Global Navigation Satellite System

Wildlife Tracking Collar Positioning Accuracy

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ABSTRACT

Global Navigation Satellite Systems (GNSS) enable researchers to track the positions of many terrestrial vertebrate animals, which is a powerful tool for wildlife management. GNSS-determined positions are highly accurate in the absence of errors, but the environments in which wildlife tend to live provide ample types and numbers of error sources. We studied the impact of several common errors by assessing the performance of four manufacturers' wildlife tracking collars in a mountainous region of Patagonia, Chile, South America and in the deciduous forests of Connecticut, USA, against geodetic-quality control.

This study evaluated position accuracy against these quantifiable error sources: satellite geometry, sky visibility obstructions, and data drop-out. **Position dilution of precision** (PDOP) is a readily available, epoch-by-epoch position accuracy metric reported by GNSS receivers as part of their output. Our methodology produced a region-specific, collar-specific PDOP threshold value that is suitable for screening out egregiously erroneous positions, which might contribute to fallacious analyses and conclusions. We also show how PDOP values are useful to determine when and how it is appropriate to use position-derived information in wildlife management decisions. It is already reported in the GNSS literature that higher data collection rates yield higher accuracies; however, data collection rate has previously unreported implications for designing wildlife tracking experiments with GNSS technologies.

Chapter One
OVERVIEW OF GLOBAL NAVIGATION SATELLITE SYSTEM POSITIONING: A CRITIQUE FOR WILDLIFE RESEARCH

INTRODUCTION

Wildlife tracking is a key component of wildlife management, because it enables the monitoring of animal presence, movements and behaviors. This monitoring is necessary, because management agencies need to know: what species are present, the population health of those species, and the biological requirements (food, water and space) of those species (Samuel and Fuller 1996, Amstrup 2007) in order to balance their requirements with those of other species (Amstrup 2007). In an increasingly developing world, balancing the needs of wildlife with the needs of people is an especially important function of wildlife managers (Messmer 2000, Amstrup 2007).

Wildlife tracking has historically been done in many ways. It was first done by indigenous people hunting for food. “Tracking,” in that sense, is the combination of identifying the tracks and sign of an animal and then following the animal’s trail until it is within target range (Liebenberg 1990, Stander 1997). Researchers still use tracking to detect species presence, but new positioning technologies, such as radiotelemetry collars, are more common. In radiotelemetry, field crews triangulate a position by measuring the direction to the collar from at least two fiducial locations (Nams 1989, Rodgers et al. 1996, Samuel and Fuller 1996, Rettie and McLoughlin 1999). The crew uses a radio receiver with a directional antenna that detects a signal emitted by a radio transmitter attached to the collar. Radiotelemetry allows researchers, who may be unskilled with animal tracks and sign, to detect and monitor otherwise undetectable animals, especially cryptic species. Triangulation is time consuming, so only a few positions can be collected by a field crew in a typical day (Samuel and Fuller 1996).

The advent of satellite-based positioning created a new way to track wildlife using collars, as with radiotelemetry, but with several advantages. These advantages include: autonomous operation of the collar (so the number of positions collected depends on the number of collars deployed rather than the size of the field crew); variable and programmable data collection rates; data collection in any weather condition both in the day and in the night; data collection in any terrain type; operation for years, subject to battery capacity, without direct control of the field crew; and with greater positional accuracy than the alternatives (Friar et al. 2004). Furthermore, although understanding satellite-based positioning requires some technical expertise, it is nonetheless a simpler and easier technology to use than either radiotelemetry or following the fresh trail of an animal to its maker.

The technical expertise that underlies satellite-based positioning comes from electrical engineering, geodesy, astronomy, physics, and geophysics (Meyer et al. 2005); fields that are not usually studied by researchers using satellite-based positioning wildlife collars. However, as with any instrument, ignorance of its theory of operation and of its practical use and limitations generally leads to erroneous results and flawed analyses. This chapter will explain how satellite-based positions are computed and how they are applied to problems in wildlife tracking.

OVERVIEW OF SATELLITE-BASED POSITIONING SYSTEMS

The **NAVSTAR Global Positioning System** (GPS) was designed and built by the US Department of Defense (DoD) for timing, targeting, and navigation (Parkinson 1996a). To these ends, GPS functions in all weather, day and night, anywhere, and at all times. GPS receivers compute positions and the time of day when the position was computed, which are necessary and sufficient to meet GPS design goals (Spilker 1996a).

Navigators use **navigation systems** to determine the position of their craft and to enable the transit between locations. **Global navigation systems** are navigation systems that have global applicability. A **Global navigation satellite system** (GNSS) is a global navigation system that functions by means of artificial satellites (Hofmann-Wellenhof et al. 2003). The satellites in a GNSS are collectively called a **constellation** and individually called a **space vehicle** (SV) (Van Sickle 2008).

“Global navigation satellite system” is a generic term; there are several of them, including: the US NAVSTAR GPS; the Russian **GLO**bal'naya **NA**vigatsionnaya **S**putnikovaya **S**istema[1] (GLONASS); the European Union’s Galileo (Leick 2004, Van Sickle 2008); and the People’s Republic of China’s prototype *Beidou* system to be followed by the Compass system (Van Sickle 2008). Of these, the most widely used is the Global Positioning System.

GNSS’s are divided into three **segments**, being the organizational compartments needed to operate the system. The **control segment** is the people and equipment that monitor and operate the SVs. The US control segment consists of a dozen unmanned monitor stations scattered around the globe, which feed telemetry information to the **master control station** (MCS). The MCS is operated by the US Air Force 50th Space Wing’s 2nd Space Operations Squadron, located at Schriever Air Force Base in Colorado. The **space segment** consists of the SVs themselves. The **user segment** consists of all the users of the system (Spilker 1996a, Francisco 1996).

The SVs are placed in orbits that are practically circular, having almost zero eccentricity (see Figure 1.1). A circle is a planar figure and the orbit is, therefore, called an **orbital plane.** The constellation’s SVs are arranged in six, roughly equally separated, orbital planes. Each plane is designed to have four SVs, also separated roughly equally in the plane (Logsdon 1998, Parkinson 1996a, Spilker 1996c). Figure 1.2 shows the six orbital

[1] Which translates to “global navigation satellite system”

planes with dots representing the locations of the SVs over time. The figure shows how the SVs surround the Earth, in an image known as the “bird cage” (Logsdon 1998). This configuration always places at least two SVs in each orbital plane overhead all places at all times. On the Earth, the ground blocks line-of-sight to SVs below the horizon, resulting in visibility of only somewhat less than half of the constellation (see Figures 1.3 and 1.4). The tracks of the SVs across the sky as seen from the ground and as if the Earth were not rotating are shown in Figure 1.5. Other GNSS’s have different orbital plane configurations and different numbers of SV’s in a full constellation (Daly 1996).

The GPS constellation’s configuration is designed for a total of 24 SVs: six orbital planes, and each plane with four SVs (Spilker 1996a). The United States launches one SV at a time, however, so the population and maintenance of the constellation is an ongoing proposition. Two design groups of SVs have been built and deployed; they are called Block I and Block II (Parkinson 1996a, Spilker 1996a). The next generation Block III SVs is scheduled to begin deployment in 2009. A SV that is functioning properly and that is in use is called **healthy**. Obsolete or malfunctioning SVs are moved out of the operational orbits into higher, parking orbits (Francisco 1996). There are currently 32 healthy SVs.

The number and geometry of the visible SVs impact positional accuracy: fewer SVs result in less accurate positions than more SVs; and SVs clustered together in the sky, as seen from a ground receiver, result in less accurate positions than if they were widely separated. This quality of the visible constellation geometry is called **strength of figure** (Spilker 1996d). Position error can be caused by anything in the environment that attenuates (or blocks) SV signals, thus weakening the strength of figure in the visible constellation. These environmental factors include: type and density of canopy obstruction (Rempel et al. 1995; Blake et al. 2001; D’Eon et al. 2002, Dussault et al. 1999, Hebblewhite et al. 2007, Sager-Fradkin et al. 2007), and solid mass surface features, such as topography and buildings (D’Eon et al. 2002, Friar et al. 2004).

GNSS POSITIONING

Unlike triangulation, no directions are observed in GNSS positioning. GNSS positions are *entirely* distance-based, using a method called **multilateration**, which is a generalization of **trilateration** (Leick 2004, Hofmann-Wellenhof et al. 2003, Seeber 2003, Van Sickle 2008). Trilateration is a positioning technique wherein positions are determined using observed distances between the unknown point of interest and three control stations (Moffitt and Bossler 1997). With GNSS positioning, the unknown point of interest is the GNSS receiver on Earth, and the control stations are the SVs (Van Sickle 2008). If more than three distances are used, the positioning technique is called **multilateration**.

Orbital mechanics and the navigation message

Because the SVs are used as control and they are in constant motion, it is important to know where they are at all times. This is possible using Kepler's three laws of planetary motion, which describe idealized orbits (Russel1964, Meeus 1998). Kepler's laws are equations from which the positions of orbiting bodies can be determined at any moment in time, called an **epoch** (Van Sickle 2008). For GPS, these equations can be simplified into a single polynomial, whose coefficients are called the **Keplerian elements**. Therefore, given the Keplerian elements and an observation epoch, we can determine where an SV was at that epoch (Spilker 1996c).

Keplerian elements are determined for each SV, but there are small fluctuations between where the SVs are predicted to be using Kepler's laws and where they actually are. Therefore, the SVs need to be continually monitored and their Keplerian elements need to be continually updated. In order to do this, constellation monitoring data are collected and analyzed by the St. Louis monitor station, operated by the National Geospatial-Intelligence Agency (NGA). NGA St. Louis compiles and relays these data to the MCS, which uses them to compute the **broadcast ephemerides**. The MCS then uploads the broadcast ephemerides to the SVs, which, in turn, continuously broadcast them to the user segment as part of a message called the **navigation message** (aka, nav message) (Spilker 1996c). Each SV broadcasts its own ephemeris; they also broadcast a compendium of truncated ephemerides for the entire constellation, called the **almanac**.

Time systems

The distance between a receiver and an SV, called a **range**, is determined by measuring the time-of-flight, or **transit time**, of the radio signals broadcast by the SVs. This is done by subtracting the time of transmission from the time of reception, so the receivers' clocks need to be synchronized with the time kept by the atomic clocks in the SVs (Van Sickle 2008) (atomic clocks utilize atomic resonance for timekeeping) (Spilker 1996a, Parkinson 1996a). The GPS time system is called **GPS time**. GPS time is coordinated with time kept at the US Naval Observatory in Bethesda, Maryland; a time called **Universal Time, Coordinated**, or UTC(USNO) with "USNO" denoting "U. S. Naval Observatory." This distinction is necessary because other authorities, e.g., in France and in Russia, maintain their own coordinated universal time. UTC is an atomic time kept in the **International Atomic Timescale** (TAI). TAI is based on the statistical average of time kept by a large number of atomic clocks (Spilker 1996c).

Carriers, bands, and codes

The satellites broadcast radio signals in up to five frequencies (Spilker 1996b). In World War II, the allied militaries divided the radio frequency spectrum into **bands** that were assigned arbitrary code letters (Parkinson 1996a). SVs transmit in the L band; the frequencies are designated L1 through L5. Table 1 tabulates the frequencies and gives a broad notion of what the band is intended to be used for. An unmodulated GPS transmission is a nearly-constant-frequency wave, called a **carrier**. The carriers are generated by circuitry that is driven by the atomic clocks onboard the SVs (Spilker 1996b). The atomic clocks are very stable, but not perfectly so. Therefore, the carrier waves have nearly-constant wavelengths, whose variability is far below detectable levels (Spilker 1996c, Zumberge and Bertiger 1996).

GPS receivers determine a signal's transit time using timing codes broadcast on the different L bands by the SVs. A **timing code** can be thought of as a sequence of bits that repeat on a regular basis. GPS positioning is based on two timing codes, the **coarse/acquisition code** (C/A-code) and the **precise code** (P-code). Each SV is assigned one particular, distinct C/A code, so upon receiving the entire code, a receiver is able to determine which SV transmitted it. The codes are said to be **pseudo-random noise** (PRN) because, apart from serving as a unique identifier, they contain *no* information. However, the codes are built into the satellites' and receivers' circuitry, so they are not random from that perspective. Since the timing codes contain no information, they are said to be composed of **chips**, not bits. The C/A-code has 1023 chips, and the entire code takes one millisecond to transmit. The P-code's chips are 1/10 as long as those of the C/A-code, which allows a finer measurement of the signal's transit time. Thus, P-code positions are more precise than those determined from the relatively coarse C/A-code (Spilker 1996b).

The C/A-code is broadcast only on L1 whereas the P-code and the navigation message are broadcast on L1 and L2 (Spilker 1996b). Receivers that have additional circuitry to receive both L1 and L2 are called **dual frequency receivers**, and are generally more precise than single frequency receivers because of the redundancy in calculating transit times using both frequencies. Receivers that receive only one frequency are called **single frequency** receivers. All single frequency receivers receive L1 because the C/A code is only available on L1 (Van Dierendonck 1996).

Pseudo-ranges

Ranges are determined from a signal's transit time, so it is imperative that all the clocks in a GNSS be synchronized. However, the SVs' clocks are not synchronized with each other, or with GPS time kept by the MCS. Moreover, a receiver's clock is not synchronized with any other clock. These two problems are solved entirely differently; the former by the control segment, and the latter by the receivers themselves (Spilker 1996e).

The St. Louis monitor station monitors the discrepancy between the SVs' clocks and GPS time (Francisco 1996). This discrepancy is called the **satellite clock time bias** (Zumberge and Bertiger 1996). A clock correction for each SV is computed and included as part of that SV's navigation message (Francisco 1996). The SVs' clocks do not have a constant bias; they drift. This makes it necessary for the time bias correction to be a function of time. Therefore, the SV clock correction consists of the parameters of an equation used to compute a particular SV's clock's correction at a desired observation epoch. Although the SV clocks are allowed to drift, knowing their error effectively synchronizes them to GPS time while neatly avoiding the difficult problem of actually synchronizing them (Spilker 1996c, Zumberge and Bertiger 1996).

Receiver clocks need to be synchronized to GPS time as do the SVs' clocks but the same method used for monitoring the SVs' time biases will not work for receivers. It is technically possible to build receivers with their own atomic clocks – the clocks in the monitor stations are so equipped. However, atomic clocks are very expensive and would make GNSS positioning impractically expensive. Receiver clocks have quartz-crystal oscillators, which are relatively inexpensive but are less stable and less accurate than atomic clocks. Therefore, there is an unknown receiver time bias that is computed, epoch by epoch, during the positioning computations. The receiver's time bias corrupts the transit time measurements, so a transit time measured directly from a receiver's clock is called a **pseudo-range** (Spilker 1996a).

Timing with codes

The observed transit time is computed by subtracting the reading of the SV's clock at the moment of transmission from the reading of the receiver's clock at the moment of reception (Parkinson 1996a, Spilker 1996a). Receivers are designed to observe at the boundaries between chips, e.g. at integer millisecond intervals for the C/A-code. Therefore, the SV-clock's reading is deduced by knowing which chip in the code's sequence is being observed and knowing the time of day when that code began (Spilker 1996a). The former is performed by a receiver's circuitry; the latter comes simply from the receiver's clock (Parkinson 1996a, Spilker 1996a).

The receiver's clock needs to be read with finer precision than the duration of an entire chip; not doing so would limit pseudo-range precisions to 300 m and 30 m for the C/A- and P-codes, respectively. Internal circuitry in the receivers creates replicates of all the codes, which begin on millisecond intervals according to the receiver's clock. The time that a chip arrives at a receiver from an SV equals the time it left the SV plus its transit time multiplied by the speed of light. The transit time multiplied by the speed of light will generally not be an integer multiple of a millisecond, so codes received from a SVs are time shifted from those generated by a receiver. Circuitry in the receiver, called a **code correlator**, conceptually shifts the receiver-generated code to match the received code, thus measuring their offset, up to a millisecond, with resolution approaching 1/20 of a chip (15 m for the C/A-code). This process is called measuring **code phase**. Code phase plus the observation epoch's time of day equals a pseudo-range (Spilker 1996b).

Carrier phase

GPS signals are modulated with the timing codes and the navigation message. Unmodulating the signal returns it to a sinusoidal carrier wave. The carrier wave will generally not travel an integer multiple of wave lengths for the same reason that a code will not travel an integer multiple of chips. The additional part of the carrier wave beyond the integer multiple is called the **carrier phase**. Carrier phase can be measured on the order of 1/100, for a spatial resolution on the order of millimeters. Carrier-phase capable receivers can, therefore, potentially be used for millimeter accuracy positioning (Spilker 1996b).

The positioning equation

There are, thus, four unknowns in determining a position: three spatial and one temporal. The spatial unknowns are the receiver's coordinates, denoted x_r,y_r, and z_r. These coordinates refer to a Cartesian coordinate system that is said to be **Earth-Centered, Earth-Fixed** (ECEF); whose *z*-axis is nearly parallel to the Earth's mean axis of rotation, whose *x*-axis is in both the equatorial and Prime Meridional planes, and whose *y*-axis is also in the equatorial plane (Spilker 1996c), forming a right-handed system (McCarthy and Petit 2003). The subscripted *r* indicates that these are a receiver's coordinates; SV coordinates will have a superscript. The receiver-clock's time bias is the temporal unknown, to be denoted by dt_r; a SV-clock's time bias is denoted by dt^s. A time bias can be either positive or negative.

The fundamental positioning equation relates the range *r* between an SV and a receiver to a signal's transit time (Spilker 1996a, Van Sickle 2008) :

$$r = c\,\Delta t, \tag{1}$$

where *c* is the speed of light in m/sec and Δt is transit time in seconds. The range is a straight line distance (Figure 1.6), so it can be determined using Pythagoras' formula for right triangles:

$$r = \sqrt{\left(x^s - x_r\right)^2 + \left(y^s - y_r\right)^2 + \left(z^s - z_r\right)^2}\,. \tag{2}$$

Substituting (1) in to (2) gives

$$c\,\Delta t = \sqrt{\left(x^s - x_r\right)^2 + \left(y^s - y_r\right)^2 + \left(z^s - z_r\right)^2}\,. \tag{3}$$

Δt is unobservable; it is inferred by reading the SV's and receiver's clocks. These readings differ from GPS time by their respective time biases. So,

$$\Delta t = (t_r + dt_r) - (t^s + dt^s)\,, \qquad (4)$$

where t_r and t^s denote the SV- and receiver-clock's readings at the reception and transmission times, respectively. The SV-clocks' time biases are accounted for using clock correction equation described above, and, therefore, play no further role; dt_r needs to be determined. Taking dt^s to be zero and substituting (4) into (3) gives

$$c\,(t_r - t^s + dt_r) = \sqrt{(x^s - x_r)^2 + (y^s - y_r)^2 + (z^s - z_r)^2}\,. \qquad (5)$$

The unknowns in (5) are dt_r, x_r,y_r, *and* z_r because t_r is read off the receiver's clock, The SV's coordinates come from Kepler's laws via the Keplerian elements in the navigation message (Spilker 1996a, Spilker 1996c, Zumberge and Bertiger 1996). Equation (5) has four unknowns, so it is necessary to acquire at least four SVs to have as many equations as unknowns (Spilker 1996a). Acquiring more SVs is better still because the additional SVs provide redundancy, which improves positioning accuracy by a least-squares solution of (5) (Axelrad and Brown 1996).

GNSS RECEIVER CATEGORIES

GNSS receivers are categorized according to different requirements of use, expertise, budget, and accuracy. These categories are commonly known as survey-, mapping-, and navigation-grade (Serr et al. 2006, Wing et al. 2005, Wing and Karsky 2006). Receiver categories often reflect differences in the quantity and quality of circuitry. Survey-grade receivers always have circuitry to observe carrier phase (Van Dierendonck 1996), which sets them apart from mapping receivers that might not, and from navigation-grade, which do not. The accuracy possible from phase observables enables survey-grade receivers to be used on engineering projects (such as the construction of roads, bridges, and buildings) and to set geodetic control (Aparicio et al. 1996, Van Dierendonck 1996). Wildlife-tracking receivers fall into the navigation class; they need to be as lightweight and power sparing as possible (Rodgers et al. 1996), so they have minimal circuitry, and are single-frequency, code-only.

In addition to differences in circuitry, there are also differences in antenna hardware design (Van Dierendonck 1996). It is undesirable for a signal to reflect off an object in the environment and be reflected along an indirect path to the receiver. This situation is called **multipath** (Figure 1.7) (Braasch 1996, Parkinson 1996b, Spilker 1996a, Seeber 2003). Multipath from reflective objects below an antenna can be reduced or eliminated by a **ground-plane**: a dielectric plate on the bottom of the antenna that blocks signals coming from below (Braasch 1996). Ground planes add weight and cost, and they can even be deleterious to animal tracking: if an animal is situated so that the ground plane is not between the antenna and the ground, then the ground plane will block non-multipath signals. Therefore, wildlife tracking collars do not, and should not, have ground planes.

GNSS AND WILDLIFE MANAGEMENT

GNSS receivers that are mounted on animal collars are known as **GPS collars**. GPS collars record animal positions according to a programmed schedule. The receiver and antenna are on top of the collar; a heavier battery pack mounted to the bottom of the collar hangs under the neck of the animal. The battery acts as a counter-weight to keep the antenna on top of the animal's neck, just behind the head, with line-of-sight of the SVs. Positions are stored in the receiver until retrieval. Retrieval requires recapturing the animal, using a remote-collar-release mechanism, or a two-way communication link (Rodgers et al. 1996).

