low DOP values by a factor of almost four, however.

Celestial DGPS

This study will use the term "Celestial DGPS" to refer to DGPS systems that are integrated into the GNSSs. The most commonly used one is the “Wide-Angle Augmentation System” (WAAS), which is built into many commercially available GPS receivers in the United States, even low cost recreational hand held units. It's European counterpart is the “European Geostationary Navigation Overlay Service” (EGNOS). The Federal Aviation Administration (FAA) developed WAAS to employ several base stations over a wide area that continually collect data and generate corrections for each visible SV at each base. A correction grid is interpolated, and the data uploaded to a geostationary satellite over North America (WAAS) or Europe (EGNOS). The correction data are distributed by this additional SV to WAAS/EGNOS capable receivers on the same L1 frequency used for positioning. Though relatively complex in design and implementation, the advantage of WAAS is that it provides DGPS solution that can be used without the end user even thinking about it or needing to understand how it works.

The accuracy improvement potential of data collection using WAAS is remarkable. Witte and Wilson (2004) collected movement data using similar WAAS and non-WAAS enabled receivers, and found that absolute positioning error medians of 0.37m and 4.8m respectively, with 75 percent of positions falling within 0.80m and 10.6m of their true positions. WAAS, however, is based on DGPS technology, so it cannot compensate for rover errors based on locally induced phenomena such as multipath.

CHAPTER 3
Methods

The effectiveness of differential correction on GPS measurements tends to erode with an increase in distance between base station and rover (Montiero et al. 2005). The reasons for this are not entirely known, but use of base data collected from within 100km distance generally improves the accuracy of rover data. However, preliminary data collected at Fort Huachuca suggested that GPS data corrected using CORS base data from stations within 100km distance achieved only marginally better, and sometimes worse, accuracy than uncorrected data. This suggests that unique conditions in the Sky Islands of southeastern Arizona may reduce the effectiveness of differential correction over short distance in the region. Two possible causes are that availability of SVs between the rover and CORS differ due to differences in horizon, or that atmospheric/environmental conditions differ greatly over short distances. The focus of this study is on the former. The primary purposes of this study are: 1) to examine the effectiveness of producing base GPS data on site to be used in DGPS correction, and 2) to test whether differences in satellite intervisibility due to divergent horizons at base and rover locations influence the ability of base data to provide accurate corrections to rover data. To accomplish these tasks, this study aims to:

- Develop datasets to be post-processed in multiple ways.
- Analyze and compare the accuracy achieved using multiple DGPS techniques.
- Quantify the horizon visibility/height at the CORS at the base and rover locations.
- Analyze whether differences in satellite intervisibility due to horizon differences between rover and base locations may be influencing the effectiveness of base data.

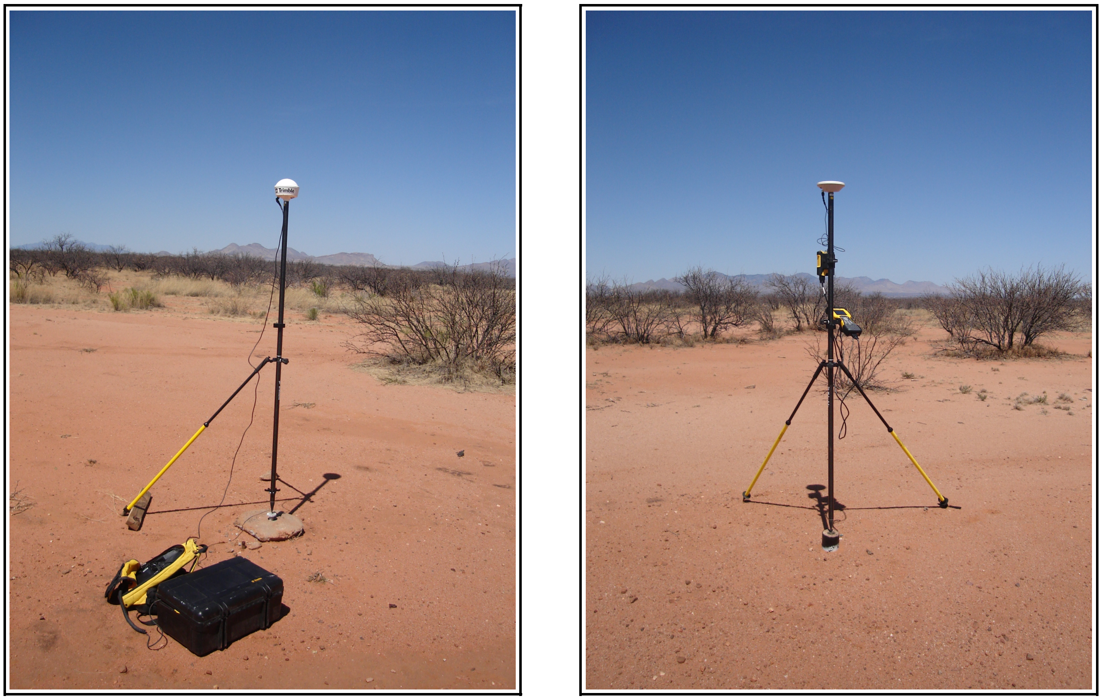
GPS Dataset Creation

Equipment

The basic requirements for performing GPS data collection with differential correction using a field unit as a base station are two GPS field units with similar capabilities and computer hardware and software with which to perform differential correction. Trimble field units with L1-only reception were used to collect both base and rover data. One of the units is a ProXRS unit purchased in 2002, and one is a newer ProXH receiver with Hurricane antenna, purchased in 2007 (Figures 3.1 and 3.2). Though different, both units are similar in capability, are currently in production, and are commonly used for research purposes. A two meter range pole and bipod complement each GPS unit, enabling the antenna to be leveled at a known height above the point that is being collected. A desktop computer with Trimble Pathfinder Office was used to upload the collected data from the units and perform all differential corrections. Version 2.9 was used to differentially correct the data using the local base, and version 3.1 was used to correct the data using CORS. Two versions were used because v3.1 is geared towards the use of CORS data and does not allow convenient use of locally corrected base data, and the newer version is now required to correctly perform DGPS corrections using CORS data due to necessary updates, like the 2008 leap second update, not being available for v2.9.

Data Collection

Twenty-one ASA points divided between two separate areas of Fort Huachuca were selected to be used as points on which to collect base and rover data. The points



Figures 3.1A and B. A) The base station is a Trimble ProXRS backpack L1 capable unit. B) The rover is a Trimble Ranger with Hurricane antenna, also L1 capable. Each unit is pictured set up at an ASA point on the East Range of Fort Huachuca.

Figures 3.2A and B. A) The base station and B) rover pictured set up on an ASA point on the South Range of Fort Huachuca.

each have precisely known X, Y, and Z coordinates, as surveyed and verified by a Registered Land Surveyor. Points in two areas were used: 12 points in the 'South Range' that lie in a valley bottom of the foothills of the Huachuca Mountains (Figures 3.2 and 3.3), and nine in the 'East Range,' in an area between the mountains and the San Pedro River where terrain is flatter and gently sloped toward the river (Figures 3.1 and 3.3). Four attributes were examined in the selection of study areas: 1) Availability of clusters of ASA points, 2) The areas must be reachable in the available vehicle (a two wheel drive truck), 3) The points could not be in or near sensitive military facilities, and 4) Topographic conditions between the areas should be highly variable to help determine whether the surrounding terrain impacts the quality of GPS measurements after application of a variety of post-processing techniques.

Maximum distance between points is < 2km on the East Range Study Area and <1km on the South Range Study Area. Mean elevation of the ASA points used on the East Range is 1321m, with a range of only 11m, reflecting the flatness of the terrain. The mean elevation of points used on the South Range is 1535m, with a range of 41m. Within 5km of the mean geographic center (MGC) of the East Range Study Area, elevation ranges from 1273-1408m, with a mean of 1341m. Within 5km of the South Range Study Area, elevation ranges from 1436-2560m, with a mean of 1745m, reflecting the more undulating topography in the foothills. The South Range Study Area lies in Lower Garden Canyon, and is surrounded by mountains and ridges on three sides, while the canyon opens to the East.

Three sets of seven rover points were collected on the East Range, and one set of

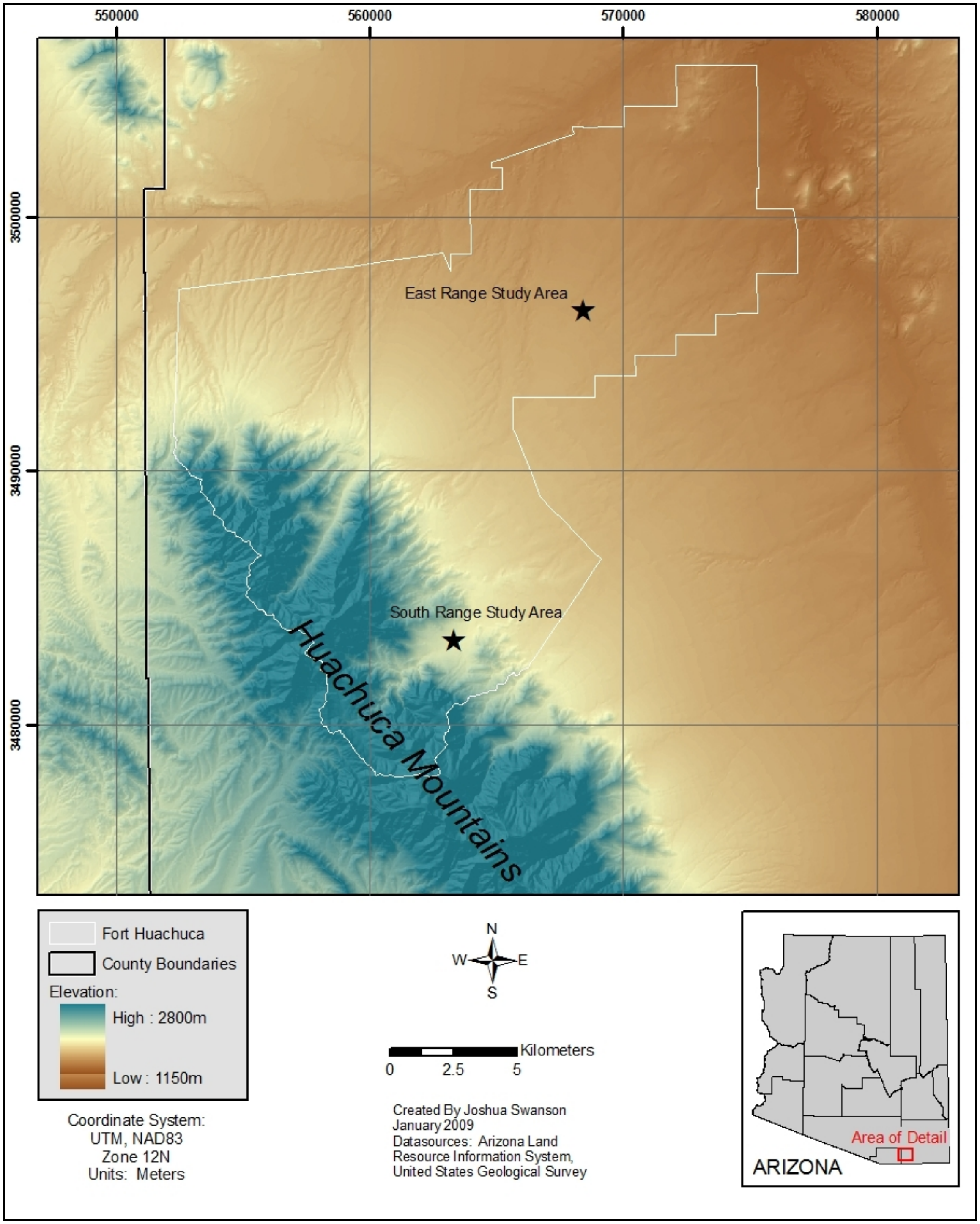


Figure 3.3. The East Range and South Range Study Areas and surrounding terrain.

ten and one set of eleven rover points were collected on the South Range. It was possible to collect the same number of points with only two sets on the South Range because more points were available for use in a concentrated area (Figure 3.4). A single ASA point could be used for more than one collected point, but was used only once in a set. For each rover point collection the Trimble Hurricane antenna was held steady directly over the point using a 2m range pole with a bipod, and left to collect twenty positions, one every 5 seconds. The points and the positions that make up the points can each be independently used for analysis. Therefore, the dataset for each study area, as collected, contains 21 *points,* made up of 420 *positions*. While the points can be used to test accuracy of the various post-processing methods, the positions can also be independently analyzed as if they were points made up of only one position. The data can also be examined as two sets of twenty one clusters of twenty positions, each known to have been collected while the antenna remained stationary.

Local base data were collected simultaneously with the rover data. The Trimble ProXRS GPS unit was set up on an ASA point near the rover collection area, and left to run continuously during collection of each of the five rover sets. The base antenna was also held in place directly above the ASA point using a 2m range pole and bipod. The base station collected one point every five seconds for the entire period each rover dataset was collected. A separate ASA point was used for base data collection for each of the five rover datasets. Both the base and rover were set to mask out SV signals below five degrees above the horizon.

Two CORS sites were also used for base data: City of Tucson 2 (COT2) and

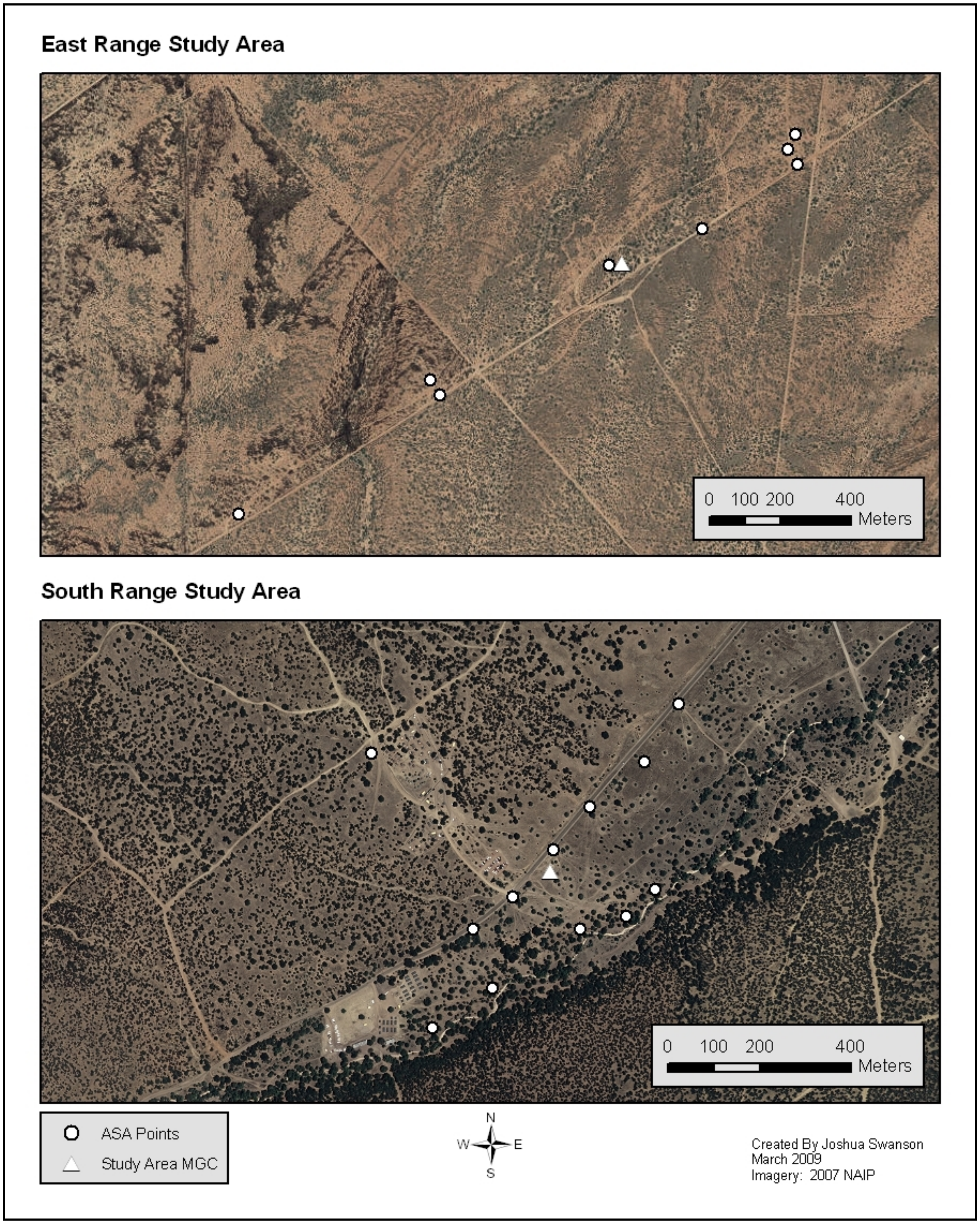


Figure 3.4. Distribution of ASA Points used at each Study Area.

Arizona Cochise County (AZCO). Base data are continuously collected at these locations. Files for the corresponding time periods were downloaded after rover data collection. COT2 lies approximately 90km northwest of Fort Huachuca at an elevation of 781m, while AZCO lies approximately 40km to the southeast at an elevation of 1494m (Figure 3.5). COT2 has a 5 second sampling rate, while AZCO has a 15 second sampling rate (http://www.ngs.noaa.gov/CORS/GoogleMap/ (last accessed 19 January 2009)).

These CORS transmit RTK correction data in addition to being downloadable from the CORS website. The RTK transmissions, however, are not reliably available at Fort Huachuca. This study uses only differential correction via post-processing so that multiple base datasets can be applied to the same set of rover data. Thus one dataset is collected, then multiplied into four through the application of multiple post-processing techniques, enabling direct comparison of the points and positions.

Post-Processing

Four GPS data types were produced from the collected data to use in accuracy comparison: 1) Raw rover data that has not been differentially corrected, 2) Data corrected using the COT2 CORS, 3) Data corrected using the AZCO CORS, and 4) Locally corrected data that were corrected using base data collected using the second field GPS unit. These are not four separate samples of data; the datasets compared in this study are the same collections of GPS positions, only treated differently after collection. Each of the four data types in each study area was exported as both a set of 21 points, and also as a set of 420 positions.

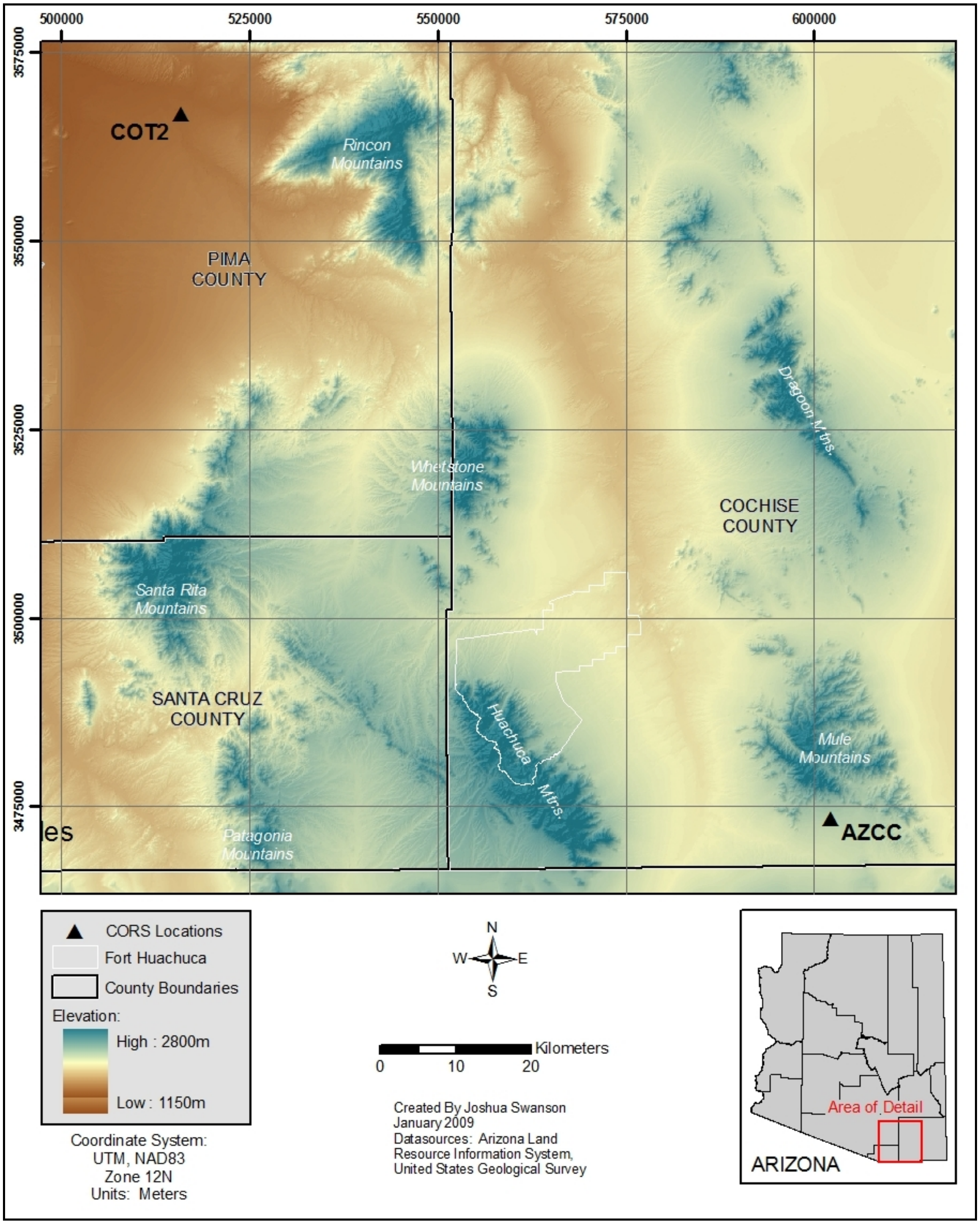


Figure 3.5. Locations of the utilized CORS in relation to Fort Huachuca.

Accuracy Comparison of Collected Data

Visualization of the collected data was the first step in analyzing the quality of the datasets. Both the recorded points and positions relative to the actual location at which they were recorded were examined using geographic information systems (GIS) software (ArcGIS 9.3—ESRI 2008). This visualization expedited initial examination of relative accuracy and consistency of the points and positions generated using each of the post-processing methods. It also facilitated inspection for errors and trends that may not have been apparent in the forthcoming tabular/statistical analysis.

The horizontal error of each recorded point and position for each post-processing type was measured. Average horizontal accuracy of each post-processing type, as well as the number of times a given technique provided the best accuracy was recorded (best data cases). The rate at which points and positions using each technique in each study area achieved sub-meter accuracy, and CEP values at the 50 and 95 percent thresholds were also recorded. These statistics provide a yardstick for absolute accuracy comparison between data types.

The concentration of positions that make up a point also gives some insight into the consistency of various types of post-processing. It is known that for each point collection the antenna occupied precisely the same geographic location for 100 seconds, during which 20 positions were collected. However, separate coordinates are recorded for each individual position. The spatial dispersion of these coordinates was measured to analyze the consistency of recorded positions using each technique at each study area. Each 20 position collection was analyzed as a cluster; the distance of each position from the mean geographic center of the positions in the cluster was measured. The mean distance of each position from the mean geographic center, or geographic dispersion of positions, gives some insight into variability of site conditions at the rover vs. base that impact GPS accuracy. In the hypothetical case that the conditions were identical, all points would occupy the same space. Distribution of the differentially corrected points will expand with increased variability in site conditions between the two locations.

Finally, the mean horizontal locational improvement of each DGPS type as compared to uncorrected data for each study area was recorded, as well as the number of cases that accuracy was improved using each DGPS technique in lieu of using uncorrected rover data. This offshoot of the initial accuracy measures was used to simplify analysis of horizon's potential impact on DGPS accuracy using CORS at Fort Huachuca.

Horizon Analysis

The horizons of the mean geographic centers for each of the two study areas, the AZCO CORS, and the COT2 CORS were measured. Raster datasets representing viewsheds of the four points were generated using the viewshed tool in the ArcGIS Spatial Analyst extension (ESRI 2008). Portions of the AZCO and East Range Study Area viewsheds extend into Mexico, denying continuous coverage from the National Elevation Dataset. Thus, Shuttle Radar Topography Mission (SRTM) elevation data provided the best coverage for this project. Antenna heights were added to the ground height when performing the analysis, and the option to consider earth curvature was used.

A series of feature classes was then created for each of the four points. First, a line feature class was created that plotted 36 lines from each study point to a location 225,000 meters distant at 10 degree azimuth intervals. This distance was beyond the furthest viewable terrain feature at any of the four locations. Each of these feature classes were then intersected with the corresponding viewshed. The result is linear segments that emanate from each study point, showing line of sight of the earth's surface at azimuth intervals of 10 degrees. The end of the furthest segment of each line from the study point is the furthest point viewable at that azimuth. A point feature class with a point placed at the end of each of the thirty-six segments was generated for each study area (Figure 3.7).

Each point was attributed with UTM coordinates and elevation, which was acquired from the SRTM elevation model. Horizontal and vertical distances from the study point were calculated for each of the 36 points that represented maximum viewable terrain at ten degree azimuth intervals. These distances of two sides of a right triangle enabled the calculation of a height angle for the viewable horizon (Figure 3.6).

