11-30-2001

MONITORING THE MOVEMENT OF ST. CATHERINE'S POINT LIGHTHOUSE USING THE UNITED KINGDOM's ACTIVE GLOBAL POSITIONING SYSTEM NETWORK

Jared L. Ware
United States Military Academy, jared.ware@usma.edu

Recommended Citation

Ware, Jared L., "MONITORING THE MOVEMENT OF ST. CATHERINE'S POINT LIGHTHOUSE USING THE UNITED KINGDOM's ACTIVE GLOBAL POSITIONING SYSTEM NETWORK" (2001). *Faculty Theses and Dissertations*. 1.
https://digitalcommons.usmalibrary.org/gene_etd/1

Cranfield
University

No. 86 ARMY SURVEY COURSE
MSc PROJECT REPORT

Monitoring the Movement of St. Catherine’s Point Lighthouse Using the United Kingdom’s Active Global Positioning System Network

By

CPT J.L. Ware

ROYAL SCHOOL OF MILITARY SURVEY

30 NOVEMBER 2001

DISCLAIMER

CRANFIELD UNIVERSITY
ROYAL SCHOOL OF MILITARY SURVEY

MSc THESIS

ACADEMIC YEAR 2001

CPT JARED L. WARE

MONITORING THE MOVEMENT OF ST. CATHERINE'S POINT LIGHTHOUSE USING THE UNITED KINGDOM's ACTIVE GLOBAL POSITIONING SYSTEM NETWORK

Supervisor: Maj. P. Maye

30 November 2001

Submitted in Partial Fulfilment of Requirement of Cranfield University for the Degree of Master of Science

ABSTRACT

This report provides a study of the statistical data extracted from the United Kingdom's National Global Positioning System (GPS) Network, specifically Station SCP1 at St. Catherine's Point Lighthouse on the Isle of Wight. The entire network consists of 30 continuously operating GPS reference stations located throughout Great Britain. These stations are permanently installed, precisely coordinated active GPS stations. The station at Saint Catherine's Point on the Isle of Wight appears to have shifted from its original position. This was attributed to the extensive rainfall in the autumn and winter of 2000, which could have caused soil erosion at the base of the lighthouse. This perceived movement has impacted the initial coordinates of the site.

The receivers used in the network are designed to provide users with their relative location to within a few centimetres. All stations record dual-frequency GPS data 24 hours a day at a 15 second epoch rate. The receiver at Saint Catherine's Point (SCP1), a Trimble 4000 SSI with a Model 33429.00 antenna, is affixed upon a lighthouse. Between September 2000 and March 2001 the lighthouse moved in a southern direction and produced GPS residuals outside of the accepted 95% confidence level. There is a strong correlation between the amount of rainfall experienced at Saint Catherine's Point and the rate of change of movement south of the lighthouse.

The results are based upon the GPS data provided by the Ordnance Survey and the data gathered in the field by the author. The analysis indicates St. Catherine's Lighthouse has moved approximately 10 centimetres south over the past seven months. A future cumulative rainfall total equivalent to that of the autumn of 2000 could potentially produce an additional southward shift of 2 centimetres.

TABLE OF CONTENTS

ANNEXES

TABLE OF EQUATIONS, FIGURES, AND TABLES

NOTATION AND ACRONYMS

A	Receiver and/or antenna
J	Satellite
σ	Standard Error
λ	Wavelength of a GPS Observable
ρ	Geometric range from a satellite to a receiver
φ	Phase of the carrier code observable
c	Speed of light
$d\mathrm{T}$	Clock bias error for a satellite and/or receiver
ε	Errors associated with satellite observations
τ	Atmospheric delay (ionospheric and/or tropospheric)
t	GPS clock time (unbiased)
N	Integer Ambiguity
Δ	"Change in"
BLAC	Ordnance Survey Office Blackpool Airport
BRIS	Ordnance Survey Office Bristol
BUT1	Butt of Lewis Lighthouse Antenna #1
C/A Code	Clear Acquisition Code
CARL	Ordnance Survey Office Carlisle
CARM	Ordnance Survey Office Carmarthen
CODE	Center for Orbit Determination in Europe
COLC	Ordnance Survey Office Colchester
DARE	LCRC Daresbury Laboratory
DROI	Ordnance Survey Office Droitwich
ECEF	Earth Centred Earth Fixed

EDIN	Ordnance Survey Office Edinburgh
ENU	Eastings, Northings, Up
ETRS	European Terrestrial Reference System
FLA1	Flamborough Lighthouse Antenna #1
GDOP	Geometric Dilution of Precision
GIR1	Girdle Ness Lighthouse Antenna #1
GLAS	Ordnance Survey Office Glasgow
GPS	Global Positioning System
HDOP	Horizontal Dilution of Precision
INVE	Ordnance Survey Office Inverness
IGS	International GPS Service for Geodynamics
IOMN	Ramsey Cottage Hospital Isle of Man
IOMS	Ronaldsway Airport Isle of Man
ITRF	International Terrestrial Reference Frame
KING	Ordnance Survey Office Kings Lynn
L1, L2	Carrier waves for the Global Positioning System C/A and P codes
LEED	Ordnance Survey Office Leeds
LIZ1	Lizard Lighthouse Antenna #1
LOND	Ordnance Survey Office London
LYN1	Point Lynas Lighthouse Antenna #1
MALL	Mallaig Fish Market
NAS1	Nash Point Lighthouse Antenna #1
NEWC	Department of Geomatics, Newcastle University
NFO1	North Foreland Lighthouse Antenna #1
NORT	Ordnance Survey Office Northampton

NOTT	Ordnance Survey Office Nottingham
ODN	Ordnance Survey Newlyn
OSHQ	Ordnance Survey Headquarters Southampton
P Code	Precise positioning code modulated on L1 and L2
PDOP	Position Dilution of Precision
PLYM	Ordnance Survey Office Plymouth
RINEX	**R**eceiver **I**ndependent **EX**change **F**ormat
RMSE	Root Mean Square Error
SCP1	St. Catherine's Point Lighthouse Antenna #1
SLR	Satellite Laser Ranging
SUM1	Sumburgh Head Lighthouse Antenna #1
SV	Satellite Vehicle
TDOP	Time Dilution of Precision
THUR	Visitor Centre, Dounreay, Thurso
UK	United Kingdom
VDOP	Vertical Dilution of Precision
VLBI	Very Long Baseline Interferometry

1. INTRODUCTION

The United Kingdom's Global Positioning System (GPS) National Network is an active station network that consists of 30 permanently installed geodetic GPS receivers. The entire network is controlled from the Ordnance Survey headquarters in Southampton, England. The GPS receivers are located at sites throughout Great Britain, spanning from Ronaldsway Airport on the Isle of Man to Saint Catherine's Point on the Isle of Wight. Most locations in the U.K. are within 100 kilometres of an active GPS station. These stations record dual-frequency GPS data 24 hours a day at a 15 second epoch rate. The active stations communicate automatically with the Ordnance Survey's RINEX data server, and the data is compatible with all GPS processing software. The network deployment was not designed for real-time kinematic GPS surveying, but designed in such a way to minimise disruption and expense if Ordnance Survey ever required it.