A researcher can program a GPS-collar with a position acquisition schedule, i.e. how frequently the receiver will attempt to acquire a position. A schedule of twice-per-day (once during the day and once during the night), or one position every few hours, is most common. Also included in programming is the duration of time for which a GPS collar will search for enough SVs to acquire a position before shutting down until the next scheduled attempt.

This search duration is generally scheduled at 90 to 180 seconds (Cain et al. 2005, Mills et al. 2006, Rodgers et al 1996).

A GPS collar costs thousands of dollars. It is typically necessary to deploy many collars at once in a research project to achieve a statistically viable sample size. Collars often cannot be redeployed between sexes or age groups in a species, or on different species, due to neck size differences. Redeployment requires expensive refurbishing and battery replacement from the manufacturer. Capture and recapture fees to collar, un-collar, and re-collar a sample of animals during a study can be as expensive as the equipment itself (Johnson et al. 2002; Hebblewhite et al. 2007).

GPS-determined positions are frequently viewed superimposed over remotely-sensed digital imagery, such as topographic maps or photographs in a **geographic information system** (GIS). A GIS is a combination of hardware and software used to view, store, analyze, and present location information (Longley et al. 2005). ArcGIS, (Environmental Systems Research Institute [ESRI]), is the GIS used most frequently in wildlife management. Home ranges can be visualized by drawing a polygon that encloses the GPS-determined positions. Positions are entered into a GIS database with their geographic coordinates. The enclosing polygon that represents the home range is the convex hull of the positions, which is computed by the GIS (O'Rourke 2001). The area of the polygon, if it has been rasterized, is calculated by adding up the number of pixels contained within the polygon and multiplying by their resolution (Amstrup 2007), or if left in vector form, using $A = 1/2 \sum_i x_i y_{i+1} - y_i x_{i+1}$, where *i* is an index over the polygon's vertexes, and *x* and *y* are the vertexes' coordinates (Weisstein).

PROBLEMS TRACKING WILDLIFE WITH GNSS

Decisions regarding natural resources management, land use, and environmental policy are increasingly based on research using GPS data (Hulbert and French 2001). Environmental assessments and impact statements often require baseline information about what species live in the area of interest. If location data are incorrect, the decisions made from them can have catastrophic consequences for the viability of a species or an enormous economic impact if rehabilitation, remediation, relocation, or reintroduction efforts become necessary (Gu et al. 2004, Visscher 2006, Witmer 2005).

The three main types of errors in GPS-collar technology have been identified as (i) positioning errors (the distance between the GPS-determined position of an animal and the true position of the animal), (ii) collar malfunctions, and (iii) fix-rate bias (missing data from scheduled but unrecorded positions) (D' Eon 2003; Graves and Waller 2006).

These errors can have common sources and are not always easily identified. Position error can be assessed only if the collar determined a position at a place with known control coordinates; this does not happen during most field experiments. It can also be difficult to separate fix-rate bias due to a malfunctioning collar and fix-rate bias caused by environmental variables or poor satellite geometry. Sometimes a collar malfunctions before deployment; sometimes it works for a while and then stops altogether; sometimes it works sporadically: it can be hard to determine if this is a mechanical or electrical malfunction or some other factor that prevented the receiver from recording a position (Graves and Waller 2006).

The GPS error budget

The GPS **error budget** consists of factors that increase positioning error. These factors should be avoided, if possible, when planning to use GPS (Parkinson 1996b). Factors that have already been discussed include:

- orbital inconsistencies (see section titled GNSS POSITIONING) (Braasch 1996, Spilker 1996d),
- SV and receiver clock errors (see section titled GNSS POSITIONING) (Zumberge and Bertiger 1996),

- and multipath (see section titled GNSS RECEIVER CATEGORIES) (Braasch 1996, Spilker 1996a).

The error budget also includes:

- signal noise – interference from power lines and other electromagnetic signals (Spilker 1996b),
- the ionosphere (Klobuchar 1996) and the troposphere (Spilker 1996f) - interference from atmospheric particles such as water, solar winds, and sun spot activity,
- SV elevation with respect to the receiver - signals traveling to the receiver from the horizon must travel further and pass through more atmosphere than a signal coming from overhead (Spilker 1996a), and
- selective availability (SA) - a deliberate timing error introduced into the GPS transmissions that degrades positional accuracy to 100 m 95% of the time. SA was intended to deny high-accuracy real-time positioning to non-US military users. SA was disabled in 2000 by executive order from President Clinton (Rodgers et al. 1996, Graves and Waller 2006, van Graas and Braash 1996).

Position accuracy metrics

If only three satellites have been acquired, the receiver can *assume* a value for one of the four unknowns in order to provide a position in this circumstance. The height of the receiver is always the assumed coordinate, so such a position is 2-dimensional (2-D). Four or more SVs result in 3-dimensional (3-D) positions (Parkinson 1996a, Spilker 1996d). Epoch-by-epoch dimensionality is reported by some receivers; others report the number of SVs. Dimensionality, or the number of SVs, is a measure of position accuracy (Cargnelutti et al. 2007, Graves and Waller 2006, Parkinson 1996a, Spilker 1996d, Van Sickle 2008).

The most accurate positions come when the SVs are spread out across the sky: the best geometry is one SV directly overhead and three or more near opposing horizons. This geometry yields an optimal strength of figure (Dussalt et al. 2001, Parkinson 1996a, Spilker 1996d, Wing et al. 2005). The constellation's geometry is quantified by **position dilution of precision** (PDOP). PDOP is correlated with dimensionality: 2-D positions lack the SVs needed for good strength of figure. PDOP is a positive real number; accuracy decreasing with increasing PDOP. PDOP values less than six are thought to indicate the best positions (Dussalt et al. 2001, D'eon and Delparte 2005, Cargnelutti et al. 2007, Parkinson 1996a, Spilker 1996d, Van Sickle 2008). Receivers report PDOP for each observation.

GIS and remotely sensed images

SA-induced position errors in wildlife studies prior to 2000 were not as concerning because the position errors were comparable to the resolutions of most remotely-sensed images (Rempel et al. 1995, Hebblewhite et al. 2007, Hulbert and French 2001, Lillesand et al. 2007). Positional uncertainty was < 31 meters 95% of the time, so the positions were at least as accurate as the images they were being mapped with (D'eon et al. 2002, Hebblewhite et al. 2007, Rempel et al. 1995).

LANDSAT images are frequently used in GIS for wildlife studies because they are freely available and their resolution is fine enough to capture many terrestrial vertebrate movements. LANDSAT has a 30-meter pixel resolution for multispectral images and a panchromatic resolution of 15 meters (Jensen 2000, Lillesand et al. 2007). The ten-meter average error proclaimed by GPS collar manufacturers is smaller than the resolution of modern LANDSAT images, so merging GPS-collar positions and LANDSAT images is technically sound (Flemming et al. 2004). Higher resolution imagery is available, such as CBERS (20 meters) and ASTER (15 meters); ALOS, CARTOSAT, FORMOSAT, and SPOT have better than five meter resolution (Chen et al 2002); GeoEye, IKONOS, QuickBird, and

WorldView, have sub-meter resolution (Lillesand et al. 2007; Lasaponara and Masini 2006; Serr et al. 2006).

Position error becomes more problematic as imagery resolution improves, especially in habitat selection studies of cryptic or specialized species (Hebblewhite et al. 2007). In the best circumstances, position error is sub-meter; however, it can exceed the size of the pixels being used to deduce other information, possibly leading to erroneous conclusions (e.g., the misclassification of habitat as unnecessary to a species). The repeated failure of the GPS collar to acquire a position can lead to similar erroneous conclusions (Villepique et al. 2008).

GPS-collar performance in wildlife studies

There have been wildlife studies that have mentioned GPS collar errors. D'Eon et al. (2002) and Friar et al. (2004) noted that physical obstructions, such as buildings and topography, caused position errors; others mentioned vegetation (Rempel et al. 1995; Blake et al. 2001; D'Eon et al. 2002, Dussault et al. 1999, Hebblewhite et al. 2007, Sager-Fradkin et al. 2007). Errors caused by vegetation include signal blockages and/or multipath from woody obstructions in stems and trunks, and signal interferences from water contained in the chlorophyll of leaves (Spilker 1996g). Other causes of errors include low batteries (Gau et al. 2004), data collection schedules (Rodgers et al. 1996; Cain et al. 2005) animal behavior (Coelho et al. 2007; D'Eon and Delparte 2005; D'Eon and Serrouya 2005; Hebblewhite et al. 2007), and type of GPS collar (Hebblewhite et al. 2007, Hulbert and French 2001).

Arguably, the most problematic issues with GPS collar positions are the things that cause positions to not be collected (called **fix-rate bias)** (D'Eon 2003; Graves and Waller 2006; Hebblewhite et al. 2007). Cain et al. (2005) conducted a review of GPS/wildlife literature published from 1995 to 2004, concluding that all researchers reported problems with GPS malfunctions and fix-rate bias leading to misclassified habitat from undersampling.

They advise that positional error and fix-rate bias can inflate type II error (false negatives) in habitat selection studies.

Many wildlife studies have published reports indicating low equipment reliability. In the Central Canadian Rockies ecosystem, Hebblewhite et al. (2007) experienced LOTEK 3300sw GPS collar failure rates of 41% on wolves (*Canus lupus*), and 38% on elk (*Cervus elaphus*). In western and northern Canada, Gau et al. (2004) deployed 71 Televilt GPS-Simplex collars on grizzly bears (*Ursus arctos*) over a period of two years. Of these collars, 38 performed as expected, 20 failed at least partially, and 13 were not retrieved. Ten additional collars failed completely before they were deployed. They state that collar failures "caused a significant unexpected increase in research costs and time to troubleshoot problems and significantly reduced the volume of location data we were able to collect." They also note that collar performance and collar reliability decreased with passing time. They recommend that researchers add extra considerations to their budgets for collar failures and recapture of animals.

Animal behavior may also account for some unexplained fix-rate bias (Graves and Waller 2006). The potential for fix-rate bias is greater for species that are reclusive, nocturnal, or live in remote areas than for species with behaviors and habitat preferences that facilitate clear SV signal reception (Moen et al. 1996; Moen et al. 2001; Di Orio et al. 2003; Friar et al. 2004; Jerde and Visscher 2005). Coelho et al. (2007) attribute a temporal fix-rate bias (collecting more positions during the night and fewer during the day) to the nocturnal hunting behavior of maned wolves (*Chrysocyon brachyurus*). During the day these animals sleep under cover; cover blocks SV signals and results in fewer positions. During the night, they hunt in open areas. Similarly D'Eon and Delparte (2005) found that a GPS collar's antenna, turned away from the sky or blocked from the sky by an animal's body, contributed to fix-rate bias in bears. Graves and Waller (2006) found that fix-rates decreased as the sizes and girths of bears increased.

Data screening

It is desirable to screen out erroneous positions. Villepique, et al. (2008) found that 27% of their GPS-collar positions were 2-D. They retained these lower-accuracy positions, nonetheless, because excluding them could cause errors of omission: 2-D positions are reasonably expected to be correlated with steep or high-cover habitats, often preferred by wildlife. Lewis et al. (2007) screened black bear (*Ursus americanus*) positions in Idaho with PDOP and dimension. They found that screening out positions with high values of PDOP resulted in retention of outliers; screening out 2-D values resulted in removal of outliers but with high data loss. A combination of DOP < 6 at all dimensions resulted in the best compromise.

Position acquisition schedules

In a review of 15 peer-reviewed journals between 1995 and 2004, Cain et al. (2005) determined that shorter intervals between scheduled position acquisitions increased the likelihood of acquisition. They attributed this to the need for a receiver to acquire updated navigation messages and locate the constantly moving SVs: out-of-date almanacs can cause a receiver to waste time trying to acquire SVs that are not above the horizon. A receiver might fail to find enough SVs for a position during the user-programmed acquisition interval and power down to conserve battery power. However, less frequent positioning is often scheduled due to the limitations of battery capacities; Cain et al. (2005) reported a trade-off between the number of positions a receiver can record and battery life. Biologists often require at least one continuous year (four seasons) of position data to make useful generalizations about animal movements and resource selection patterns. Obtaining a full year, or more, of positions often requires reducing the amount of scheduled positions to extend battery life, or recapturing the study animals and recollaring them with a receiver containing a fully-charged battery (Cain et al. 2005, Gau et al. 2004).

THESIS OBJECTIVES

This research created a methodology for GPS-collar accuracy assessment; and a collar-specific, PDOP-based model for position screening in Connecticut forested habitats. This research tested the accuracy of GPS collars manufactured by four different companies. GPS-collar positions were compared with geodetic quality control. The study areas were in Torres del Paine National Park in Patagonian Chile and in Connecticut deciduous forests. Torres del Paine is in the Andes Mountains, and their topography varies from open steppe to near-vertical granite cliffs. In Connecticut, the vegetation is characterized by an oak-hickory, broadleaf canopy.

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TABLES

Table 1.1. The frequencies and intended uses of each GPS band.

Band	L1	L2	L3	L4	L5
Frequency	1575.42 MHz	1227.60 MHz	1381.05 MHz	1841.40 MHz	1176.45 MHz
Intended Use	Civil	Military	Nuclear Burst Detection	Ionosphere Correction	Civil

FIGURES

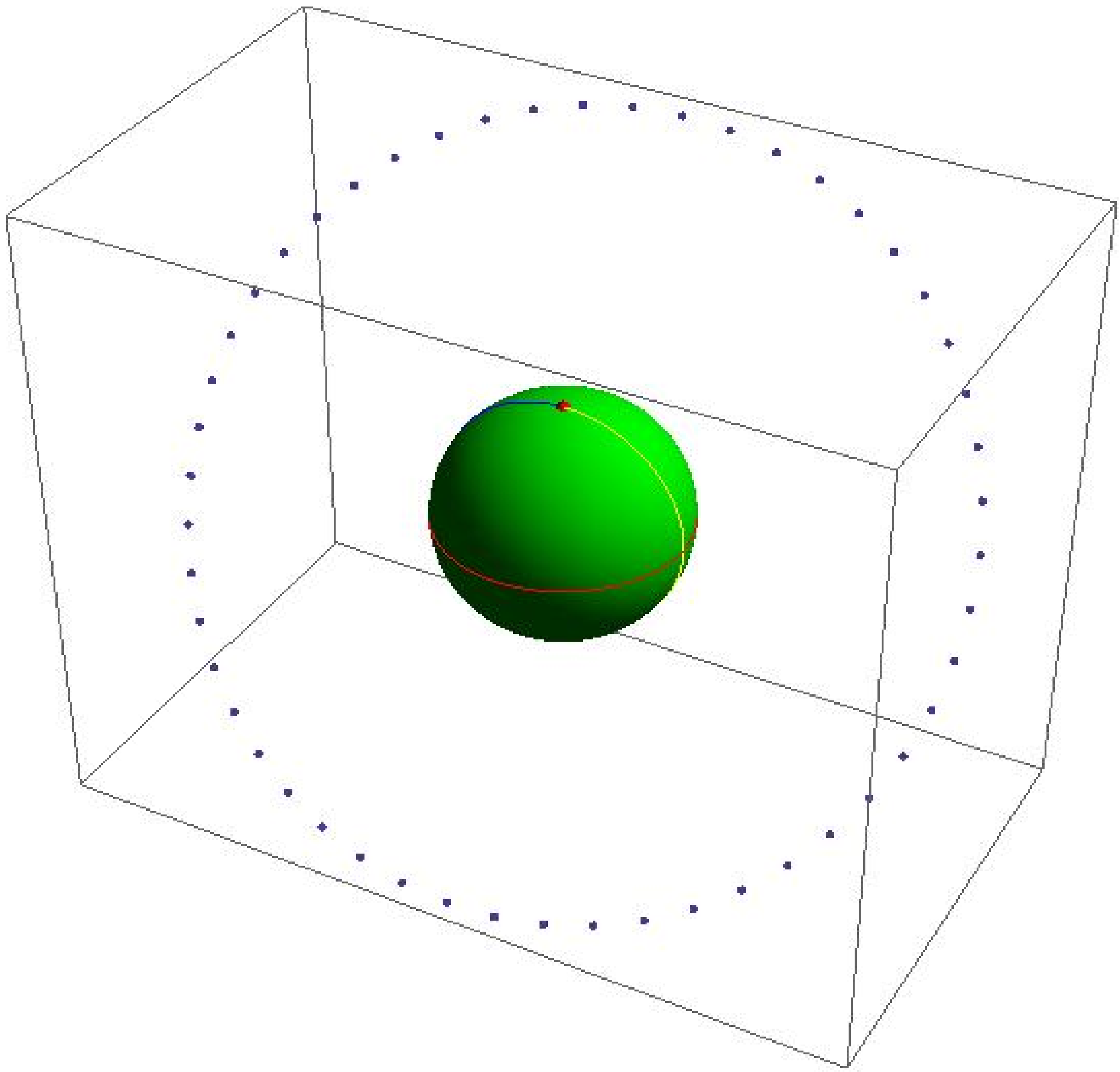

Figure 1.1. An orbital plane of one SV around the earth. Dots denote various locations of the SV at different points in time.

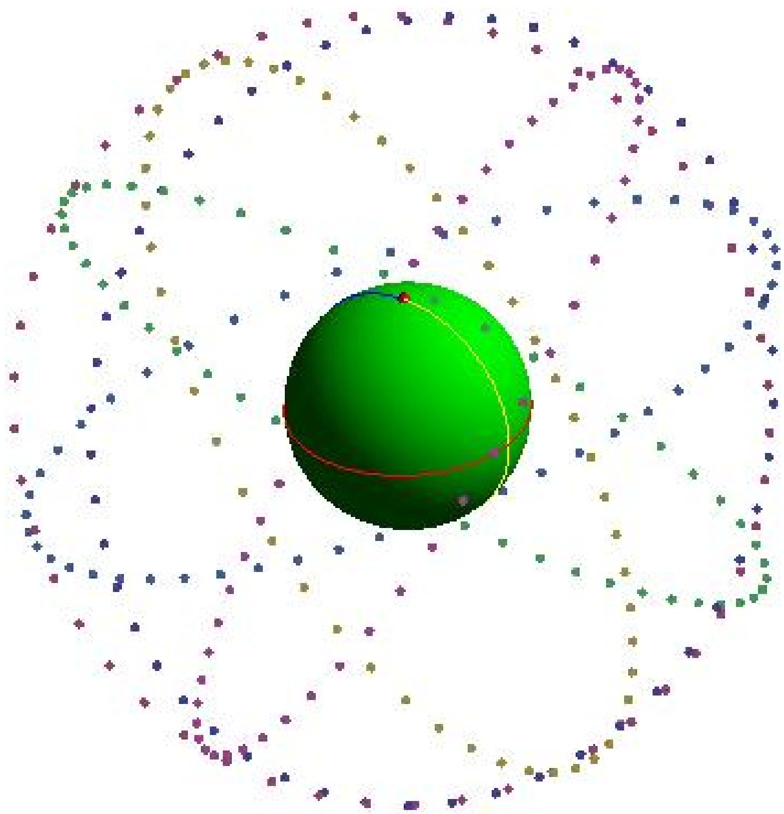

Figure 1.2. The "bird cage" showing six orbital planes used by SV in GPS.

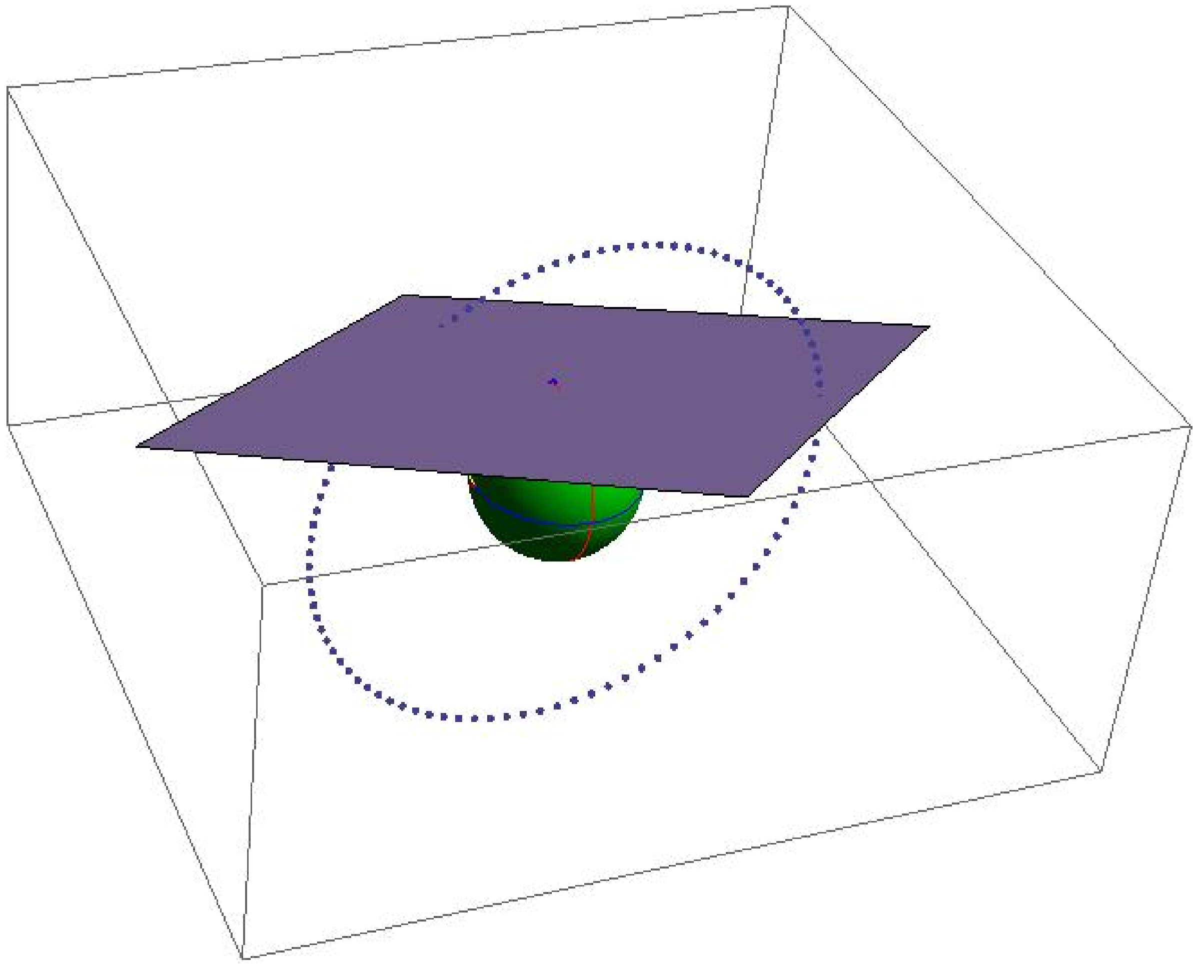

Figure 1.3. From a point on the surface of the Earth, just under half of the orbit of one SV is visible, because the Earth blocks the visibility of the remaining orbit.