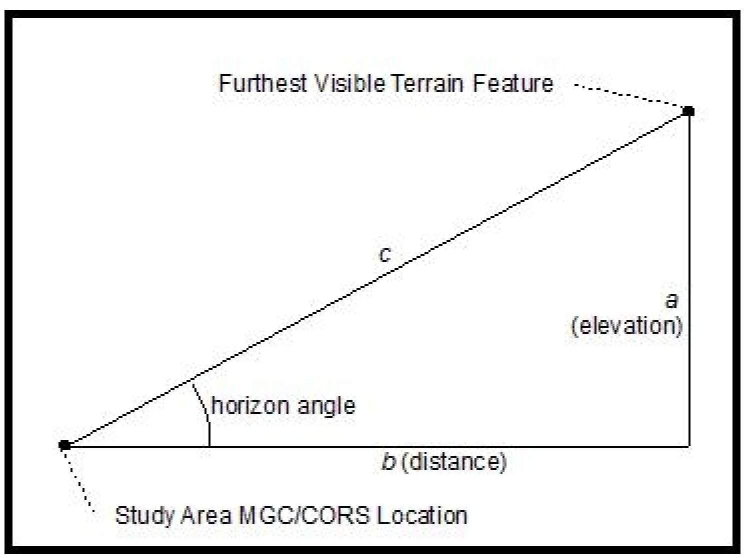


Figure 3.6. Horizon angle = arctangent(a/b)

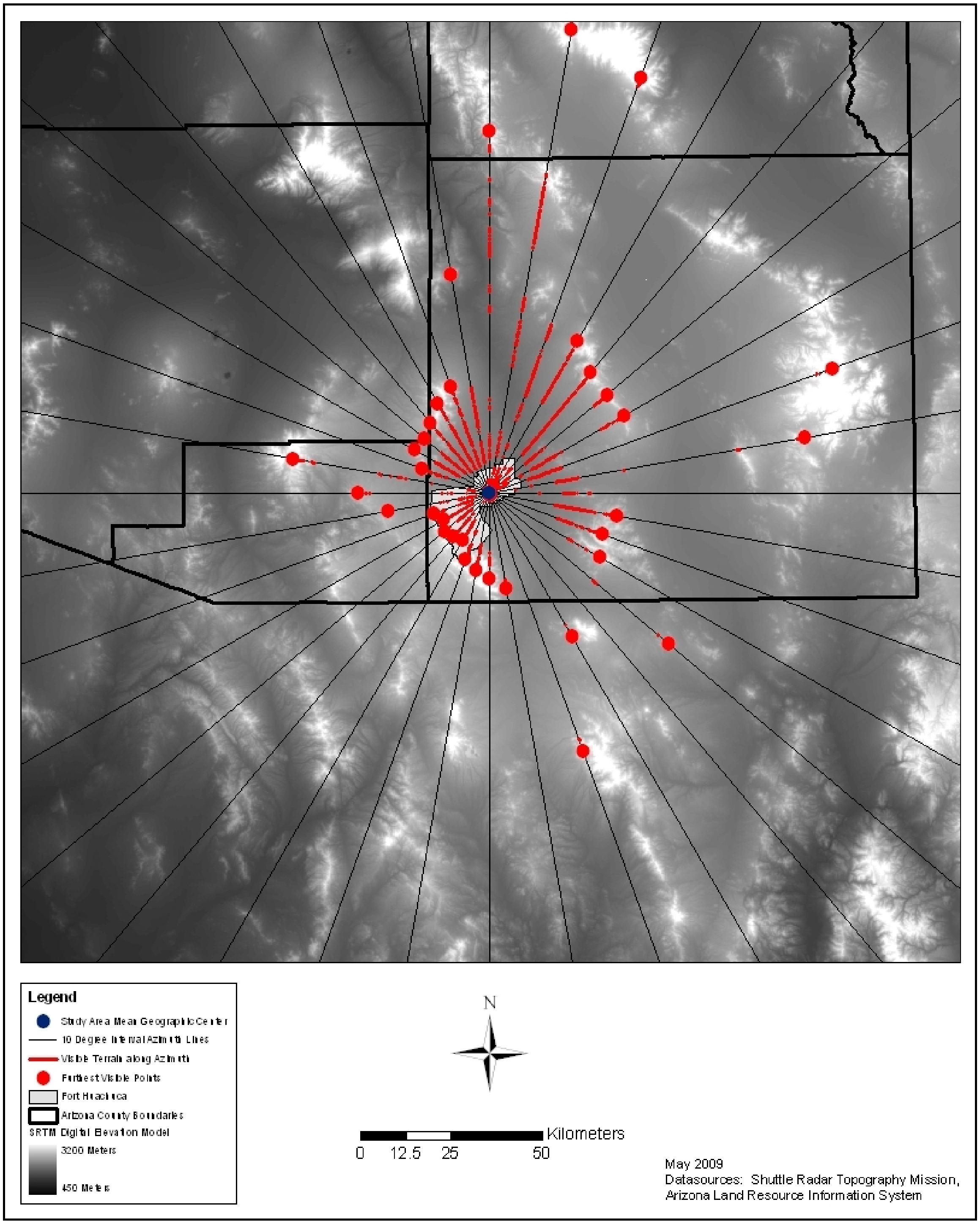


Figure 3.7. Generation of data to acquire horizon height at ten degree azimuth intervals.

A similar horizon at rover and base locations that are relatively near one another improves the potential for better satellite intervisibility, while drastically different horizons would decrease the potential for SVs located near the horizon, which are the ones that improve DOP, to be intervisible. The height of the horizon at each azimuth by study area and CORS location was directly compared using a visual analysis and direct measurement of horizon height difference in degrees. This comparison measure of visible horizon at base stations and rover locations differs from the measure of Available Sky tested by Cain et al. (2005) by comparing the azimuths where blockage of satellite visibility may occur, rather than a non-locational quantification of how much sky is available at each location. The four horizons were graphed together for visual comparison, while the difference in height of the horizon at each study area and CORS were calculated for one to one comparison.

Examination of Horizon's Impact on DGPS Accuracy

The potential for a positive correlation between similarity in rover and base horizons and increased horizontal accuracy improvement potential was initially qualitatively examined after the similarities and differences were discovered. The potential for local base corrected data to be the most accurate could be attributed to any number of factors, as all site conditions at base and rover locations, including horizon, are most similar in these datasets. Therefore, this assessment focused on the relationships between the CORS corrected datasets to attempt to isolate horizon differences between rover and base as the main difference in site conditions on the East vs. South Range study areas.

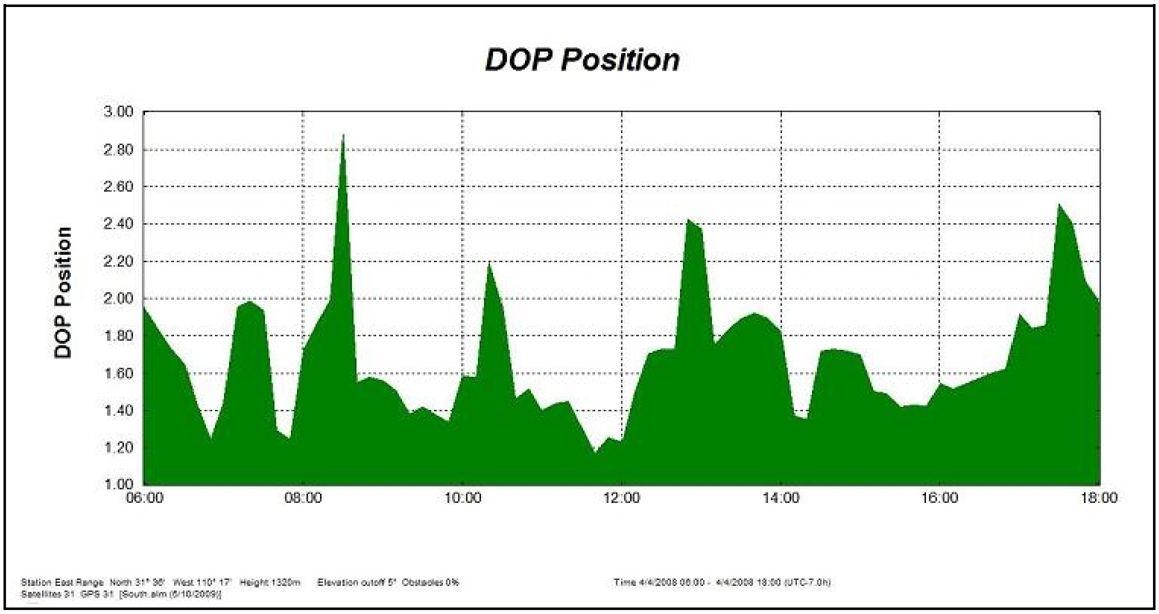
Both horizontal accuracy and dispersion of positions were examined in relationship to similarity or dissimilarity in horizon between rover and base. While horizontal accuracy is the overarching goal, loosely clustered positions while the rover is stationary would indicate rapidly changing conditions variably affecting GPS reception at the two locations. While the horizon does not change at any location, the visibility or lack thereof of SVs can vary and change due to horizon. Improved horizontal accuracy and tighter clustering of positions was the anticipated outcome where the horizons at the rover and base are similar. This outcome would demonstrate that satellite intervisibility, rather than variable density or thickness of the atmosphere or other site conditions that may vary little over 100km or less, impacts the ability of a base station to provide useful information for DGPS corrections in the region.

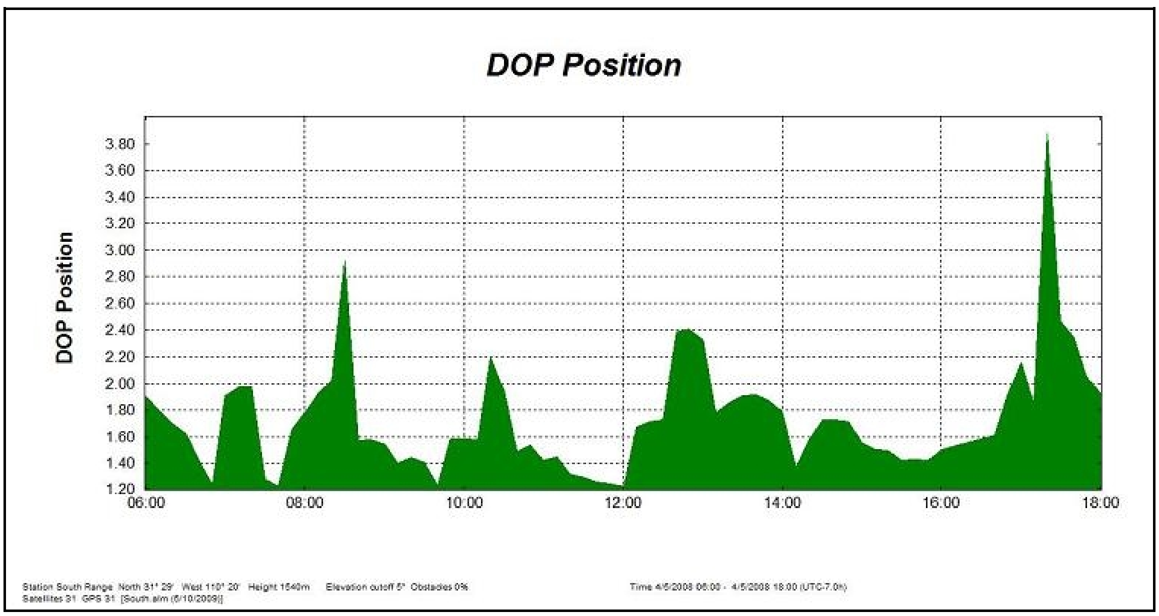
CHAPTER 4
Results

Points and positions post-processed using base data from the locally operated base station proved to be the most accurate in both study areas, while post-processing using CORS tended to slightly degrade horizontal accuracy. Data collected on the East Range tended to be more accurate regardless of post-processing technique, while accuracy increased more on the South Range after DGPS correction using the local base. Sub-meter accuracy was attained in >90% of the cases in both study areas when post-processing using the local base station, while <50% of the points attained sub-meter accuracy using any other post-processing technique. Horizon similarity between the CORS and study area appears not to play a role in effectiveness of using CORS base data. The following sections in this chapter detail step by step results obtained in this study.

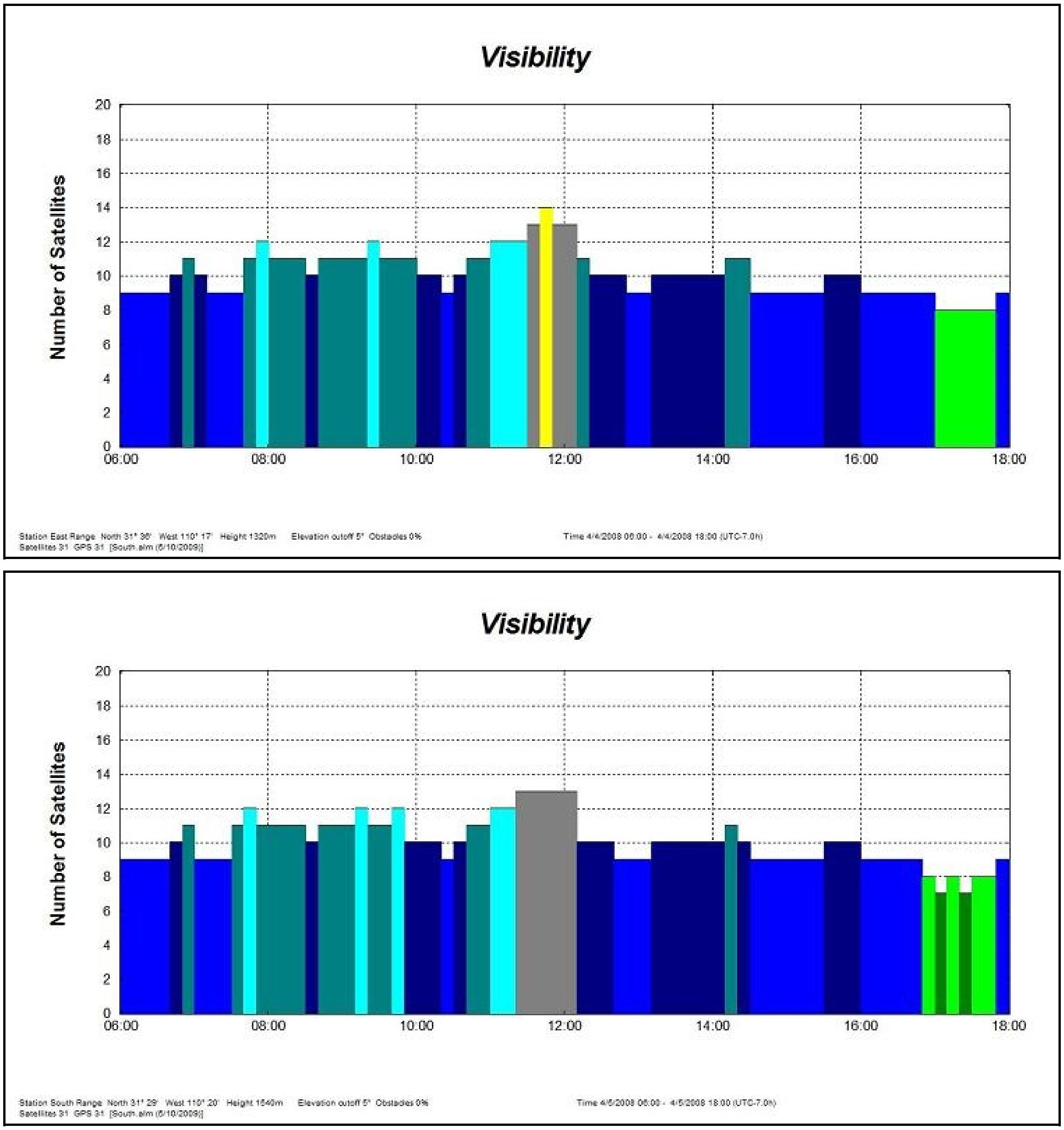
GPS Data Metrics

PDOP values averaged 2.14 and 2.37 on the East and South Ranges, respectively, with standard deviations of 0.33 and 0.8. Horizontal precision values averaged 5.66 and 5.76 meters in the uncorrected datasets. The slightly higher values obtained on the South Range likely result from the more mountainous, closed surrounding terrain of the study area. These values are consistent with the expected DOPs according to satellite availability/geometry calculated using the Trimble Planning Tool v2.8. Figures 4.1A and B show the expected PDOP at each study area for a twelve hour period on the day in which data were collected. On the East Range, data were collected between 11:32AM and 12:36PM, while on the South Range the time of collection spanned from 10:48AM to 12:41PM. Along with relatively low expected DOP values at the time of collection, the expected number of visible SVs was highest at these times, with nine or more at all times (Figures 4.2A and B).





Figures 4.1A and B. Expected DOP values on the East Range (top) and South Range (bottom) for a twelve hour period on the day of data collection.

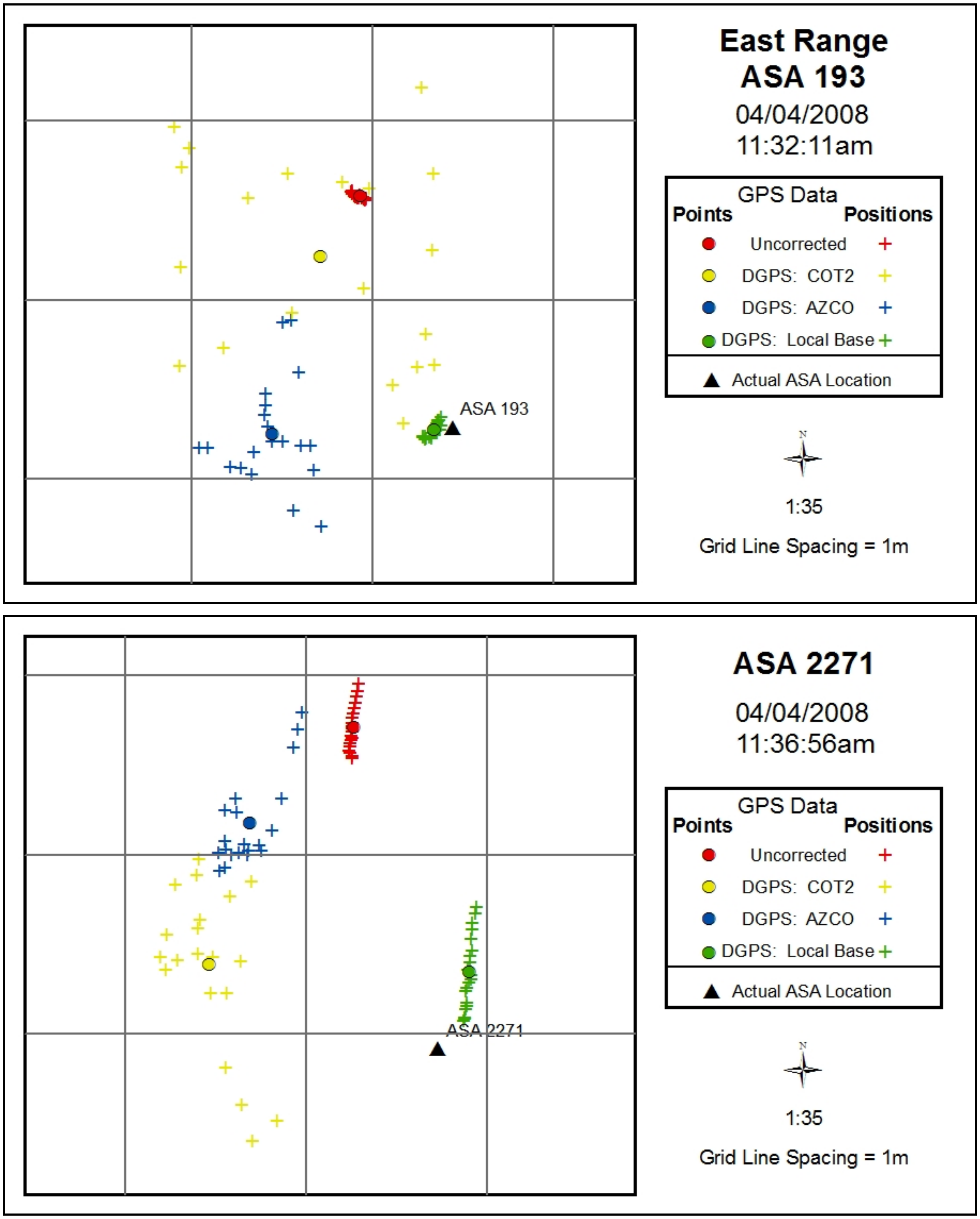


Figures 4.2A and B. Expected number of visible SVs on the East Range (top) and South Range (bottom) for a twelve hour period on the day of data collection.

Data Visualization

The initial visualization of the points and positions generally demonstrate phenomena observed by the author in previous collections of GPS points on Fort Huachuca, as illustrated by the examples in Figures 4.3A and B. First, positions collected at a given location that were not differentially corrected or corrected using the local base station tended to cluster, while positions corrected using either CORS were more dispersed. This was an initial clue to a limited utility, or at least inconsistency, of DGPS using CORS at Fort Huachuca. Second, that points corrected using the local base station would tend to be the most accurate was also immediately clear. Their clusters of positions tend to take the same form as the uncorrected clusters, only slightly 'looser' and closer to the actual point in which the receiver was located. CORS corrected position clusters are less consistent. Distinctions in these observations between datasets in the two study areas is not visually apparent.

Data corrected using the locally operated base station appear to consistently provide the most accurate data, but an accuracy distinction between uncorrected points and the CORS corrected points is not as visually discernible. Whether post-processing using CORS tended to add accuracy value to the points is not visually apparent, as several instances in which differential correction using CORS degraded accuracy are easily observable. Appendix A contains graphical representations for the full set of collected points in the same format as Figures 4.3A and B, which show the relative locations of both points and positions generated using each post-processing technique for a single GPS point collection.



Figures 4.3A and B. Graphical representation of points and positions produced using each post-processing technique for one point collection on the East Range (top) and South Range (bottom).

Overall Accuracy Potential

As indicated by the initial visualization of data, the accuracy analysis showed that the most accurate post-processing technique in this case is unequivocally DGPS using the locally operated base station (Figure 4.3). This method provides the best horizontal accuracy in 100 percent of the points on the East Range, and 91 percent on the South Range. The numbers are similar when each individual position is treated as a point (98.6 percent and 91 percent, respectively).

Table 4.1. Best data cases. The number of times in each study area that each post-processing technique provided the best data, as points (out of 21) and as positions (out of 420).

Data Type	East Range		South Range	
	Points	Positions	Points	Positions
Uncorrected	0	5	1	8
CORS-AZCO	0	1	0	20
CORS-COT2	0	0	0	10
Local Base	21 (100%)	414 (98.6%)	20 (91%)	382 (91%)

Operation of the local base station showed a significant improvement in accuracy in both study areas as compared to the uncorrected data ($p<0.0001$ in both study areas). The coordinates of local base corrected points on the East Range average horizontal offsets from their true coordinates of only 28.3 centimeters, an improvement of over 75 centimeters as compared to uncorrected points (Table 4.2). All post-processing techniques prove less accurate on the South Range, but absolute improvement using the local base vs. uncorrected points is higher (59.6 cm vs. 1.55m; 95.8 cm improvement). However, the 26.3 and 42.4 centimeter standard deviation values indicate the presence of a wide accuracy range. In fact, when using the local base, accuracy ranges as high as

1.217 meters and 2.071 meters on the East and South Ranges, respectively (Table 4.3).

Table 4.2. Horizontal error, points (meters). The 21 points collected on the East Range tend to be more accurate than the 21 collected on the South Range, regardless of post-processing technique.

Data Type	East Range Horizontal Error		South Range Horizontal Error	
	Mean	Standard Dev.	Mean	Standard Dev.
Uncorrected	1.034	0.449	1.550	0.569
CORS-AZCO	1.319	0.361	1.562	0.562
CORS-COT2	1.500	0.423	1.628	0.520
Local Base	0.283	0.263	0.596	0.424

Table 4.3. Horizontal accuracy range, points (meters). The minimum and maximum accuracy measures of the 21 points collected on the East Range tend to be more accurate than those measures for the 21 points on the South Range, except that the most accurate points corrected using CORS were collected on the South Range.

Data Type	East Range Accuracy Min/Max		South Range Accuracy Min/Max	
	Min	Max	Min	Max
Uncorrected	0.387	1.976	0.620	3.157
CORS-AZCO	0.831	2.431	0.579	2.915
CORS-COT2	0.852	2.179	0.661	2.679
Local Base	0.073	1.217	0.148	2.071

The single case of a >2 meter maximum offset on the South Range when corrcting using the local base appears to be an anomaly, as nineteen of twenty-one points attained sub-meter accuracy in that area (Table 4.4). Thick vegetation likely interfered with reception when that point was collected; the last three points collected on the South Range were in a heavily vegetated riparian area (Figure 4.4). Dismissing this outlier, the mean accuracy value of local base corrected points drops to 52.2 centimeters, still > 20 centimeters higher than on the East Range. The maximum offset without the outlier, however, drops to 1.042 meters, almost 20 centimeters less than the maximum observed on the East Range.