The 30 stations in the network are precisely coordinated active GPS stations that can serve as base stations for survey purposes. The GPS data allows the surveyor to achieve horizontal and vertical accuracies to within a few centimetres, and in some instances, to within a few millimetres. A user can download precise GPS data from any of the active stations within 90 minutes of the time of observation, and process it with their own GPS data. The user can obtain precise ETRS89 coordinates anywhere within Great Britain to within single-centimetre level accuracy. The coordinates can then be converted to OSGB36, National Grid, and Newlyn Datum height coordinates.

One station within the network, St. Catherine's Lighthouse (SCP1), has produced errors outside the acceptable level of 95% confidence of the coordinate mean. The lighthouse is believed to have shifted south due to soil slippage caused by record levels of rainfall in the autumn and winter of 2000. The focus of the project is to determine the sources of error (if any) in the network, provide information that determines (1) the extent to which the lighthouse has shifted south and (2) if the lighthouse has ceased moving, and to establish new coordinates for the SCP1 station based upon coordinate corrections. In terms of rainfall, the Isle of Wight experiences approximately 800 millimetres of rainfall annually. During the year 2000, St. Catherine’s Point had 941millimetres of rainfall, and experienced 1068 millimetres of rainfall from 1 May 2000 to 1 April 2001.

The GPS data used to conduct the analysis was collected by the Ordnance Survey from the active network stations throughout the United Kingdom. The rainfall data used to conduct the analysis at St. Catherine’s Lighthouse was collected by the Meteorological (MET) Office of Great Britain. The MET Office established a rainfall collection station on St. Catherine’s Point, which is within 100 metres of the lighthouse.

2. AIM

The aim of this project is to investigate the sources of data from St. Catherine’s Point to determine the magnitude of movement of the lighthouse. The investigation will look into the GPS, rainfall, and soil information available during the time interval in which the lighthouse shifted south. The objective is to statistically determine whether the lighthouse has moved, and to provide information that can help develop potential solutions to mitigate the effects of the lighthouse’s movement during periods of extensive rainfall. The overall result will be produce adjusted coordinates for St. Catherine’s Point Lighthouse within the United Kingdom’s Active GPS Network, based upon statistical analysis of the data set provided by Ordnance Survey.

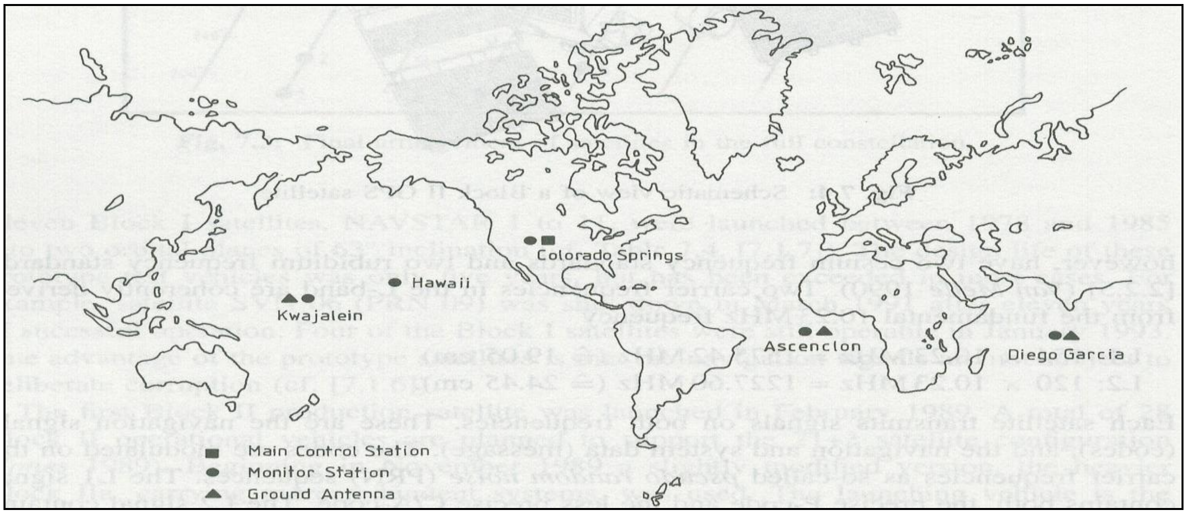
3. THEORY

The Ordnance Survey maintains the National GPS Network for the United Kingdom. This system is based upon the Global Positioning System, which is an all-weather, continuous coverage, satellite-based radio-navigation system (Farrell and Barth, 1999). GPS consists of three components, which are the space, control, and user segments. The space segment consists of the GPS Operational Constellation comprised of 24 operational satellites. The satellite constellation orbits the earth at approximately 20,200km on six orbital planes. The orbits are nearly circular at an inclination to the equator of 55° with 4 satellites per orbital plane. The satellite vehicles (SVs) emit coded radio signals that a GPS receiver decodes to determine system parameters. A satellite orbits the earth once within a twelve-hour period and rises four minutes earlier each subsequent day. Theoretically, this satellite constellation ensures that between four and eight satellites (normally seven) will be continuously visible from any location on earth. The control segment's function is to manage and monitor the status and health of the space segment. It consists of a system of tracking stations positioned throughout the world. The system is comprised of 6 monitor stations, four ground antennas, and a master control station located in Colorado Springs, Colorado. The control system monitors the satellite transmissions continuously, to predict the satellite ephemeris corrections, calibrate the satellite clocks, and to update the navigation message periodically. The user segment is comprised of the entire user community, which includes military and civilian GPS receivers. The user segment embodies millions of users equipped with GPS receivers that can track signals transmitted from the GPS satellites. The user receiver operates passively on land, sea, and air, to observe and record transmissions of several satellites and applies solution algorithms to obtain position, velocity, and time. The table below demonstrates the functionality and products of the three GPS segments.