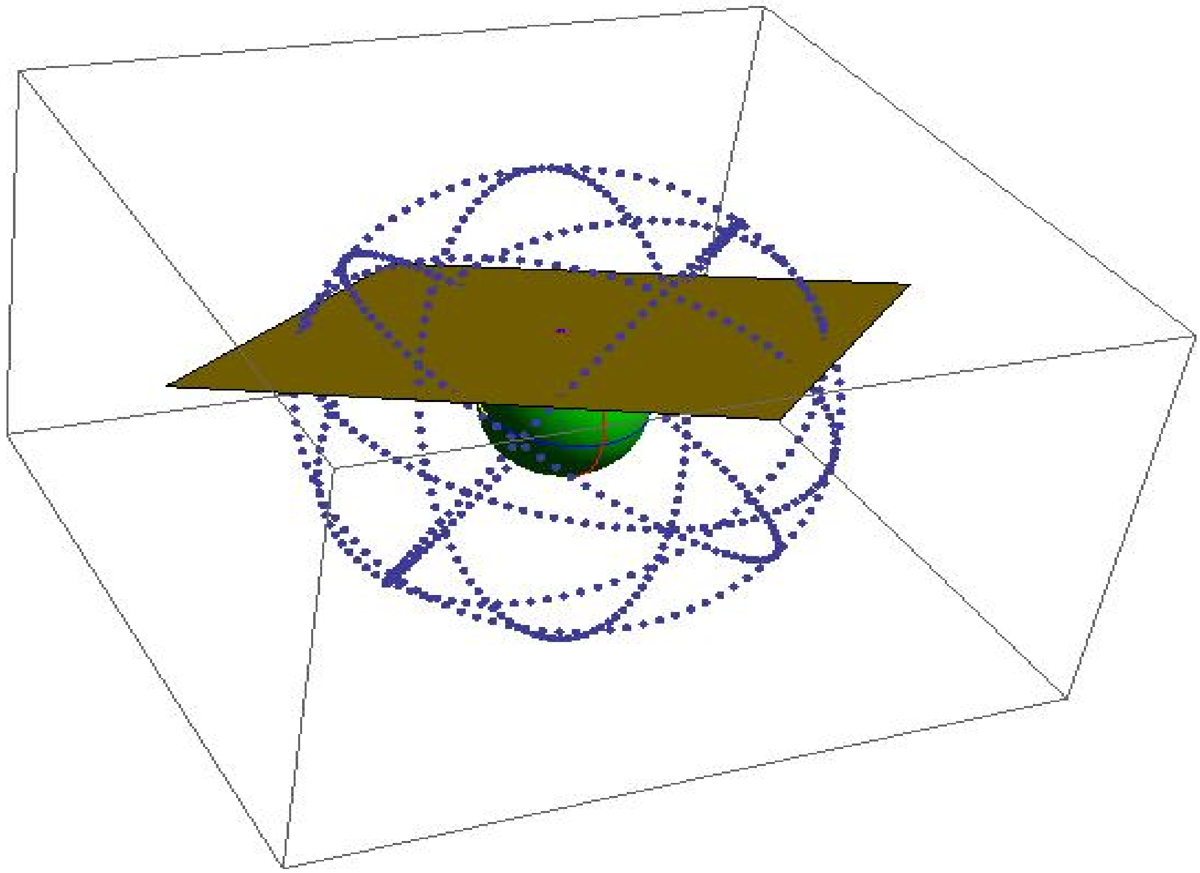

Figure 1.4. From a point on the surface of the Earth, just under half of the orbits of the constellation are visible, because the Earth blocks the visibility of the remaining orbits.

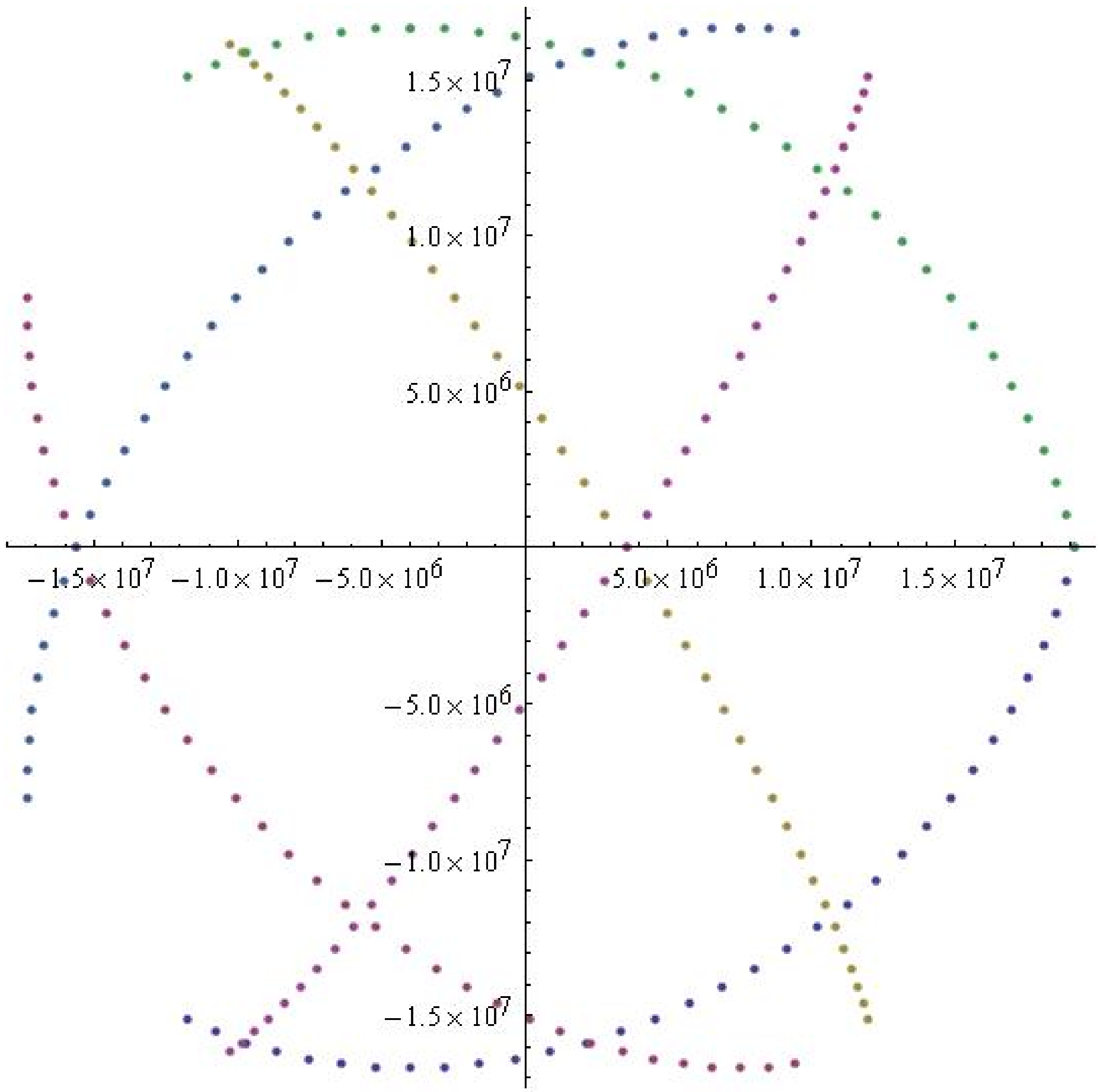

Figure 1.5. The tracks of the SVs across the sky as seen from the ground and if the Earth were not rotating.

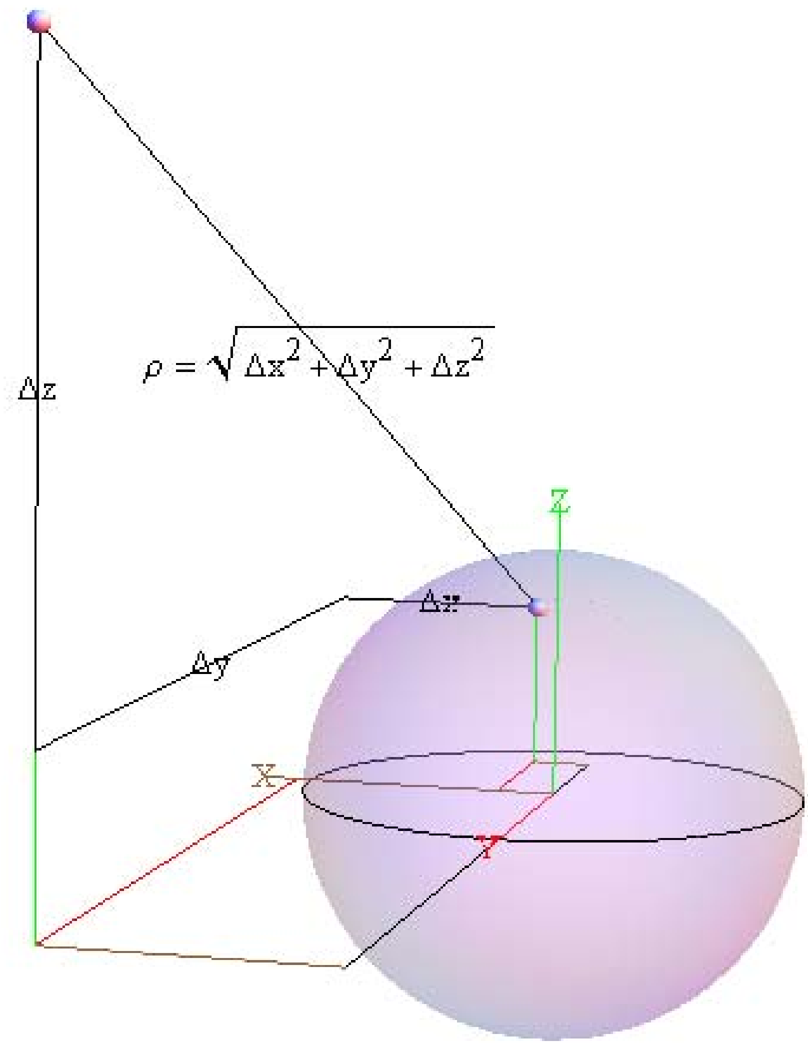

Figure 1.6. Pythagoras' formula is used to calculate the straight line distance an electromagnetic signal travels from an SV to a point on the surface of the Earth.

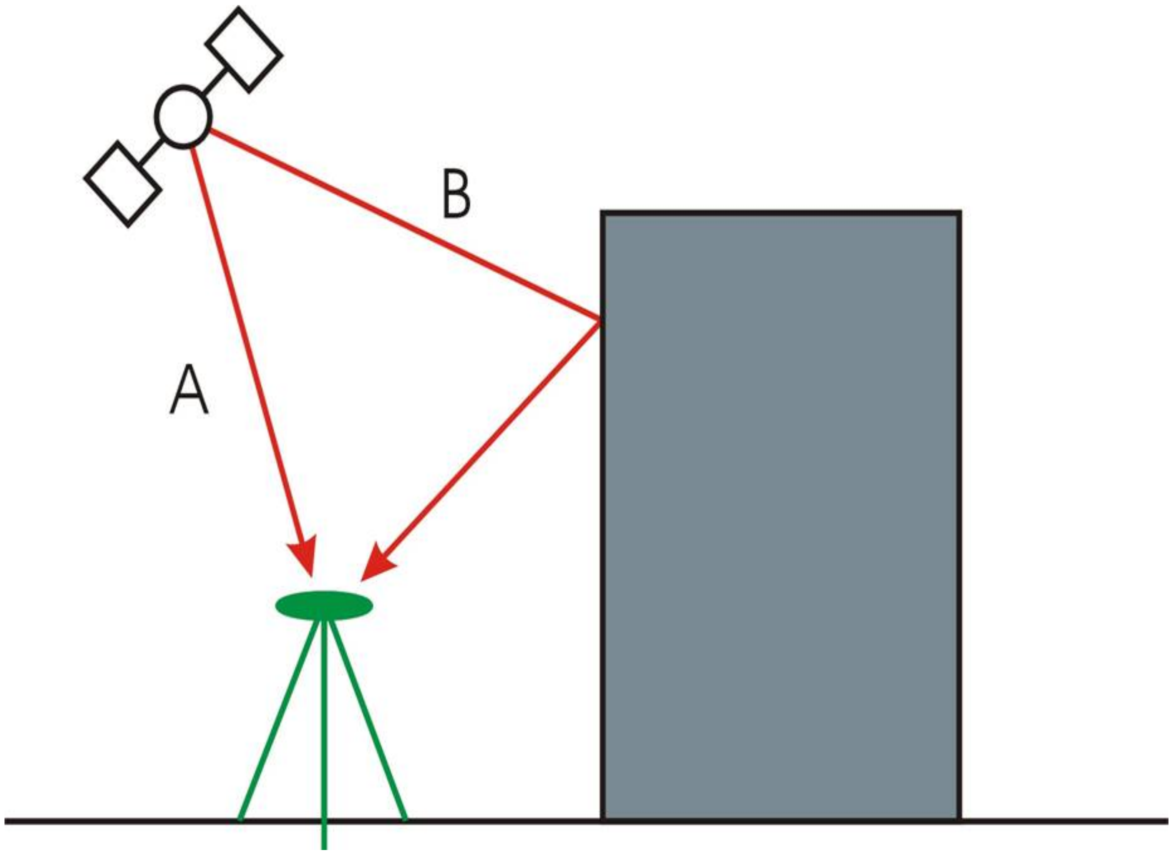

Figure 1.7. Multipath: signal A is an unobstructed signal traveling from an SV to a receiver; signal B has reflected off a nearby object and then reaches the receiver.

Chapter 2
MODELING POSITIONAL ACCURACY OF TELEVILT GPS COLLARS IN CONNECTICUT DECIDUOUS FORESTS

ABSTRACT

Our research shows that Global Positioning System (GPS) wildlife tracking collars have position errors that can be predicted using position dilution of precision (PDOP), which makes PDOP an effective tool for providing positions-by-position error estimates. This is crucial in the correct interpretation of GPS collar data. Manufacturers of GPS collars used in terrestrial vertebrate research claim an average position accuracy of ten-to-fifteen meters under ideal conditions. Factors such as percent and type of canopy obstruction, antenna angle, the number of satellites available, and the geometric arrangement of satellites can decrease GPS positioning accuracy or cause a receiver to fail to acquire a position. GPS collars have been tested for accuracy, but there are no published records of accuracy tests in New England. We conducted stationary tests of *Televilt* Simplex Budget collars in the unique oak- (*Quercus spp.*) and hickory- (*Carya spp.*) dominated forests of Connecticut, and we compared collar positions with TOPCON high-accuracy receiver positions for position accuracy. We measured sky obstruction from canopy, and we manually manipulated GPS collar antenna angles. We also considered two internal measures of positioning accuracy: Position Dilution of Precision (PDOP), and whether a position was 2-dimensional or 3-dimensional. Of greatest concern in our results was the amount of positions that were scheduled but not recorded by the collars, and the range (in meters) between minimum and maximum positional errors recorded. We used *SAS Trend Analysis* to model positional error by canopy obstruction, antenna angle and with PDOP, and we offer suggestions for data collection, screening, and display in Connecticut deciduous forests. This study is easily replicable with other GPS collars in other study areas.

INTRODUCTION

Positions acquired by Global Positioning System (GPS) tracking collars used in terrestrial vertebrate wildlife research are generally claimed accurate to approximately 15 m under good conditions (Hebblewhite et al. 2007). The accuracy of these positions is important because they are used in wildlife management decisions and in land use policies (Amstrup 2007, Gu and Swihart 2004, Hulbert and French 2001, Messmer 2000, Witmer 2005). Positional accuracy is often dependant on the type of habitat a species uses; some habitats are known to decrease positional accuracy (Blake et al. 2001, D'Eon et al. 2002, Dussault et al. 1999, Friar et al. 2004, Hebblewhite et al. 2007, Rempel et al. 1997, Sager-Fradkin et al. 2007); leading researchers to conclude that GPS collars should be tested in different habitats before they are deployed on wildlife (Hebblewhite 2007). Screening inaccurate positions out of a data set is not common unless those positions are extremely egregious outliers (Lewis et al. 2007, Villepique et al. 2008). It is important to retain as many positions as possible because eliminating positions could result in misclassifying a habitat as unimportant to a species (Hebblewhite et al. 2007). Just as some GPS collars are more accurate than others (Hebblewhite et al. 2007, Villepique et al. 2008); some GPS collar positions are more accurate than others. Display and reporting of position data currently does not indicate a position's reliability in terms of its accuracy.

Positions are frequently displayed superimposed over remotely sensed images in Geographic Information Systems (GIS) (Flemming et al. 2004, Jensen 2000, Lillesand et al. 2007). Classified images, such as the National Land Cover Dataset (NLCD) (Vogelmann et al. 2001), are images that are parceled according to the different electromagnetic radiance properties generated by their different land uses and land covers. For example, a parcel of land that is paved will reflect light in a different band of the light spectrum than a parcel that is covered in forest. Fine levels of rendering are possible, allowing differentiation between types of vegetation, such as between a predominantly coniferous forest and a deciduous one. Classified images are used to discern the habitat types that are used by a species. Classification processes can require several steps: preprocessing, classification by supervised or unsupervised methods, and post-processing; each step propagating its own uncertainties. Images are typically classified at the landscape level, which often means that smaller patches and edges are absorbed into larger areas of dominant land-use/land-cover (LULC). (Flemming et al. 2004, Lillesand et al. 2007).

Error can be compounded when GPS Positions, with unknown accuracy levels, are superimposed over a GIS-classified image with its own uncertainties. This can result in flawed wildlife management decisions and land use policies.

Differencing and CORS

Error-free GPS phase observables can yield positions accurate at millimeter levels. Errors corrupt the observables and degrade the positional accuracy. Subtracting phases observed across various combinations of SVs and receivers removes or mitigates many types of errors in the SVs' signals; this is called **phase differencing**. There are three types of phase differencing: **single differencing**, **double differencing** and **triple differencing**. Double differencing yields the highest accuracy possible with GPS, however, phase differencing is not used in wildlife tracking. Phase differencing requires that at least two receivers in close proximity (less than 10 km is ideal) simultaneously collect phase observables (Goad 1996, Parkinson 1996c, Van Sickle 2008), and wildlife tracking collars do not (currently) observe phases nor are they always deployed more than one at-a-time (Samuel and Fuller 1996).

High-accuracy GPS positioning requires knowing the location of at least one receiver in the survey, called a **base receiver**. The base receiver's coordinates are surveyed with the best and most careful methods; its coordinates are accepted as being correct. All other positions are statistically adjusted to conform to the base receiver's position; the base position is said to **control** the survey. Land surveyors routinely use phase differencing by deploying one receiver in the field and using a permanent base receiver for control (Goad 1996, Parkinson 1996c, Van Sickle 2008). The National Oceanic and Atmospheric Administration's (NOAA) National Geodetic Survey (NGS) operates a network of base receivers called the Continuously Operating Reference Stations (CORS) (Snay and Soler 2008). CORS data are freely available from an NGS website (http://www.ngs.noaa.gov/CORS/).

Data from all the receivers collecting phase observables are gathered together into a **network** and statistically adjusted to produce the most probable values of the stations' coordinates. The adjustment occurs after the data are collected (as opposed to in the field), so this is called **post-processing** (Goad 1996, Parkinson 1996c, Van Sickle 2008). We used double-differenced, post-processed coordinates to control this study.

Establishing control and verifying accuracy with GPS collars

Position error can be assessed directly only if the GPS collar determined a position at a place with known control coordinates; this does not happen during most field experiments (Moen et al. 1997, Rempel et al. 1997, Villepique et al. 2008). In wildlife research, dual-frequency receivers are not typically available to determine control site coordinates, so the mean coordinates of a control site, if established at all, are determined from averaging many positions acquired by a stationary GPS collar at that site. Lacking true control site coordinates, stationary GPS collars tested at field locations measure positioning precision, rather than positioning accuracy (Villepique et al. 2008).