Differential correction using the local base station is the only option with this equipment at Fort Huachuca if sub-meter accuracy is desired (Table 4.4). Using this technique, collected horizontal coordinates are within one meter of their true positions over ninety percent of the time in both study areas. The sub-meter threshold could not be reliably achieved in this study using any of the other post-processing methods.

Figures 4.4A and B. Examples of vegetative conditions that may have played a role in limiting accuracy of some of the points collected on the South Range.

Table 4.4. Sub-meter accuracy, points.

Data Type	East Range		South Range	
	Cases	Percent	Cases	Percent
Uncorrected	10	47.6%	2	9.5%
CORS-AZCO	4	19.0%	4	19.0%
CORS-COT2	2	9.5%	1	4.8%
Local Base	20	95.2%	19	90.5%

Circular Error Probability values were attained using only the positions, with the increased sample size of 420, as the smaller sample of twenty-one points does not lend itself to calculation of fifty and ninety-five percent thresholds (Table 4.5). These datasets were generated using all 420 positions from each study area. When ranked, the trends follow those previously noted. Higher accuracy (lower CEP) was again attained on the East Range, and regardless of where the points were collected, local base corrected were most accurate, followed by uncorrected, AZCO, then COT2. The exception was that on the South Range the AZCO value of 2.68m(95%) superseded that of the uncorrected value of 3.14m(95%). Sub-meter accuracy cases measured in both CORS corrected sets of positions collected on the South Range also exceeded the number of cases in the uncorrected dataset (Table 4.6).

Table 4.5. Circular Error of Probability, positions (meters).

Data Type	East Range Horizontal Error		South Range Horizontal Error	
	50% CEP	95% CEP	50% CEP	95% CEP
Uncorrected	1.00	1.88	1.48	3.14
CORS-AZCO	1.31	2.03	1.50	2.68
CORS-COT2	1.53	2.71	1.57	3.22
Local Base	0.20	0.86	0.55	1.46

Table 4.6. Sub-meter accuracy, positions.

Data Type	East Range		South Range	
	Cases	Percent	Cases	Percent
Uncorrected	209	49.8%	35	8.3%
CORS-AZCO	76	18.1%	77	18.3%
CORS-COT2	66	15.7%	78	18.6%
Local Base	403	96.0%	363	86.4%

In addition to the horizontal accuracy degradation observed when using CORS base data, spatial consistency in CORS corrected positions was also diminished as compared to the other datasets. The twenty position clusters tended to be most disperse when corrected using CORS data , with the most separation occurring when using COT2 base data (Table 4.7). This increased dispersion of recorded position coordinates while it is known that the antenna remains stationary suggests a greater inconsistency in environmental and/or space based (satellite) variables affecting reception at the rover vs. the base. The elevated dispersion experienced when post-processing using CORS reinforces the reduced utility of using this base data for differential correction. As with the accuracy measures, COT2 results were worse than those obtained using AZCO base data in this measure.

Table 4.7. Dispersion of positions. The distance of each position from the mean geographic center of it's twenty position cluster was measured to gage the consistency of each post-processing method.

Data Type	East Range Dispersion		South Range Dispersion	
	Mean	Standard Dev.	Mean	Standard Dev.
Uncorrected	0.07	0.09	0.24	0.36
CORS-AZCO	0.28	0.17	0.37	0.27
CORS-COT2	0.62	0.37	0.69	0.48
Local Base	0.09	0.11	0.21	0.25

Application of CORS post-processing to the raw data points actually degraded, rather than improved, their positional accuracy, using almost all measures. Mean improvement values are therefore reported as negative in Table 4.8, showing the distance of the accuracy degradation. The degradation was highest in the East Range study area, independent of which CORS was used. The degradation when using COT2 was higher than when using AZCO in either study area. The values of less than 8 centimeters of degradation on the South Range when using CORS coupled with the fact that the each CORS improved the accuracy of roughly 50 percent of the points show that, while use of CORS tended to degrade the data, accuracy impact was almost negligible in that area. The 28.5 and 46.6 centimeter values on the East Range, and that use of either CORS degraded accuracy in fifteen of twenty one cases demonstrated the existence of a larger threat to accuracy resulting from use of CORS in that area. Accuracy improvement as compared to uncorrected rover data was only reliably achieved in both study areas when applying differential correction using the local base station. The average accuracy improvement was higher on the South Range (95cm vs. 75cm), but the number of cases of improvement was higher on the East Range (100 percent vs. 95 percent for points).

Table 4.8. Improvement/degradation, DGPS vs. Uncorrected GPS Points.

Data Type	Mean Improvement (m)		Num Cases Improvement	
	East Range	South Range	East Range	South Range
CORS-AZCO	-0.285	-0.011	6	11
CORS-COT2	-0.466	-0.077	6	9
Local Base	0.751	0.955	21	20

Overall Accuracy Summary

The tendency toward degradation of accuracy resulting from differential correction using CORS was not expected. While this phenomenon had been previously observed, it appeared unusually consistent within this dataset. That improvement potential was better with CORS correction using AZCO rather than COT2 was, however, consistent with previous observations. Variation of this improvement (or degradation) potential in different portions of Fort Huachuca had not been previously noted. The dramatically higher improvement potential using the local base station was expected and had been previously observed.

Three general conclusions from the proceeding tables in this chapter must be noted for use in the final examination of whether horizon is the site condition reducing the efficacy of using CORS data in DGPS corrections at Fort Huachuca:

1) Average accuracy and sub-meter potential trended better in the East Range Study Area regardless of post-processing technique. This tendency was stronger with the uncorrected and local base corrected data than with the CORS corrected data.
2) The AZCO CORS data was more accurate than the COT2 CORS data, regardless of how accuracy was measured. Thus, the data corrected using AZCO was not degraded as much as that using COT2, regardless of study area. Position clusters using AZCO were also tighter.
3) Post-processing using base data from either CORS degraded accuracy of GPS measurements on the East Range more than on the South Range.

Multiple possible explanations exist for these findings. The AZCO CORS lies 50km closer to Fort Huachuca than COT2, and is also closer to each study area in elevation. While at 1494m AZCO sits only 41m lower than the mean elevation of South

Range points and 173m higher than the mean elevation of East Range points, COT2, at 791m, is 530m lower than the East Range points and 703m lower than the South Range points. Though seemingly minor, the increased distance and elevation difference may help explain the decreased ability of COT2 to provide adequate DGPS corrections at Fort Huachuca. This would not explain the inability of either CORS to consistently provide improvements to rover data at Ft. Huachuca, as both are within an acceptable distance for the provision of base data. A lack of satellite intervisibility between rover and base, caused by differences in horizon at the rover vs. base when using CORS data, may also be the cause, or at least a contributor.

The remainder of this chapter will examine this hypothesis. The results of the measurement and comparison of the horizons at each study area and CORS will be followed by analysis of whether the similarity or differences in horizons could contribute to enhanced or diminished accuracy potential of the CORS.

Horizon Analysis

As with initial analysis of the GPS data, the horizons were initially examined visually. Similarity of horizon profiles of the two CORS is apparent in Figure 4.5, generated by overlaying the profiles of both CORS and study area horizon heights at ten degree azimuth intervals. Like the horizon profile on the East Range, both CORS have relatively open horizons. The dissimilarity of the profile at the South Range Study area from the other profiles is notable, especially at azimuths ranging from 150 to 300 degrees, where a ridge line effectively blocks visibility of the sky at higher angles than in other directions. Blockage due to horizon exceeds ten degrees in areas of the South

Range study area that face the Huachuca Mountains, whereas the horizon angle does not exceed seven degrees in any of the other profiles.

The apparent similarity of the horizons at the two CORS was confirmed through averaging of height differences; the average difference of height at each azimuth, is only 1.36 degrees, indicating that the horizon variable is similar at the CORS (Table 4.9). The mean differences between the East Range and the COT2 and AZCO CORS are 1.86 and 1.89 degrees, respectively, indicating that the horizon variable at this study area is similar to that of both CORS. The differences between the horizons of the South Range and each CORS are also similar, at 5.49 and 5.09 degrees mean difference between that study area

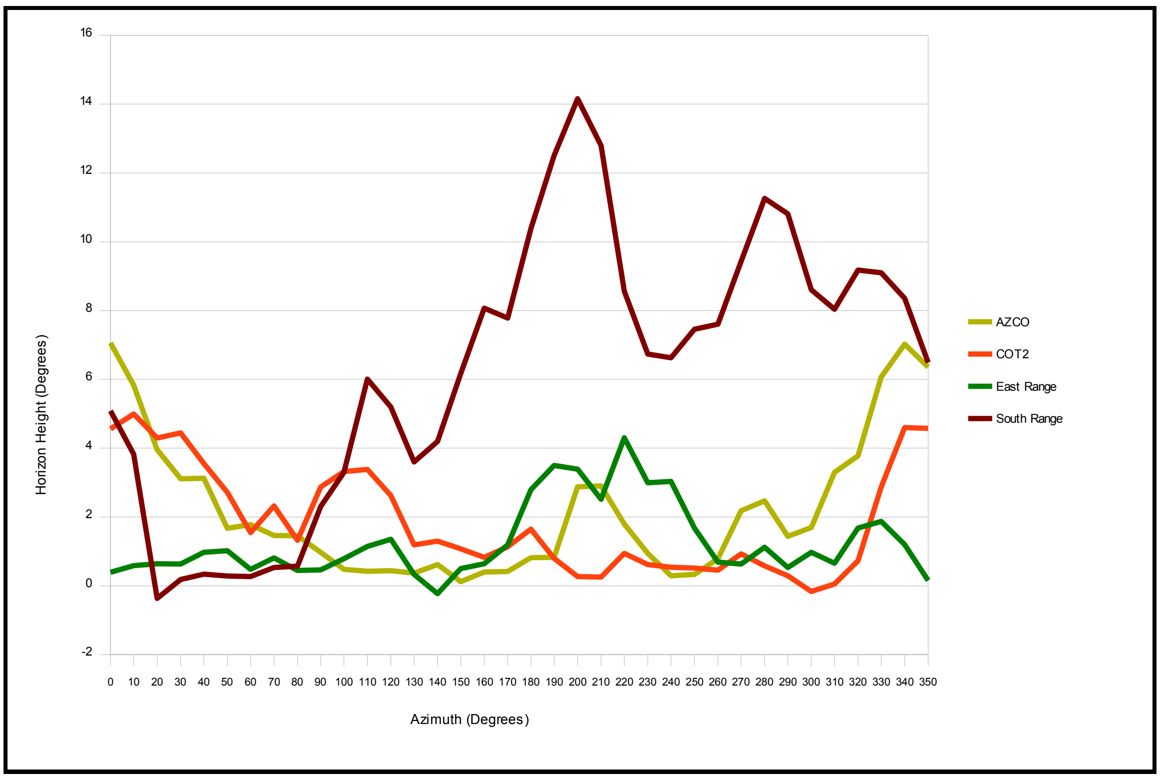


Figure 4.5. Horizon profiles of the mean geographic center of each study area and each CORS location.

and the COT2 and AZCO CORS. The difference in horizons between the two study areas also differs by more than five degrees. The visualization and matrix in table 4.9 therefore shows that the horizon variable of note is that the South Range Study Area has a horizon that suffers from more difference from the horizons at the CORS than does the East Range (5.09-5.49 degrees vs. 1.86-1.89 degrees of variation).

Table 4.9. Mean divergence matrix, in degrees, by azimuth, of the horizon heights.

	AZCO	COT2	East Range	South Range
AZCO	0	1.36	1.89	5.09
COT2	1.36	0	1.86	5.49
East Range	1.89	1.86	0	5.17
South Range	5.09	5.49	5.17	0

CORS and study area locations were selected based partially on availability; the study areas were chosen by selecting what seemed to be the flattest (East Range) and most topographically diverse (South Range) areas with a high concentration of ASA points that were reachable by 2WD vehicle. CORS were selected simply by using the two nearest the study areas. Though selection of study area or base station area based on ideal conditions for isolating the horizon variable was not possible, the conditions described by this horizon analysis do serve the purpose of this study. It is clear that the horizon on the East Range is much more similar to the conditions at both CORS than is the horizon on the South Range.

These conditions provided two possibilities to consider: 1) If SV intervisibility due to variable horizons is the primary influence on accuracy improvement potential of DGPS, one would expect the East Range to benefit more by using base data from either of the CORS than would the South Range due to the more similar horizons at the rover and base locations, and 2) Given the similarity of horizons at each CORS, the presence of a differing ability between them to provide benefit to the rover data at either or both of the study areas would indicate that something other than horizon is influencing of the CORS to provide quality base data.

Horizon's Impact on GPS and DGPS Accuracy at Fort Huachuca

Reduced accuracy of uncorrected data on the South Range (Table 4.2) may be due to sky blockage resulting from a higher horizon in this study area. This blockage can also increase DOP values by blocking visibility of low SVs, thus decreasing quality of satellite geometry. In fact, PDOP and HDOP values recorded on the South Range averaged 2.5 and 1.26, vs. 2.1 and 1 on the East Range, respectively. While these results suggest that an intrusive horizon can negatively impact the accuracy of raw GPS measurements, the hypothesis that varying visibility of the sky due to horizon differences at the base station vs. rover locations causes reduced DGPS efficacy was not substantiated.

Table 4.8 clearly shows that application of CORS base data more negatively impacted GPS measurements on the East Range than on the South Range. It also widened dispersion of positions more on the East Range (Table 4.7). Though we cannot state that differential correction using CORS was more successful on the South Range due to the accuracy degradation caused by use of CORS base daa, we can state that it was less of a failure in that study area. This fact coupled with the finding that the East Range horizon is more similar to the CORS horizons demonstrates a lack of support for the hypothesis that reduction of utility of CORS base data in the region correlates with a decrease in satellite intervisibility due to horizon dissimilarity.

That the South Range rover data was not degraded as much as that collected on the East Range through the application of CORS base data is not currently explainable. The differing efficacy of the base data from the two CORS, despite their similar horizons, suggests that other variables may be involved. COT2 base data consistently provided higher dispersion of positions and CEP values, and lower horizontal accuracy. COT2 is more distant from the study areas than AZCO, and also occupies a lower elevation.

CHAPTER 5
Discussion

DGPS and Accuracy at Fort Huachuca

Accuracy enhancement using DGPS relies on the ability of the base station to be similarly influenced by the same error sources as the rover. Measurement of the error using the base station enables partial removal of the effects of that error at the rover. Assuming the procedure functions properly and reliably, the exact causes of the mutually recorded errors are irrelevant. That rover data corrected with local base data was more accurate than the other datasets used in this study was not surprising, as the influences of any and all error sources should be very similar at rover and base locations when the two are so close to one another.

The result less expected and less explainable, but previously observed, was the consistent limited utility of post-processing using base data obtained from the two nearest CORS stations. I obtained mixed results when using CORS data in past collections at Fort Huachuca dating back through mid-2004, and the results obtained in this study appear consistent with the reliability obtained in some previous collections. The problem with this limited utility is that researchers could simply assume that application of CORS base data will improve their rover data without ground control checks, as I did with the rover files I first collected at Fort Huachuca, as literature and common sense suggest that use of base data from CORS reference stations located within the distances experienced in this study should improve accuracy (e.g. Kintner and Ledvina 2005, Montiero et al. 2005, Morgan-Owen and Johnston 1995).

The apparent lack of reliability of use of CORS data over relatively short distances in the region necessitates questioning why use of the data is unreliable. If the cause is a common one, like horizon differences, then the implications may be broad, as the effect may impact data collectors in other locations experiencing similar variables. DGPS tests are frequently conducted using systems designed for maritime operations, or along coast lines, where terrain conditions are relatively ubiquitous over long distances (e.g. Montiero et al. 2005). Studies of this type have examined error growth with distance between rover and base, but the influence of highly variable terrain conditions are a lesser understood potential detriment to efficacy of the use of base data collected over relatively short distances.

Terrain and Accuracy

The possibility that diminished satellite intervisibility due to variability in sky blockage resulting from differences in visible horizon between the rover and base when using CORS reference data at Fort Huachuca correlates with diminished efficacy of the use of CORS would seem to make sense. However, it was not supported by the results of this study. The lack of correlation between reference station and rover horizon similarity and increased DGPS accuracy necessitates a reevaluation of the potential cause(s) of the lack of utility of CORS reference data that was experienced at Fort Huachuca. Lack of satellite intervisibility due to increased distance or horizon remains a potential confounding factor that may explain the diminished utility of COT2 as opposed to AZCO, but other conditions likely contribute more to the phenomenon. These conditions may still be attributed to something that has to do with terrestrial conditions of the region, however.

Although DGPS measurements using only two CORS were used in this study, an error growth with distance was experienced. While neither CORS added value to the uncorrected data, the more distant one, COT2, degraded the measurements more than the closer one, AZCO. COT2 is not only further from Fort Huachuca than AZCO, but it also lies at a lower elevation. The results suggest that error growth may be increased over shorter distances than found in Montiero et al. (2005), and/or that site conditions, like elevation, may variably impact reception over relatively short distances in the region.

Tropospheric Influence?

"There are three different GPS errors which decorrelate with displacement between Reference Station and user: satellite ephemeris errors, ionospheric errors, and tropospheric errors (Montiero et al. 2005, 211)." These are in addition to lack of satellite intervisibility, also identified as a factor that increasingly differs with a growth in distance between reference station and user. Assuming 100 percent satellite intervisibility, maritime DGPS accuracy should be within 0.44m(95%) with a 100km separation between reference station and user (214).

Maritime conditions are relatively ubiquitous compared to environmental conditions in the Sky Islands of southeastern Arizona. Variability in the troposphere, the lowest portion of the atmosphere, would now seem candidate for a variable differentially impacting GPS reception over relatively short distances on the Earth's surface in the region. It is understood that the dry component of tropospheric delay, caused by lower atmospheric conditions like surface pressure and temperature, causes over eighty percent of the tropospheric delay in GPS reception (Montiero et al. 2005, 209). Temperature is one variable that can fluctuate greatly in the region; Tucson is frequently 10 degrees Fahrenheit or more warmer than the foothills of the Huachuca Mountains during the day, and the often gusty conditions in the region indicate frequent variability in lower atmospheric pressure. The wet component of the troposphere, while impacting reception to a lesser extent, may also play a role, as moisture availability tends to increase with elevation in the region.

An Outside Possibility-Noise

CORS site logs contain an entry for "Radio Interferences: (TV/CELL PHONE ANTENNA/RADAR/etc)." The entries were left blank on the sitelogs for the two CORS used in this study, but their inclusion raises the question of whether radio interference, i.e. noise, may be impacting reception at the rover locations. One potential factor that may complicate the effectiveness of using CORS data at Fort Huachuca, and by extension the results of this study, is that frequencies generated through electronic testing, and/or the presence of a Radar transmitter and other communications equipment at Libby Army Airfield/Sierra Vista Regional Airport or an adjacent meteorological station, may be differentially impacting the rover and CORS locations. As an employee at Fort Huachuca I sometimes received bulletins pertaining to tests that would interfere with the efficacy of GPS, and know that none were scheduled for the dates that data were collected for this study. However, the previously unconsidered possibility that regular usage of radio frequency generating electronic equipment at Fort Huachuca may be acutely impacting GPS reception is within the realm of possibility until proven otherwise.

This possibility could actually explain why the East Range GPS measurements are more negatively impacted through application of CORS reference data than those on the South Range. While the South Range study area lies further from the airfield and areas where electronic testing regularly occurs, and is sheltered from view by the foothills of the Huachuca Mountains, the East Range study area is in proximity to, and within the viewshed of Libby Army Airfield/Sierra Vista Regional Airport and is likely in the viewshed of many other radio frequency transmitters used by the military just to the South of the airfield (Figure 5.1). If noise is impacting the measurements at Fort Huachuca, then the effect is likely highly localized, and not of much concern to the wider GPS data collection community.

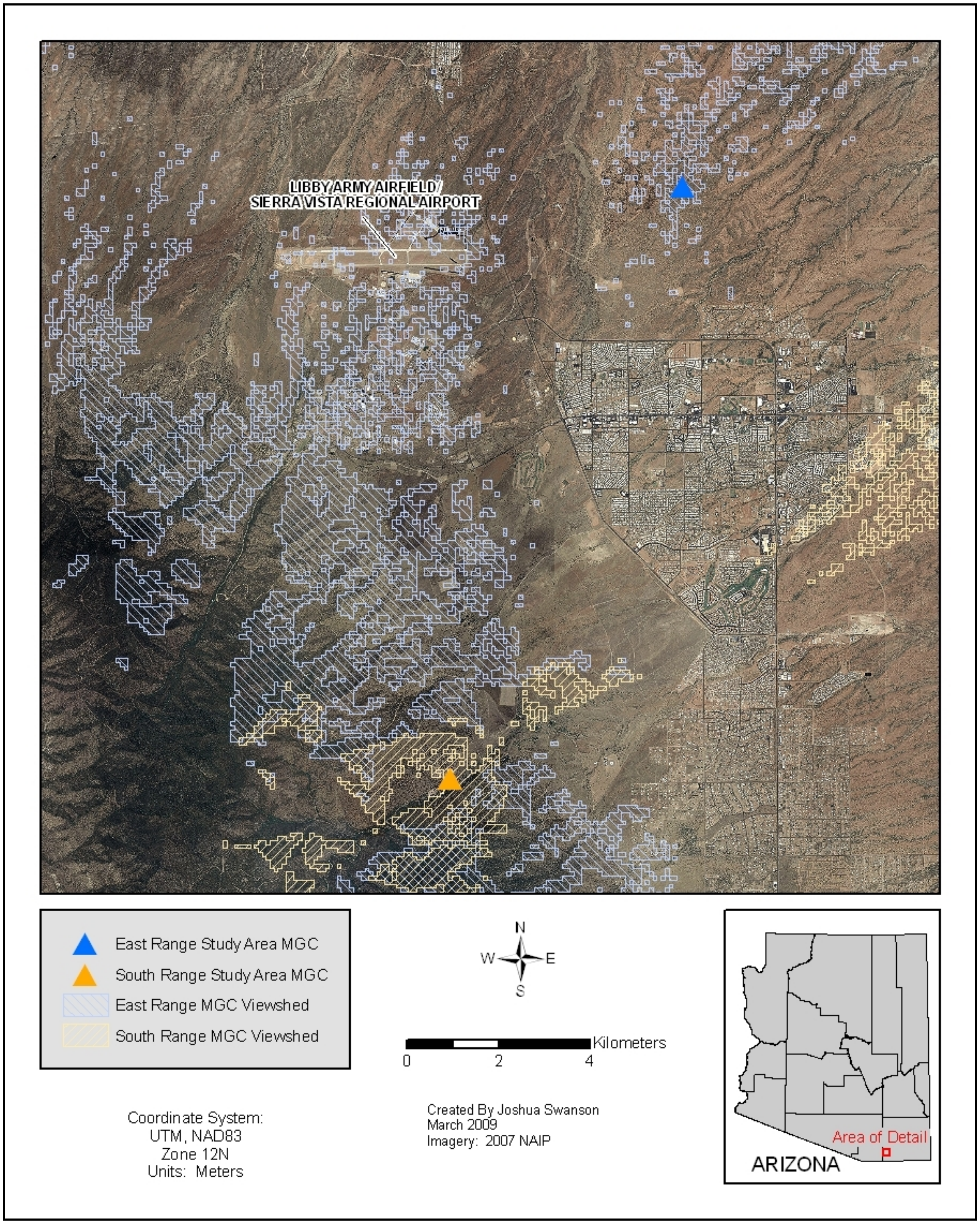


Figure 5.1. East and South Range Study Areas and their viewsheds in relation to Libby Army Airfield, a potential generator of noise. Other potential noise generators exist adjacent to the airfield to the South.

CHAPTER 6

Conclusions

The achievement of sub-meter accuracy over 90 percent of the time obtained using a local base station, combined with comparatively poor accuracy attained when using CORS base data reinforces the previous observation that the utility of CORS at Fort Huachuca, and likely the surrounding areas, is limited. Data collectors in the region should therefore avoid the presumption that use of CORS reference data equals added value. This condition is likely to exist elsewhere in the Sky Islands, and possibly in other areas where site conditions vary greatly over short distances. As this study was unable to pinpoint a specific cause for degradation of CORS base data utility over short distances, it is not possible to explicitly identify other locations where collectors should be skeptical about the use of CORS or other base data.

Isolation of a single site condition variable for testing the efficacy of DGPS is extremely difficult. While it remains possible that horizon impacts the efficacy of DGPS over relatively short distances, it appears to be overshadowed by other influences in this region and this study. For the practical GPS data collector, the condition causing the error is not an issue; the goal is simply to minimize error. DGPS is often an excellent method to reduce positioning errors, but this study has highlighted an area in which application of the most used source of base data, the CORS network, fails to produce the desired result. Clearly, identifiable conditions that reduce or negate CORS utility around the study areas remain to be discovered.

Until these conditions are identified, terrestrial GPS users in the region should be wary of the efficacy of CORS usage. When post-processing, the use of ground control to directly test its influence on rover data would be prudent. Those using an RTK feed to apply differential corrections on the fly may have previously assumed that the application of base data positively impacts their GPS measurements, and should be aware that this may not be the case. Whether raw rover or RTK corrected data is collected, ground control can be useful in testing whether accuracy thresholds are being met.