Table 1: GPS Segments and associated functionality

Segment	Input	Function	Product
Space	Navigation Message	Generate and transmit code and carrier phases, navigation message	P(Y)-codes, C/A codes, L1, L2 carrier, navigation message
Control	P (Y)-code, observations, time (UTC)	Produce GPS time, ephemeredes, manage SVs	Navigation message
User	Code and carrier phase observations, navigation message	Navigation solution, relative positioning, OTF, etc.	Position, Velocity, Time

Figure 1: GPS Control Stations (Adapted from Seeber, Page 214)



3.1 GPS Signals

GPS satellites transmit three types of signals: two carrier frequencies, two navigation codes, and one navigation data message. All satellite transmissions are coherently derived from the fundamental frequency of 10.23 MHz (Leick, 1995). Each satellite transmits ranging code and navigation data by using code-division multiple access (CDMA) on the same two carrier frequencies, L1 at 1575.42 MHz and L2 at 1227.60 MHz. The two navigation codes are P-code (precise) and C/A-code (coarse acquisition), with three pseudorandom noise (PRN) ranging codes associated with each satellite. The precise (P) code modulates on both L1 and L2 carrier phases. The P code is a 7-day 10.23-MHz PRN code. It is available to military and other authorised users and is modulated on both the L1 and L2 frequencies at a chipping rate of 10.23 MHz with a 30-metre wavelength that repeats itself every 37 weeks. The United States Department of Defense can deny the use of the P code using Anti-Spoofing, which is designed to encrypt the P code signal. This denies unauthorised users the ability to decipher the signal into a Y (encrypted) code. The C/A code is available to military and civilian users and is modulated only on the L1 frequency at a chipping rate of 1.023 MHz with a wavelength of 300 metres and repeats itself every 1 millisecond. The table below outlines the GPS observables in terms of frequency and wavelength (λ).

Table 2: Satellite Transmission (GPS Observables)

	C/A	**P (Y)**	**Navigation Data**
Frequency	1.023 MHz	10.23 MHz	50 MHz
Wavelength	293m	29.3	5950 km
Repetition	1 millisecond	1 Week	
Code Type	Gold	Pseudo Random	
Carried On L1 – 1.57452 GHz, λ = 19cm L2 – 1.22760 GHz, λ = 24cm	L1	L1, L2	L1, L2
Advantage	Easy to Acquire	Precise Positioning Jam Resistant	Time and Ephemeris

3.2. GPS Observables

There are two types of GPS observations: Pseudo-range and carrier phase. The code phase observable is used primarily for navigational purposes. To determine the signal propagation time, the user needs a copy of the code sequence in his receiver. The carrier phase observable is the preferred observable in high-precision surveying. For precise geodetic applications the pseudoranges have been derived from phase measurements on the carrier signal because of the much better resolution (Seeber, 1993). Hence, the carrier phase signal is used for data collected within the UK Active GPS Network.

3.2.1. Carrier Phase Observable

Carrier phase tracking is a technique that provides the essential framework for precise geodetic positioning. The carrier phase observable has a much shorter wavelength for L1 (19 cm) and for L2 (24 cm), which can result in a more precise solution than that found using code phase observables. GPS receivers can code correlate the C/A and P whilst tracking the L1 and L2 carrier waves. The frequency of carrier waves is much higher and the wavelengths are shorter, resulting in the pseudorange of the carrier wave to be determined much more accurately. A good geodetic GPS receiver can resolve a phase of a carrier wave to 1% of the wavelength. A receiver using the two carrier frequencies can make phase measurements with a resolution of approximately 2 mm, and surpasses the code correlation pseudorange accuracies of several metres (Ashkenazi et. al, 1990).

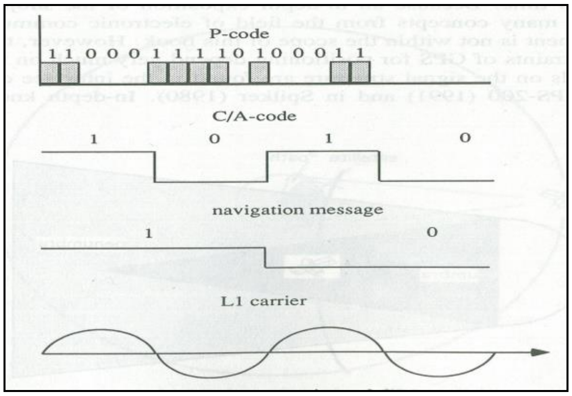
The carrier phase observable is the number of full carrier wavelengths plus any fraction of a wavelength between the satellite and the receiver at any given epoch (Leick, 1995). Once the carrier wave is received, the receiver can determine the fractional wavelength it receives. However, it cannot determine the number of whole wavelengths that are received before the fractional wavelength. To determine the fractional wavelength, the Doppler shifted carrier phase transmitted from the satellite is differenced with the oscillator generated carrier phase of the receiver. This calculated difference is known as the carrier beat phase. The integer ambiguity, or number of whole carrier wavelengths, is initially estimated. It is later solved in the processing techniques applied for a solution. The integer ambiguity is converted to a distance by multiplying it with the wavelength of the carrier phase (19 cm or 24 cm). The carrier phase equation, representing the carrier phase observable from the satellite to the receiver, is listed below (RSMS, 2001).

Equation 1: Carrier Phase Observable
(Adapted from RSMS Lecture "GPS Phase and Range Equations, 26 June 2001)

$$\varphi_A^j(T_A) = \varphi^j(T_A) + fdT_A - f\left\{\frac{\rho_A^j\left(T^{GPS}\right) - \rho_A^j\left(T^{GPS}\right)dT_A}{c}\right\} - \varphi_A(T_A) + N_A^j + \varepsilon_L$$

The initial term is the phase reading in receiver time from satellite *j* to receiver *A*. The first term on the right-hand side of the equation, $\varphi^j(T_A)$, refers to the phase of the emitted signal in receiver time. The next term, $f dT_A$, is the receiver clock error bias expressed in terms of range by multiplying receiver time error by the frequency of the carrier wave. The next term is the phase of the signal when it was transmitted by the satellite in satellite time. The term is linearised using Taylor's theorem to account for the motion of the satellite during the transmission of the signal. The next term, $\varphi_A(T_A)$, is the phase generated by the oscillator of the receiver in receiver time. It can be defined as the phase of the generated wave in the receiver multiplied by the receiver time. The fifth term denotes the integer ambiguity (N) between the satellite and the receiver. It represents the initial integer ambiguity or the full number of wavelengths between the satellite and the receiver. The final term, ε_L, represents the carrier phase measurement error due to random noise. Additional errors associated with the ionosphere and troposphere are omitted to preserve simplicity within the equation. Ionospheric conditions have differing effects upon code and carrier phase signals, and cannot be adequately addressed using this specific equation. The discussion of ionospheric, tropospheric, and multipath effects will be addressed later in this paper.