Villepique et al. (2008) deployed 32 Televilt POSREC-Science™ 600 series 12-channel GPS collars on ungulates in California mountain ranges. They noticed "numerous implausible movements" and confirmed the imprecision of the collars by documenting errors at field sites of >1000 m for 3-D positions, and >1,600 m for 2-D positions. It is notable that many of these implausible movements on animals were not detected until positions were viewed sequentially, instead of as a polygon in a GIS. Viewing positions in sequence showed “thousands of improbable out-and-back movements” in star-shaped patterns; these movements were improbable because they ranged over very long distances, in nearly impossible conditions, and were within only a few hours of each other. Televilt acknowledged that some of their POSREC GPS collars contained a receiver yielding a wider, but “not unacceptable,” range of positions.

Receiver precision often reflects differences in the quantity and quality of internal circuitry, and differences in hardware design. Villepique et al. (2008) conducted the same precision tests as above with six other types of GPS collars made by three different manufacturers; none evidenced the same lack of precision as the Televilt POSREC-Science™ 600 series GPS collars.

GPS-collar accuracy in CT broadleaf forests

The two most commonly cited and overlapping causes of GPS collar position error and fix-rate bias are topography and vegetation. Topography and vegetation vary by region; hence, positional accuracy can also be highly variable from region to region (Blake et al. 2001, D’Eon et al. 2002, Dussault et al. 1999, Friar et al. 2004, Hebblewhite et al. 2007, Rempel et al. 1995, Sager-Fradkin et al. 2007). Researchers recommend that GPS collars are tested in the region they will be used before deployment (Hebblewhite et al. 2007, Villepique et al. 2008). Although it is important to detect and report post-hoc errors acquired by GPS collars on animals, carefully planned studies designed specifically to test the precision and accuracy of GPS collars should form the baseline for comparison.

We modeled this study, in part, on research conducted by Meyer et al. (2002) who used a dual-frequency receiver and CORS positions to determine a two-millimeter increase of positioning error in survey-grade receivers for each percent of increasingly obstructed sky in the broadleaf forests of Connecticut. To our knowledge, this is the first GPS collar accuracy assessment conducted in Connecticut broadleaf forests.

OBJECTIVES

Our objects were the following:

- Determine the significance of percent of sky obstruction on GPS collar positioning accuracy and fix rate.
- Determine the significance of antenna angle on GPS collar positioning accuracy and fix rate.
- Determine the significance of PDOP on GPS collar positioning accuracy and fix-rate.
- Evaluate data screening options for GPS collar positioning accuracy.
- Develop and compare predictive equations for GPS collar positioning accuracy, based on percent of sky obstruction from canopy, antenna angle, PDOP, and dimension.

STUDY AREA

Site 1 was a pre-existing threaded metal rod, set into the cement of the southeast corner of the roof of the W. B. Young building on the University of Connecticut (UConn) campus in Storrs, Connecticut. Sites 2, 3, and 4 were located on a forested, private, twelve-acre property in North Franklin, Connecticut. Sites 2 - 4 were established by driving a two-meter, threaded metal rod into the earth until approximately 35-40 centimeters remained above ground, or until refusal.

Site 1 was in an open area devoid of canopy. Site 2 and Site 3 were characterized by mature intermediate to climax successional-stage deciduous trees: Red Oak (*Quercus Rubra*), Shagbark Hickory, (*Carya ovata*), Red Maple (*Acer rubrum*), American Hornbeam (*Carpinus caroliniana*), and Spicebush (*Lindera benzoin*). Site 4 was added in the second year of the study. It was characterized by similar canopy as in Sites 2 and 3, but it included a mature Eastern Hemlock (*Tsuga Canadensis*).

GENERAL METHODS

We performed control surveys at all sites (Control 1, 2, 3 and 4) with a *TOPCON Odyssey*, dual-frequency, dual constellation (GPS+GLONASS) receiver set atop an adjustable height tripod set at two-meters. Observations were downloaded using *TOPCON's PCC-DU* program, post-processed with *TOPCON's Pinnacle* software, and controlled using CORS coordinates. CORS observables were downloaded from at least three stations surrounding each study area. Site coordinates (Table 1) were calculated to within 4 cm. State Plane Coordinate System 1983, (Stem 1990) zone 0600, grid distances between control and collar coordinates were analyzed with *Mathematica* (Wolfram 1999) using ANOVA procedures and the add-on package *GeometricalGeodesy* (Meyer 2007, Pers. Comm.). These coordinates were hereafter assumed to be the true location of each site, and were used as control for GPS-collar position comparisons.

Televilt Simplex Series GPS collars were used at each location. The collars were used by Williams et al. (2008) in a study of white-tail deer, *Odocoileus virginianus,* and were expected to perform according to their manufacturer specifications. Positions recorded by *Televilt Simplex Series* GPS collars are claimed by their manufacturer to be accurate to +/- 15 meters, for 90% of 3-D fixes (Williams et al. 2008).

The canopy at each location was measured using photos obtained with a 35mm *Nikon* N-60 camera and a 180 degree field-of-view hemispherical lens on an adjustable height tripod leveled at one-meter above each control point. Photos were scanned to digital images and imported into the program *GAP Light Analyzer* (*GLA*). *GLA* registered the photos according to their Northernmost and Southernmost points and Latitude and Longitude to remove any hemispherical distortion. Threshold values were manually adjusted to increase contrast between sky and non-sky items; dark pixels were counted as obstructions and light pixels were counted as open sky (Figure 2.1). Percents of sky obstructed due to canopy were measured as: **Site 1** - 0% of sky obstructed, **Site 2** - 40% of sky obstructed, **Site 3** - 65% of sky obstructed, and **Site 4** - 85% of sky obstructed (Table 2).

A GPS collar stand was constructed using a 1.5 m PVC pipe and the threaded metal rods already in the ground at the control sites. The PVC pipe enabled simultaneous deployment of six GPS collars at each control site and manipulation of their antenna angles. GPS collars were along the length of the PVC pipe, 16 cm apart, and the pipe was threaded onto the metal rod and stabilized with locking nuts and washers.

GPS collars were programmed to record positions at their maximum allowable schedule -- twice an hour; at 15 and 45 minutes past each hour. Information recorded by the receivers included date, time, geographical position, the PDOP value, and dimensionality. Each GPS collar was programmed to search for at least three SVs for a maximum of 240 seconds before shutting off. If a GPS collar was unable to locate three SVs within 240 seconds it would not record a position at that scheduled time. We could have chosen a shorter search interval for the GPS collars, which is often done to conserve battery power, but we felt that maximizing the opportunity for a GPS collar to record a position was in the best interest of our study. All experimental manipulations (site changes and antenna position changes) were conducted in the early morning, between 6 and 7:30 am. GPS collars acquired positions for a minimum of 24 hours during each treatment (Tables 3 and 4) of sky obstruction and antenna angle.

We used *Mathematica* and *GeometricalGeodesy* to convert the position information from latitude and longitude (degrees:minutes:seconds) into UTM/CT State Plane coordinates, and calculated a total error distance in meters from the control point for each

GPS collar position. In the second year of the study, we used *SAS* for further statistical analysis and *Microsoft Excel* for validation of models developed in *SAS*.

2007 Data Collection Methods

We supplied six GPS Collars with power by constructing a battery supply unit to replicate the power normally supplied by the manufacturer's battery. This battery supply unit consisted of a 12 volt motorcycle battery and two quick disconnect cables that allowed us to switch a depleting battery to a fully charged one without interrupting the supply of power. The battery and other electrical components were encased in a waterproof plastic container. The top of the container was removable to allow access to the battery. We drilled a hole in the side wall of the container and six electrical leads were threaded out of the container and the hole was closed with silicone waterproofing sealant. These six leads were fitted with connectors that enabled secure connection with the GPS collars. The battery supply unit was designed to simultaneously supply six GPS collars with 3.6 volts of electricity each.

We collected positions at Site 1 with three out of six collars, and at Sites 2 and 3 with all six collars at each site. The reason three GPS collars at Site 1 did not acquire positions was because one of the two electronic leads from the battery supply unit (going to three collars) failed. The lead was replaced in subsequent tests.

The PVC pipe was directionally oriented with a hand-held compass, so that the pipe's length ran from magnetic North to South. This replicated placement of collars around the neck of an animal that was traveling in a North/South direction. We also varied the directional orientation of the pipe to test data collected in an East/West direction. We expected there would be differences in the accuracy of the recorded positions relative to the direction an "animal" was facing, but that they would be attributable to physical obstructions such as nearby tree trunks.

GPS collar antenna angles were changed every 24 hours by rotating the collar incrementally on the PVC pipe. The antenna angle treatments were measured with a protractor and included: 0° (straight-up/vertical), 45°, 90° (horizontal), 135°, 180° (straight-down), 225°, 270°, and 315° (Table 3). All treatments were conducted with the PVC pipe oriented in the North/South direction, and then repeated in the East/West orientation. This procedure was repeated at each control site.

We used *Mathematica* and *Microsoft Excel* to calculate descriptive statistics resulting from our treatments and the internal GPS collar metrics on mean positioning accuracy, these included: directional orientation of GPS collars(North/South vs. East/West oriented PVC pipe), percents of sky obstruction, antenna angles, PDOP values, and whether a position was 2 or 3 dimensional. We also calculated the fix-rate bias for each GPS collar, and as an overall percentage of positions scheduled but not acquired. Finally, we conducted a sensitivity analysis where all positions that were 2-dimensional or with a PDOP > 5 were removed from the analysis to determine if these position screening methods increased location accuracy without removing an large amount of positions from the dataset.

2008 Data Collection Methods

Positions recorded from complementary antenna angles, i.e. 90° and 270° resulted in similar positioning error for 2007 data so we repeated testing in 2008 with antennas angled only in the 0, 45, 90, and 135 degree positions (Table 4). We also did not manipulate the direction of the PVC pipe in 2008, also because mean positioning errors at different directional orientations of GPS collars were similar in 2007. After eliminating poorly performing and non-performing collars we selected one collar that had performed according to schedule and used a refurbished battery from the manufacturer for further position accuracy analysis. The experiment was repeated at **Sites 1-3,** and we added **Site 4** after determining its control coordinates and percent of sky obstruction (Tables 1. and 2.).

Fix-rate bias was calculated by dividing the number of positions scheduled by the number of positions actually recorded. We determined fix-rate bias for each site (% sky obstruction), each antenna angle, and as a overall percentage of positions scheduled. We calculated the positioning error distances of GPS collar positions, in meters, from control site coordinates with *Mathematica* and *GeometricalGeodesy*, and used *SAS* for statistical analysis; normality tests, descriptive statistics, and transformations of position errors in meters to the natural log (nlog) of those position errors in meters.

We used *Trend Analysis* in *SAS* to model the best predictive equation for positioning error. We analyzed PDOP separately from sky obstruction and antenna angle based on the premise that PDOP values are not independent from the view of the sky as seen through levels of sky obstruction and antenna angle. We used the *Mixed Procedure* to determine the significant polynomial orders, and interactions of polynomial orders, and used the *Reg Procedure* to obtain the coefficients of these parameters for the models. and the *RSREG Procedure* for lack-of-fit tests.

We verified the models by calculating how closely the predicted error actually explained the real positioning errors of the positions acquired. We used Microsoft Excel and put the resulting parameter values back into their respective equations, back-transformed the nlog into average positioning errors in meters, and compared the model output values with the actual positioning errors acquired by the GPS collars. This last step was accomplished by subtracting the predicted error values from the actual positioning error values for each position, yielding the model error estimates for each position acquired at each treatment level.

RESULTS

Positions recorded in 2007 indicated a high degree of fix-rate bias (Figure 2.2). Only 6,743 positions were acquired out of the scheduled 15,863, resulting in a 43% GPS collar success rate. Some GPS collars performed as expected, while others did not: Collar 4 failed to acquire any positions; collar 5 performed adequately at all sites except site 3, where it only acquired one position; and collar 6 collected <10% of the total scheduled positions across all sites (Figure 2.2). The resulting 2007 dataset was extremely unbalanced so we limited our analysis to computing how fix-rate bias increased as sky obstruction increased (Figure 2.3), mean positioning errors, and the effects of data screening with PDOP and dimension on positioning accuracy.

There were three positions that were extremely egregious and were removed from the analysis (Table 5). These three outliers were all collected on the same night, under 40% sky obstruction, and all had antenna angles oriented at 225 degrees from vertical. The outliers were each from a different collar; collar numbers 1, 3, and 5. It is notable that these three extreme outliers were the last three collected before the battery was changed, thus, the three outliers were likely caused by a failing battery.

Out of 6,740 positions remaining, 22 positions (0.3%) were between 500 and 2005 m in error, 80 positions (1.1%) were between 100 and 500 m in error, 1024 positions (15%) were between 30 and 100 m in error, and 1997 positions (29.6%) were between 15 and 30 m in error; this left 3617 positions (54%) with < 15 m in error (Table 6). It is noteworthy to mention that there were no GPS collar positions acquired that were closer than two meters away from the control coordinates as determined by the dual-frequency receiver, even under the best conditions: without canopy obstruction, with the antennas pointed straight up at the sky, with PDOP < 6, and 3-D.

Mean position error increased with increasing percents of sky obstruction from 10 meters at 0% canopy obstruction, to 19 meters at 40% canopy obstruction, and to 70 meters at 65% canopy obstruction (Table 9). Position error also increased as antenna angles were turned away from the sky, however, mean error ranged from 19 to 26 m, with similar standard deviations (15-25 m) at all but one antenna angle. The antenna angle at 0° from vertical (straight-up) had a mean error of 24 m with a 78 m standard deviation (Table 10), but all 22 positions that were between 500 and 2005 m in error were in this category, as well as in the highest percent of sky obstruction, and 47 positions out of 80 that had between 100 and 500 m of error were also in this category (Table 6).

We conducted two different data screenings to calculate the percentage of data reduction caused by each, and to determine whether or not screening increased mean positional accuracy; we removed positions that were two dimensional, and we removed positions with PDOPs > 5. In each test this resulted in keeping only the points regarded as most accurate by GPS theory. Removing all 2-D points increased mean data accuracy by 14 meters (Table 8) and resulted in a 72% data loss. Removing data with PDOPs > 5 resulted in a 8% data loss (Figure 2.11), increased mean data accuracy by 51 meters (Table 7) , and removed more than half (76 out of 122) of positions with errors > 100 m (Table 6).

In 2008, we repeated the experiment with one collar that had performed according to our expectations in 2007 and were able to achieve a 92% acquisition rate in a more balanced dataset. Similarly to the 2007 dataset, fix-rate bias increased as percents of sky obstruction increased (Figure 2.4) and as the antenna was turned away from the sky (Figure 2.5). Mean positioning error also increased with increasing percents of sky obstruction (Figure 2.6), as the antenna was turned away from the sky (Figure 2.7), as dimension changed from 3-D to 2-D (Figure 2.8), and with increasing levels of PDOP (Figure 2.9).

The predictive equations used in *Trend Analysis* were:

1) **nlog of positioning error = % sky obstructed x antenna angle x interactions (between % sky obstructed and antenna angle)**

2) nlog of positioning error = PDOP

The *Mixed Procedure* and the *Reg Procedure* gave us the following three models:

Model 1) nlog = 2.02736 + 0.01410*(Can) + 0.00461*(Zen) – 7.6E-5*(Can*Zen) + 5E-7*(Can^2*Zen) + 8E-11*(Can^2*Zen^3) – 2E-10*(Can^3*Zen^2)

Model 2) nlog = 2.79006-0.23464*(PDOP) + 0.0763*(PDOP^2) - 0.00381*(PDOP^3)

Model 3) nlog of error = 2.264 + 0.1666*PDOP

We explored Model 3, the linear order of PDOP, because scatterplots (Figures 2.10 and 2.11) indicated that it was it was similar, yet a simpler, version of the more complex Model 2, which included PDOP values at the linear, quadratic and cubic orders. All three models were significant at the 0.05 level: Model 1 (p <0.0001, F 26.36 DF 6); Model 2 (p <0.0001, F 46.97, DF 3); Model 3 (p <0.0001, F 120.37, DF 1). The *Reg Procedure* also provided R-Square values, and Adjusted R-Square values. All three models had very similar, small, R-Square values (Model 1 = 0.1848, Model 2 = 0.1674, Model 3 = 0.1462), and Adjusted R-Square values (Model 1 = 0.1777, Model 2 = 0.1638, Model 3 = 0.1450). We used the *RSREG Procedure* for Lack-of-fit tests; Model 1 (p 0.3918, F 0.94, DF 2) fit the data slightly better than Model 2 and 3, and Model 2 (p 0.3690, F 1.07, DF 4) fit the data slightly better than Model 3 (p 0.0970, F 1.69, D F7) (Table 11).

We calculated descriptive statistics for all three models in Excel. The mean error of Model 1 to the GPS collar positions ranged from 2 m (st. dev. 7 m) under the best conditions (0% sky obstruction and 0° antenna angle) to 14 m (st. dev. 27 m) under the worst conditions (Table 12). Table 12 also indicated that means and standard deviations of the model may be more influenced by percent of sky obstruction than by antenna angle. The mean error of Model 2 to the GPS collar positions ranged from 3 to 6 m (st. dev. 12 - 21 m) under the best conditions (PDOPs 1 through 5) to 2 - 22 m (st. dev. 21 - 48 m) under the worst conditions (PDOPs 6 through 11) (Table 13). The mean error of Model 3 to the GPS collar positions ranged from 2 to 6 m (st. dev. 12 - 21 m) under the best conditions (PDOPs 1 through 5) to 9 - 38 m (st. dev. 21 - 48 m) under the worst conditions (PDOPs 6 through 11) (Table 14).

Line plots of the models show that: in Model 1 the predicted mean error is within 2 to 14 m (st. dev. 7 - 35 m) of the actual mean positioning error (Figure 2.12); in Model 2 the predicted mean error is within 2 to 22 m (st. dev. 12 - 48 m) of the actual mean positioning error (Figure 2.13); and in Model 3 the predicted mean error is within 2 to 38 m (st. dev. 12 - 48 m) of the actual mean positioning error (Figure 2.14).

CONCLUSIONS

Televilt Simplex Series GPS collars are claimed accurate by their manufacturer to +/- 15 meters, for 90% of 3-D positions (Williams et al. 2008). This statement is true, but it is misleading because the majority of positions acquired are 2-D in the areas in which wildlife live (in this study: 72% in 2007 and 58% in 2008). As evidenced by this research, 3-D positions do, indeed, have mean accuracy of +/- 15 m (2007: mean 13 m, st. dev. 11 m; 2008: mean 15 m, st. dev. 11 m), but the majority of positions acquired are 2-D and these positions have greater error (2007: mean 27m, st. dev. 74 m; 2008: mean 29 m, st. dev. 27 m). Removal of 2-D positions would result in culling an unacceptable amount of positions from a dataset, and may lead to erroneous conclusions that an animal does not use an area.

Our tests indicate that positioning error of *Televilt Simplex Series* GPS collars increases with increasing percents of canopy obstruction. One reason for the poor accuracy performance of these collars is that they one collect one epoch of data for the position computation instead of making an estimation from a set of observations. The errors we observe are consistent with single-epoch position errors documented in Axelrad and Brown

(1996). These tests also suggest that GPS collar antennas that are not aligned with the antenna pointing up towards the sky may also increase positioning error. An antenna oriented straight-down at the ground should therefore result in the most error, but because GPS collars lack a ground-plane, the signal basically flips in the receiver and travels through the electronics, resulting in the same sky-view as with the antenna pointed straight up. It appears that antenna angle only becomes significant when the visible sky is reduced. The accuracy is therefore less dependent on antenna angle than on local physical obstructions such as trees and rocks, topography, or when animal behavior or the animal itself acts as a physical obstruction. For example, a bear digging with its head and neck down in a hole, or a cat sleeping on its back. Directional orientation of collars, i.e. north-south, vs. east-west, may only play a role if topography presents an obstruction trend, i.e. a nearby canyon or mountain range runs north-south, resulting in fewer observable SVs in those directions.

There is a wide range between the minimum and maximum errors for each category (% sky obstruction, antenna angle, and PDOP) of positions acquired, but on average, all three models fit the data well, allowing us to draw general predictive conclusions. Model 1, with coefficients of canopy and antenna angle was a statistically better predictive equation than both PDOP models as an overall predictor of positioning error; however, the differences were so small that practical considerations could make the PDOP models a better choice, i.e. PDOP is an internal measurement recorded by GPS collar receivers and no environmental calculations are necessary. All three models fit the mean positioning averages well but there was so much “noise” in the positions, meaning the large standard deviations and ranges between minimum and maximum values recorded that it is difficult to predict the error in any one position. This is indicated by the low adjusted r-square values for the models. The differences between the R-Square values of all three models were less than 0.04. We found that the third model, linear PDOP predicting positioning error was a reasonable estimate of the mean errors, especially those with PDOP < 6. As PDOP increased and became larger than 5, the positioning errors increased and the predictive ability of the model decreased.

These results indicate that while estimating canopy and antenna angle may statistically model the error better than PDOP, practical considerations such as budget and time constraints allow an appropriately comparable model using PDOP to predict mean positioning errors with *Televilt Simplex Series* GPS collars in Connecticut forested habitats. Additionally, if researchers desire to use all of their data, they should use a cubic order predictive equation (Model 2), or if they choose to screen their data and use only positions with PDOP < 6 (an 8% data loss) they can use a simple linear regression (Model 3).