Opportunities for Future Research

This research begs the question of how widespread the issue of inefficacy of DRPS over short distances is. Suitable ground control is available for use in many locations, albeit not typically in concentrations as seen with the ASA points at Fort Huachuca. Furthermore, dispersion of points tests can be performed without ground control, and may be useful if an inverse relationship can be drawn between dispersion of points and horizontal offset in DGPS measurements. Other research that may elucidate the nature and extent of the problem includes:

- Tests on geographic extent of the problem: Tests on the efficacy of CORS within the region and in other regions of the country/globe can be useful in determining whether this phenomenon is geographically isolated or a widespread issue.
- Accuracy test elsewhere in the Sky Islands: An attempt to replicate or approximate the results in this study that show the derogatory impact of application of CORS data, but in (an)other mountain range(s), could help confirm or disprove whether noise from military testing activities or Libby Army Airfield/Sierra Vista Regional Airport is to blame.

- Elevation tests could be performed over short distances in the region to attempt to correlate error growth with elevation difference. Too few CORS exist in the region to use for this purpose, so such a test would require the use of portable base stations.

Potential Methodological Improvements

- Perform the study at night to reduce effects of ionosphere. Ionospheric influence is greatest at the solar maximum, in early afternoon. This study was performed on two consecutive days in late morning into early afternoon. Collection of data at night presents safety considerations in the Sky Islands, however, as drug and human traffickers tend to be encountered more often from dusk to dawn.
- Simplify methodology by using only one point per location. Multiple collections of twenty positions were used to simulate routine data collection, but it may be just as effective to set up a receiver to collect more positions, even into the thousands, in a study like this. In this study, this methodology would have necessitated the use of only one point per study area, and may have enabled the selection of two study areas with more divergent horizons.

The results of this study may become less relevant as time goes on. L2 capable units, and those that utilize signals from other GNSSs are becoming more common, and will likely become increasingly affordable. These technological advancements could enable data collectors to surmount the CORS problem identified in this study, provided they can afford the new equipment. However, given the popularity of using GPS in a wide variety of fields, the use of legacy GPS equipment, and therefore the issues identified in this study, will likely be relevant to some for years to come.

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APPENDIX A
Accuracy Summary

The following charts contain summary statistics on each point collection in each study area. The charts are broken down by study area and statistic type. For each study area there is one chart showing horizontal accuracy of each collected point using each post-processing technique, and another showing the mean distance of the twenty positions from the mean geographic center of the position cluster.

East Range: Horizontal Accuracy, Points

ASA	Time Collected	Horizontal Accuracy-Points (meters)			
		Uncorrected	DGPS-COT2	DGPS-AZCO	DGPS-Local
193	11:32:11am	1.388	1.203	1.011	0.116
2271	11:36:56am	1.859	1.354	1.639	0.470
199	11:40:31am	1.976	2.162	2.431	1.217
197	11:43:26am	1.572	1.354	1.444	0.214
614	11:46:21am	1.394	1.179	0.922	0.136
200	11:56:11am	1.174	2.094	1.450	0.684
196	11:59:06am	1.006	1.590	1.391	0.203
197	12:21:21pm	0.550	1.377	1.088	0.094
614	12:32:51pm	0.546	1.462	0.831	0.101
2271	12:38:26pm	0.798	1.247	0.928	0.488
193	12:51:21pm	0.387	1.216	1.274	0.144
196	01:05:16pm	0.568	0.908	1.183	0.106
200	01:08:21pm	0.591	1.922	1.321	0.073
296	01:12:21pm	0.840	1.112	1.389	0.221
200	01:47:46pm	1.392	1.134	1.652	0.319
196	01:50:36pm	1.266	0.852	1.219	0.201
296	01:55:41pm	1.084	2.179	1.442	0.203
2271	02:01:41pm	0.505	1.903	1.477	0.318
199	02:05:26pm	1.031	1.769	1.613	0.303
197	02:08:06pm	0.907	1.337	0.838	0.207
614	02:11:01pm	0.885	2.150	1.167	0.126
Mean		1.034	1.500	1.319	0.283
Standard Deviation		0.449	0.423	0.361	0.263

East Range: Dispersion of Positions

ASA	Time Collected	Positions-distance from center of cluster (mean,meters)			
		Uncorrected	DGPS-COT2	DGPS-AZCO	DGPS-Local
193	11:32:11am	0.028	0.740	0.287	0.048
2271	11:36:56am	0.102	0.402	0.242	0.168
199	11:40:31am	0.255	0.709	0.421	0.371
197	11:43:26am	0.040	0.576	0.163	0.041
614	11:46:21am	0.136	0.631	0.250	0.040
200	11:56:11am	0.231	0.524	0.274	0.259
196	11:59:06am	0.016	0.694	0.175	0.019
197	12:21:21pm	0.026	0.454	0.232	0.032
614	12:32:51pm	0.035	0.346	0.286	0.023
2271	12:38:26pm	0.118	0.394	0.225	0.105
193	12:51:21pm	0.014	0.568	0.221	0.071
196	01:05:16pm	0.013	0.478	0.245	0.029
200	01:08:21pm	0.012	0.426	0.284	0.028
296	01:12:21pm	0.082	0.465	0.173	0.095
200	01:47:46pm	0.063	0.556	0.478	0.086
196	01:50:36pm	0.031	0.895	0.360	0.039
296	01:55:41pm	0.064	0.642	0.304	0.071
2271	02:01:41pm	0.154	0.891	0.334	0.109
199	02:05:26pm	0.094	0.770	0.313	0.171
197	02:08:06pm	0.031	0.728	0.412	0.044
614	02:11:01pm	0.015	1.112	0.280	0.020
Mean		0.074	0.619	0.284	0.089
Standard Deviation		0.071	0.194	0.082	0.089

South Range: Horizontal Accuracy, Points

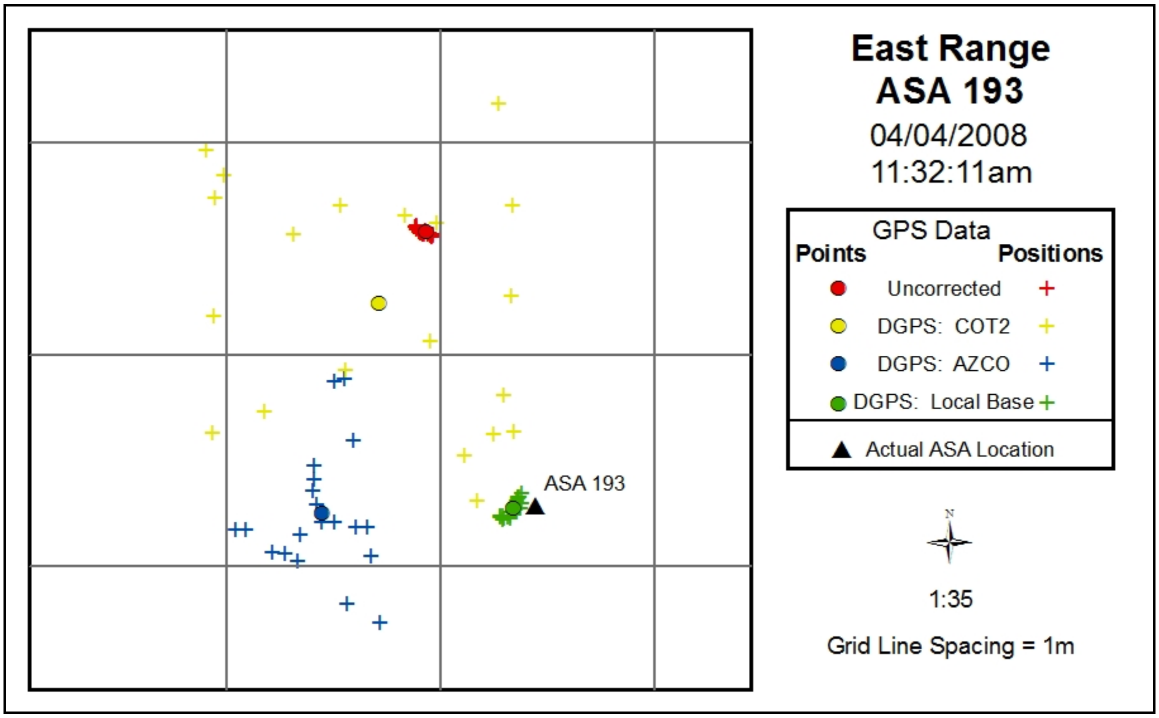
ASA	Time Collected	Horizontal Accuracy-Points (meters)			
		Uncorrected	DGPS-COT2	DGPS-AZCO	DGPS-Local
193	11:32:11am	1.194	1.758	0.579	1.042
2271	11:36:56am	1.316	1.015	1.294	0.274
199	11:40:31am	1.183	1.517	1.797	0.389
197	11:43:26am	1.153	0.661	0.868	0.558
614	11:46:21am	1.679	2.115	1.878	0.921
200	11:56:11am	1.543	2.532	1.198	0.655
196	11:59:06am	1.764	1.867	1.386	0.438
197	12:21:21pm	1.866	1.920	2.157	0.418
614	12:32:51pm	1.783	1.220	0.973	0.274
2271	12:38:26pm	1.912	2.132	1.959	0.369
193	12:51:21pm	1.369	1.145	1.216	0.148
196	01:05:16pm	1.378	1.164	1.209	0.340
200	01:08:21pm	1.587	1.074	1.676	0.418
296	01:12:21pm	3.157	1.587	2.380	0.830
200	01:47:46pm	1.195	1.633	1.422	0.839
196	01:50:36pm	1.500	1.405	2.083	0.725
296	01:55:41pm	1.028	1.213	0.896	0.249
2271	02:01:41pm	1.679	2.160	1.657	0.696
199	02:05:26pm	2.714	2.679	2.915	2.071
197	02:08:06pm	0.939	1.496	1.388	0.167
614	02:11:01pm	0.620	1.891	1.868	0.689
Mean		1.550	1.628	1.562	0.596
Standard Deviation		0.569	0.520	0.562	0.424

South Range: Dispersion of Positions

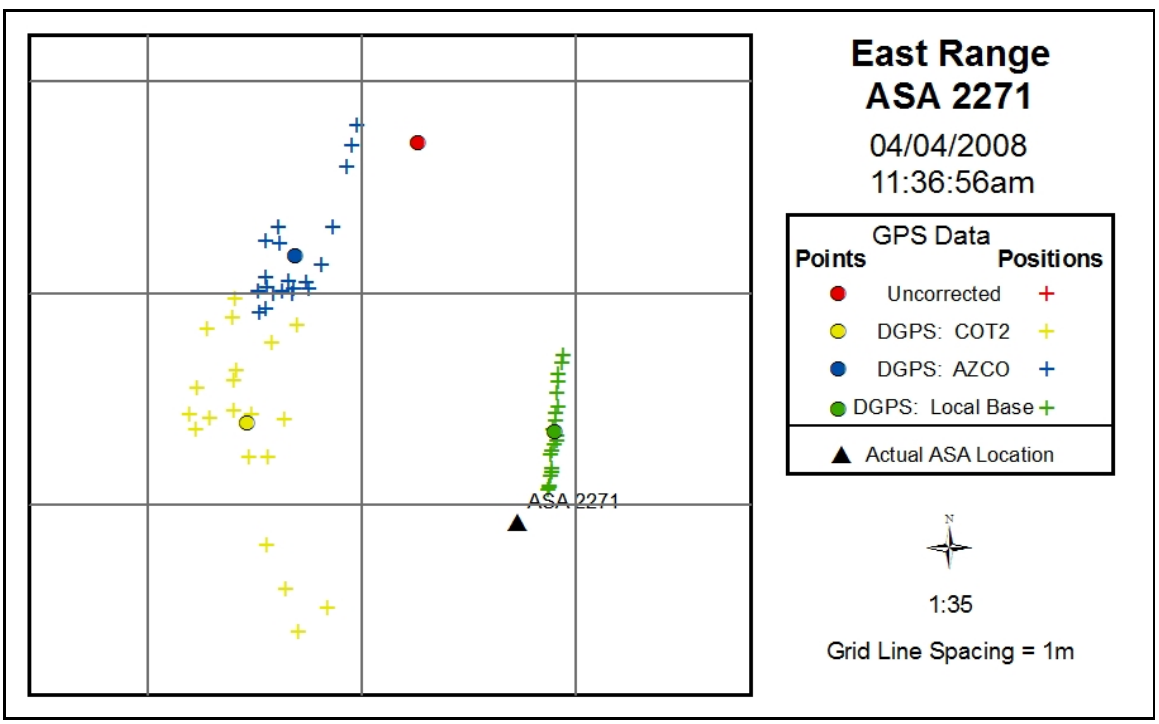
ASA	Time Collected	Positions-distance from center of cluster (mean,meters)			
		Uncorrected	DGPS-COT2	DGPS-AZCO	DGPS-Local
193	11:32:11am	0.195	1.048	0.319	0.502
2271	11:36:56am	0.221	0.681	0.932	0.104
199	11:40:31am	0.083	0.777	0.475	0.173
197	11:43:26am	0.103	0.433	0.254	0.099
614	11:46:21am	0.148	0.699	0.231	0.272
200	11:56:11am	0.039	0.553	0.281	0.096
196	11:59:06am	0.088	0.742	0.350	0.119
197	12:21:21pm	0.321	0.724	0.500	0.340
614	12:32:51pm	0.513	0.852	0.398	0.316
2271	12:38:26pm	0.301	0.851	0.342	0.305
193	12:51:21pm	0.043	0.308	0.222	0.039
196	01:05:16pm	0.084	0.399	0.279	0.094
200	01:08:21pm	0.121	0.434	0.408	0.113
296	01:12:21pm	0.103	1.042	0.293	0.132
200	01:47:46pm	0.176	0.479	0.177	0.186
196	01:50:36pm	0.084	0.366	0.283	0.113
296	01:55:41pm	0.051	0.544	0.186	0.087
2271	02:01:41pm	0.453	1.065	0.458	0.275
199	02:05:26pm	0.748	1.115	0.581	0.614
197	02:08:06pm	0.103	0.535	0.196	0.086
614	02:11:01pm	1.127	0.887	0.538	0.319
Mean		0.243	0.692	0.367	0.209
Standard Deviation		0.271	0.250	0.175	0.150

APPENDIX B
Raw Data Diagrams

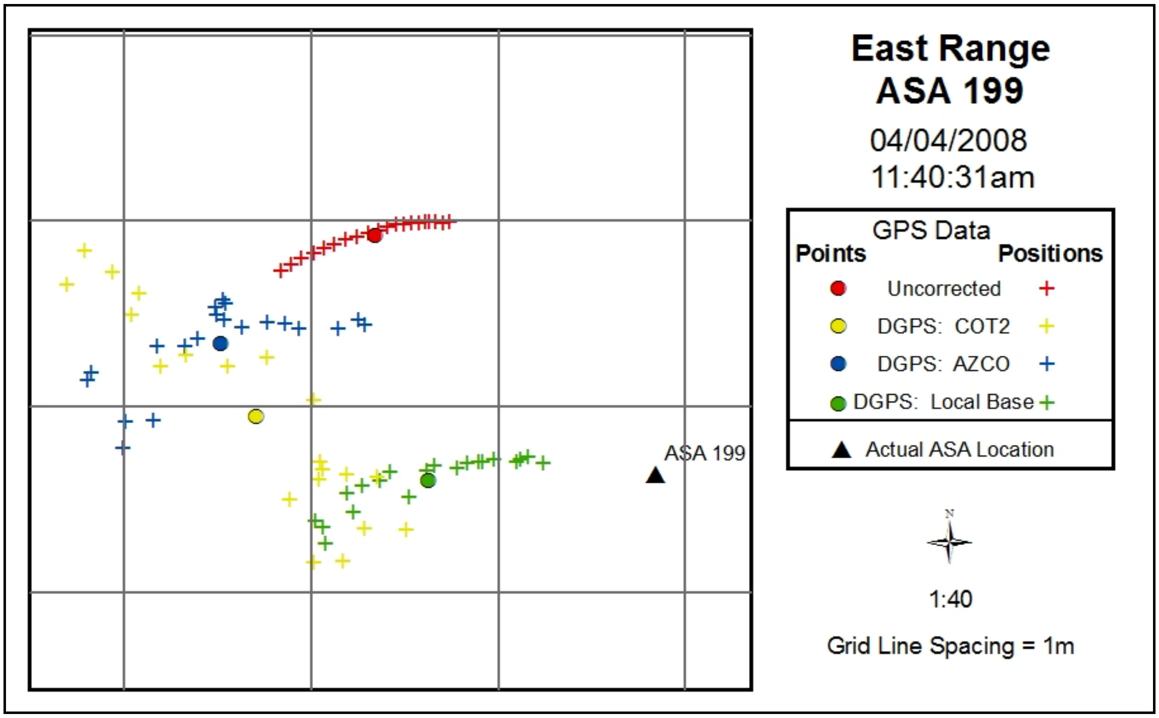
The following pages contain forty-two diagrams, each representing a single collection of one point, made up of twenty positions collected in five second increments. All point collections in each study area are represented, and both points and positions for each post-processing technique are visible. Scale of the diagrams ranges from 1:30 to 1:50, and a one meter grid is superimposed on each in order to facilitate visualization of dispersion of positions and the spatial relationships between the features. The actual location of the ASA point on which the data were collected is also visible.

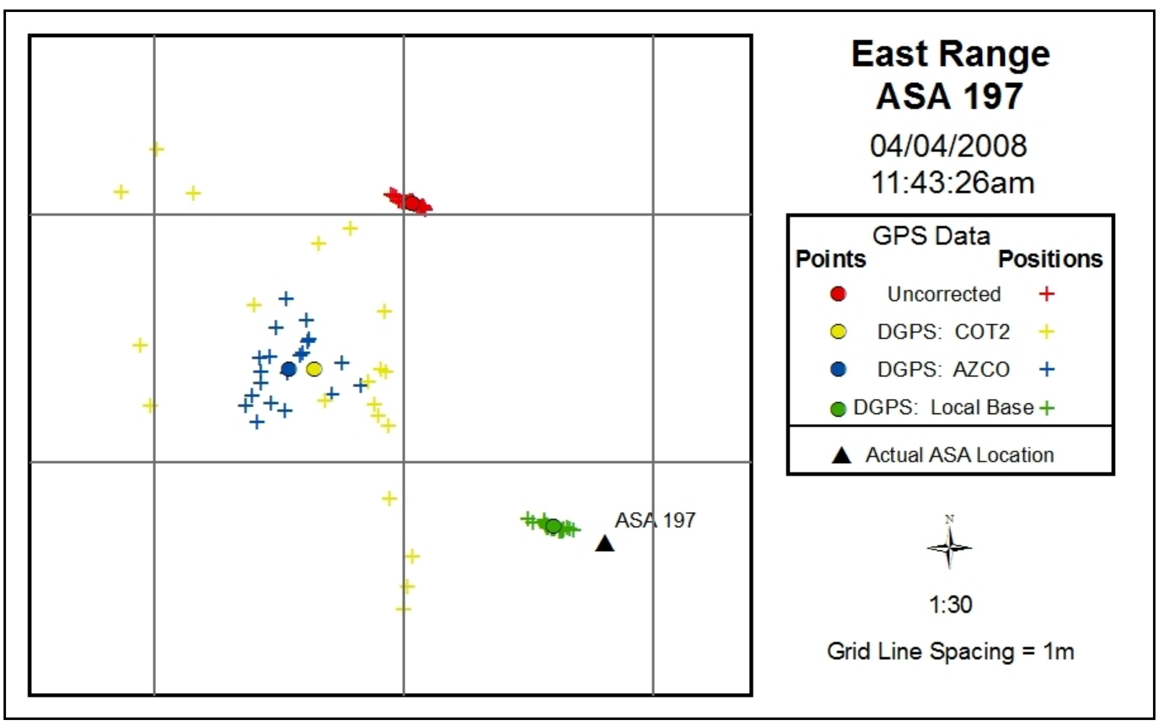


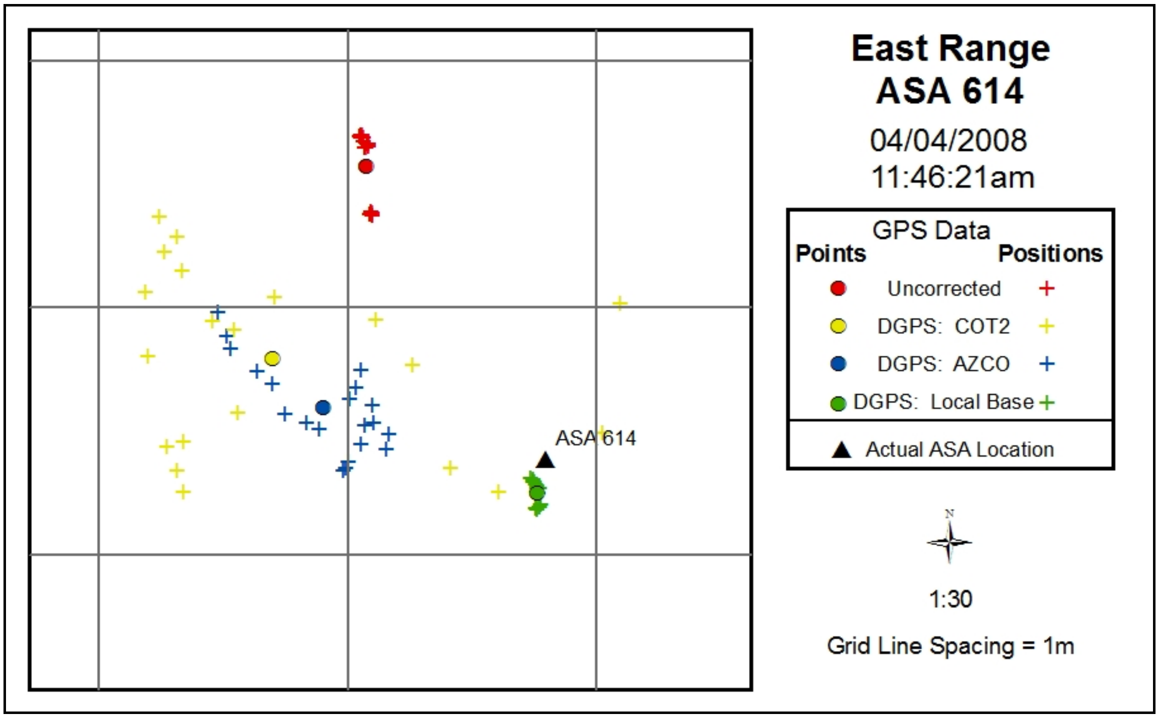
ASA 193
East Range
ASA 193
04/04/2008
11:32:11am
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
N
1:35
Grid Line Spacing = 1m