Figure 2: Composition of a Satellite Signal (Adapted from Leick, Page 66)



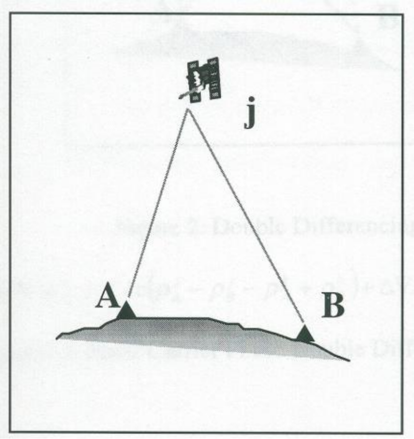
3.3. Differencing

The use of relative GPS positioning techniques is required for the high accuracy requirements of most geodetic applications. The concept of relative positioning consists of using code and carrier phase measurements between two receivers and the same satellite at the same epoch. This allows for the relative position of the two receivers to be calculated. A principle advantage of relative positioning is the elimination of errors. Errors associated with GPS signals, satellite and receiver clocks, and ionospheric/tropospheric conditions exhibit a degree of correlation when receivers at several stations are tracking signals from several satellites simultaneously (Wells et al, 1986). Taking the differences between several measurements will reduce and remove many errors associated with satellite surveying. The three methods to be discussed are single, double, and triple differencing. Although differencing can be accomplished with both code and carrier phase observables, the focus within this paper will be on carrier phase observables.

3.3.1. Single Differencing

The first step in relative positioning is a process known as single differencing. If two receivers A and B are observe the same satellite j at the same preset nominal receiver epoch, then the effect of the satellite clock errors cancel (Leick, 1995). Single differencing can be accomplished using epochs, satellites, or receivers. It is normally done by subtracting the measured observables between a satellite and one station from the simultaneously measured observables between the same satellite and a second station (Seeber, 1993). The overall effect is single differencing is that clock errors between the receivers are averaged and multiplied to produce a solution that is free of satellite clock errors. The figure below outlines the concept of single differencing.

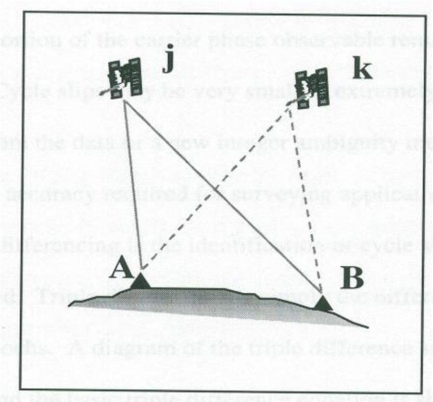
Figure 3: Single Differencing
(Adapted from RSMS Lecture "GPS Phase and Range Equations, 26 June 2001)



3.3.2. Double Differencing

Double differenced solutions remove receiver clock errors when observations are taken at two receivers to two satellites at the same epoch. The most important feature of double differencing is the cancellation of large receiver clock errors in addition to the cancellation of the large satellite clock errors (Leick, 1995). If the receiver clock drifts between successive observations are negligible, then receiver clock errors will cancel. The figure below demonstrates the concept of double differencing.

Figure 4: Double Differencing
(Adapted from RSMS Lecture "GPS Phase and Range Equations, 26 June 2001)



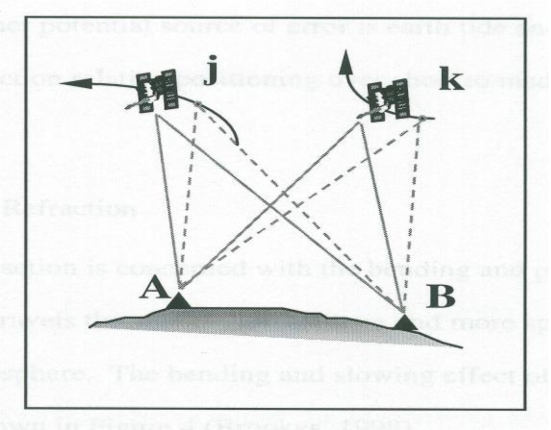
3.3.3. Triple Differencing

The accuracy demanded for most geodetic applications requires the use of a GPS receiver able to continuously measure the whole number of full wavelengths and the length of the partial wavelength between the satellite and the receiver. The receiver 'counts' the number of whole cycles that have passed for each epoch after the integer ambiguity is solved. Integer ambiguity is normally fixed to an integer value using Taylor's theorem with iterative least squares techniques to refine the estimates until a value is converged upon after successive iterations. The triple differenced solution is the difference of two double differences between different epochs or intervals (Leick, 1995).

Triple differencing is used to identify outliers from the double differenced solution and cycle slips. Cycle slips occur when the receiver loses signal lock with the satellite, which results in a jump in the number of integer cycles. It is essentially a sudden jump in the carrier phase observable by an integer number of cycles. Cycle slips can be very large or extremely small. In either case, cycle slips must be removed from the data or a new integer ambiguity must be determined to achieve the accuracy required for geodetic applications. Triple differences have a major advantage in that cycle slips are recorded as individual outliers in the computed residuals. After outlying measurements are removed the double difference solution can be re-computed to obtain a more reliable integer ambiguity value. It should be noted that triple differences lose some geometric strength because of additional differencing over time (Leick, 1995). The figure below outlines the concept of triple differencing.

Figure 5: Triple Differencing

(Adapted from RSMS Lecture "GPS Phase and Range Equations, 26 June 2001)



3.4 Software

Typical GPS relative surveys rely on the assumption that the effects of systematic errors are eliminated or significantly reduced through double differencing methods found in software packages. This assumption is based upon the fact that the distance from the receiver to the satellite is over 20,000 kilometres and the baseline lengths are several orders of magnitude shorter in length. In effect, the signals follow the same path and are equally affected by systematic errors. In relative GPS schemes with 30-40 kilometre baseline lengths this assumption is valid. However, as the baseline lengths increase this becomes invalid due to GPS signals having to penetrate the atmosphere from various angles to reach the stations with a network.

GPS is an interferometric technique and requires good a priori coordinates for at least one reference station site to be known. The orbit, earth rotation parameters, and the station coordinates must be given together in the same reference frame to achieve an accurate solution. The reference frame itself has seven degrees of freedom, which are three translations, three rotations, and a scale factor. The development of GPS software has been focused on taking environmental and statistical factors into account to produce the best overall solution for station coordinates.