Modeling positioning error with PDOP is a reasonable substitute for percent of sky obstruction due to canopy in CT broadleaf forests with Televilt™ Simplex Series GPS collars. Researchers should retain 2-D positions to avoid Type II errors but use error ellipses to represent animal locations instead of points, these error ellipses should increase in scale according to the reported accuracy at each value of PDOP

DISCUSSION

The allures of GNSS positioning are that, without human monitoring or manipulation, it can provide accurate location information on wildlife at any time, in any weather conditions, and in any place. GPS technology, however, varies in the quality of its electrical and mechanical components, and it also has a well-documented error budget. Many of the variables in the GPS error budget are common in the places animals live and move. There are also additional variables inherent to species behavior and the particular habitat an animal frequents that contribute to GPS error. Even though researchers are aware of many of these error variables, many fail to consider their effects in their planning and in their reporting of their wildlife studies. For example, it’s understood that topography affects position accuracy and fix-rate, but it's not clear that it's understood that this is because fewer SVs are in view and with poor strength of figure. It's also not clear that it's understood that PDOP accounts for these errors, and therefore results should be considered accordingly. It is also recognized in the GPS literature that infrequent position acquisition intervals (epoch), provide the least accurate results, due to lack of precision, yet single epoch positioning is commonly used in wildlife research. GPS collars should be programmed for maximum position acquisition to provide redundancy of positions, and research budgets should include capture and recapture fees to refurbish batteries.

As a general rule, statistically it is true that more data generally yields stronger conclusions than less data, but another general rule that is also true is that "garbage in = garbage out." In spite of widespread GPS collar malfunctions, fix-rate biases, and positional errors, unscreened GPS positions are used to determine what habitats are crucial to a species, which are of marginal importance, which are unimportant, and if individuals of a species can travel between or across these areas. Position screening, while recommended, is used only to remove egregious errors from datasets, usually after identifying them visually as outliers in GIS. The magnitudes of other positioning errors, however, are often unknown.

Positions lost due to equipment malfunction should be a primary concern of researchers. All collars should be tested, in the environment where they will be used, before deployment. Only the best performing collars, in ideal environmental conditions, result in average positioning accuracy of ten to fifteen meters. Nonperforming or poorly performing collars will result in missing data and/or increased positioning error and should not be deployed. This is especially important as collars age; they should be tested before each deployment. It may be a relatively simple and valuable addition to the testing process to allow collars to record positions and develop screening models for other habitats based on

PDOP. In Connecticut broadleaf forests, it took us ~24- hours to record positions with PDOPs 1-5, and ~12 days to record positions with PDOPs 1-11.

Because of the extreme range of positioning errors possible at each value of PDOP or combination of canopy and antenna angle, we do not suggest using a point position to display wildlife locations. A PDOP-based error ellipse would be best, showing the average error and standard deviation possible around each position. Positions with a PDOP exceeding 5 should not be disregarded but should be highly suspect for extreme distance errors. Caution should be used when screening positions so that this does not lead to the erroneous conclusion that an animal does not use a habitat because higher PDOPs are likely to occur in habitats that have a challenged view of the SVs, i.e. closed canopies and vertical terrain. Special consideration should be given to any imagery used to display positions recorded by GPS collars, and the positions should be "fit" to the scale of the image so as not to distort animal movements and habitat considerations.

Further research is recommended utilizing more sites with additional and different percents of increasing canopy coverage. This may allow development of a more rigorous equation modeling positioning error. Tests should be repeated in areas where challenging topography is present and during seasons where there are no leaves on the trees to rule out confounding factors. Furthermore, if results from studies in other areas and with other collars indicate similar levels of positioning error and fix-rate bias, it may benefit the wildlife management community not to base decisions entirely on GPS positions. GPS may not be the best tool to use with cryptic species or species whose behavior and habitat preference interferes with or precludes GPS signal transmission

Our recommendations are that GPS positioning data should be used to determine gross animal movements and locations, which should then be followed with ground-truthing of habitats and corridors, such as with remotely triggered camera traps and track and sign surveys, to confirm presence or absence of the species in question.

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TABLES

Table 2.1. Control site coordinates determined with a TOPCON dual-frequency receiver, CORS positions, and Pinnacle software. Coordinates are in SPCS(CT), NAD83.

Site	Easting	Northing
1	346529.33	261177.36
2	354117.63	243492.05
3	354223.93	243499.17
4	354133.27	243443.85

Table 2.2. Percents of sky obstruction at control sites, determined by hemispherical photos registered in Gap Light Analyzer.

Site	% Sky Obstruction
1	**0**
2	**40**
3	**65**
4	**85**

Table 2.3. Independent variables (2007): Sky Obstruction and Antenna Angle; each treatment lasted 24 hours, where collars were programmed to acquire 2 positions per hour.

% Sky Obstruction			**Antenna Angle (°)**
Site1	Site2	Site3	Across all Sites
0	40	65	0
0	40	65	45
0	40	65	90
0	40	65	135
0	40	65	180
0	40	65	225
0	40	65	270
0	40	65	315

Table 2.4. Independent variables (2008): Sky Obstruction and Antenna Angle; Site 4 was added and complimentary angles were eliminated from treatments.

% Sky Obstruction				**Antenna Angle (°)**
Site1	Site2	Site3	Site4	Across all Sites
0	40	65	85	0
0	40	65	85	45
0	40	65	85	90
0	40	65	85	135

Table 2.5. Extreme outliers (2007) removed from Site 2, 40% sky obstruction, 225° antenna angle (PDOP= Position Dilution of Precision, DIM= 2 or 3 dimensional).

Date	Time	Northing error (m)	Easting error (m)	PDOP	DIM	Collar #
8/4/2007	0:16:24	-121204.0	-211619.0	3	2	3
8/4/2007	2:47:40	-121089.0	-208236.0	5	3	5
8/4/2007	5:16:00	1899.29	-207609.0	2	3	1

Table 2.6. Number and percent of positioning errors (2007) listed by the minimum and maximum group values of their errors, n = 6740.

# of positions	Min-max (m)	% of dataset
22	500-2005	0.3
80	100-500	1.1
1024	30-100	15
1997	15-30	29.6
3617	<15	54

Table 2.7. Positioning error by PDOP value (2007), n = 6740.

PDOP	n	Mean error (m)	St Dev error (m)	Min-max (m)
1	627	15	20	2-333
2	2031	18	30	2-710
3	1607	21	49	2-982
4	1177	21	37	2-730
5	769	23	39	3-649
6	135	75	226	3-1946
7	128	67	154	3-1300
8	87	73	187	3-1419
9	70	62	51	5-252
10	56	54	50	5-224
11	53	93	271	3-2005

Table 2.8. Positioning error by dimension (2007), n = 6740.

Dimension	n	Mean error (m)	St Dev error (m)	Min-max (m)
2-D	4883	27	74	2-2005
3-D	1857	13	11	2-227

Table 2.9. Effects of Sky Obstruction on mean positioning error, n = 6740.

% Sky Obstruction	Error (m)	St Dev error (m)	Min-max (m)
0	10	8	2-70
40	19	19	3-491
65	70	189	3-2005

Table 2.10. Effects of Antenna Angle on mean positioning error, n = 6740.

Antenna Angle (°)	Error (m)	St Dev error (m)	Min-max (m)
0	24	78	2-2005
45	19	15	3-84
90	23	24	3-209
135	24	21	3-139
180	22	24	3-235
225	23	22	3-176
270	26	25	3-218
315	19	16	3-126

Table 2.11. Model comparisons.

	Model 1	**Model 2**	**Model 3**
n	705	705	705
ANOVA P-value, F (df)	<0.0001, F 26.36 (6)	<0.0001, F 46.97 (3)	<0.0001, F 120.37 (1)
R-Square	0.1848	0.1674	0.1462
Adjusted R-Square	0.1777	0.1638	0.1450
Lack-of-fit P-value, F (df)	0.3918, F 0.94 (2)	0.3690, F 1.07 (4)	0.0970, F 1.69 (7)

Model 1 nlog = 2.02736 + 0.01410*(Can) + 0.00461*(Ang) – 7.6E-5*(Can*Ang) + 5E-7 *(Can^2*Ang) + 8E-11* (Can^2*Ang^3) – 2E-10* (Can^3*Ang^2)

Model 2 nlog = 2.79006-0.23464*(PDOP) + 0.0763*(PDOP^2) - 0.00381*(PDOP^3)

Model 3 nlog = 2.264 + 0.1666*PDOP

Table 2.12. Model 1 statistics indicating how closely the predictive equation predicted each positioning error at different percents of sky obstruction and antenna angle.

		n	Mean	Min	Max	Range	StDev
% sky obstruction & antenna angle	0 x 0	48	2	-5	22	27	7
	0 x 45	47	4	-7	98	105	16
	0 x 90	43	4	-9	46	55	12
	0 x 135	48	3	-12	55	67	14
	40 x 0	48	2	-10	71	81	16
	40 x 45	47	7	-10	39	49	13
	40 x 90	47	2	-13	42	55	13
	40 x 135	46	10	-16	110	126	28
	65 x 0	48	5	-14	56	70	15
	65 x 45	47	6	-15	161	176	35
	65 x 90	47	3	-17	131	148	25
	65 x 135	39	14	-19	107	126	33
	85 x 0	41	11	-19	110	129	28
	85 x 45	42	5	-20	88	108	23
	85 x 90	41	14	-16	95	111	27
	85 x 135	**26**	2	-18	57	75	18

Table 2.13. Model 2 statistics indicating how closely the predictive equation predicted each positioning error up to the cubic order of each level of PDOP.

	Model 2 error (m)					
PDOP	Mean	min	max	range	n	stdev
1	3	-12	70	82	107	12
2	6	-11	91	102	170	16
3	4	-12	97	109	169	15
4	6	-15	135	150	116	21
5	3	-16	95	111	87	18
6	16	-21	104	125	13	35
7	18	-27	115	142	16	42
8	-2	-34	22	56	7	21
9	22	-43	122	165	11	48
10	-4	-37	62	99	5	39
11	5	-41	56	97	4	41

Table 2.14. Model 3 statistics indicating how closely the predictive equation predicted each positioning error at the linear orders of each level of PDOP.

	Model 3 error (m)					
PDOP	Mean	min	max	range	n	stdev
1	5	-9	73	82	107	12
2	6	-11	91	102	170	16
3	3	-14	96	110	169	15
4	4	-17	133	150	116	21
5	2	-17	94	111	87	18
6	17	-20	105	125	13	35
7	36	-22	120	142	16	42
8	9	-23	33	56	7	21
9	38	-27	138	165	11	48
10	15	-16	82	98	5	39
11	24	-22	75	97	4	41

FIGURES

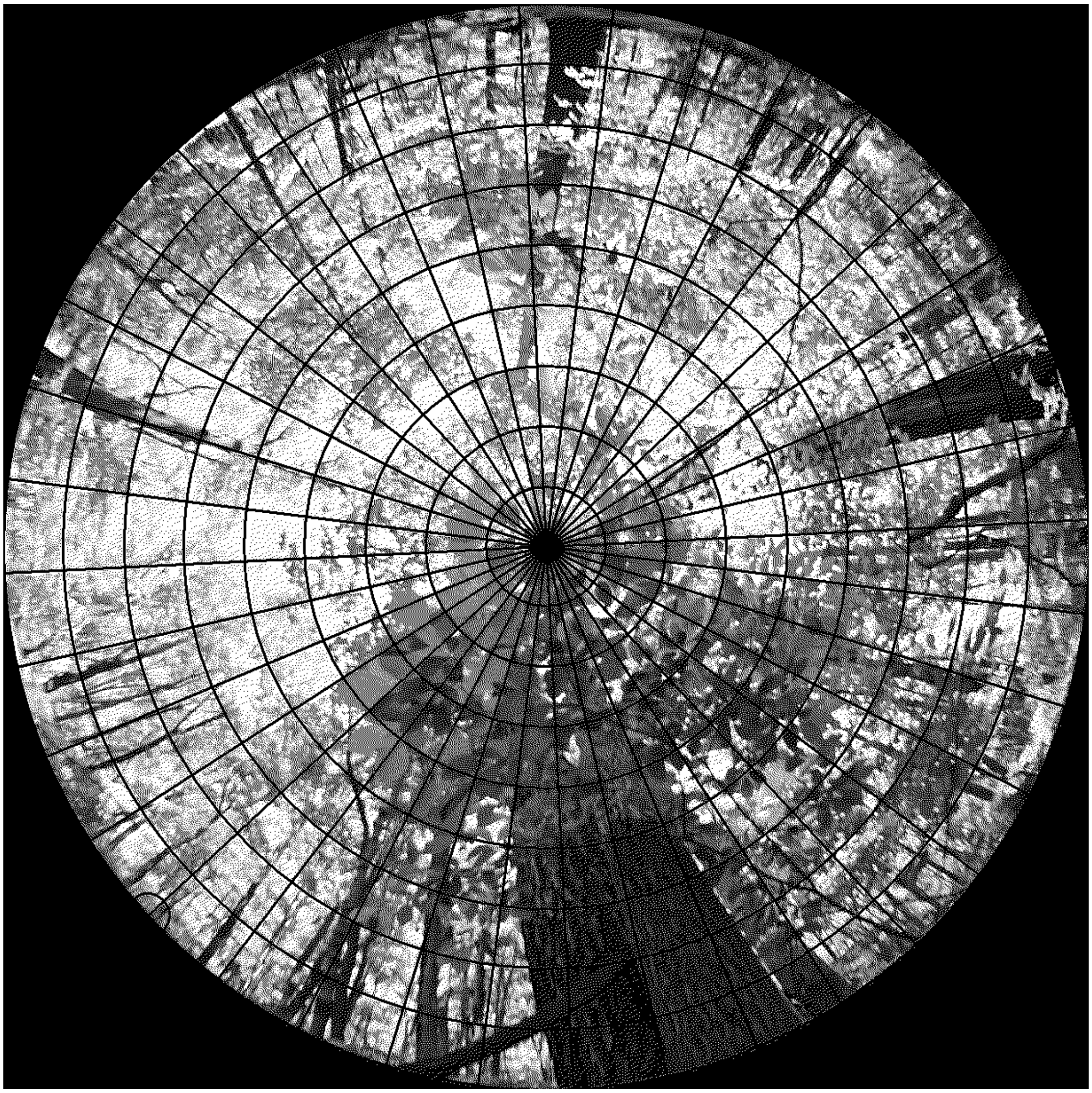

Figure 2.1. A hemispherical photo in Gap Light Analyzer. Light pixels are counted as open canopy and dark pixels are counted as closed canopy.

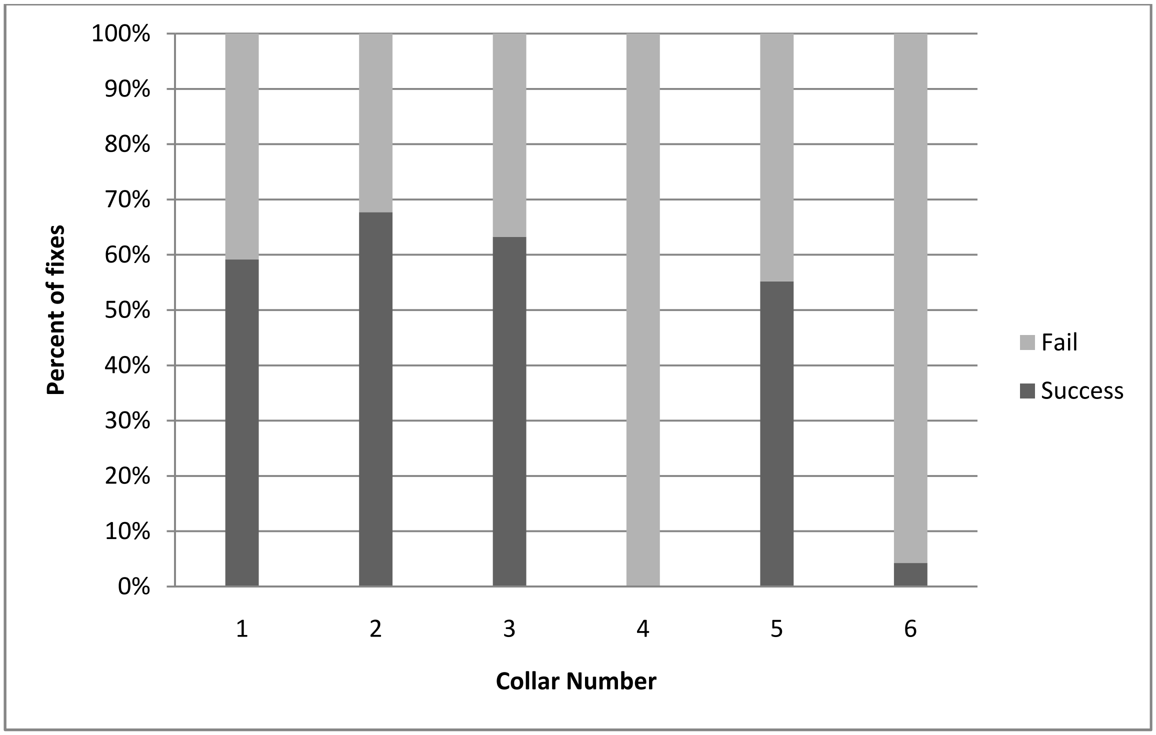

Figure 2.2. Percentages of GPS positions that were scheduled and failed *vs.* those that were scheduled and acquired in 2007.

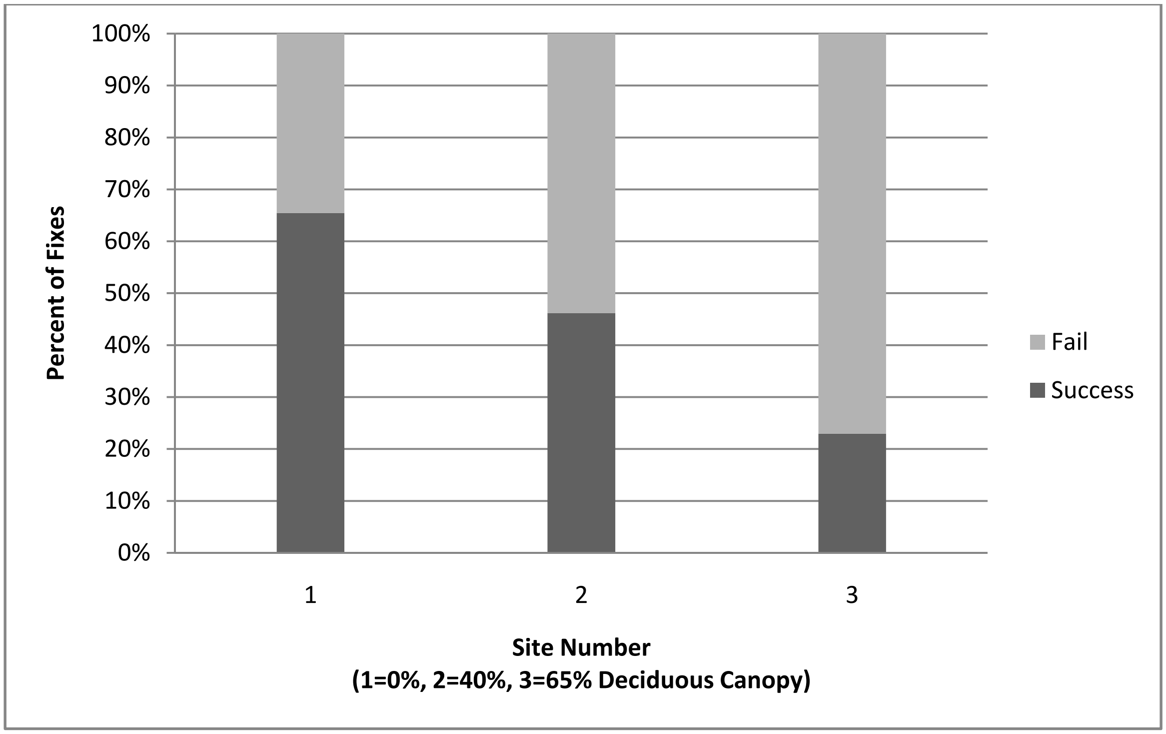

Figure 2.3. Percentages of GPS fixes that were scheduled and failed *vs.* those that were scheduled and acquired in 2007, across sites with increasing percents of sky obstruction.