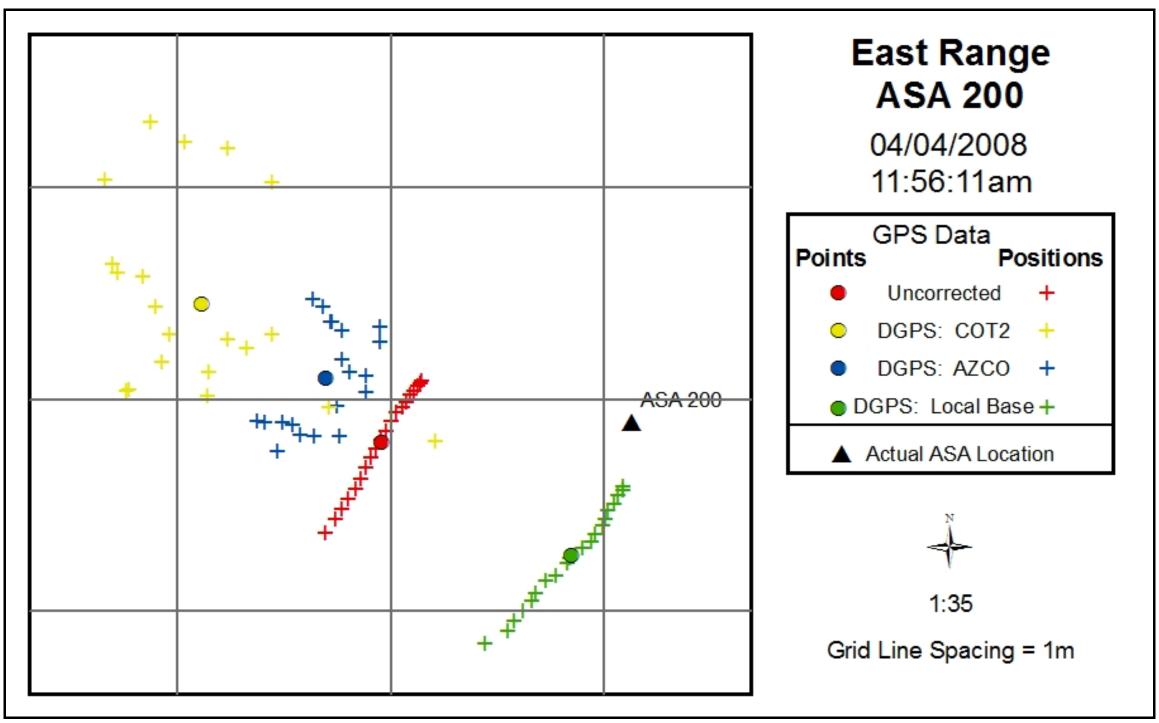


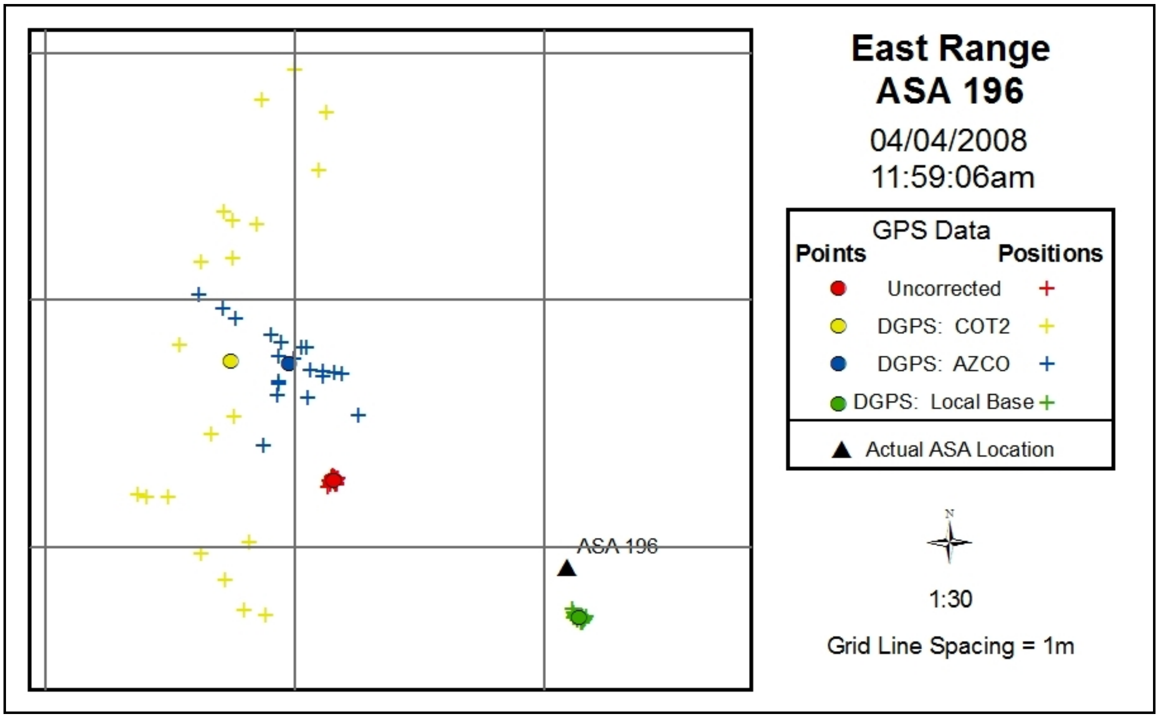
ASA 2271
East Range
ASA 2271
04/04/2008
11:36:56am
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
N
1:35
Grid Line Spacing = 1m

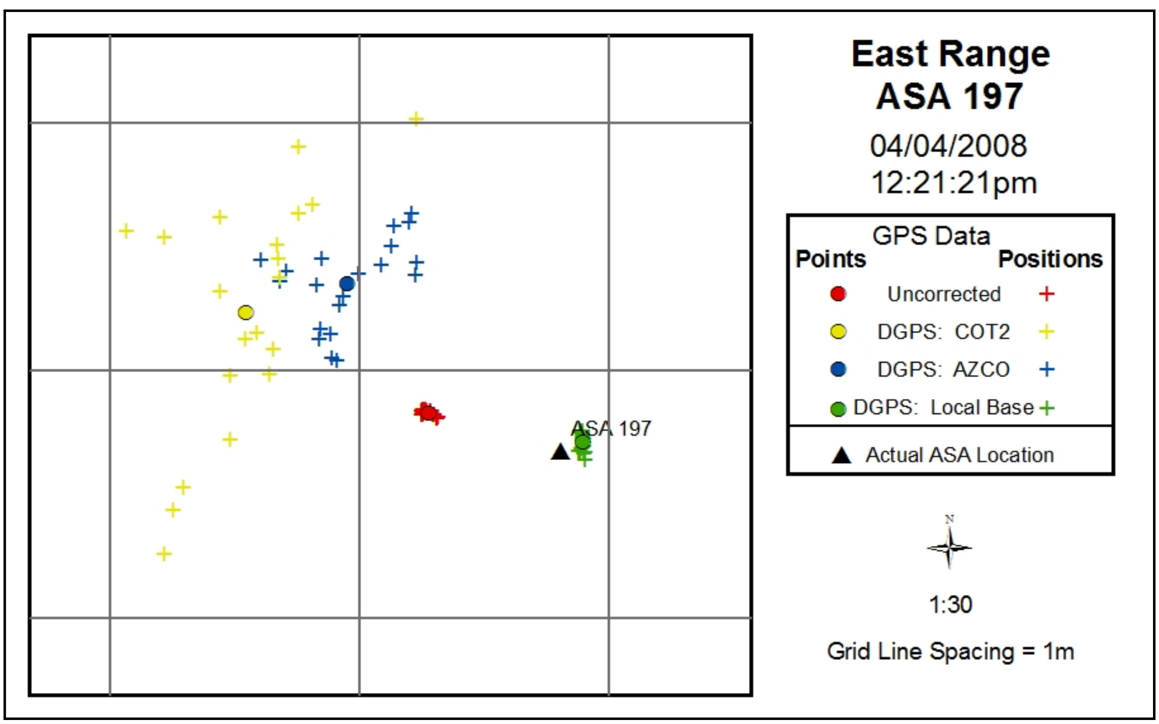

ASA 199
East Range
ASA 199
04/04/2008
11:40:31am
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
N
1:40
Grid Line Spacing = 1m

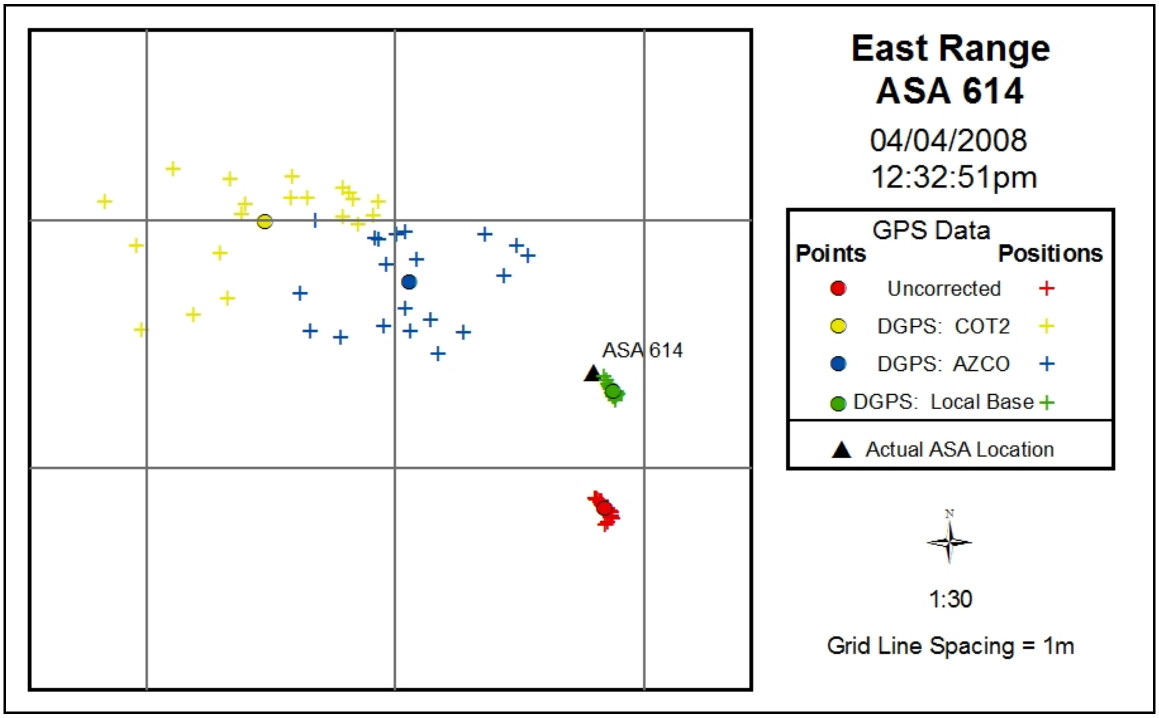

ASA 197
East Range
ASA 197
04/04/2008
11:43:26am
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
N
1:30
Grid Line Spacing = 1m


ASA 614
East Range
ASA 614
04/04/2008
11:46:21am
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
N
1:30
Grid Line Spacing = 1m

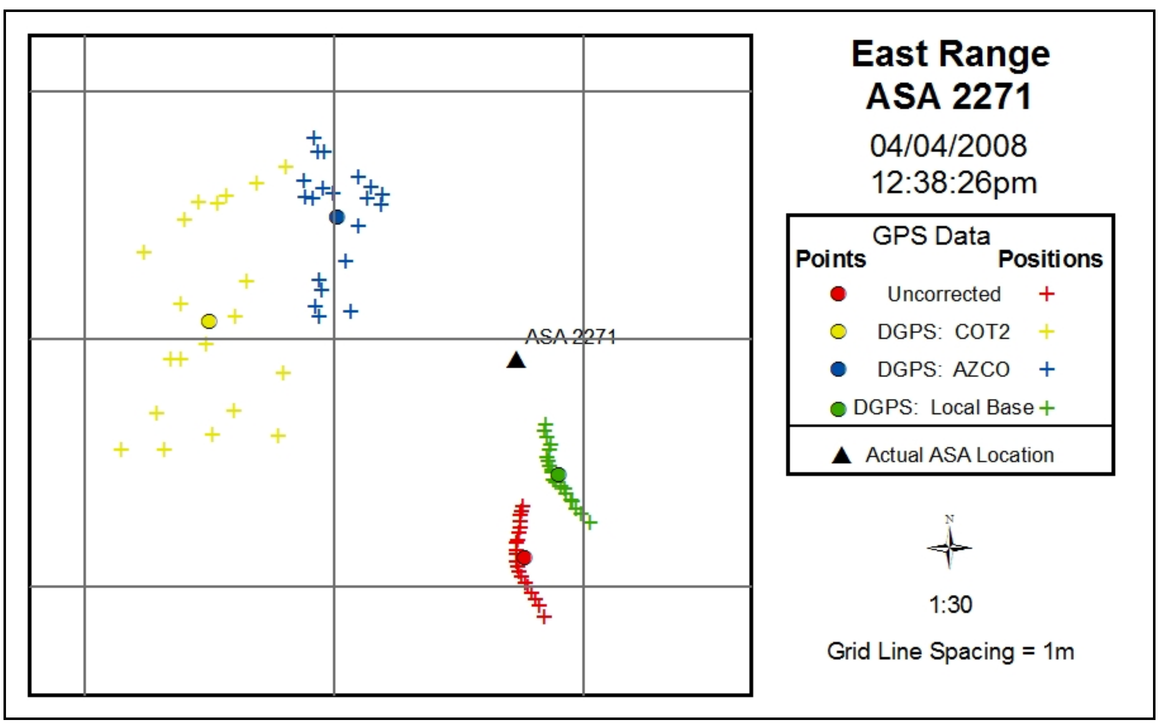

ASA 200
East Range
ASA 200
04/04/2008
11:56:11am
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
N
1:35
Grid Line Spacing = 1m


ASA 196
East Range
ASA 196
04/04/2008
11:59:06am
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
N
1:30
Grid Line Spacing = 1m

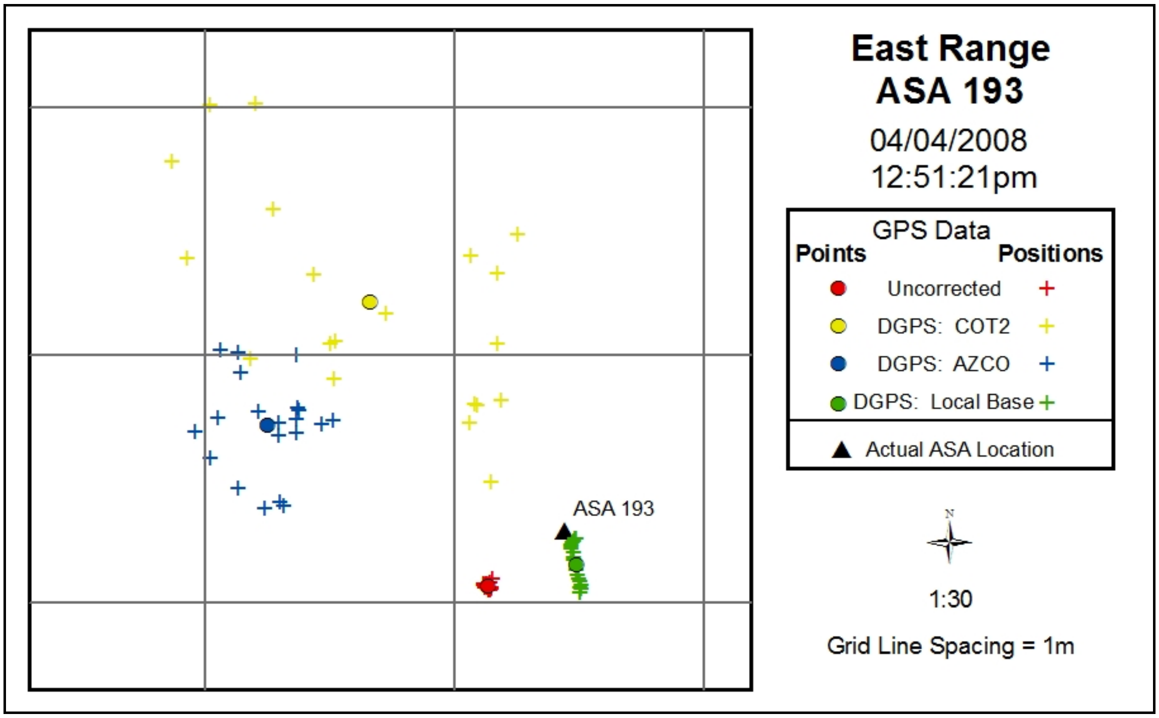

ASA 197
East Range
ASA 197
04/04/2008
12:21:21pm
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
N
1:30
Grid Line Spacing = 1m



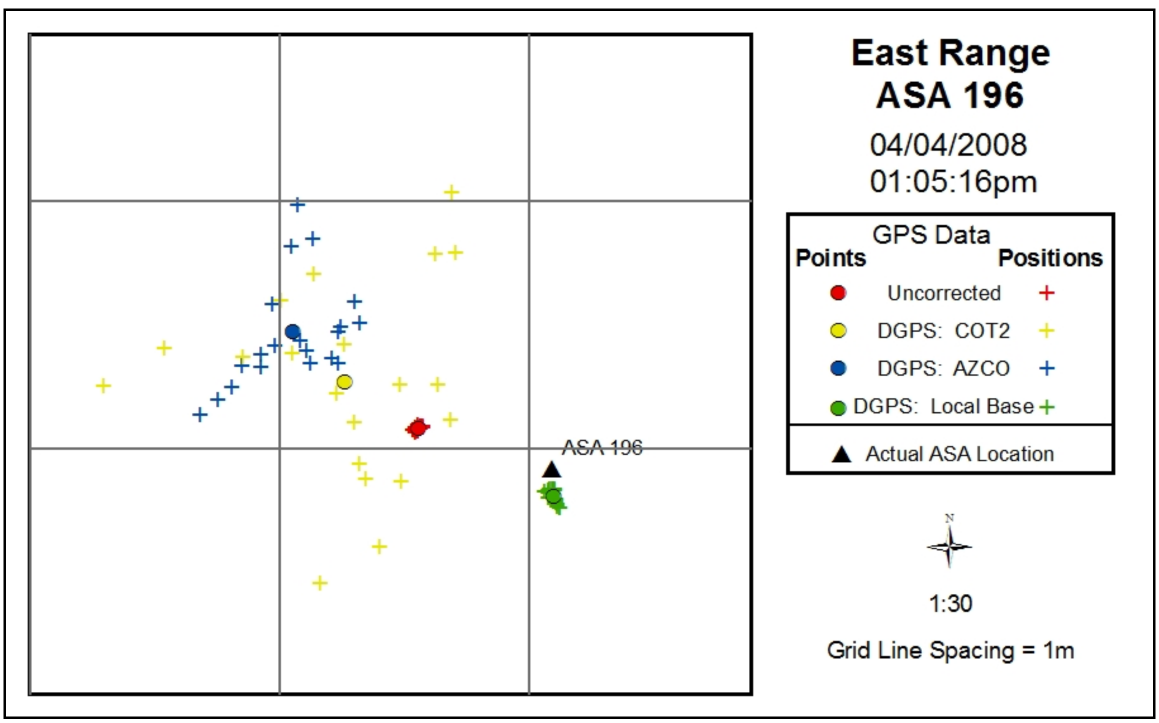
ASA 614
East Range
ASA 614
04/04/2008
12:32:51pm
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
N
1:30
Grid Line Spacing = 1m



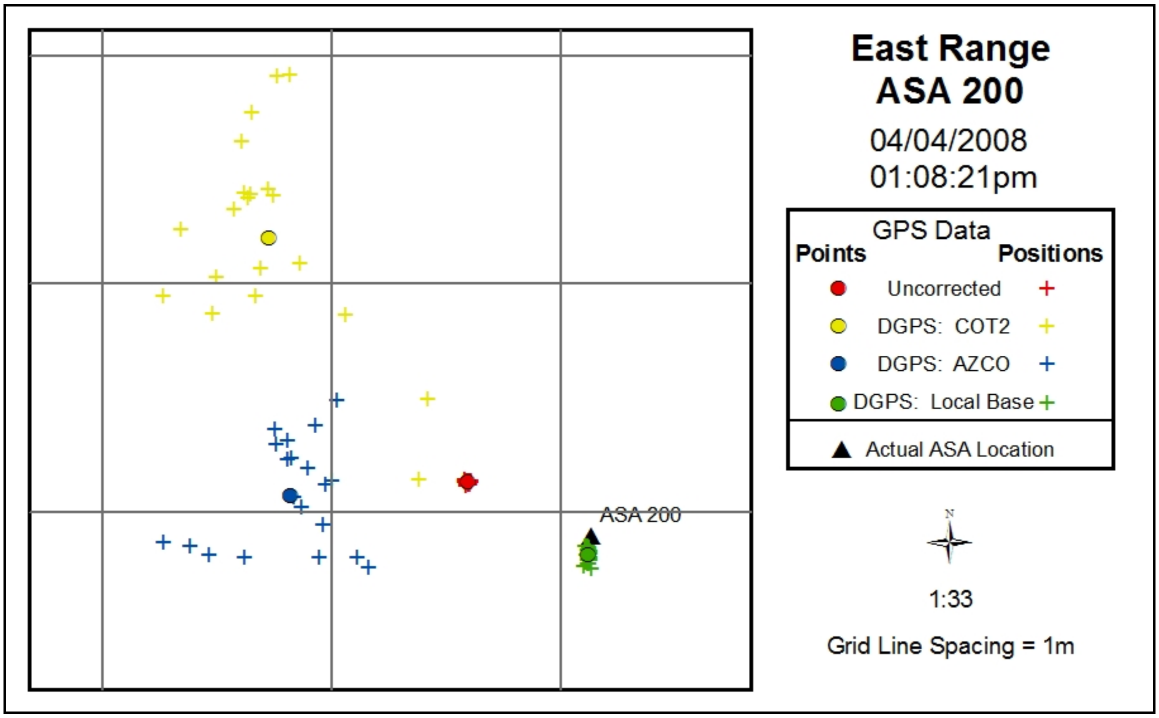
ASA 2271
East Range
ASA 2271
04/04/2008
12:38:26pm
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
N
1:30
Grid Line Spacing = 1m

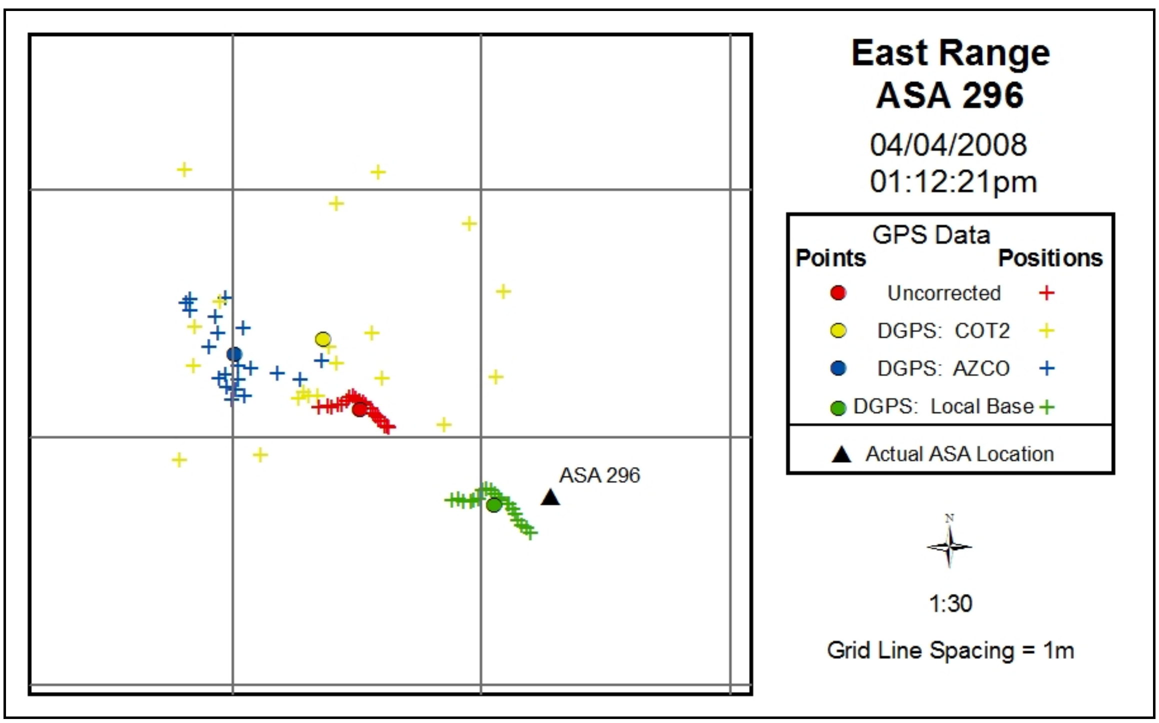


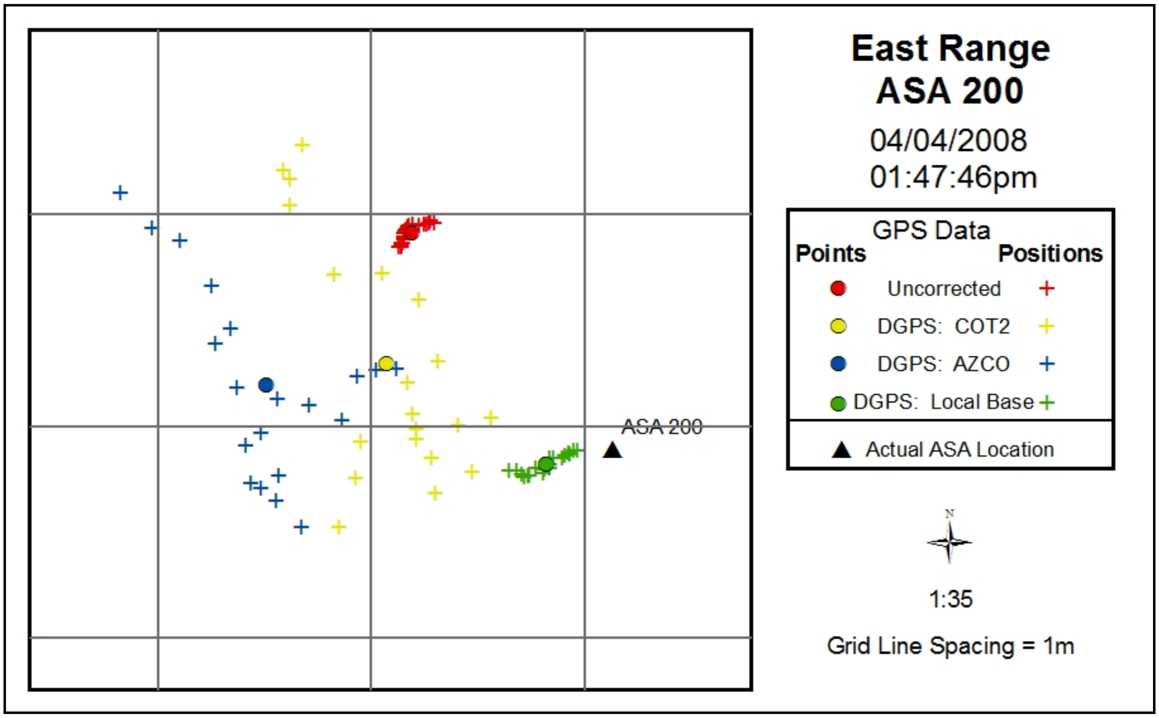
East Range
ASA 193
04/04/2008
12:51:21pm
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
ASA 193
N
1:30
Grid Line Spacing = 1m