3.4.1. Bernese Software

The United Kingdom's National GPS Network uses the University of Berne's Bernese software package for network computations. This software uses a multi-station adjustment, in that baselines are not computed, but station coordinates are. This technique is significant in that accuracy is directly exploited and the reliability of the results increases (Seeber, 1993). In a multi-station adjustment all data that have been observed simultaneously with three or more participating receivers are processed jointly, and baselines are not determined. Instead, coordinates of the network with the associated complete variance-covariance matrix are derived. It provides a rigorous adjustment of the observations using all mutual stochastic relationships. For geodetic purposes, the multi-station adjustment is preferred over the baseline concept for two reasons. First, the accuracy potential of GPS is completely exploited. Second, the reliability of the results is increased. The advantages to multi-station software are high accuracy surveys over larger distances the use of sophisticated mathematical models provides for rigorous statistical data analysis. However, it should be noted that scientific processing software requires extensive experience and a vast understanding of GPS signals and errors (Seeber, 1993).

Bernese software was developed for commercial uses requiring high accuracy, reliability, and productivity. It is well suited for permanent network processing from Receiver Independent Exchange Format (RINEX)[1] data to a high degree of accuracy. Beginning in 1994 the IGS orbits allowed for the achievement of sub-centimeter accuracy in the horizontal position and about 1 cm accuracy vertically even for regional networks with a diameter of several thousand kilometers. For example, the Center for Orbit Determination in Europe (CODE) achieved 4mm accuracy in a network of 75 stations in a geodetic survey campaign between 1992 and 1996 (Rothacher and Mervart, 1996). The software was initially developed using data from six European stations of the IGS network where the distances between the stations were between 200 and 600 kilometres. Bernese software was a practical and economical choice for use with the UK National Active GPS Network.

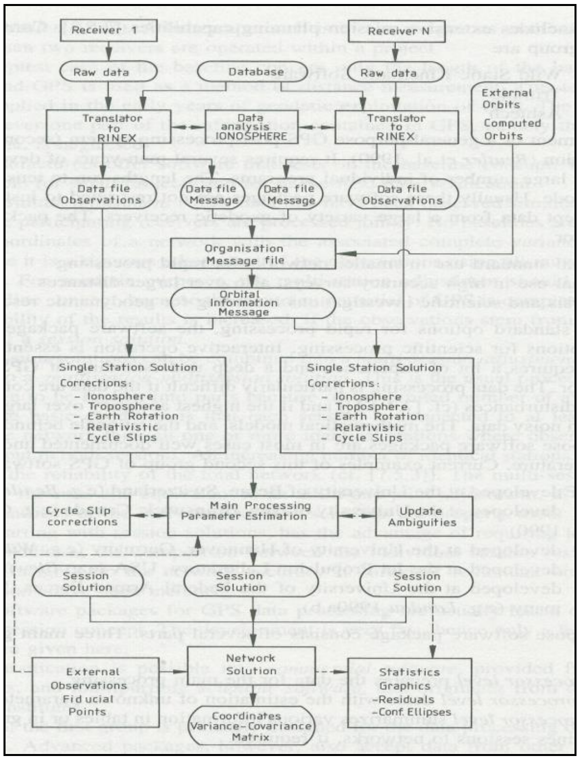
The 4.0 Version of the software uses the double difference observable as the basic observable. This allows it to approximate the satellite clocks by a single point-positioning program before the precise parameter estimation. For station coordinates, rectangular coordinates X, Y, and Z are given in ITRF93. Absolute and relative receiver clock offsets are estimated using the double difference observable. For epoch-specific station coordinates, a set of station coordinates is assigned to each epoch. Phase pre-processing is achieved using triple differencing where cycle slips are recorded as individual outliers in the computed residuals. Cycle slips are corrected simultaneously looking at different

---

[1] RINEX was first presented in March 1989 to the Fifth International Geodetic Symposium in Satellite Positioning held in Las Cruces, New Mexico.

combinations of L1 and L2 carrier waves. A check of residuals is performed after the first day solution is achieved with outliers being removed from the final solution. With Bernese software, the a posteriori root mean square error (RMSE) is expected to be approximately 3 millimetres. If the RMSE is higher, it could be due to data collected from low quality receivers, date collected in extremely bad conditions, or a pre-processing step was unsuccessful (Rothacher and Mervart, 1996). Bernese software uses a least squares algorithm and a Helmert transformation to achieve final coordinate values.

Figure 6: Typical GPS Receiver Software Application (Adapted from Seeber, Page 280)

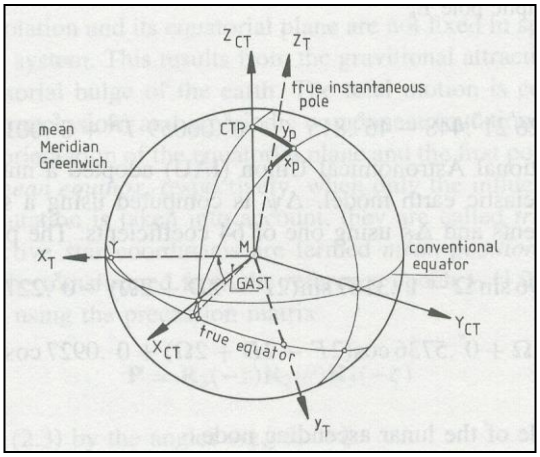


3.5. Fiducial GPS

The increasing demand for higher accuracies and a reliable scientific monitoring system has bolstered the development of the fiducial GPS network. Fiducial GPS is an extension of existing geodetic differential surveying methods. It differs from traditional systems in that the reference stations within the network are fixed to a global reference frame at sub-centimetre accuracy. Moreover, a time element is introduced to compensate for the effects of plate tectonics. At present, the stations are established in the Earth Centred Earth Fixed (ECEF) International Terrestrial Reference Frame (ITRF). The ITRF represents the realisation of the International Terrestrial Reference System (ITRS). The origin is at the centre of mass of the whole earth, including the oceans and the atmosphere. Its length unit is the metre, defined in a local Earth frame in the meaning of a relativistic theory of gravitation (Boucher and Altamimi, 1996). The ITRF was established by the Terrestrial Reference Frame Section of the Central Bureau of the International Earth Rotation Service. It represents one of three products of the bureau, the other two being the determination of Earth rotation parameters and the realisation of the International Celestial Reference System.

Figure 7: True instantaneous and mean conventional terrestrial system

(Adapted from Seeber, Page 16)



The ITRF coordinate system is fixed to a much greater degree of accuracy than the WGS-84 system. The ITRF coordinate system relies on extremely accurate measurements for baseline length and azimuth using a differential positioning system known as Very

Long Baseline Interferometry (VLBI). The implementation of the ITRF is based upon the combination of sets of station coordinates and velocities derived from observations of space-geodetic techniques such as VLBI, GPS beginning in 1991, and Satellite Laser Ranging (SLR) (Boucher and Altamimi, 1996). Satellite Laser Ranging helps fix the Earth's centre and assists the accurate modelling of the effects of earth tides, polar motion, and other geophysical anomalies. Fiducial GPS allows users to transfer the highly accurate positions of the fiducial stations to the unknown stations within a network through the inherent precision of GPS measurements and the use of post processed precise satellite orbits.