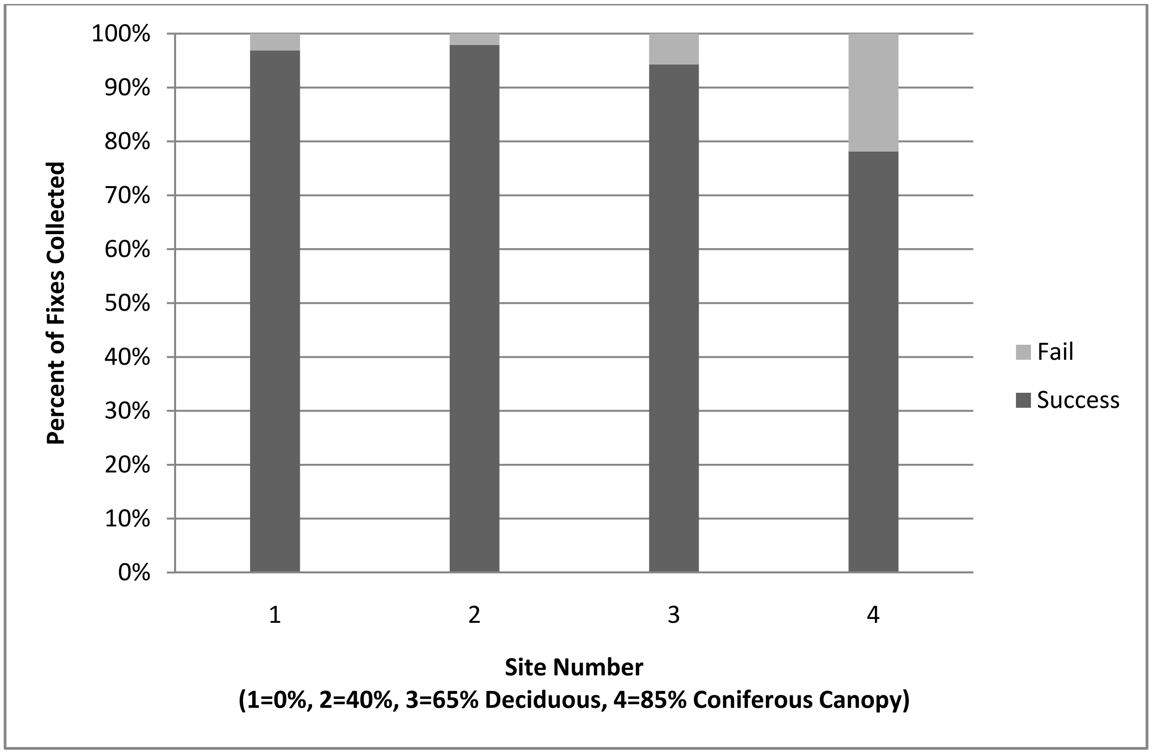

Figure 2.4. Percentages of GPS fixes that were scheduled and failed *vs.* those that were scheduled and acquired in 2008, across sites with increasing percents of sky obstruction.

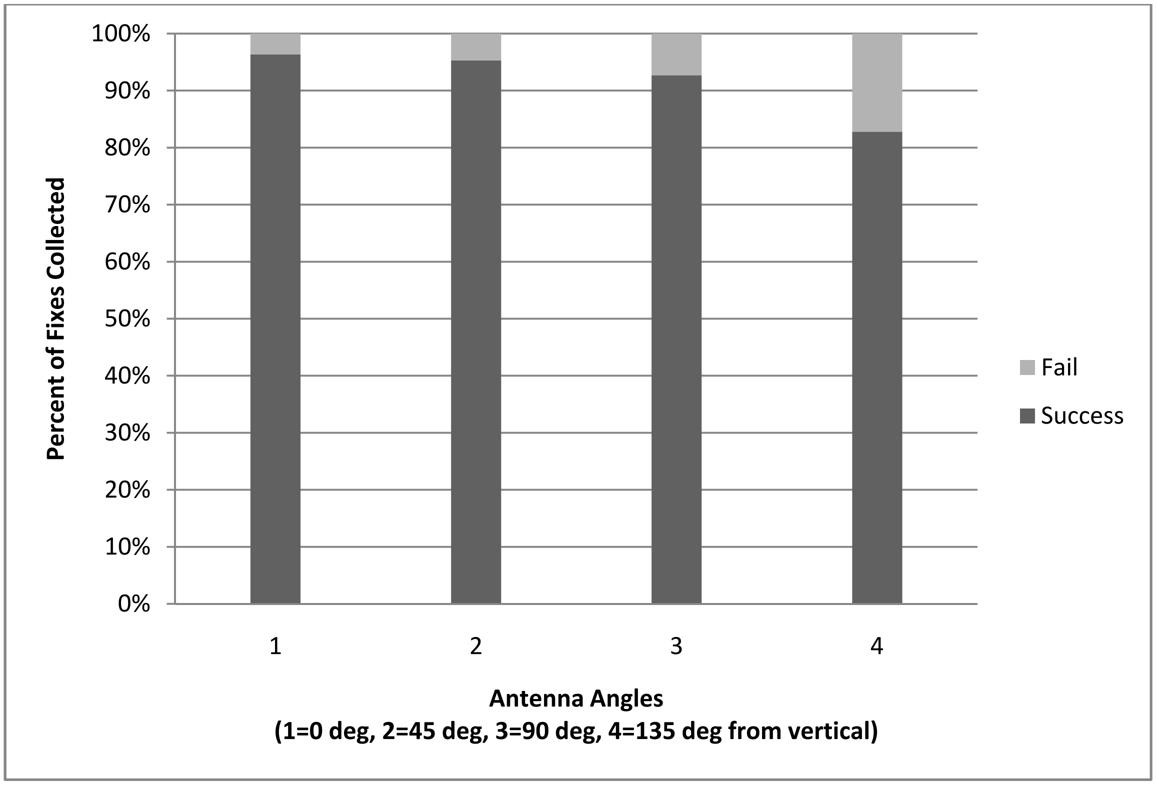

Figure 2.5. Percentages of GPS fixes that were scheduled and failed *vs.* those that were scheduled and collected successfully in 2008, separated by antenna angle.

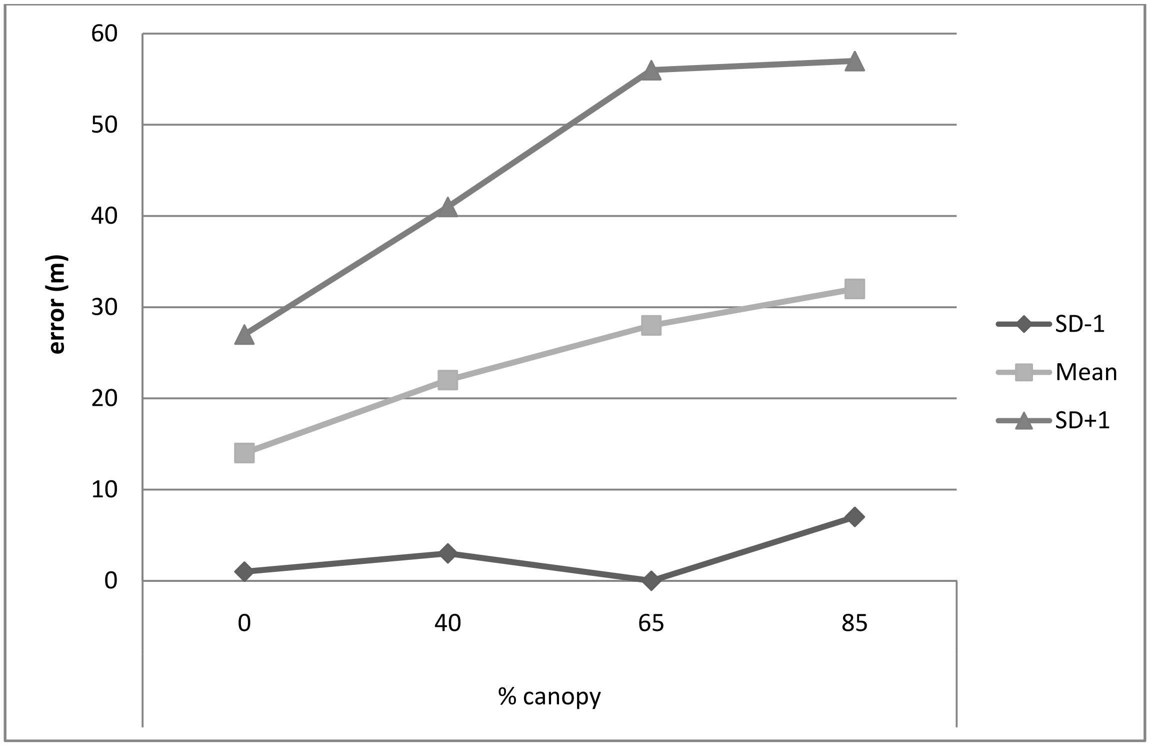

Figure 2.6. Positioning error due to percent of sky obstruction from canopy (2008).

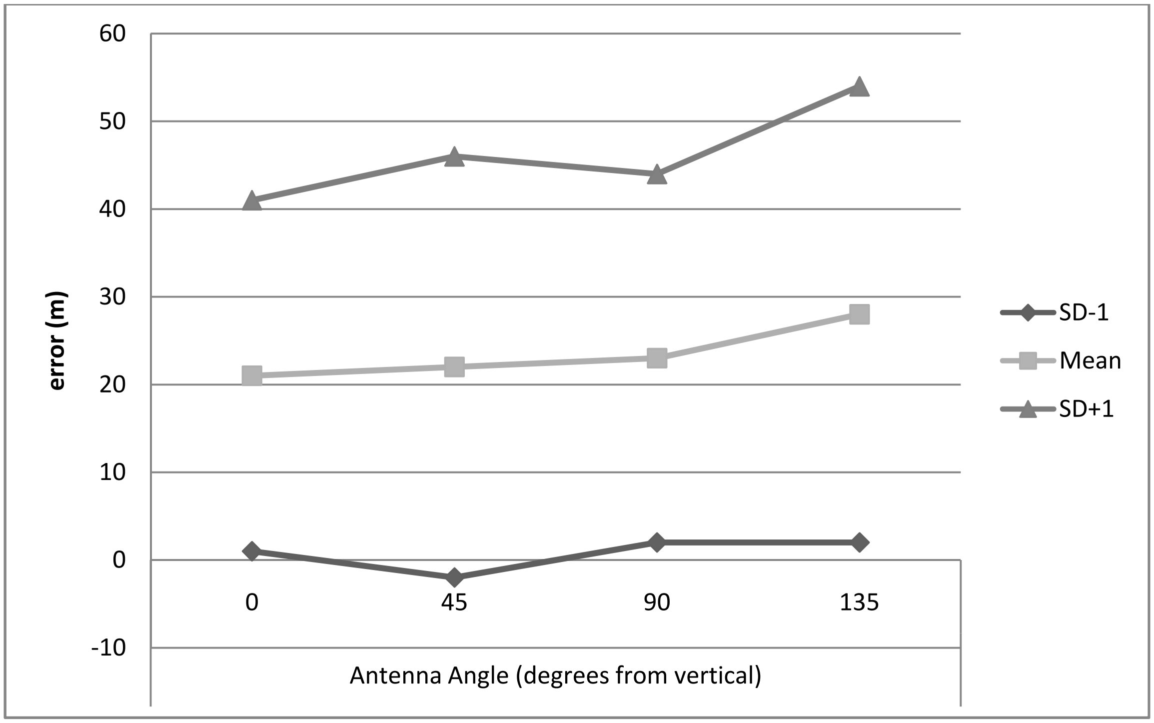

Figure 2.7. Positioning error due to antenna angle (2008).

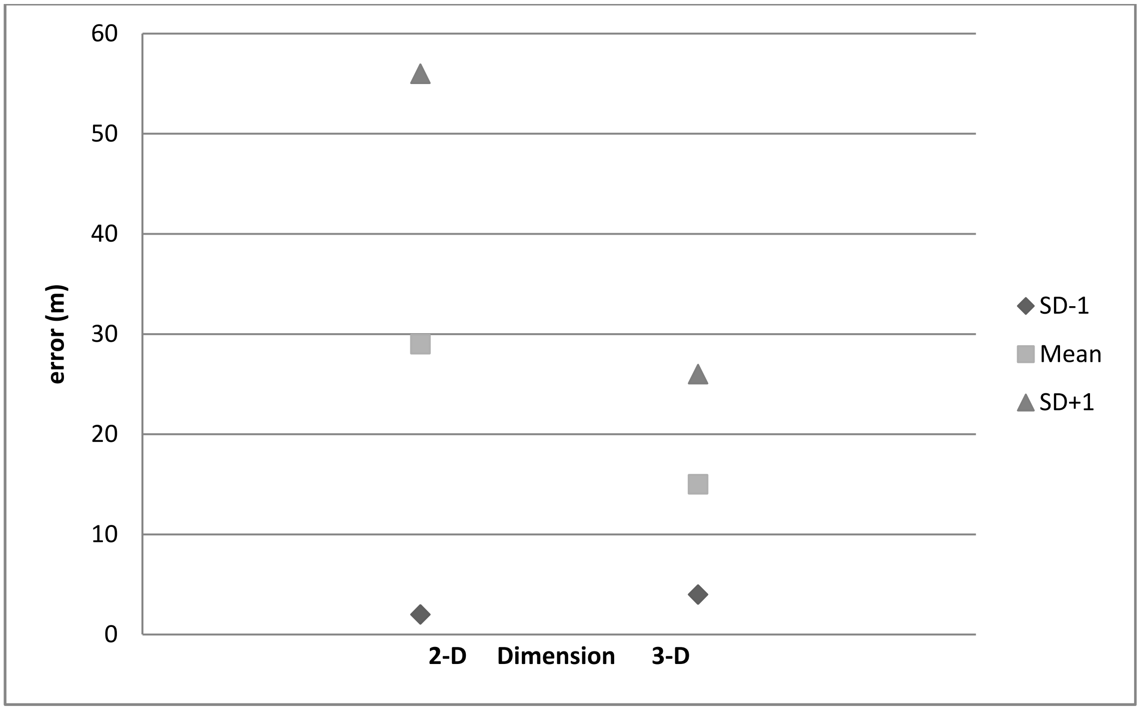

Figure 2.8. Positioning error by dimension (2008).

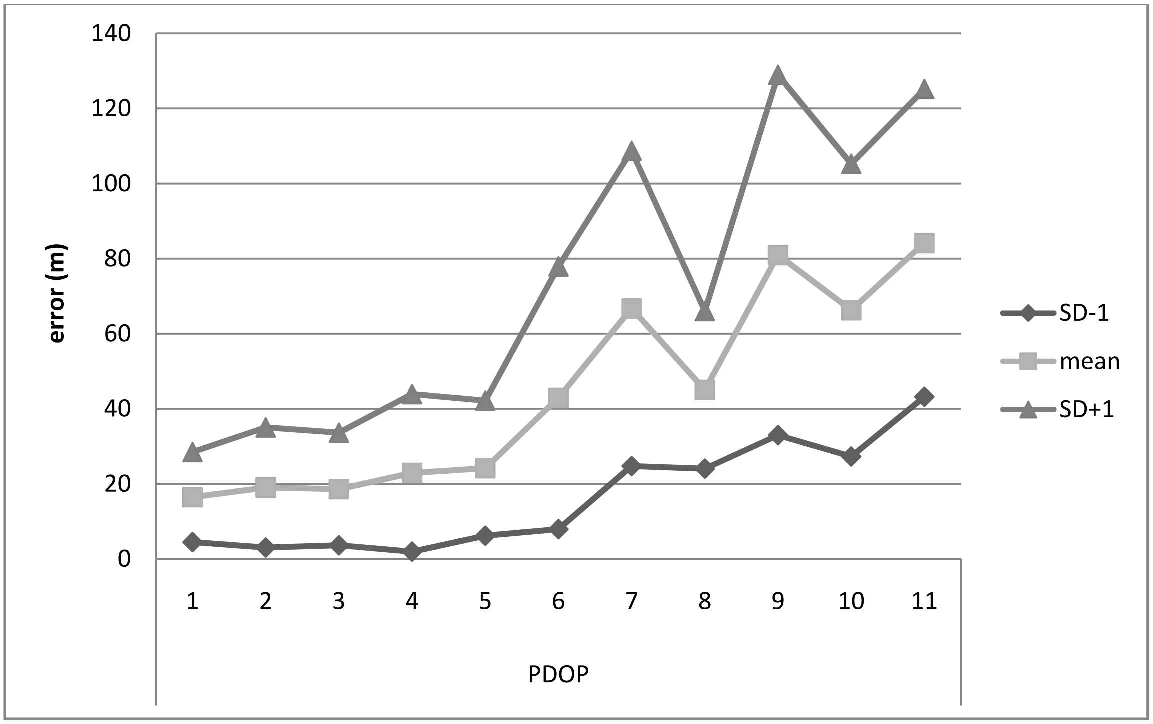

Figure 2.9. Positioning error by PDOP value (2008).

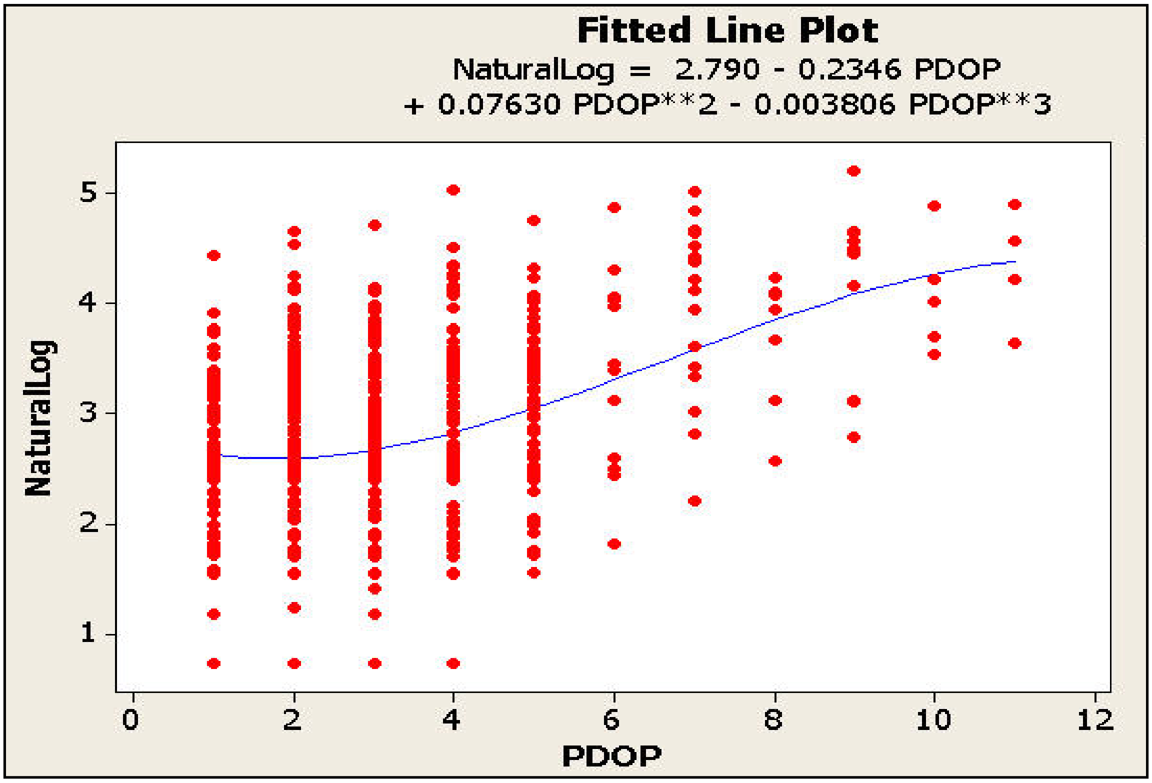

Figure 2.10. Scatterplot with fitted line to the cubic order model of PDOP – effects on the natural log of the positioning error.

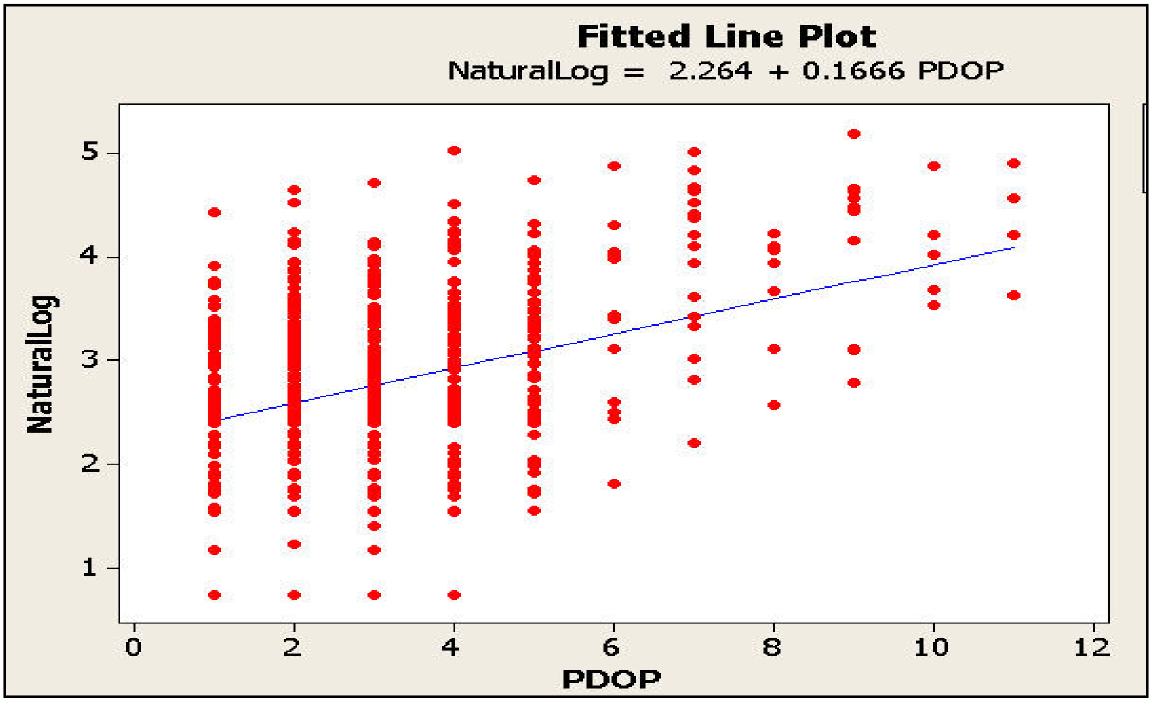

Figure 2.11. Scatterplot with fitted line to the linear order model of PDOP – effects on the natural log of the positioning error.