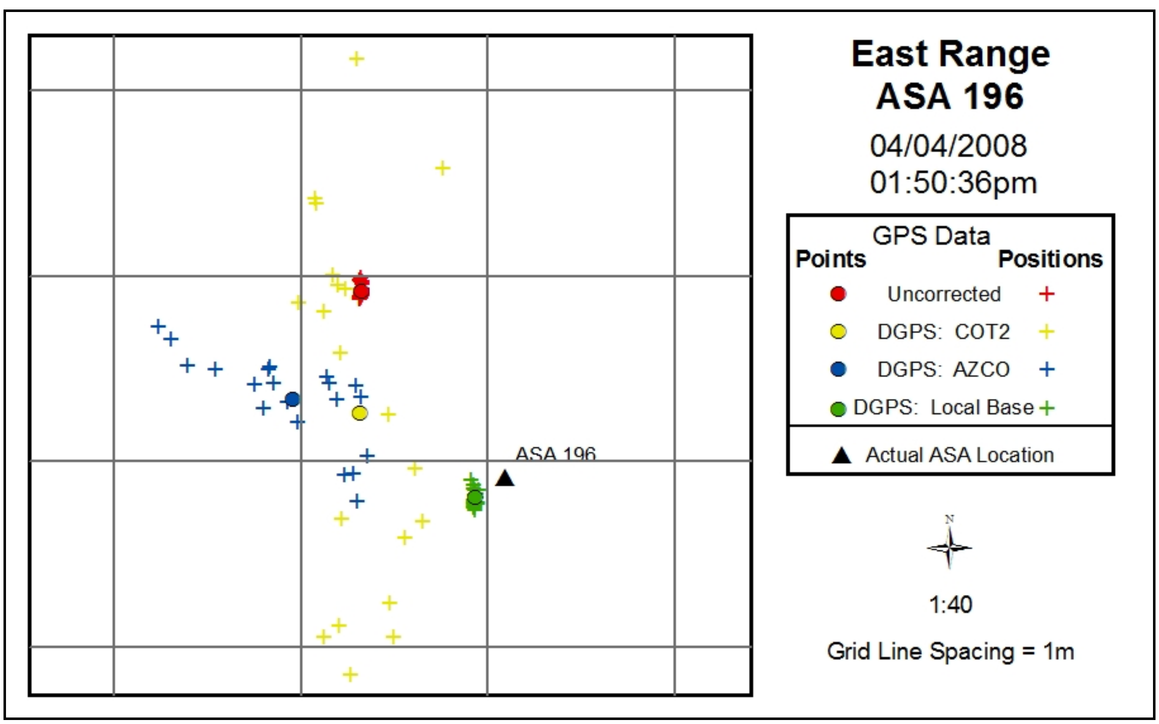


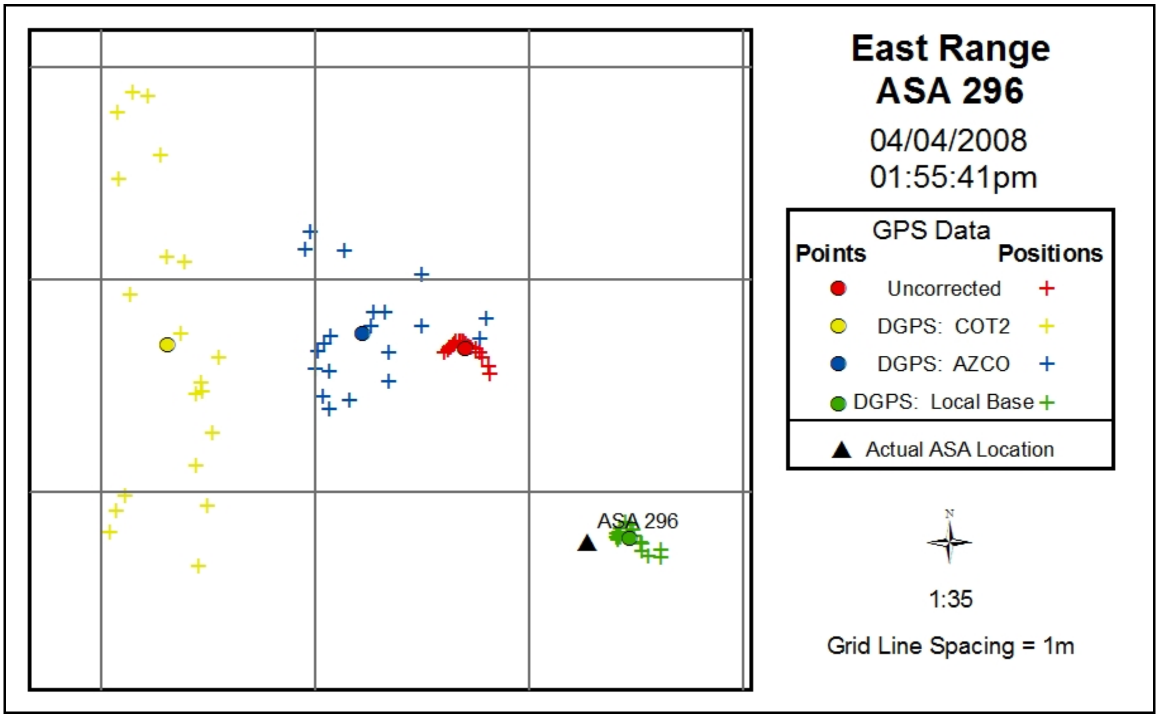
East Range
ASA 196
04/04/2008
01:05:16pm
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
ASA 196
N
1:30
Grid Line Spacing = 1m

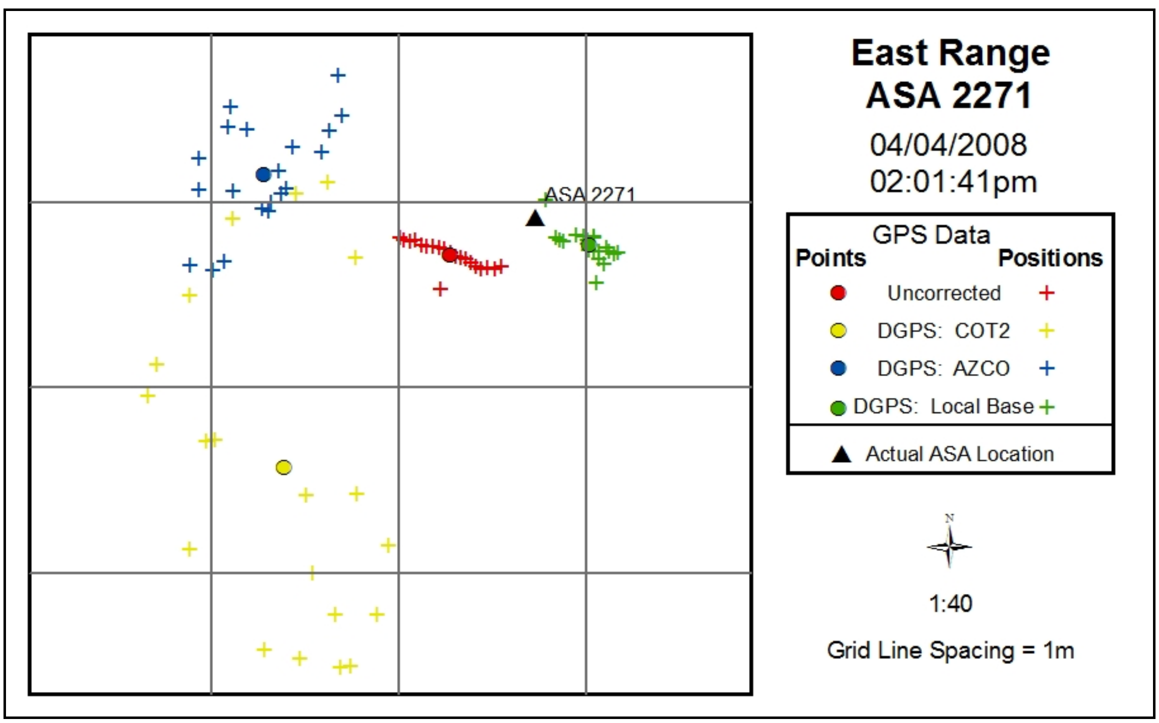

East Range
ASA 200
04/04/2008
01:08:21pm
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
ASA 200
N
1:33
Grid Line Spacing = 1m

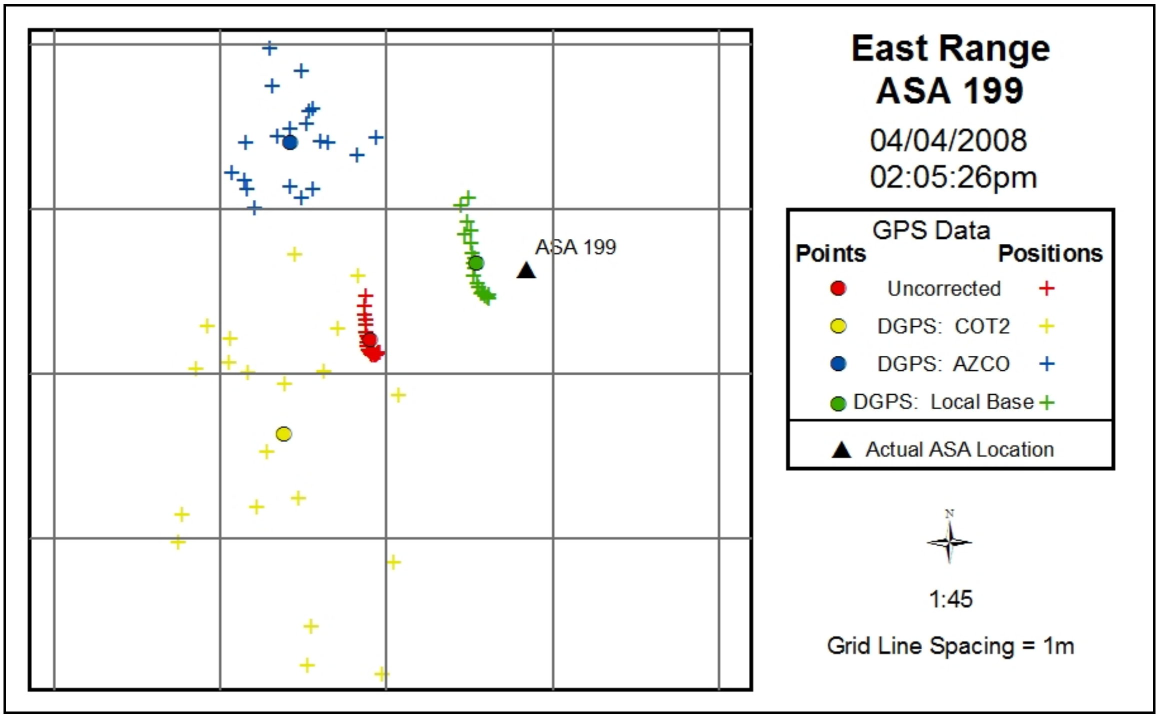

East Range
ASA 296
04/04/2008
01:12:21pm
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
ASA 296
N
1:30
Grid Line Spacing = 1m

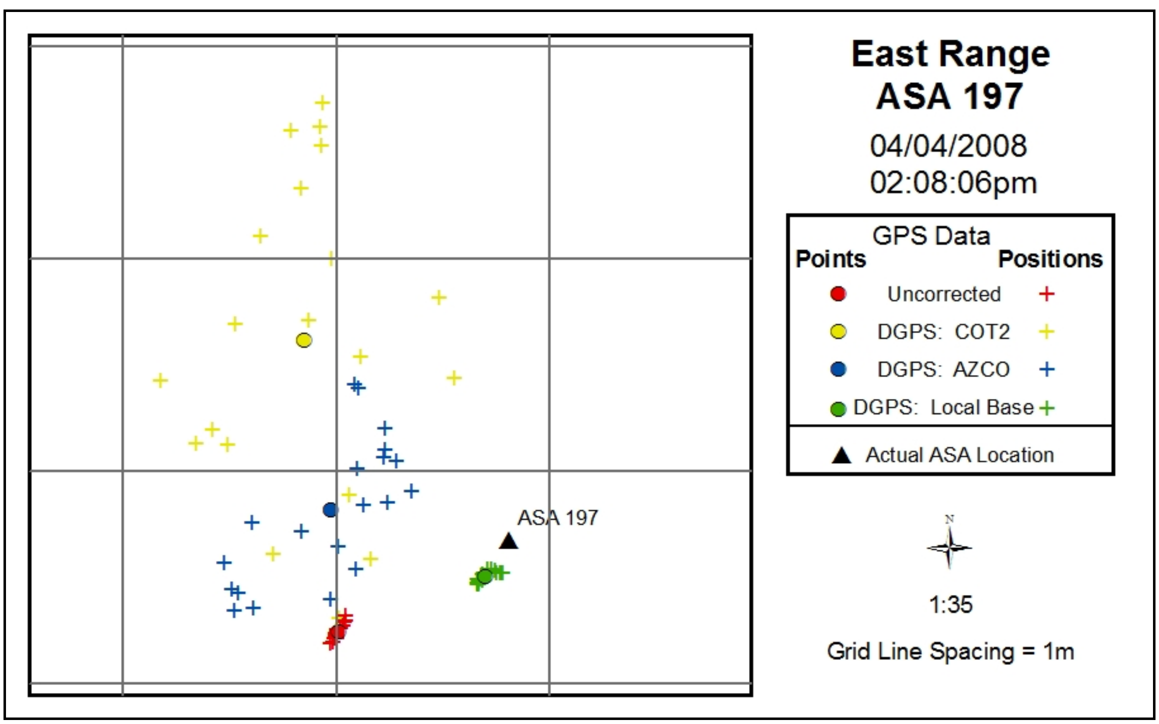

ASA 200
East Range
ASA 200
04/04/2008
01:47:46pm
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
N
1:35
Grid Line Spacing = 1m

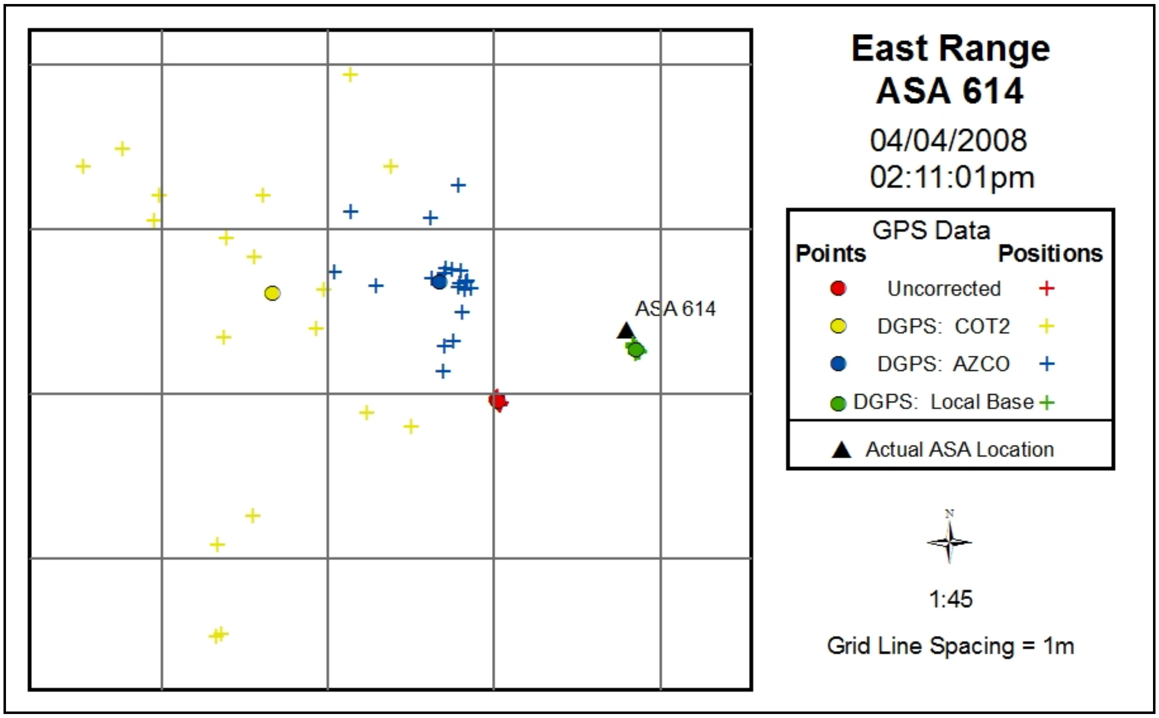

ASA 196
East Range
ASA 196
04/04/2008
01:50:36pm
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
N
1:40
Grid Line Spacing = 1m

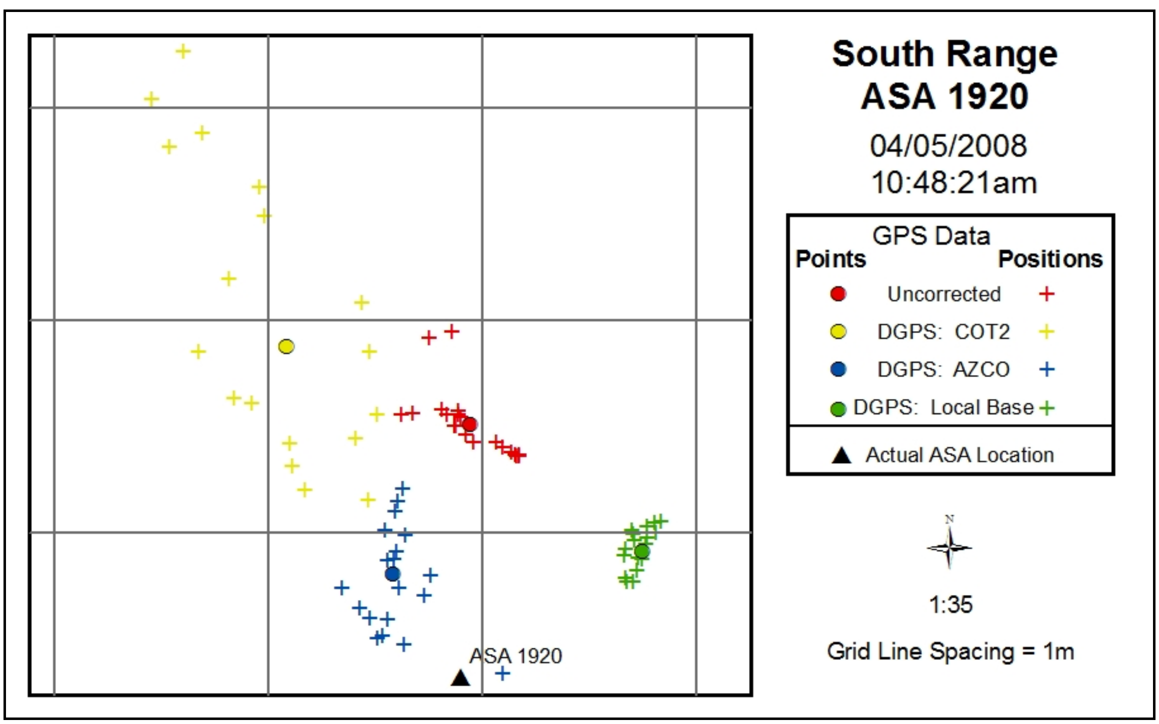

East Range
ASA 296
04/04/2008
01:55:41pm
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
ASA 296
N
1:35
Grid Line Spacing = 1m

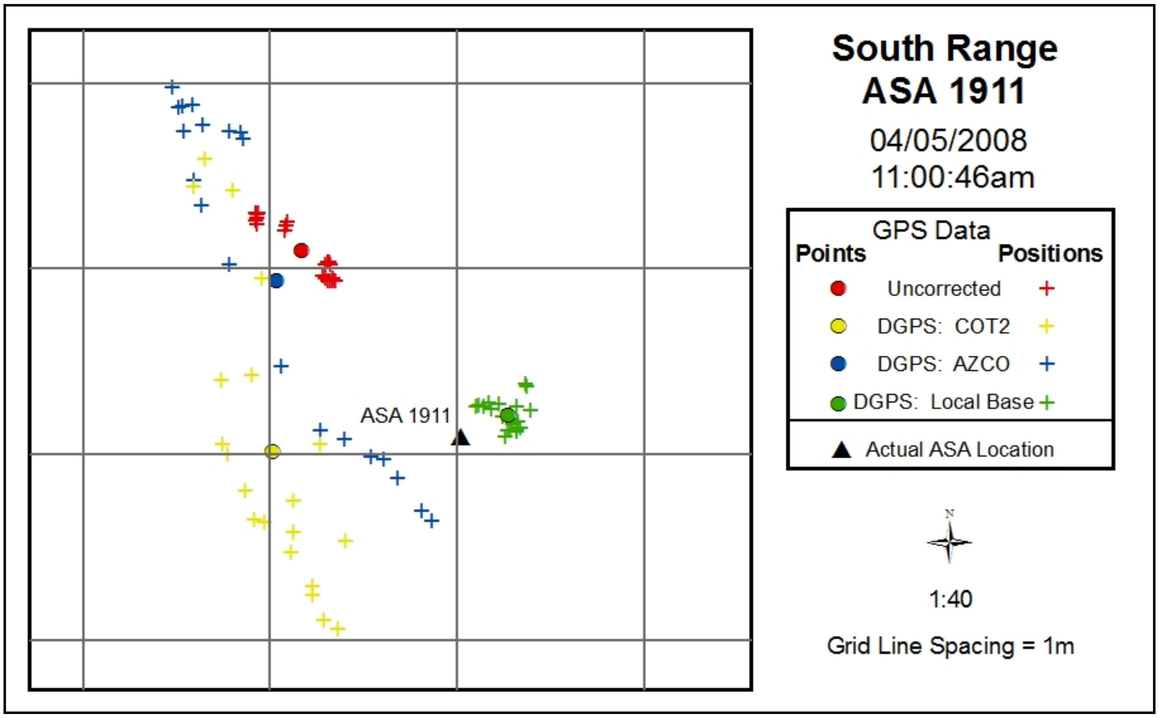

East Range
ASA 2271
04/04/2008
02:01:41pm
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
ASA 2271
N
1:40
Grid Line Spacing = 1m

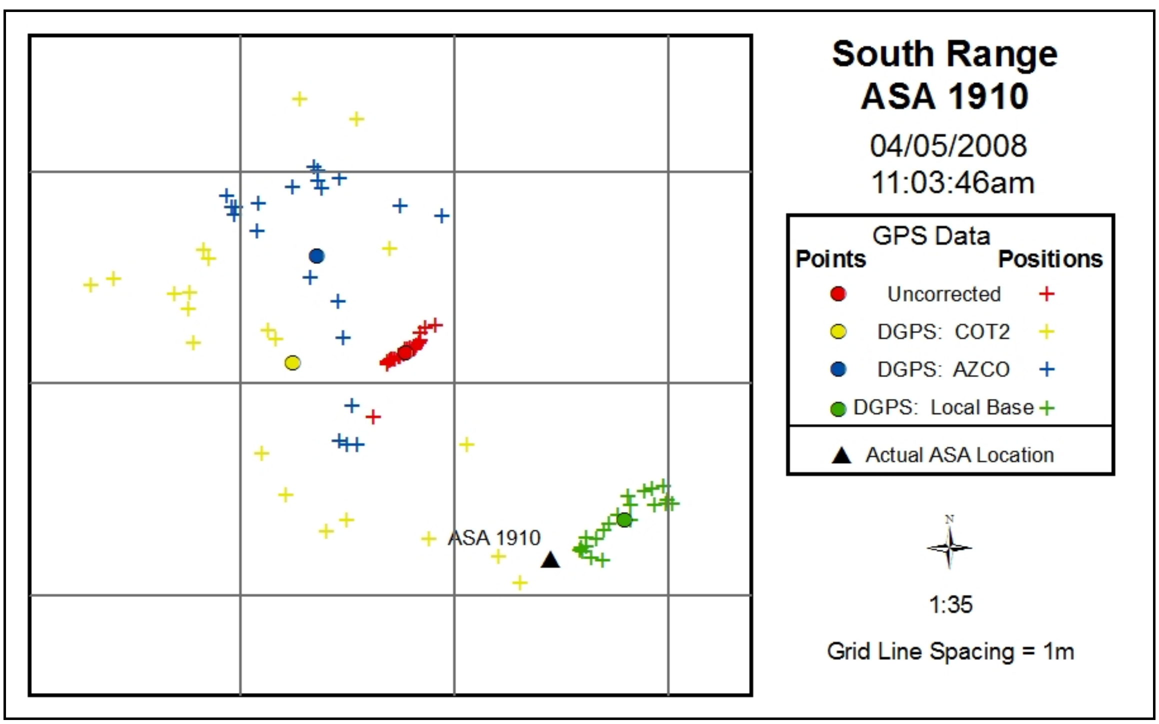

ASA 199
East Range
ASA 199
04/04/2008
02:05:26pm
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
1:45
Grid Line Spacing = 1m