Fiducial GPS requires that the known and unknown points in a network be occupied simultaneously with GPS receivers. Conceptually a two stage process can be perceived in which the precise orbits of the satellites are first determined from the known sites, and the positions of the unknown sites are then determined using computed ephemeredes. This can be achieved in a combined solution in which the orbits are determined together with the coordinates of the unknown stations simultaneously. With long baselines (500-1000km) special processing techniques are used to resolve integer ambiguities of the carrier phase measurements and compensate for the effects of atmospheric delays. Fiducial GPS can be used for the studying of crustal motions, monitoring the changes of mean sea level, and in the establishment of continental GPS reference networks (Moore, 1993).

A fiducial GPS network consists of a number of geodetic stations whose relative coordinates are known to a very high order of accuracy. These stations can be pillars sited next to SLR facilities or radio telescopes used for VLBI. Stations can be points whose coordinates have been determined by a previous fiducial GPS campaign. Fiducial GPS involves the taking of phase measurements over a number of new points, whose coordinates are required, simultaneously with observations made at the fiducial sites, such as those within the EUREF GPS network or the Royal Greenwich Observatory SLR facility. The complete set of phase measurements is adjusted simultaneously, solving not only for the three-dimensional coordinates of the new points, but also for the unknown satellite orbits in a complex computational process.

Fiducial GPS involves the computation of a theoretical orbit for each of the satellites with respect to the forces acting on it, such as gravitational attractions of the earth and other planets, the moon, and the sun. During the adjustment process the theoretical orbits are subjected to the GPS measurements made from the known fiducial stations and the unknown new points. The adjusted network of ground stations and satellite orbits is finally positioned, scaled, and oriented to the coordinate reference system defined by the fixed coordinates of the fiducial stations.

The high positional accuracies of the fiducial stations are transferred from the fiducial stations to the new points using the satellite orbits. Typically, a fiducial station maintains a positional accuracy of a few centimetres in 1000 kilometres. The next stage is to resolve the carrier phase integer ambiguities, which is best completed using a fiducial network containing a wide selection of baselines. A network of baselines between 40-1000 kilometres can be used to resolve the integer ambiguities.

Fiducial GPS has been developed as a powerful means for the determination of precise coordinate differences. It can be used for monitoring crustal motions through repeated observations at various epochs, because it is possible to achieve relative positioning accuracies averaging a few millimetres over baselines of several hundred kilometres. Thus, fiducial GPS can be used by geodesists and geophysicists as a tool for monitoring crustal dynamics and plate tectonics to accuracies comparable to those achieved by VLBI and SLR (Ashkenazi and Ffoulkes-Jones, 1990). The Yunnan Province in China was studied in 1990 for the relation between the surface deformation field, the gravity field and earthquakes, and to understand the interaction between various fields and the relation to earthquake occurrence. The first epoch measurement of the three-dimensional coordinates of the geometrical deformation field was performed with GPS over an area of 250 x 300 kilometres using a 20-station network and dual-frequency receivers (Seeber and Xian, 1989). After the processing of data using both Bernese software and GEONAP software (and resolving all ambiguities), the relative accuracy for all connections between control points was approximately 1 centimetre. To determine the apparent movement of St. Catherine's Point Lighthouse to an acceptable level of accuracy, the data from the entire UK Active GPS network (processed using Bernese software) will be compared at various epochs from fiducial GPS observations.

Deformation analysis from GPS measurements at different epochs can give information about all three dimensions (east, north, and up) simultaneously, which is necessary to determine the movement of St. Catherine's Point Lighthouse. A GPS survey of Iceland was conducted in 1987 to study the crustal deformation its subareal accretionary plate boundary to relate the results to tectonic processes. The network consisted of 63 stations over an area of 300 x 280 kilometres. Observations were taken at various epochs for a three dimensional deformation analysis to yield three-dimensional crustal data (Jahn et al, 1989). For baselines between 0 and 100 kilometres, the north vector root mean square error was 5.3mm, the east vector root mean square error was 5.2mm, and the up vector root mean square error was 10.7mm. It was determined that the plate spreading rate was 2.2cm/year and the overall GPS network accuracy was ± 1 to 2 cm. A similar accuracy in all three dimensions will be required from the UK Active GPS network to determine the centimetric movement of the lighthouse at St. Catherine's Point between epochs.

3.6. GPS Sources of Error

There are numerous sources of error that affect the accuracy of GPS observations for relative positioning. Major sources of error are due to atmospheric refraction in the ionosphere and troposphere, multipath, ephemeris data, satellite clock, and the receiver. The accuracy of a relative GPS position is largely based upon the receiver's ability to precisely measure the range to the satellites. In many instances, errors tend to prevent perfect measurements in pseudorange. In most cases, errors can be modelled and reduced or eliminated altogether in post-processing with the Bernese software package. Ranging errors can be grouped into five classes:

Class 1: Receiver. Errors affecting the range measurement of the receiver due to software capability, antenna phase centre shifts, receiver clock biases, and noise.

Class 2: Atmospheric. Errors caused by refraction in the ionosphere and troposphere.

Class 3: Ephemeris. An error in the transmitted orbital location of the satellite.

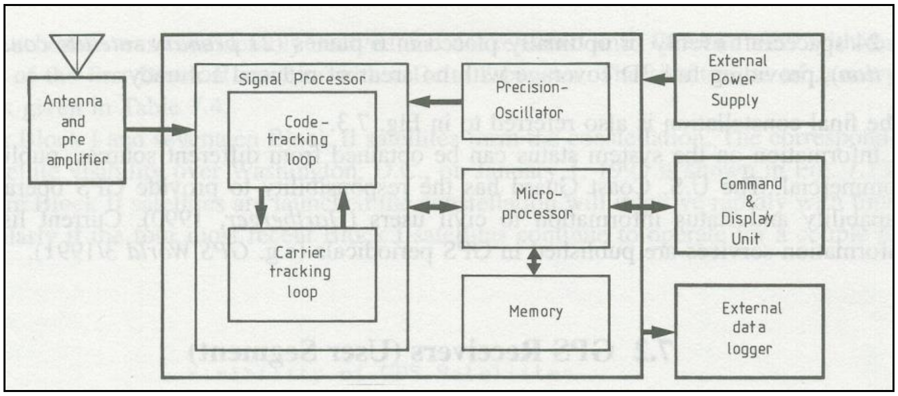
Class 4: Satellite Clock. Errors in the transmitted clock time from the satellite.