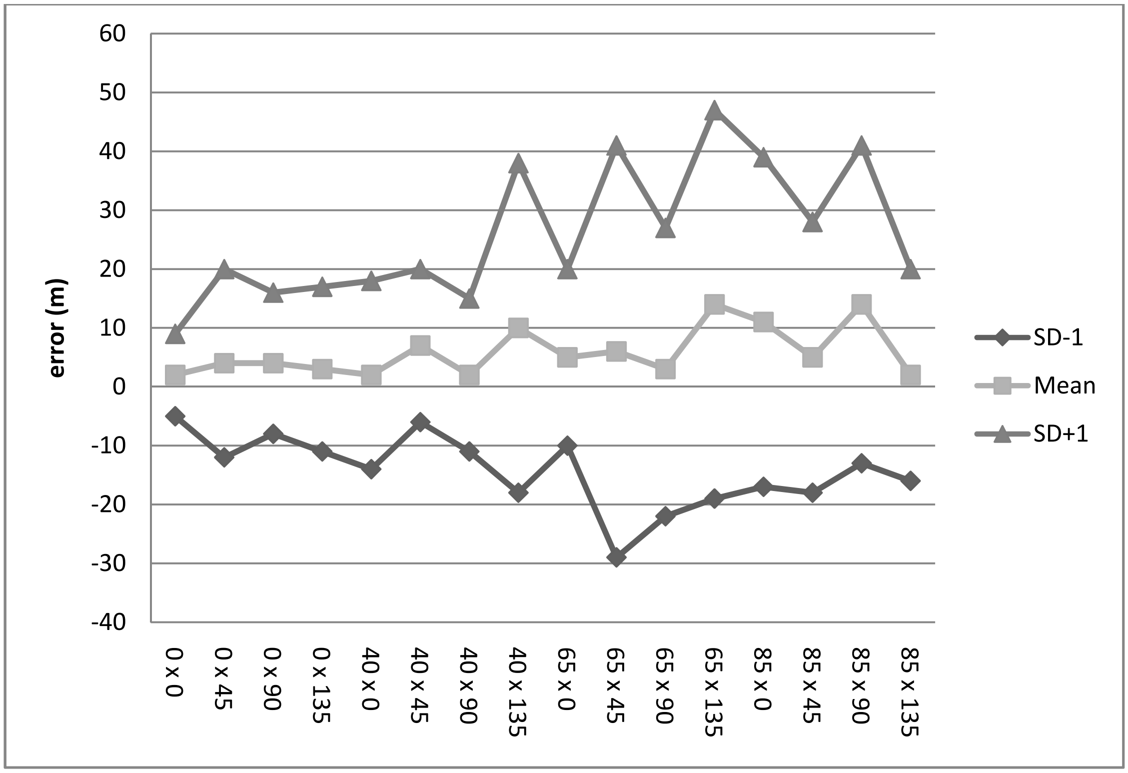

Figure 2.12. Model 1 verification line plot of the effects of sky obstruction and antenna angel on the back-transformed positions (nLog → meters) where:
(position error) – (predicted error) = model error estimate at each treatment level

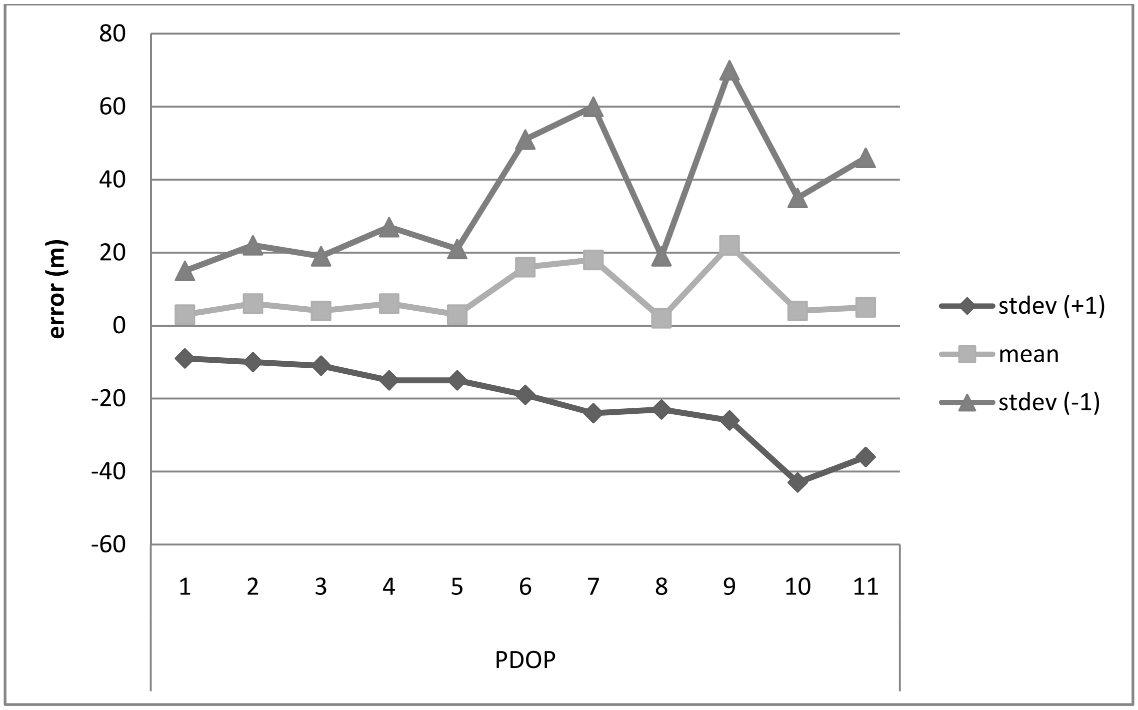

Figure 2.13. Model 2 verification line plot of the effects of cubic order PDOP values on the back-transformed positions (nLog → meters) where:
(position error) – (predicted error) = model error estimate at each treatment level

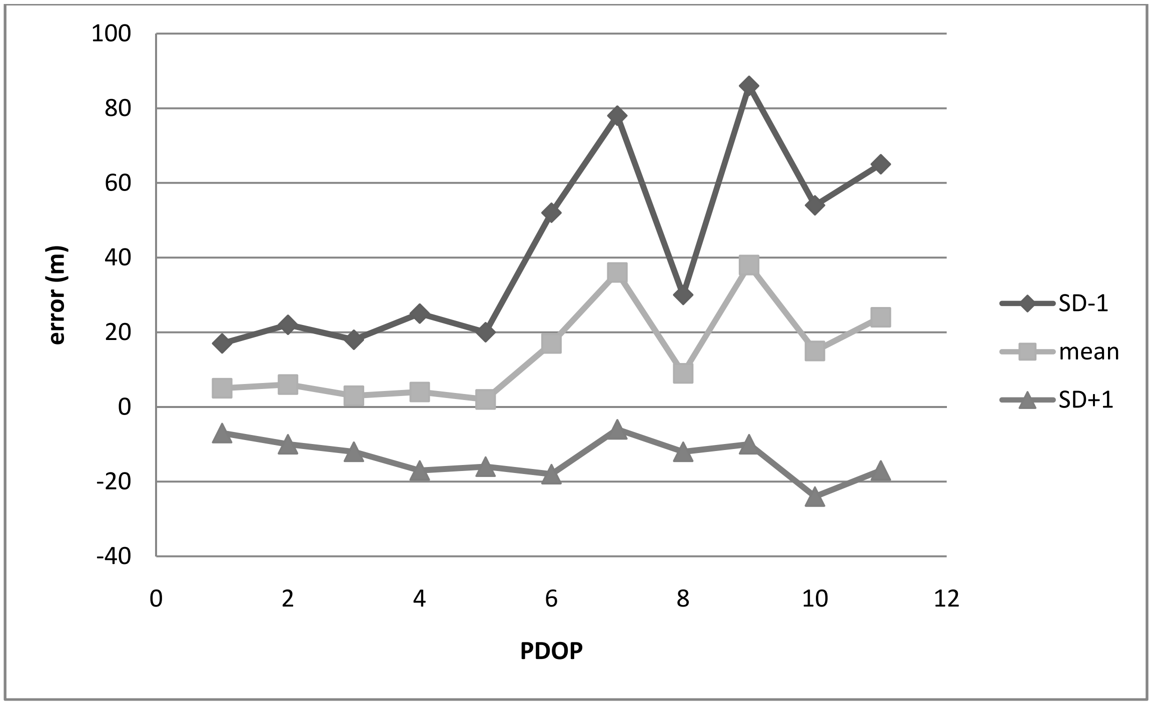

Figure 2.14. Model 3 verification line plot of the effects of linear order PDOP values on the back-transformed positions (nLog → meters) where:
(position error) – (predicted error) = model error estimate at each treatment level

Chapter 3

A FIELD COMPARISON OF GNSS COLLARS IN PATAGONIA, CHILE

ABSTRACT

We analyzed the accuracy of three different Global Navigation Satellite System (GNSS) wildlife tracking collars in Torres del Paine National Park (TDP), in Southern Patagonia, Chile. To our knowledge, GNSS collars had not been tested in this area previously. We established spatial control using dual-frequency receivers and then compared these high-accuracy receiver positions with the relatively low-accuracy, single-frequency, wildlife-tracking collar positions. The results show that, under ideal conditions, there are statistically significant differences in mean positional accuracy between the collars, but these differences are very small in practical terms. In a separate test we simulated plausible animal movements in three habitats with increasingly challenging vertical topography and canopy obstruction. Under open sky, the average errors were generally consistent with the manufacturer's claims, but mean error distances generally increased with increasingly challenging habitats, and we identified extremely erroneous positions at each site. Our results show that GNSS can be used for terrestrial vertebrate research in TDP. However, species preference for some habitats may cause increased positional error or missed positions, and should be considered.

INTRODUCTION

The promise of GNSS positioning in wildlife research is that, without human monitoring or manipulation, it provides accurate positioning information on wildlife at any time, in any weather conditions, and in any place (Friar et al. 2004, Samuel and Fuller 1996, Spilker 1996a). GPS positioning is considered especially useful for species that are hard-to-see, nocturnal, or live in remote or rugged terrain (i.e. remote, thickly forested, and/or rapidly changing topography) because the receivers can be programmed to automatically collect large numbers of positions over long time periods (Hulbert and French 2001). Researchers expect the positions acquired to meet the accuracy claims of most GPS collar manufacturers: +/- 15 m, on average, under ideal conditions (Hebblewhite et al. 2007, Samuel and Fuller 1996, Villepique et al. 2008). Position error, however, is caused by anything in the environment that attenuates (or blocks) SV signals, thus weakening the strength of figure in the visible constellation (Spilker 1996d). GPS collar positioning accuracy, therefore, decreases in habitats where the strength of figure is weakened. This includes habitats with dense canopy (Rempel et al. 1995; Blake et al. 2001; D'Eon et al. 2002, Dussault et al. 1999, Hebblewhite et al. 2007, Sager-Fradkin et al. 2007), rapidly changing topography, and other solid mass surface features (D'Eon et al. 2002, Friar et al. 2004). This further suggests that the ability of a GPS collar to acquire a position, or to acquire an accurate position, in these *GPS challenged* habitats is affected by animal activity related to species selection for different habitats (Coelho et al. 2007, Moen et al. 1996, Moen et al. 2001).

Wildlife researchers have identified egregious GPS collar errors and their probable sources during their studies (Cain et al. 2005). Few, however, have documented more common, less obvious, errors in carefully designed studies focused on the performance and positioning accuracy of their GPS collars, before deployment of those collars on wildlife (Graves and Waller 2006).

Researchers recommend testing GPS wildlife tracking collars, to determine baseline error ranges, in the areas where they will be used, before they are deployed on wildlife (Lewis et al. 2007). To our knowledge, this is the first GPS collar accuracy conducted in **Torres del Paine National Park** (TDP), Chile, in the *GPS challenged* Patagonian landscape (Figures 3.1 and 3.2). It is also the first GPS collar positioning accuracy comparison in the region, against geodetic quality control, as established with dual-frequency GPS receivers. Our goals were to determine the baseline performance of three different manufacturer's GPS collars and their potential suitability for use on wildlife in TDP.

We also used a stop-and-go differencing technique to establish control coordinates, where one dual-frequency receiver, called a **base**, acquires positions at a known reference station, and another dual-frequency receiver, called a **rover**, acquires positions at undetermined locations in the field. The rover is briefly stopped and positions are acquired. The base and the rover communicate in real-time via an FM radio link. This allows the rover to compute a survey-quality position in real-time (Goad 1996, Parkinson 1996c, Van Sickle 2008).

OBJECTIVES:

Our objects were the following:

- Stationary testing on control markers–
    - To determine if GPS wildlife tracking collars would record positions in Torres del Paine with reasonable accuracy for wildlife research.
    - To compare the performance of different GPS wildlife tracking collars in Torres del Paine.
- Simulated Animal Movement Corridor (SAMC) Tests –

- To determine the accuracy of GPS wildlife tracking collar positions in Torres del Paine in increasingly *GPS challenged* habitats in TDP.

STUDY AREA

Torres del Paine is a 25.5 sq-km national park situated in the southern tip of South America at approximately 50.98°S and 72.49°W (Figure 3.1). It is located is on the eastern edge of the Andes Mountain in the Patagonia Region of Chile (Figure 3.2). TDP is typically described as "rugged" terrain. Valleys are surrounded by steep cliffs and hills, resulting in corridors of movement where animals are channeled through canyons and dense forests in their movements from one area to another. TDP ranges from flat plains in the lowlands to the eastern edge of the Andes Mountains, this area spans from 60 m in elevation at the lowest point, to just over 3000 m at the top of the peaks. The park contains glaciers, abrupt peaks, deep valleys, shrub-land and grassland communities, unique beech deciduous forest, and even desert.

MATERIALS AND METHODS

We contacted 15 different GPS collar manufacturers to request their cooperation in testing their equipment in our region of interest. Our solicitations resulted in tests of three different GPS collar devices. In 2005, *BlueSky, ATS and SirTrack* responded, but only *SirTrack* was able to provide a test collar. In 2006, all three manufacturers provided a test collar (Figure 3.3).

GPS collar positions were collected in Dec and Jan in both 2005 and 2006. In Patagonia, these months are characterized by high winds averaging 20 m/sec. The temperature averages 49°C, and average humidity is 48%.

Three survey control markers were established, prior to this study, in 2004 by T. Meyer and A. Trani from the University of Connecticut. The markers were constructed by setting aluminum caps into bedrock outcrops by drilling a borehole, inserting a steel rod into a socket in the base of the cap, setting the cap and rod into the borehole, and cementing them in place. Their coordinates were established with dual-frequency *TOPCON Javad and Odyssey* GPS receivers. The observations were corrected using phase differencing as implemented in *TOPCON's Pinnacle* software. The survey was controlled by International GNSS Service (IGS) permanent reference stations and positional repeatability at the five centimeter level was obtained (T. Meyer 2007, pers. comm.).

Stationary Testing Methods

Three different GPS collar devices were tested at previously established control markers: a *SirTrack* Wildlife Tracking Solutions GPS collar, an *Advanced Telemetry Systems* (ATS) G2100 GPS collar, and a *BlueSky* GPS Satellite Telemetry collar. GPS collar position coordinates were compared to the established coordinates of the control markers.

Control markers used in this experiment were named TDP1 (Figure 3.4), TDP2 (Figure 3.5) and TDP4 (Figure 3.6). TDP3 was not used in this study. Each marker had minimal sky obstruction (no canopy and little topographic variation) in its immediate area, resulting in optimal conditions for consistently accurate GPS collar positions.

The antennas of the collars were oriented vertically at a zenith angle of 0° (up) for two hours. Each collar came preprogrammed from the manufacturer with a position acquisition schedule. The *ATS* collar was programmed to collect one position every 30 minutes. The *BlueSky* collar was programmed to collect one position every five minutes. The *SirTrack* collar was programmed to collect up to 10 positions every 30 minutes; if the first attempt failed it continued to try and acquire a position each second for 30 seconds.

The recorded latitudes and longitudes were analyzed separately for directional bias, and T-tests for directional bias in either north/south or east/west directions indicated whether or not the mean value of GPS collar error was zero in both latitude and longitude.

We computed a Euclidian positional error distance (in meters) from the known location of each position by transforming them into a local topocentric geodetic coordinate system (Meyer, T.H. 2009) with *Wolfram's Mathematica*. We pooled the error distances for each GPS collar; resulting sample sizes were: *ATS* n=13, *BlueSky* n=81, and *SirTrack* n=66.

We used *Statistical Analysis Systems (SAS)* to conduct Folded-F tests and two sample T-tests between the errors of each pair of GPS. We used the Satterthwaite method of T-tests on each pairing of devices. This method allowed us to make a more conservative decision and we were less likely to reject the null hypothesis of equality of means for each combination of means being tested.

Simulated Animal Movement Corridor (SAMC) Methods

Simulated Animal Movement Corridor (SAMC) testing was completed using DGPS with two *Javad*, dual-frequency, GPS receivers: a Legacy base unit and an Odyssey rover unit; and a *SirTrack* Wildlife Tracking Solutions GPS collar. The base was set on a two-meter range-pole leveled over a control marker and run continuously. The base acquired positions on the control marker while, simultaneously, the rover was carried through the SAMCs, stopping every 10 minutes to collect 20 minutes of positions at one second epochs. The data collection schedule was in 30 minute intervals because the SirTrack GPS collar being tested was programmed to acquire one position every 30 minutes; this enabled a comparison of the positional accuracy between the two types of receivers at different field locations with no previous control coordinates.

Three common habitats in the Park were selected and labeled: SAMC1, SAMC2, and SAMC3. SAMC1 (Figure 3.7) was in the comparatively open steppe “Camp Valley” area of TDP. Camp Valley was dominated by open grassland and small shrubs in a wide valley that gently sloped upwards on the Northern and Southern sides. SAMC2 (Figure 3.8) was in an area known as “Vega Puma” in TDP. Vega Puma was dominated by scrubland and small groves of 9-15 m tall deciduous trees. The Vega Puma canyon was a wide canyon running southwest to northeast with sections of steep cliff on either side. SAMC3 (Figure 3.9) was in the “Lago Grey” section of TDP near a glacial ice field. Lago Grey was dominated by mature forest of 30-50 foot tall trees with spreading canopy coverage, and consistently steep and narrow cliffs running in a southeast to northwest direction.

The *SirTrack* GPS collar was programmed by the manufacturer to collect positions every 30 minutes. Therefore, we walked for 10 minutes between each site, set up the *Javad* rover and GPS collar together and allowed them to collect positions at the same time (allowing the rover to acquire positions for 20 minutes to establish control coordinates at the field location), before moving on to the next point. We collected positions in this fashion for 3 days, one day at each site.

Positions were then downloaded using *PCCDU* and corrected using *Pinnacle* software, both produced by *TopCon*. We used Wolfram’s *Mathematica* to convert *SirTrack* GPS collar latitudes and longitudes from the SAMC positions into error distances by comparing them to the control positions collected by the *Javad* units.

RESULTS

Stationary Testing Results

All GPS collar pairings indicated unequal variances: *BlueSky* and *SirTrack* ($F=32.04$, $p<0.0001$, $\alpha=0.05$), *ATS* and *BlueSky* ($F=4.78$, $p=0.0047$, $\alpha=0.05$), and *ATS* and *SirTrack* ($F=153.22$, $p<0.0001$, $\alpha=0.05$).

Satterthwaite tests between collars on Euclidian distances from control indicate there were significant differences between mean positions GPS collars: *SirTrack* and *BlueSky* GPS collars ($t=-3.15$, $p=0.0024$, $\alpha=0.05$), *ATS* and *SirTrack* ($t=-4.20$, $p<0.0001$, $\alpha=0.05$), and *ATS* and *BlueSky* ($t=-4.48$, $p<0.0001$, $\alpha = 0.05$).

All three collars showed directional bias. *BlueSky* (latitude $p=0.2572$, $\alpha = 0.05$; longitude $p<0.0001$, $\alpha = 0.05$) had the largest overall variation in the observed positions and had one egregiously outlying position to the south and east. The mean error of the *BlueSky* positions was north of the control, while the mean error of the *SirTrack* positions is north and west of the control (latitude p=0.2397, α = 0.05; longitude p<0.0001, α = 0.05). The p-values from the *BlueSky* and *SirTrack* collar data show that there is a bias in the north to south direction but not in the east to west direction. *ATS* positions are clumped (Figure 3.10), suggesting higher accuracy than *BlueSky* and *SirTrack*; however, the mean error appears biased in both directions the (latitude p=0.0056, α = 0.05; longitude p<0.0001, α = 0.05).

Simulated Animal Movement Corridor (SAMC) Results

Out of 45 total attempts, 30 positions were acquired with the *SirTrack* GPS collar. In SAMC1, 21 positions were acquired out of 30 attempted; in SAMC2, six out of seven positions attempted were acquired, and in SAMC3 only three positions were successfully acquired in eight attempts.

Error distances calculated between the rover unit and GPS collar ranged between two and 30 m, with four other values between 30 and 84 m in the Camp Valley dataset. There was also one egregiously erroneous position recorded in each corridor. The errors of these three positions were: SAMC1 = 395 m; SAMC2 = 413 m; and SAMC3 = 528 m, from the rover determined coordinates (Figure 3.12).