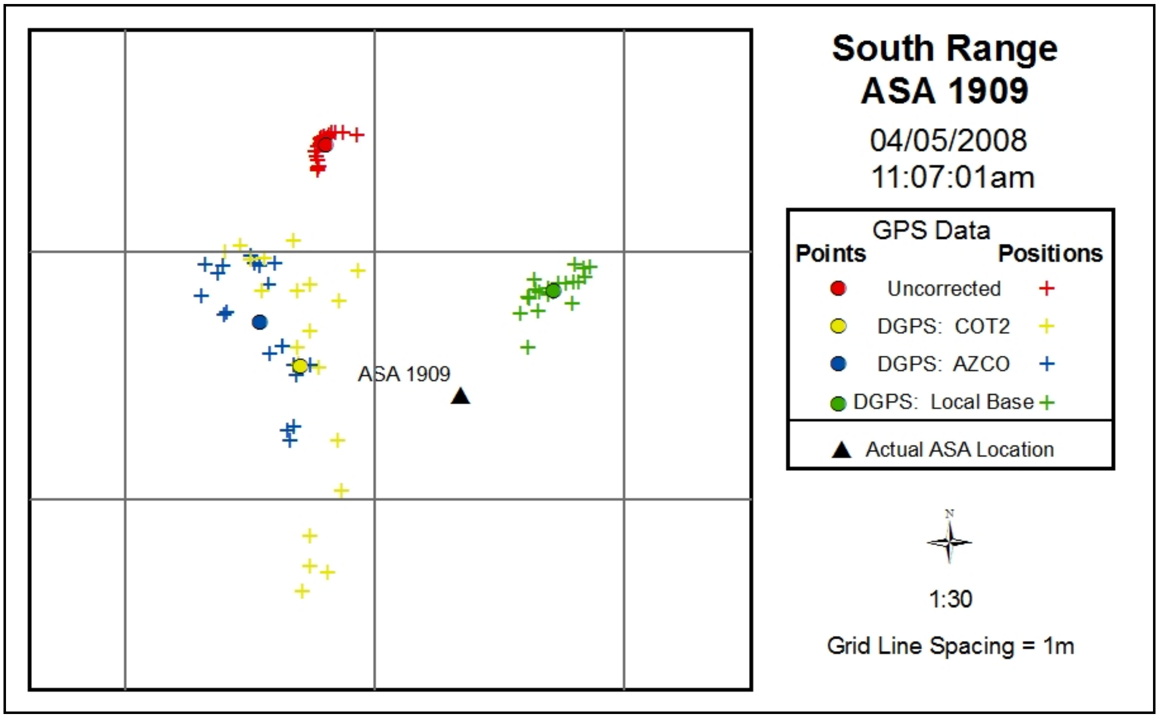

ASA 197
East Range
ASA 197
04/04/2008
02:08:06pm
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
1:35
Grid Line Spacing = 1m

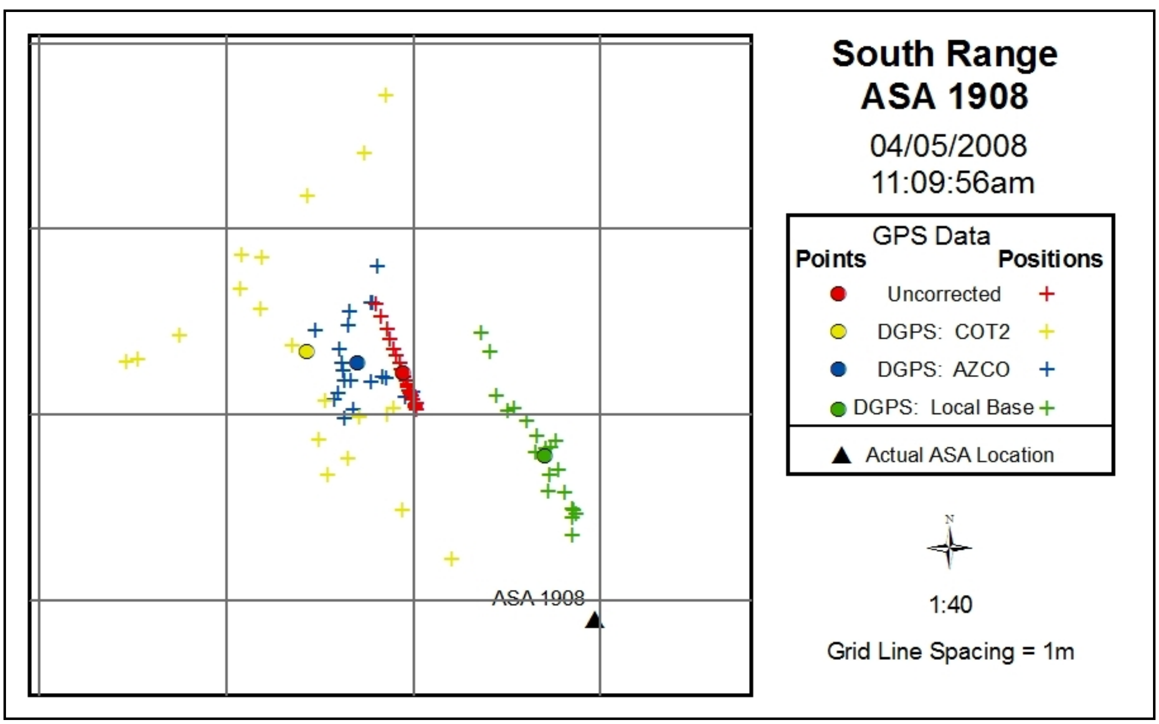

ASA 614
East Range
ASA 614
04/04/2008
02:11:01pm
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
N
1:45
Grid Line Spacing = 1m

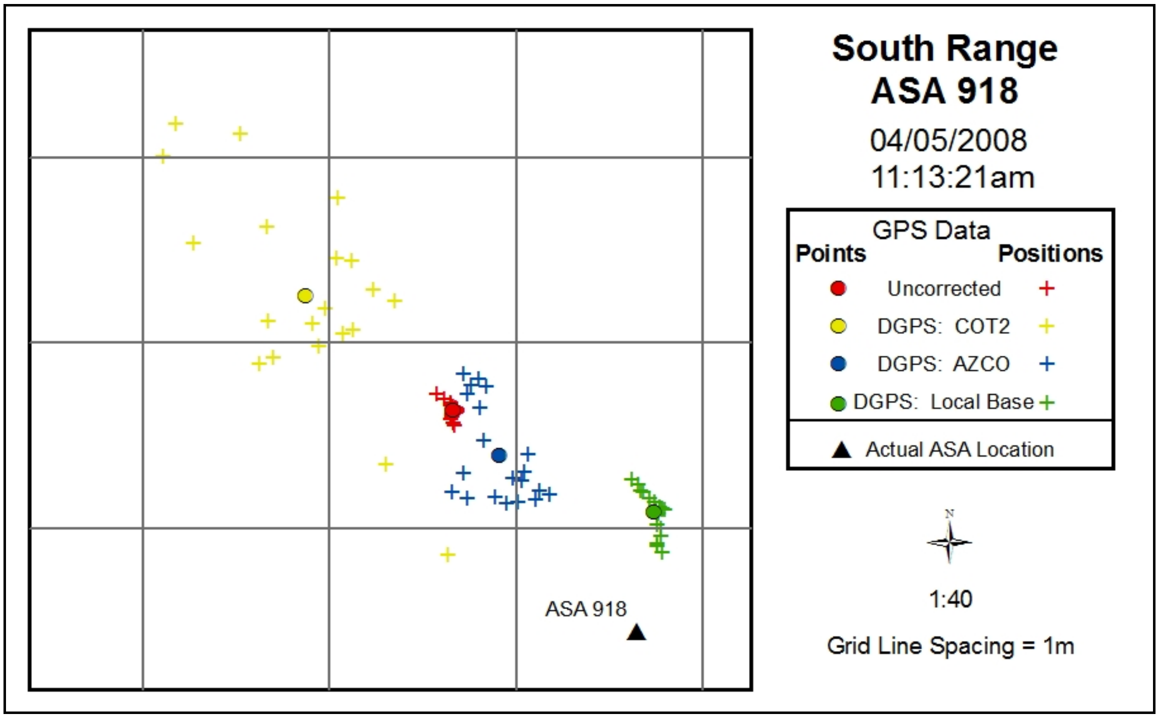

ASA 1920
South Range
ASA 1920
04/05/2008
10:48:21am
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
N
1:35
Grid Line Spacing = 1m

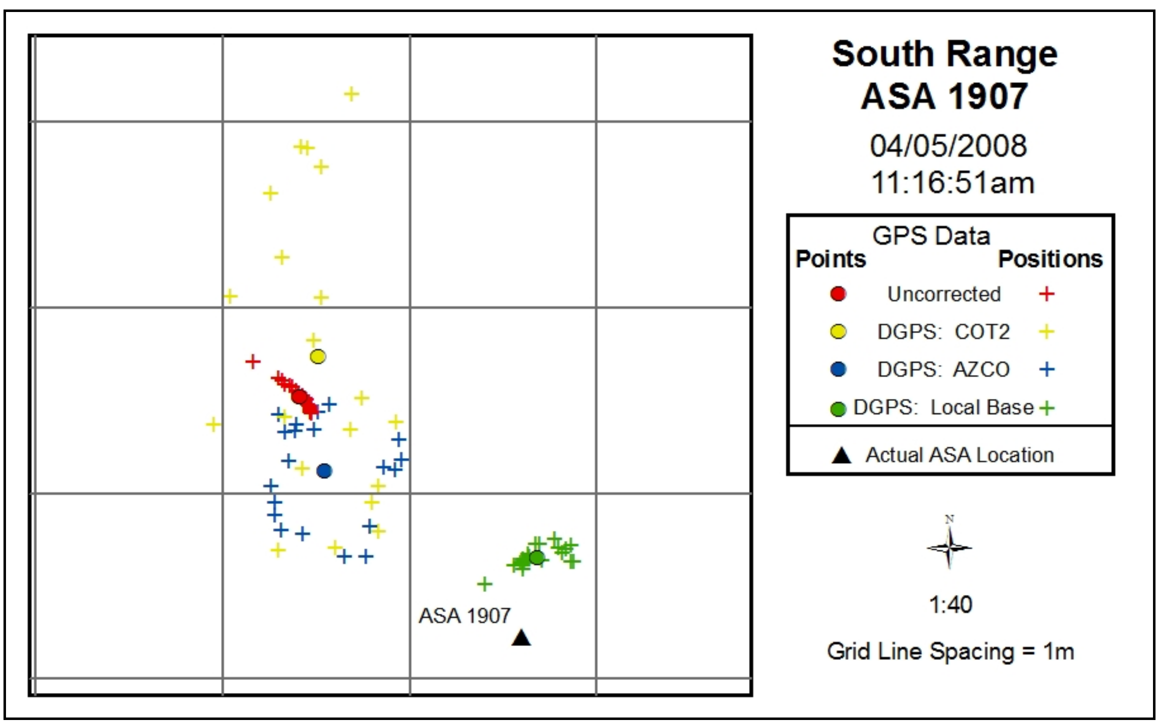

ASA 1911
South Range
ASA 1911
04/05/2008
11:00:46am
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
N
1:40
Grid Line Spacing = 1m

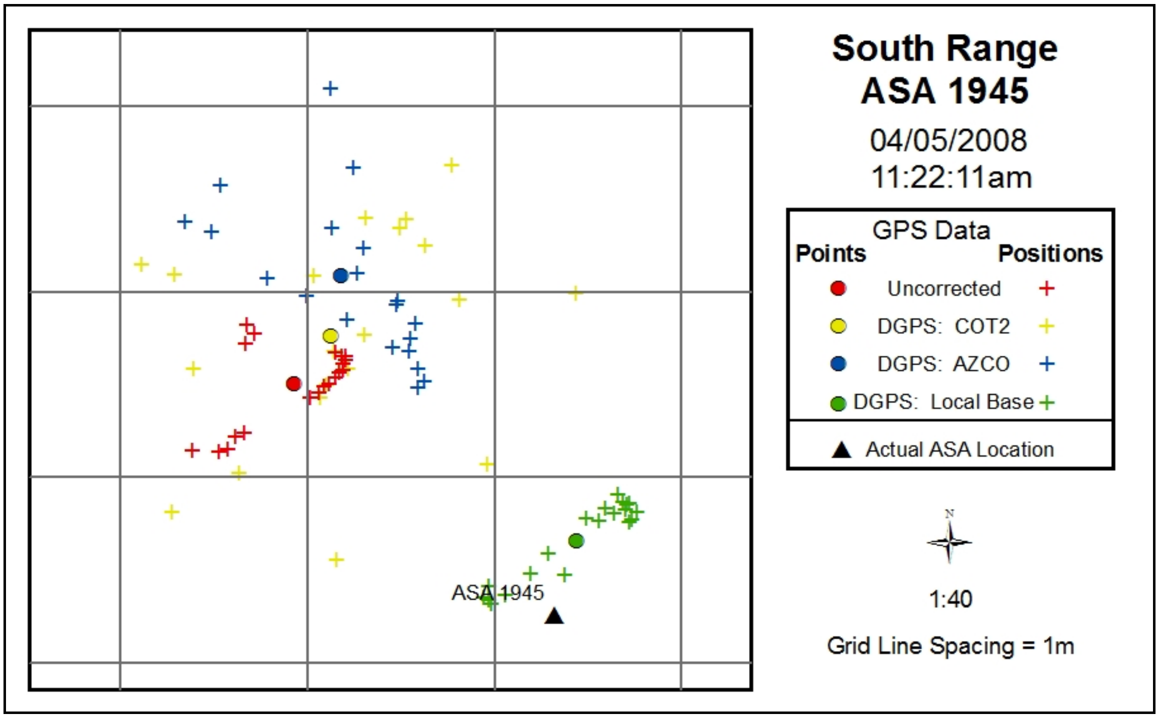

ASA 1910
South Range
ASA 1910
04/05/2008
11:03:46am
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
N
1:35
Grid Line Spacing = 1m

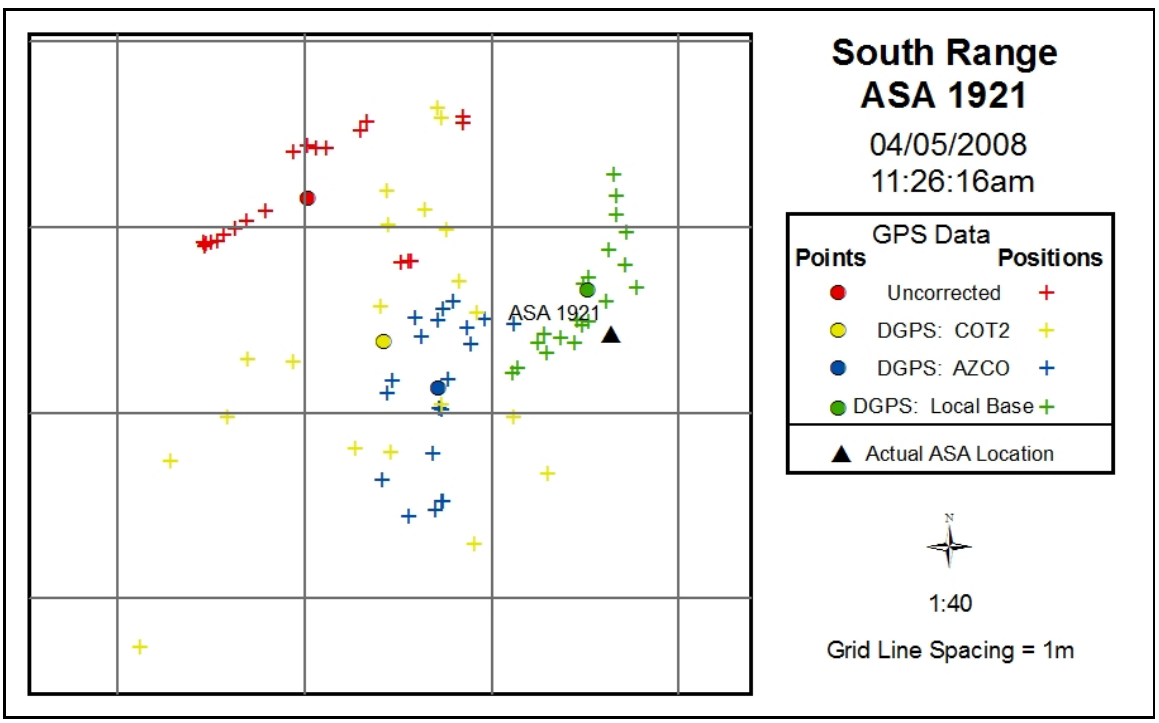

South Range
ASA 1909
04/05/2008
11:07:01am
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
ASA 1909
N
1:30
Grid Line Spacing = 1m

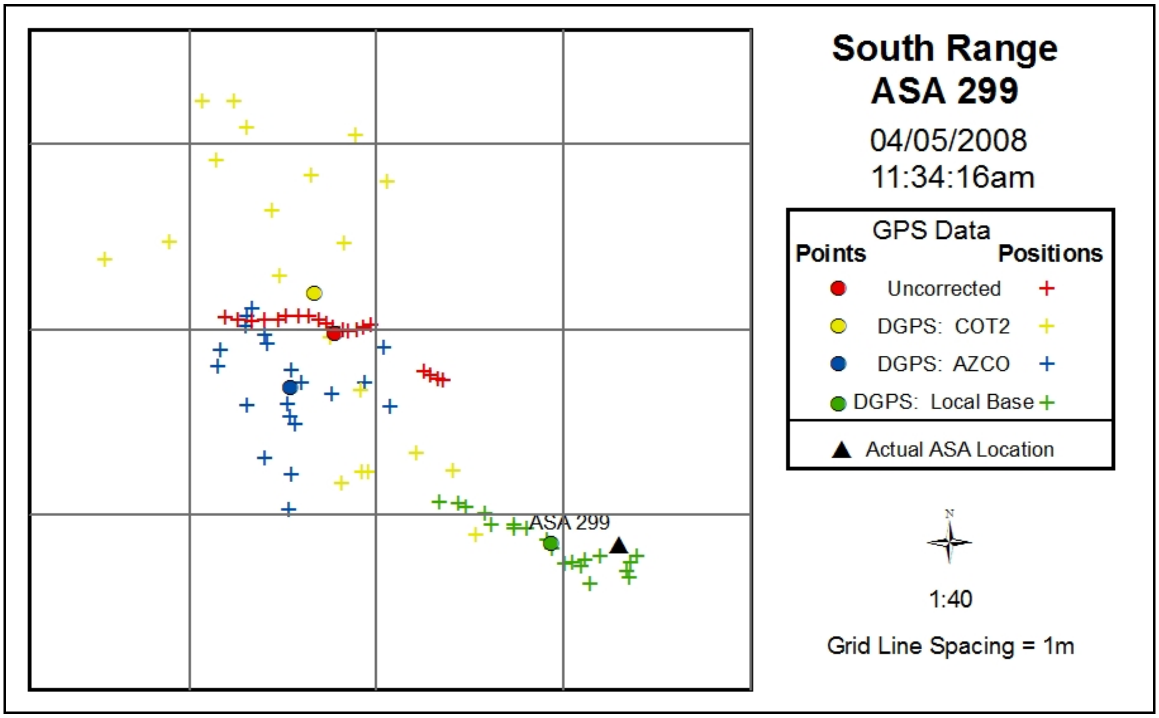

South Range
ASA 1908
04/05/2008
11:09:56am
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
ASA 1908
N
1:40
Grid Line Spacing = 1m

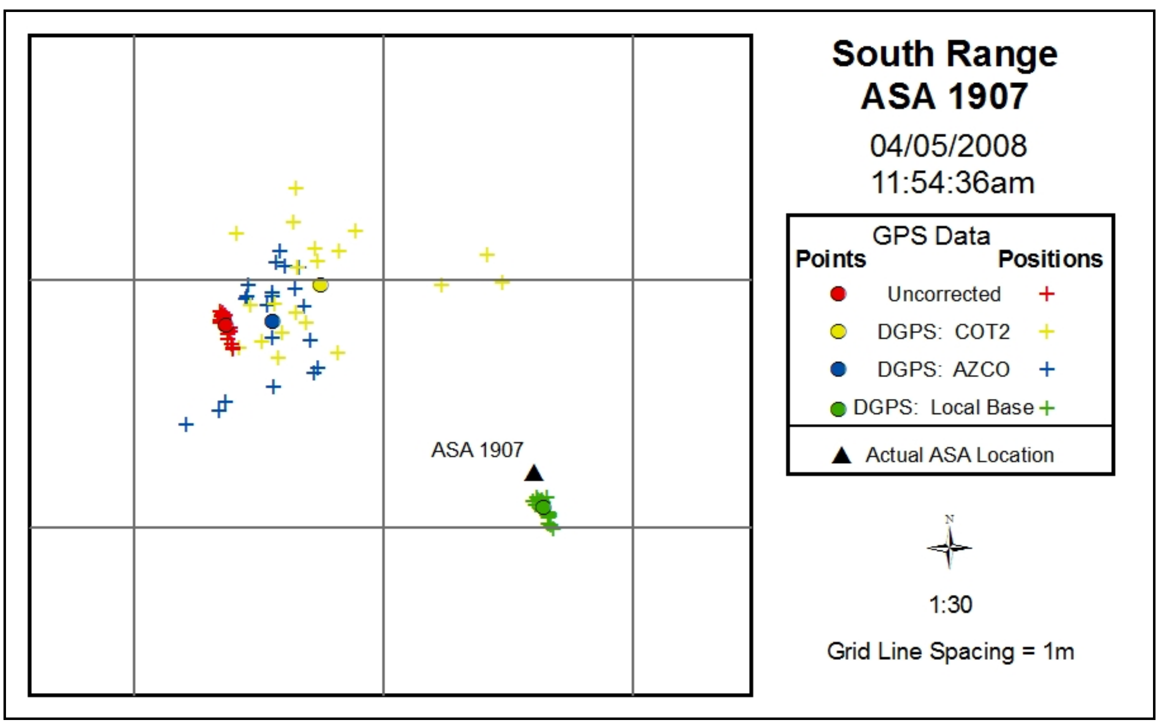

South Range
ASA 918
04/05/2008
11:13:21am
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
N
1:40
Grid Line Spacing = 1m
ASA 918

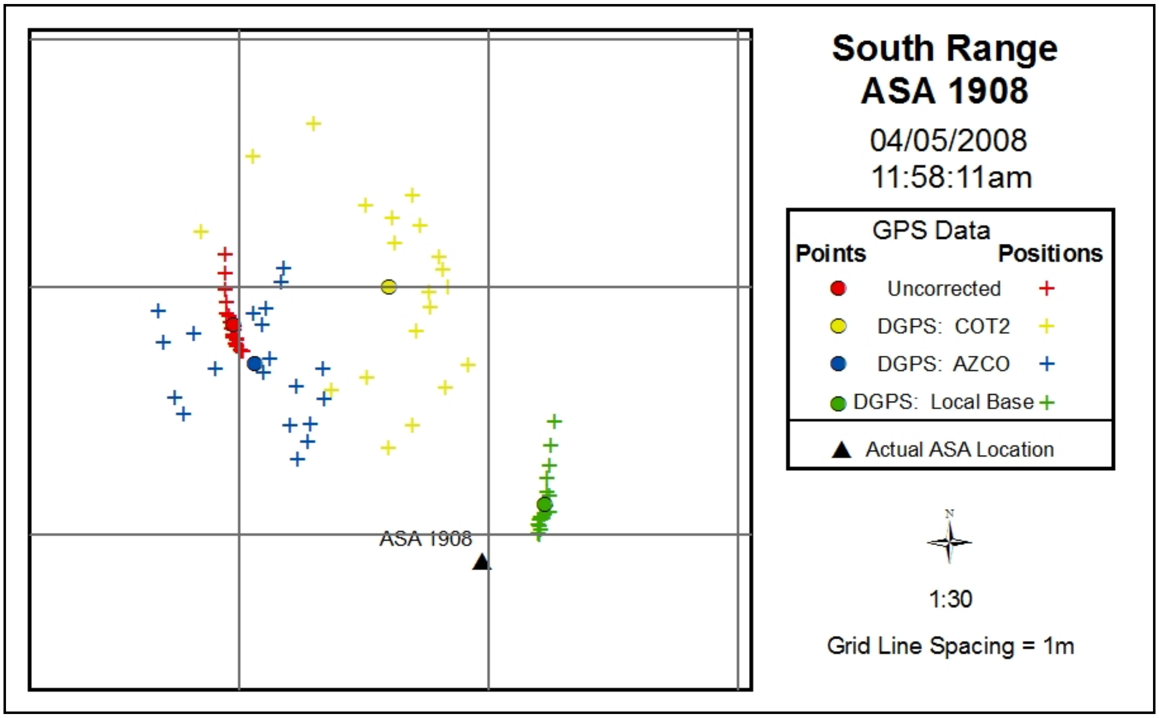

South Range
ASA 1907
04/05/2008
11:16:51am
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
N
1:40
Grid Line Spacing = 1m
ASA 1907