Class 5: Multipath: Errors caused by the receiver taking in reflected signals.

3.6.1. Receiver

Errors in the receiver's measurement of range are caused by electronic noise, matching errors in the observable signals, receiver clock errors, or flawed software computational routines. Geodetic grade GPS receivers have high signal to noise ratios as defined by the satellite signal. The signal to noise ratio is the satellite strength divided by the internal electrical noise of the receiver. Receivers with a higher signal to noise ratio perform better because they lock onto the code and phase observables faster and with more reliability. The higher the signal to noise ratio the better the receiver will perform in fast static and kinematic surveys (Leick, 1995). High signal to noise ratios are essential for receivers that use advanced signal processing techniques such as signal squaring, Z tracking, and cross correlation. Most geodetic receiver error is almost negligible when sessions are conducted in a static mode.

Figure 8: Internal Functions of a GPS Receiver (Adapted from Seeber, Page 230)



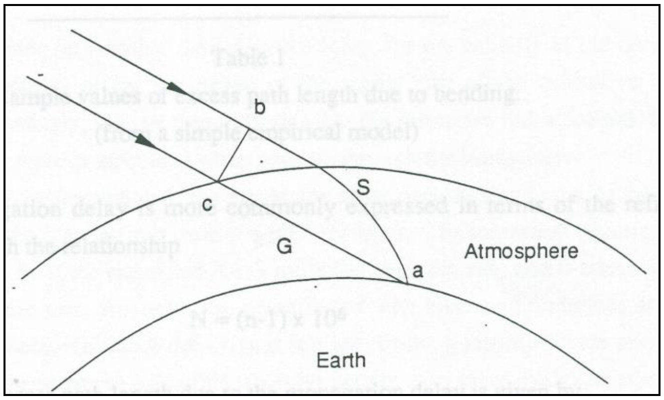
The antenna phase centre error is brought about by the fact that the electrical centre of the antenna does not correspond geometrically to the mechanical centre of the antenna. The effect will be eliminated through differencing if the same types of antennas are used on the same type of receivers in a relative positioning network. The effect in compounded when different antennae are used on different receivers in the same network scheme.

Antenna phase centres move with the elevation angle of the observed satellite signal. The movement can be between two and three centimetres on geodetic grade GPS antennae. The electrical and mechanical phase centres for L1 and L2 receivers may be off by a few millimetres (Seeber, 1993). To correct the inconsistencies, most antennae manufacturers and GPS groups provide the offset for antenna centres for GPS users. With some antennae phase centre offsets being azimuth dependent, antennas must be oriented prior to surveying to correct for the offsets. However, the lack of precise definition of phase centres tends to prevent GPS from obtaining millimetre-level accuracies, even with the high accuracies of the carrier phase measurements.

3.6.2. Atmospheric Refraction

A troublesome error that is somewhat difficult to model is the affect of atmospheric refraction. Atmospheric refraction imparts bending and propagation delay on a GPS signal as it travels through the ionosphere and the troposphere. The diagram below illustrates the effects of atmospheric refraction.

Figure 9: Atmospheric Refraction (Adapted from Dodson, Page 1)



The desired GPS straight-line signal distance G in addition to the path outside the atmosphere is required for a positioning solution. The true electrical path of the GPS signal is travelled by the path from a to b. The geometric distance is outlined in the equation below.

Equation 2: Geometric Distance

$$G = \int_{a}^{c} dG$$

The electrical path distance is outlined in the equation below.

Equation 3: Electrical Path

$$L = \int_{a}^{b} n\,ds$$

The refractive index *n* allows for the slowing and the *ds* term represents the bending of the electrical signal. The excess path length travelled is the difference between L and G. This excess path equation is listed below.

Equation 4: Excess Path Length

$$L - G = \int_{a}^{b} (n-1)\,ds + (S - G)$$

$$where: S = \int^{b} ds$$

The propagation delay is defined by the integral from a to b of (n-1)*ds*. This is a function of the refractive index of the atmosphere. The bending effect is attributed to the term (S – G). The bending effect is inversely proportional to the elevation angle of the signal. The lower the elevation angle the greater the bending affect within the atmosphere. The magnitude of bending significantly decreases when the elevation angle is between 10° and 20°. At angles less than 10° the effect exceeds 2 centimetres. To alleviate the effect of bending an elevation mask of 15° is used for GPS surveys.

Table 3 : Atmospheric Bending (Dodson, Page 2)

Elevation Angle (in degrees)	Effect (in metres)
2	0.417
5	0.075
10	0.019
20	0.005
45	0.001
90	0.000

Another aspect to be addressed is propagation delay due to the refractivity of the atmosphere, specifically in the ionosphere and the troposphere. To compensate for propagation delay it is necessary to determine the index of refractivity and the path length in order to model for the refractive errors.

3.6.3. Ionosphere

The ionosphere is generally accepted to be between 50 to 1500 kilometres above the surface of the earth. It is a dispersive medium, meaning that the refractivity index is a function of frequency, and can be modelled to more than 99% accuracy (Klobuchar, 1996). The ionosphere has different effects upon code and carrier phases, in that the code phase experiences delay and the carrier phase is quickened. The ionospheric correction for the code phase is positive whilst the correction for the carrier phase is negative. The GPS signal delay or advance is dependent upon the total electron count along the signal path. The total electron count is the parameter of the atmosphere that produces the most delay. It is defined by the number of free electrons in one square metre along the path of a signal (Leick, 1995). The ionospheric refractivity formula is listed below.

Equation 5 : Ionospheric Refractivity

$$N_I = 1 \pm \frac{40.3(N_e)}{f^2}$$

The term N_e is the free electron density and f is the signal frequency. The ionospheric delay or advance is also affected by the elevation of the satellite, the time of day of the observation, and the latitude of the receiver. The lower the elevation of the satellite the greater the amount of ionosphere the signal must travel, thus imparted a greater affect on the signal. Electron activity tends to be greater during daylight hours, reaching its peak at 1400, and tapers off to relatively constant values between 2200 and 0800 daily (Leick, 1995). The latitude of the receiver, essentially in regions near the equator or near the poles, has an effect on the delay of GPS signals. Ionospheric delay is frequency dependent and its effects can be eliminated using dual frequency GPS observations. In cases where dual frequency receivers are not used ionospheric models can be adapted to compensate for the effects of the ionosphere. Bernese software does not model ionospheric conditions because errors can be eliminated from forming ionosphere-free linear combinations of L1 and L2 carrier waves.