Including outliers, the mean GPS collar error was: SAMC1 = 38 m; SAMC2 = 80 m; and SAMC3 = 186 m (Figure 3.11). After removing the outlier from each site, mean error distances were reduced to the following: SAMC1 = 20 m; SAMC2 = 14 m; and SAMC3 = 14 m. (Figure 3.12). The mean *SirTrack* error across all sites, including outliers, was 101 m, while the mean error across sites after outlier removal was 16 m (Figure 3.13).

CONCLUSIONS

Stationary Testing Conclusion

All three types of collar appear biased from the control coordinates. The *ATS* collar is closer in distance to the controls but it is biased in both latitude and longitude. In the t-test of the mean error distance from the control, the *ATS* device performed superior to both

BlueSky and the *SirTrack* because the two-sided P-value is very small. Both the *BlueSky* and *SirTrack* collars appear biased in longitude. It's possible to have bias but still be more accurate, and it's also possible to adjust for bias. We can further suggest that these bias' may be caused by the North to South running topography of the Andes Mountains. Although *ATS*'s mean error positioning distance is smaller than the other two collars, none of the collars appear unreasonable in their mean error distances reported for plausible wildlife movements in Torres del Paine. We recognize however, that these results come from a small dataset that has unequal numbers of positions from different collars, making it difficult to draw any rigorous conclusions.

Simulated Animal Movement Corridor (SAMC) Conclusion

Mean error distances appear to increase with increasing canopy coverage and topographic challenge (elevation and line-of-sight obstructions) (Figure 3.13). Outliers, although obvious in these datasets due to the known control points, may not be as easily identified in larger datasets of widely ranging animals. If outliers are not identifiable, and a mean 101 m error is obtained, it may not greatly affect home range or movement estimates of such wide ranging species. On the other hand, certain egregious outliers could easily be misinterpreted to imply false habitat and landscape usage. Species with small, specialized home ranges and critical habitats might also be heavily impacted. Because many Geographic Information Systems (GIS) use *LANDSAT* digital imagery with a pixel resolution size of 30 m, critical habitat and corridor mapping may be overestimated with wide ranging species and miscalculated entirely with highly localized species. Based on these results, we recommend that GPS collars can be used with wildlife research in Torres del Paine, with considerations for the scale of the GIS and the species under study.

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FIGURES

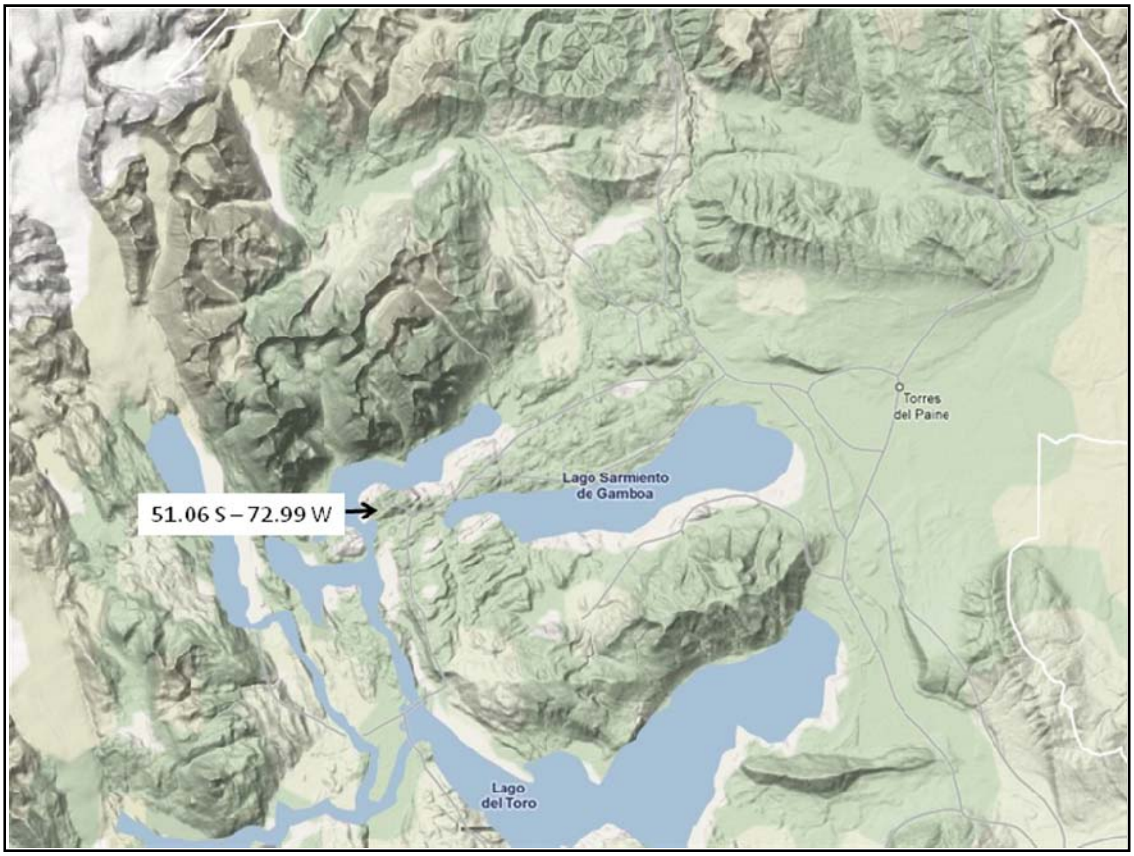

Figure 3.1 A Google Earth image of Torres del Paine National Park, grey and white is glacier, snow and ice, while shades of blue are lakes, and greens and tans are steppe-vegetation (Source: Google – Map data ©2009 LeadDog Consulting).

Figure 3.2. Location of Torres del Paine National Park, in the southern Patagonian region of Chile (Source: Google – Map data ©2009 LeadDog Consulting).

Figure 3.3. ATS, SirTrack (left), and all three GPS collars, including BlueSky (right).

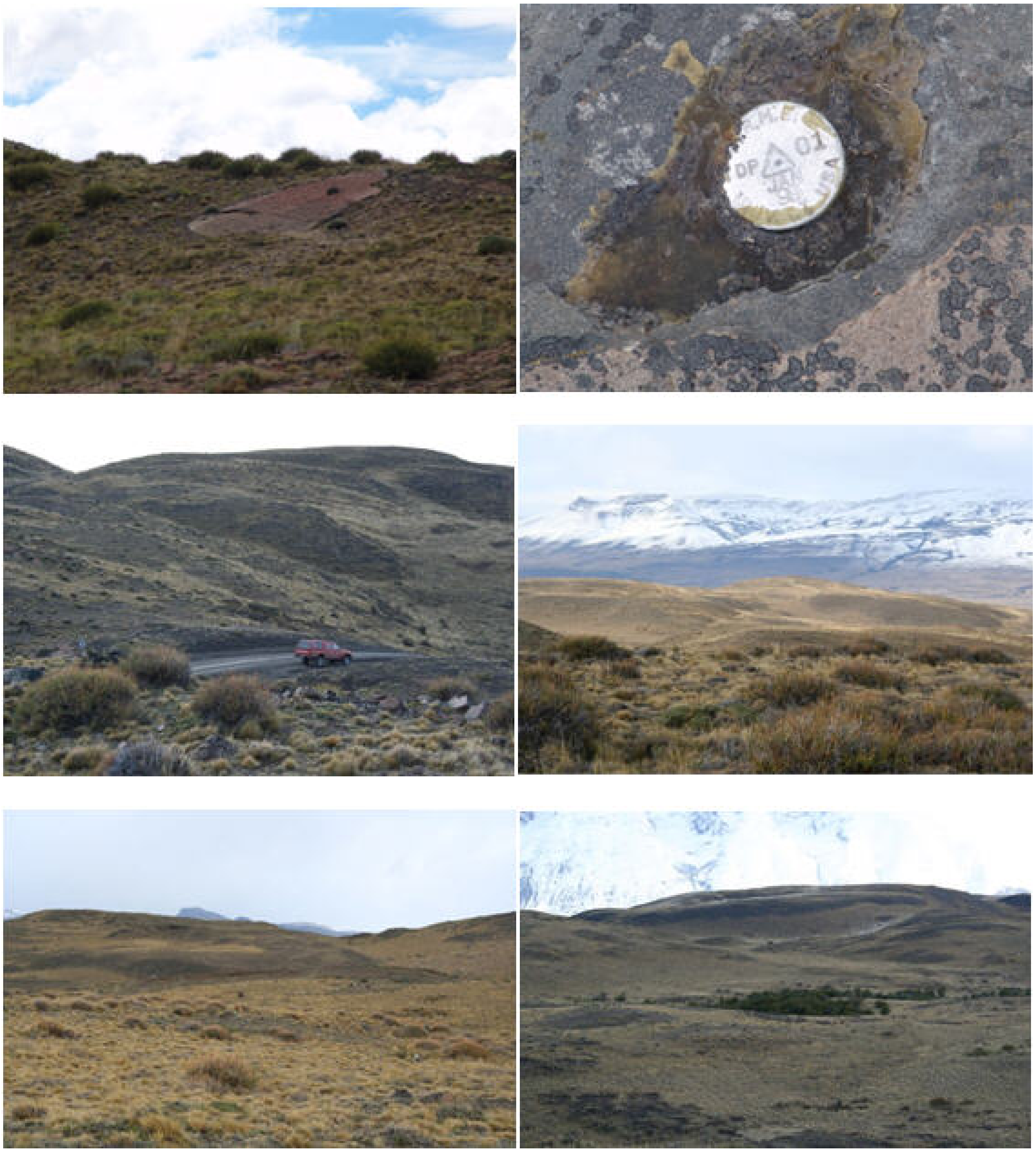

Figure 3.4. Views of the surrounding area of TDP1 at Torres del Paine National Park in the Sarmiento Lake Sector, Magallanes, Chile.

Figure 3.5. Views of the surrounding area of TDP2 at Torres del Paine National Park in the Laguna Amarga Sector, Magallanes, Chile, and the field crew setting up the Javad base unit.

Figure 3.6. Views of the surrounding area of TDP4, at Torres del Paine National Park in the Pehoe Sector, Magallanes, Chile, and the field crew setting up the Javad rover unit.

Figure 3.7. Simulated Animal Movement Corridor 1 at Torres del Paine National Park in the Laguna Amarga Sector, Magallanes, Chile.

Figure 3.8. Simulated Animal Movement Corridor 2 at Torres del Paine National Park in the Pehoe Sector, Magallanes, Chile.

Figure 3.9. Simulated Animal Movement Corridor 3 at Torres del Paine National Park in the Lago Grey Sector, Magallanes, Chile.

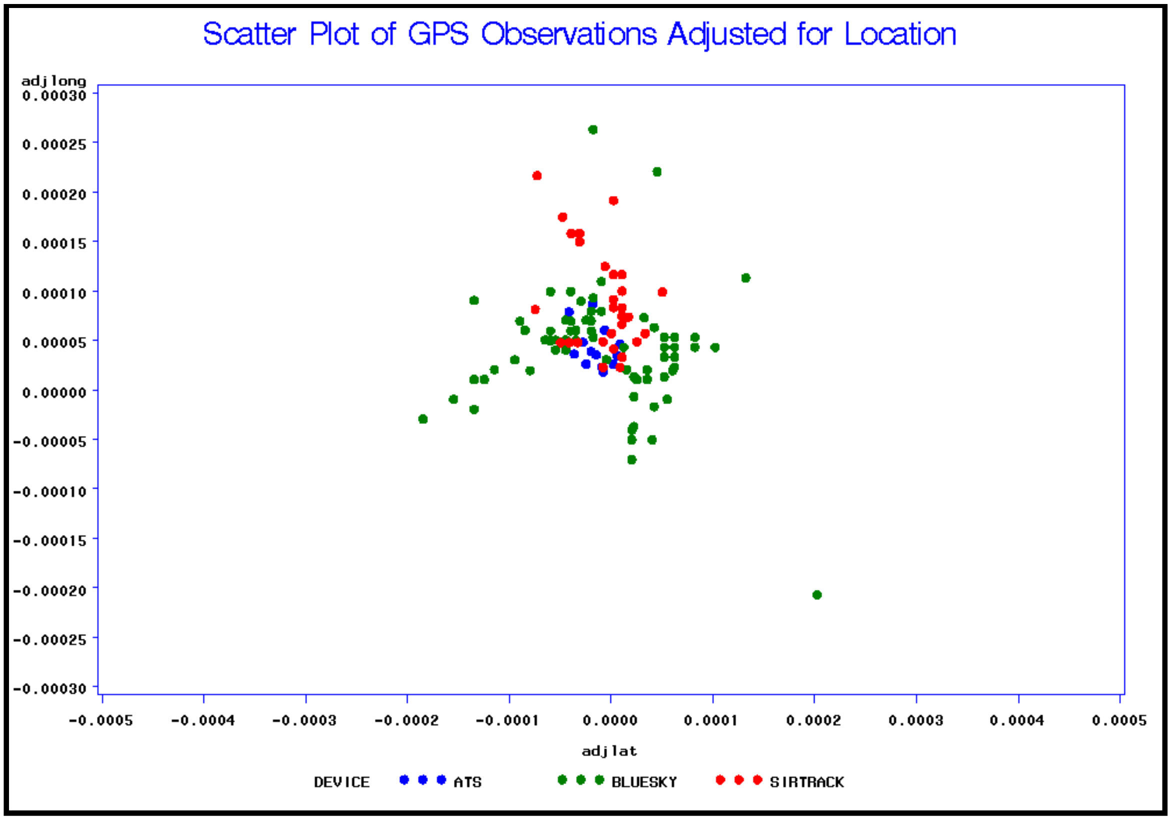

Figure 3.10. Mean positioning error, in latitude and longitude, for three different GPS collar devices on control markers in Torres del Paine National Park, Magallanes, Chile.

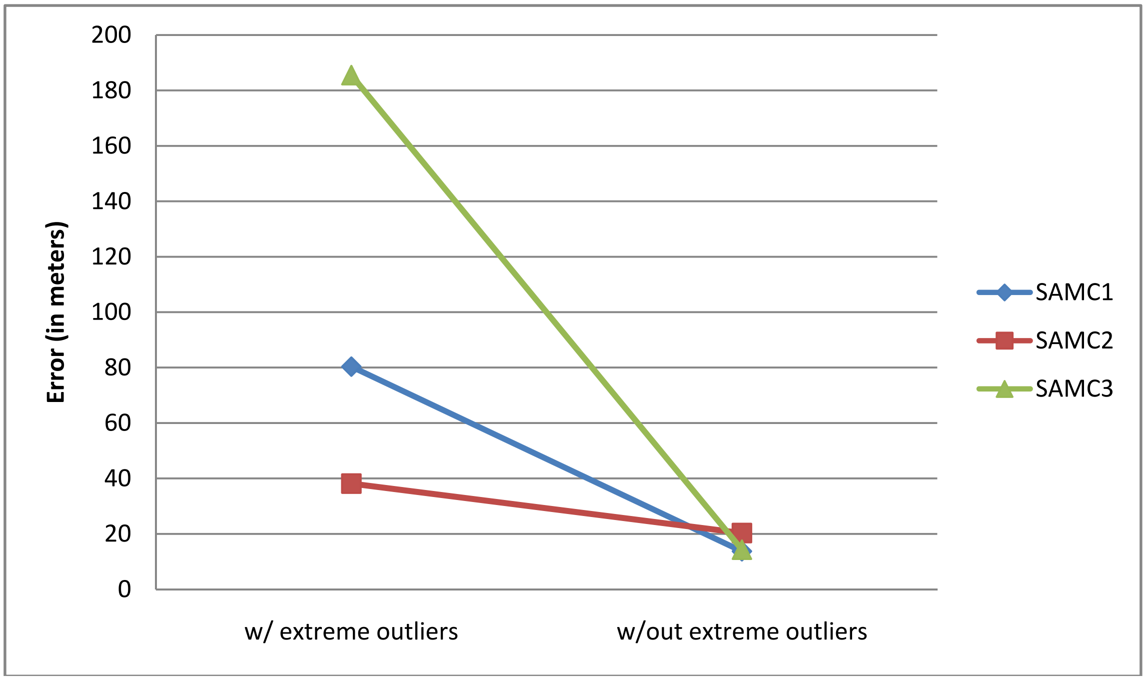

Figure 3.11. SirTrack GPS collar location error separated by site in Torres del Paine National Park, Magallanes, Chile; a mean positioning error comparison with and without the three extreme outliers; mean error is between 10 and 25 m without outliers.

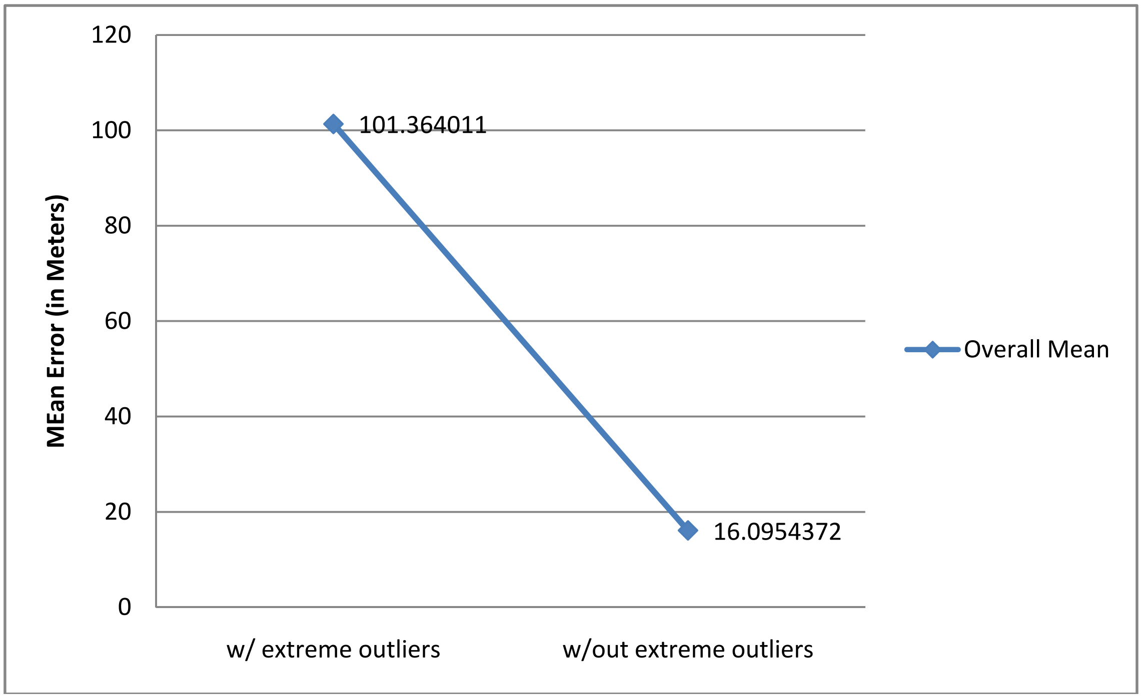

Figure 3.12. Pooled SirTrack GPS collar location error in Torres del Paine National Park, Magallanes, Chile; a mean positioning error comparison with and without the three extreme outliers; overall error is above 100m with outliers, and below 20 m with outliers removed.

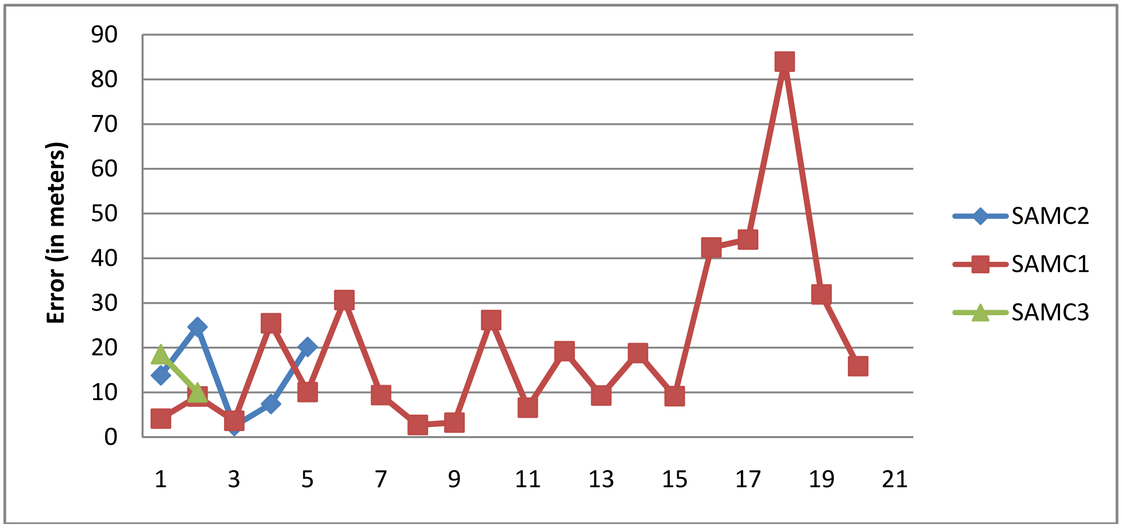

Figure 3.13. SirTrack GPS collar mean positioning error (in meters) in Torres del Paine National Park, Magallanes, Chile. Positions are separated by site, and three egregious outliers have been removed.