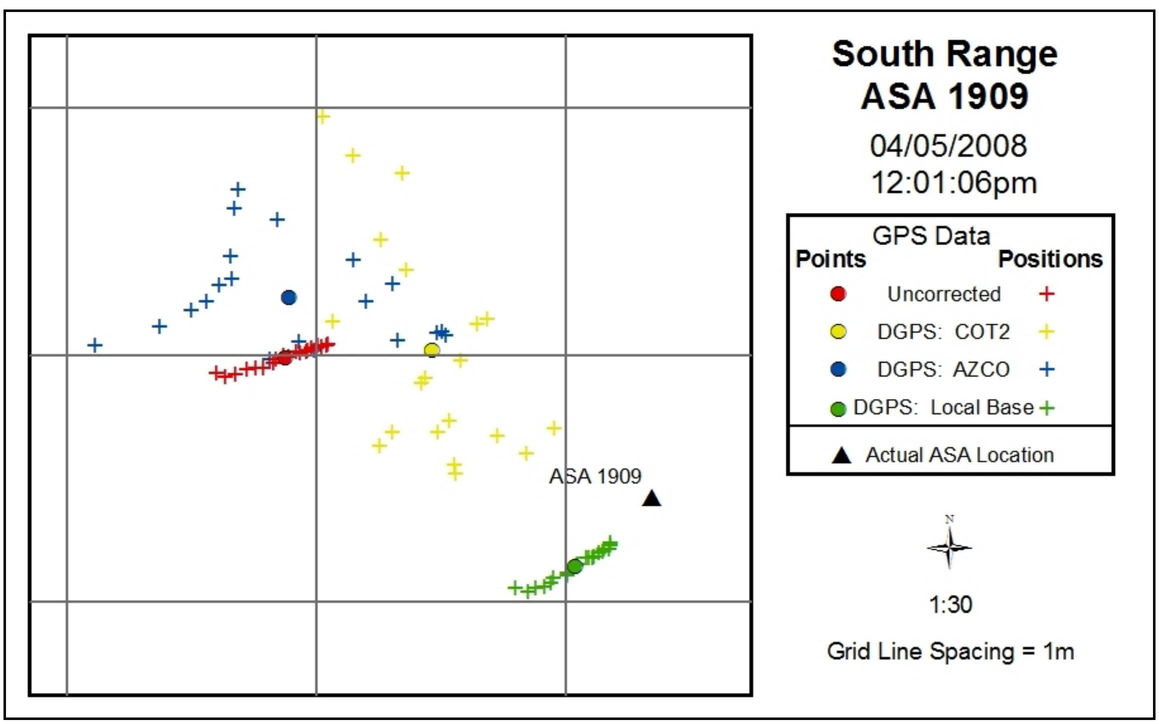

ASA 1945
South Range
ASA 1945
04/05/2008
11:22:11am
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
N
1:40
Grid Line Spacing = 1m

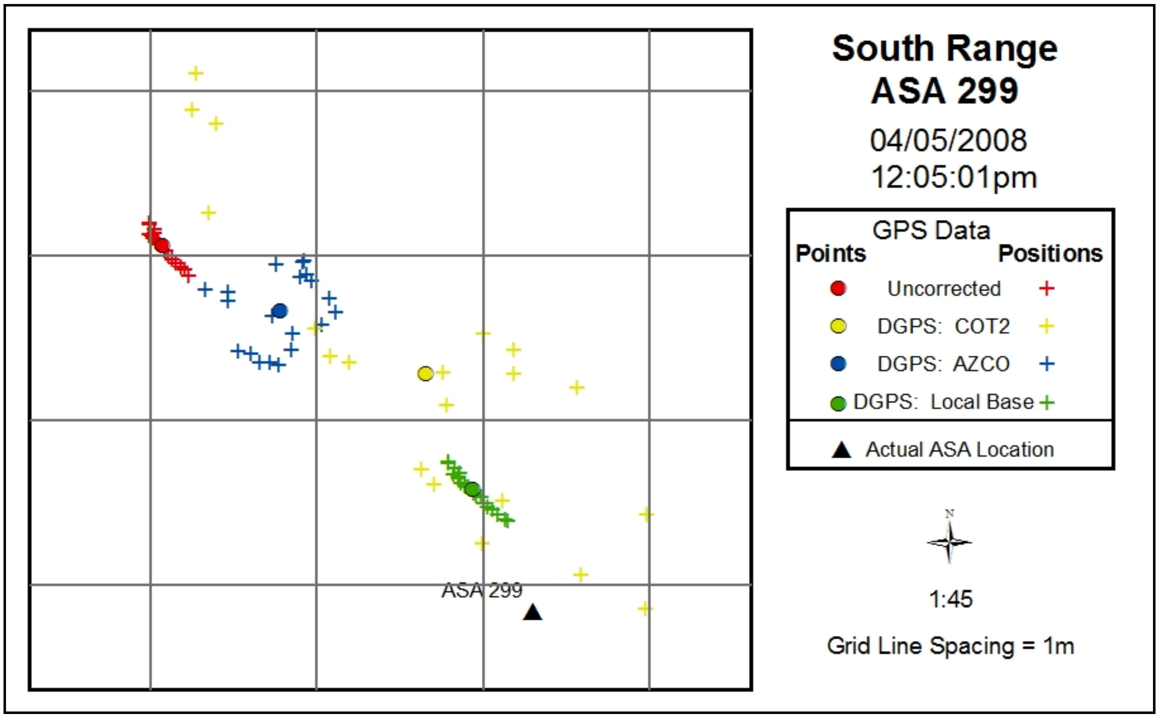

ASA 1921
South Range
ASA 1921
04/05/2008
11:26:16am
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
N
1:40
Grid Line Spacing = 1m

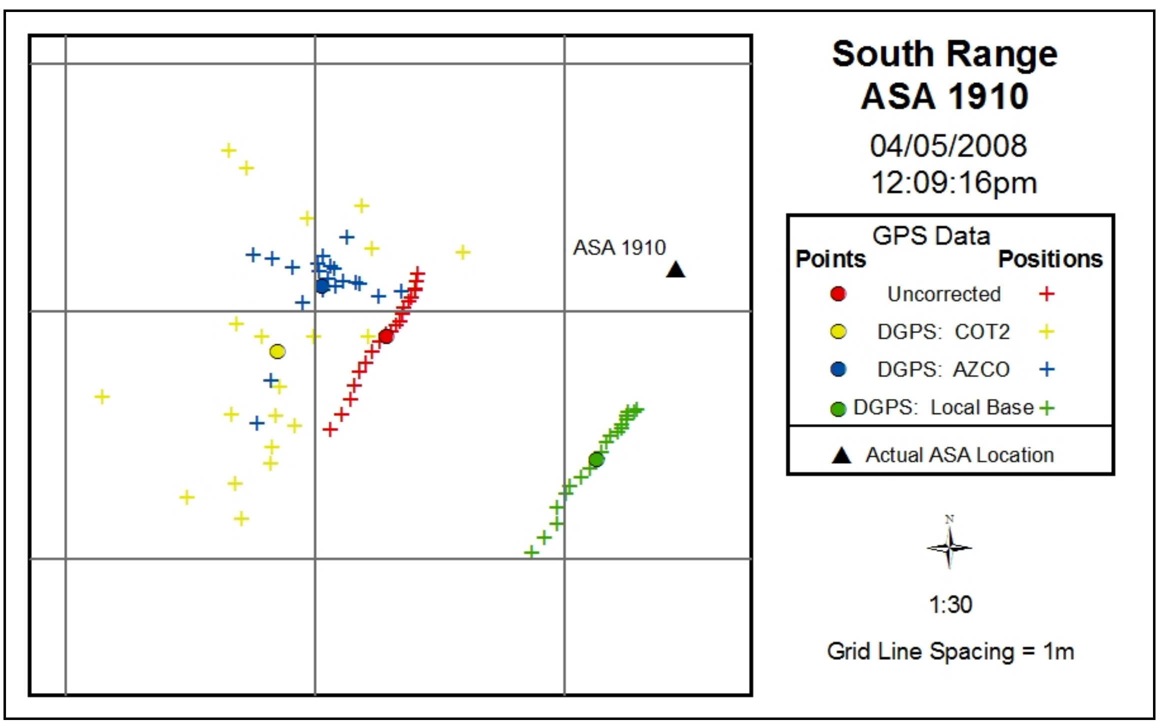

ASA 299
South Range
ASA 299
04/05/2008
11:34:16am
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
N
1:40
Grid Line Spacing = 1m

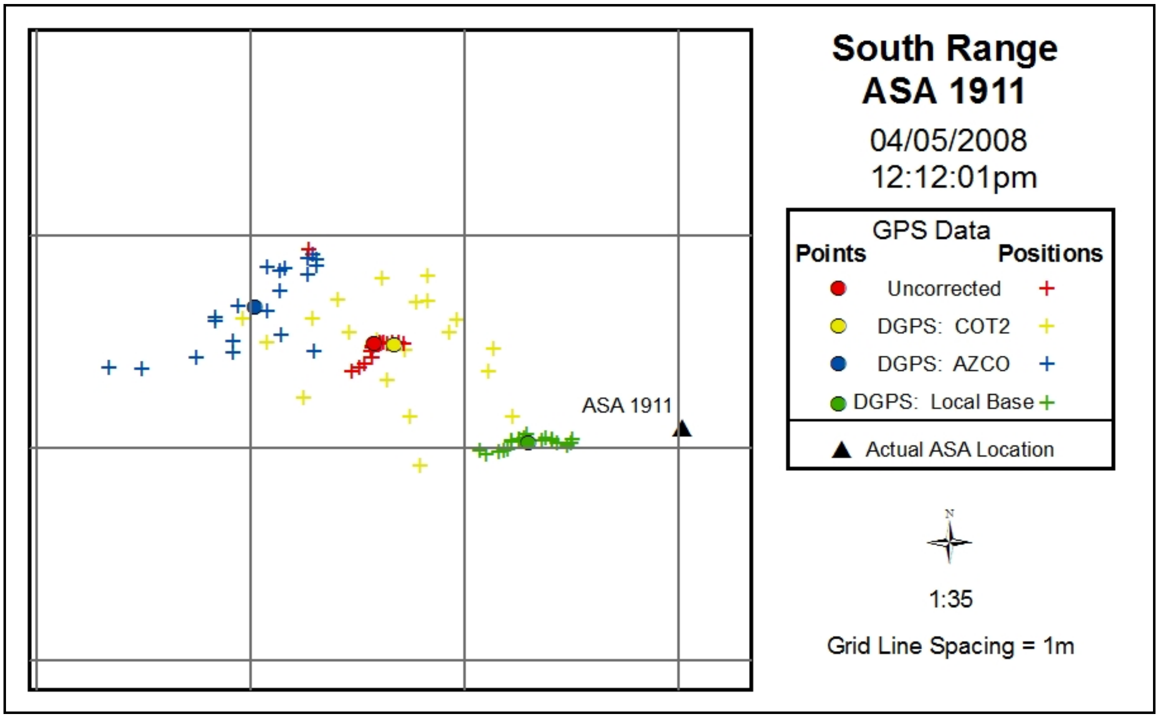

ASA 1907
South Range
ASA 1907
04/05/2008
11:54:36am
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
N
1:30
Grid Line Spacing = 1m

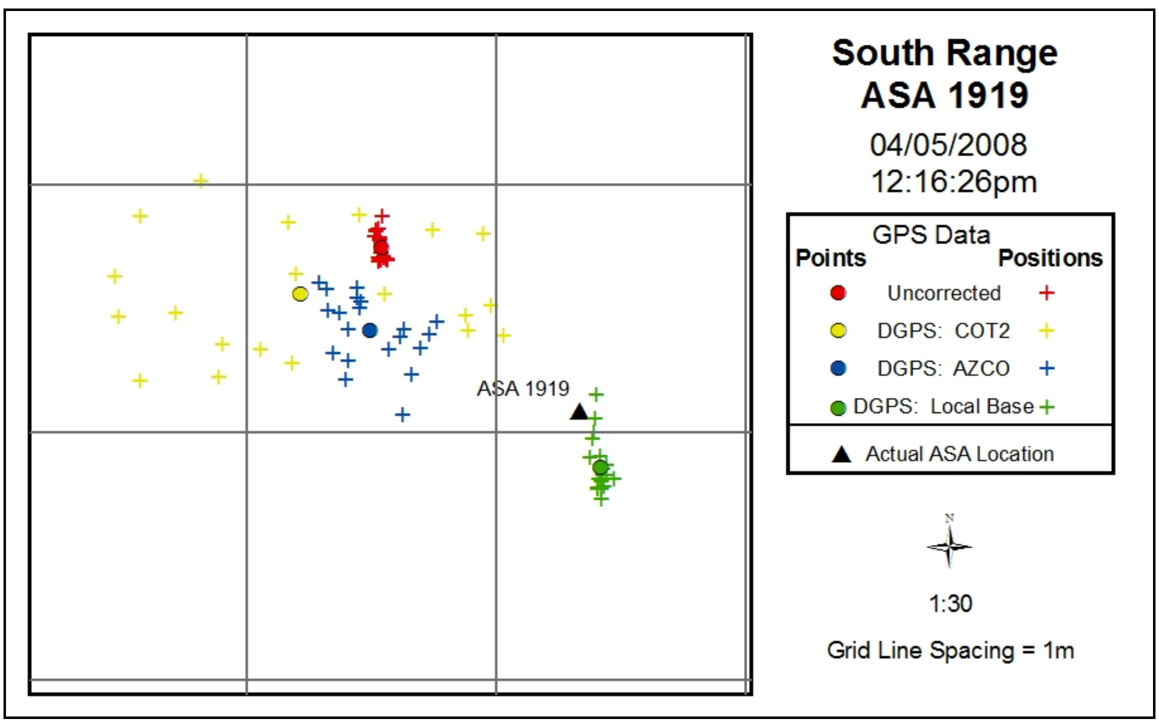

South Range
ASA 1908
04/05/2008
11:58:11am
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
ASA 1908
N
1:30
Grid Line Spacing = 1m

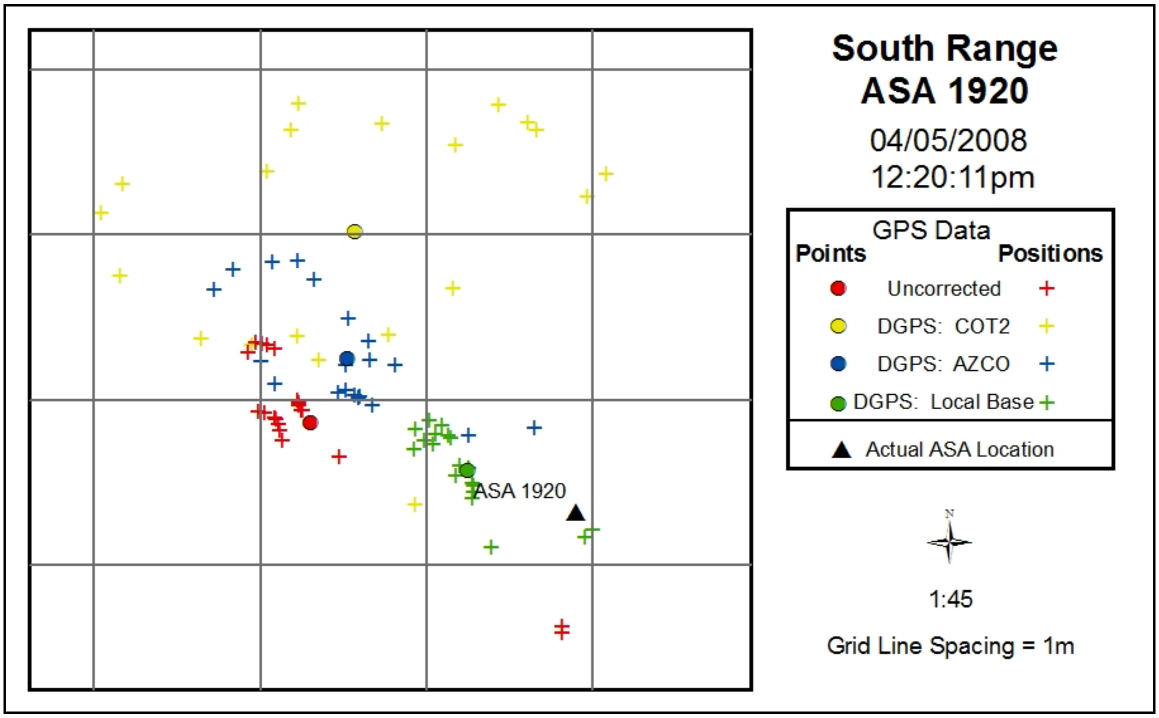

South Range
ASA 1909
04/05/2008
12:01:06pm
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
ASA 1909
N
1:30
Grid Line Spacing = 1m

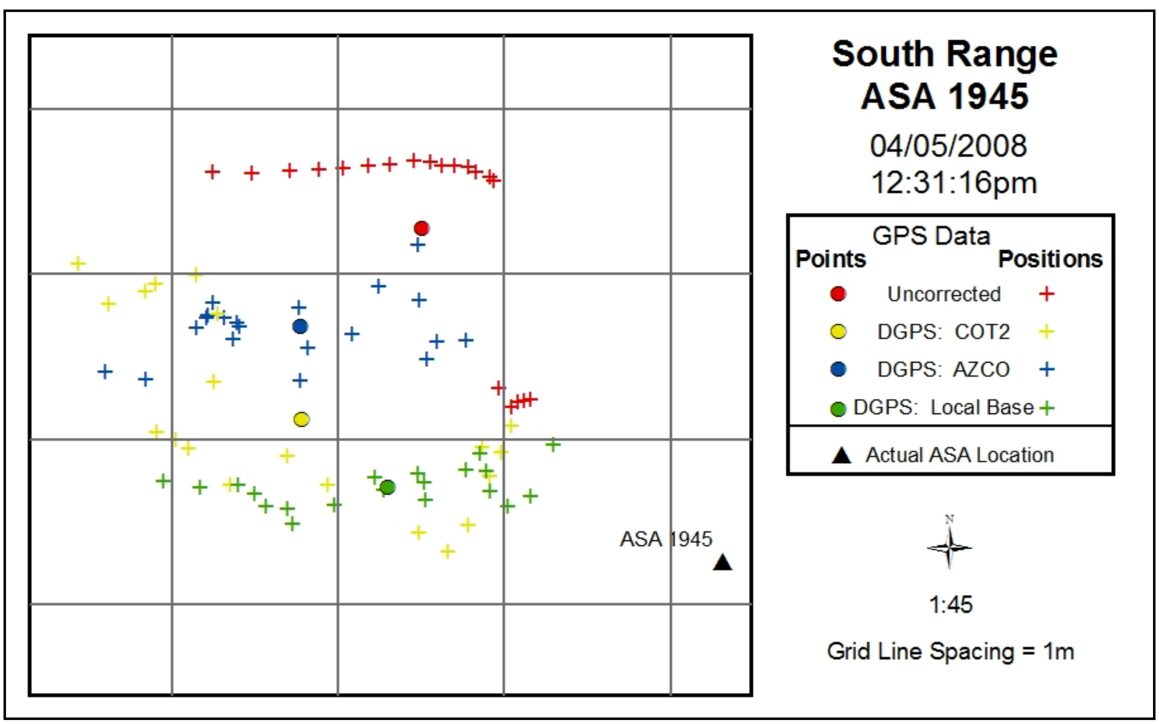

South Range
ASA 299
04/05/2008
12:05:01pm
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
ASA 299
N
1:45
Grid Line Spacing = 1m

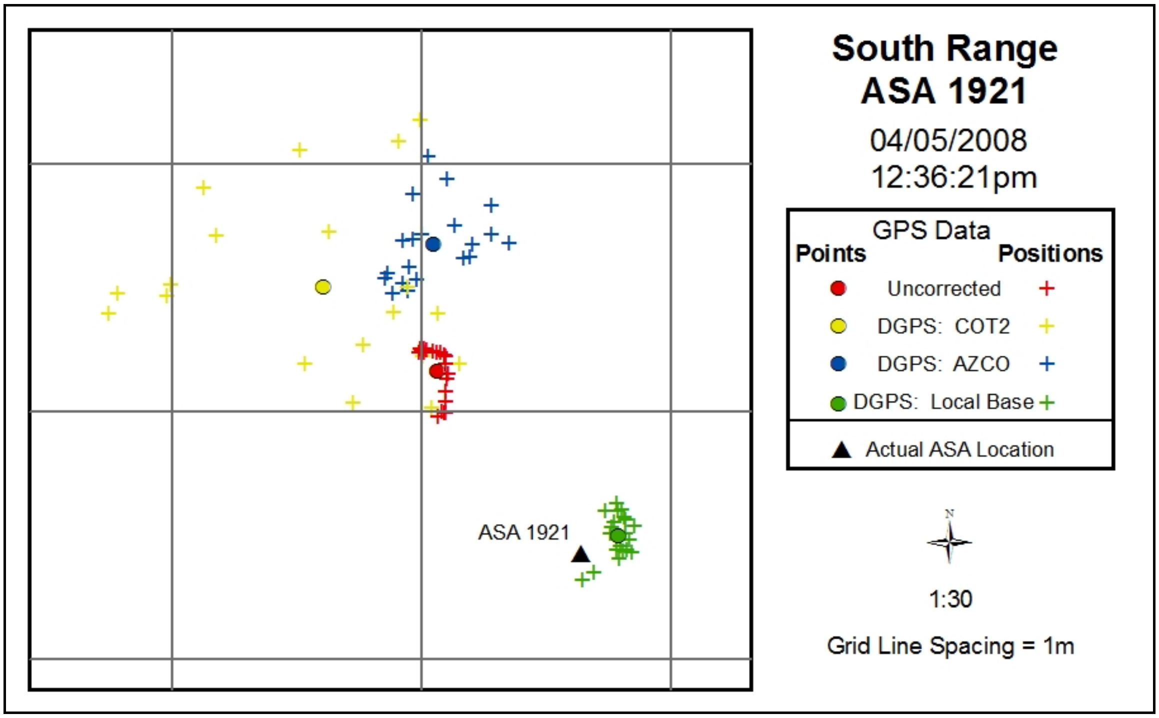

South Range
ASA 1910
04/05/2008
12:09:16pm
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
ASA 1910
N
1:30
Grid Line Spacing = 1m

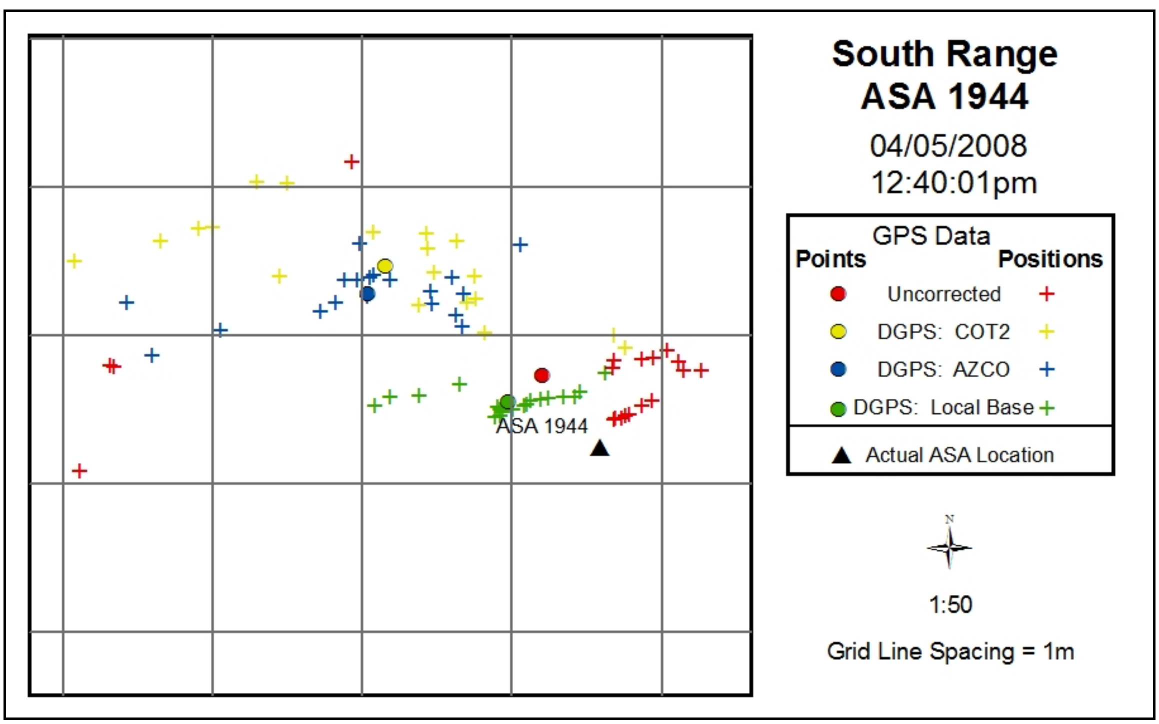

ASA 1911
South Range
ASA 1911
04/05/2008
12:12:01pm
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
N
1:35
Grid Line Spacing = 1m


ASA 1919
South Range
ASA 1919
04/05/2008
12:16:26pm
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
N
1:30
Grid Line Spacing = 1m


South Range
ASA 1920
04/05/2008
12:20:11pm
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
ASA 1920
N
1:45
Grid Line Spacing = 1m


South Range
ASA 1945
04/05/2008
12:31:16pm
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
ASA 1945
N
1:45
Grid Line Spacing = 1m


South Range
ASA 1921
04/05/2008
12:36:21pm
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
ASA 1921
N
1:30
Grid Line Spacing = 1m


South Range
ASA 1944
04/05/2008
12:40:01pm
GPS Data
Points
Positions
Uncorrected
DGPS: COT2
DGPS: AZCO
DGPS: Local Base
Actual ASA Location
ASA 1944
N
1:50
Grid Line Spacing = 1m