3.6.4. Troposphere

The troposphere is the layer of the atmosphere from the earth's surface to approximately 50 kilometres above the surface of the earth. The troposphere, unlike the ionosphere, is a non-dispersive medium. Signal delays arise in both code and carrier observations as signals pass through the earth's lower atmosphere of dry gases and water vapour. The troposphere is more subject to change than the ionosphere and is extremely difficult to model without accurate meteorological data. It is normally modelled using a combination of models based upon empirical data. The tropospheric refractivity is comprised of a wet and dry component and is outlined in the equation below:

Equation 6: Tropospheric Refractivity

$$N_T = 77.6\frac{P}{T} + 3.73x10^5\frac{e}{T^2}$$

The first term is the dry component and the second term represents the wet component. The total atmospheric pressure is represented by P, and the surface temperature is T. The partial pressure of water vapour is represented by the letter *e*. The dry component constitutes 90% of tropospheric refraction. It can be modelled to within 5% or less using the surface pressure and the surface temperature (Leick, 1995). The wet component is made up of the remaining 10%. It is difficult to model because water vapour is not as predictable because it can significantly vary over time and distance. Another phenomenon within the troposphere is that as the elevation angle of the satellites decrease, the delay increases; yet, the true height of the troposphere is difficult to determine because it varies with surface temperature and latitude. This phenomenon is shown in the table below.

Table 4: Tropospheric Component Effects (Dodson, Page 9)

Elevation Angle	Wet Term (m)	Dry Term (m)
5	2.3	26.0
10	1.2	13.0
30	0.4	4.6
90	0.2	2.3

There are a number of tropospheric models available to account for the delay within this level of the atmosphere. Various models differ with assumptions derived with respect to vertical refractivity profiles and the correlation between vertical delay and the elevation angle (Leick, 1995). The most widely used tropospheric models within GPS software include Saastomoinen, Black, and Hopfield. Bernese software uses the Saastomoinen tropospheric model in its calculations. Careful applications of the Saastomoinen model can reduce the tropospheric error to less than a centimetre, with the remaining error being comprised of the wet component (5 cm). It is possible to extract the precipitable water content over the station using Bernese software given that St. Catherine's Point is a MET rainfall station and is equipped with a GPS receiver. The software subtracts the dry component of tropospheric refraction from the estimated zenith tropospheric delay (Rothacher and Mervart, 1996).

3.6.5. Ephemeris

The accuracy of the ephemeredes, which are the satellite positions in space, is in important factor in relative GPS positioning. The position of the satellite is computed by the GPS Operational Control Station and uploaded to the satellites as part of the navigation message. Broadcast ephemeredes are sent by the GPS satellites on a stream of data superimposed upon the C/A and P codes. The message includes satellite behaviour and orbital information. The Operational Control Station predicts the orbits by fitting Keplerian orbital elements to tracking data with additional elements to account for orbit perturbations (Langley, 1997). The GPS receiver uses this information to mathematically calculate instantaneous satellite position, velocity, and clock offset values. The ephemeris data is formatted in one-hour blocks and is derived from previously observed orbits. The receiver interpolates between the one-hour estimates of orbital parameters to produce instantaneous values of the satellite's position for both code and carrier phase measurements.

The interpolation of this information with regard to the satellite's orbit inherently contains errors. To improve accuracy better estimations of the satellite orbits are needed to solve for the receiver position in post processing. Precise ephemeris data is available through many organisations that use GPS extensively, such as the IGS and Ordnance Survey. This information contains accurate satellite positions and clock offsets that are free from errors caused by earth tide and polar motion effects. The removal of the systematic errors in the processing software reduces the uncertainty of satellite orbits to between 10 and 50 centimetres. The National Geodetic Survey produces precise ephemeris within 3 days with an orbital error of 0.5 metres. The International GPS Service for Geodynamics produce very precise ephemeris within 14 days with an orbital error of 15 centimetres.

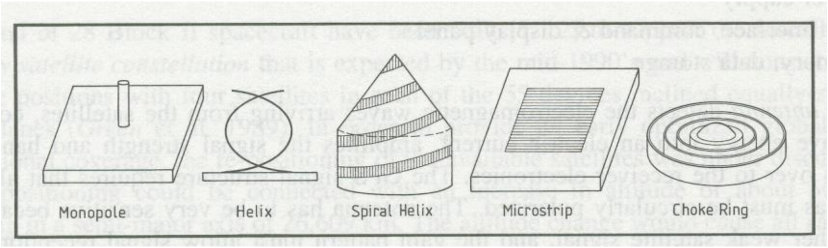
3.6.6. Satellite Clock

GPS satellites are equipped with extremely accurate atomic clocks. The clocks are synchronised to GPS time. The atomic clocks do not perform well when adjusted, and corrections to the satellite clocks are uploaded to the satellites from the navigation message and transmitted to the receivers from the satellites. Clock errors, although small in magnitude, will exist even with the when clock corrections are applied. These errors are approximately 1 to 2 parts in 10^{13} per day (Langley, 1997). However, satellite clock error can be reduced or eliminated with the application of differencing techniques.

3.6.7. Multipath

Multipath errors occur when a satellite signal bounces off a reflective surface before it reaches the receiver's antenna. A satellite signal can be reflected by a number of surfaces such as vehicles, buildings, rooftops, water, and fences. The multipath signal travels a longer path and is out of phase with direct signals. Since the geometry between satellites and the reflecting body will repeat twice daily multipath effects show the same pattern every day. The attenuation of signals at low incident angles is very small which is why satellites at low elevations tend to have strong multipath interference (Leick, 1995). Carrier phase multipath errors are typically in the order of centimetres, which could negate the actual degree of movement determined for St. Catherine's Point Lighthouse. The strongest signal reflections tend to occur near the antenna, which is why manufacturers have focused on antenna design to mitigate the affects of multipath. The figure below shows some of the innovations created by manufacturers to reduce multipath signals at the antenna.

Figure 10: Antenna Components to Reduce Multipath (Adapted from Seeber, Page 230)



According to Langley, good antenna design and the use of choke ring devices have reduced the susceptibility of multipath interference (Langley, 1997). Another consideration in reducing multipath is site location, in that locations with few reflective elements tend to experience little or no multipath. For example, rooftops are bad multipath environments since there are often many vents and other reflective objects within the antenna's field of view (Leick, 1999). The figure below illustrates this point.

Figure 11: Multipath Environment (Ordnance Survey Headquarters, Central London). Note the air conditioning vents located on the centre-right of the figure.

3.7. International Terrestrial Reference Frame

The most notable global reference frame is the IERS International Terrestrial Reference Frame (ITRF). It was determined that earth rotation parameters could not be described through theory. The parameters must be determined through actual observations by an international time and latitude service. On January 1, 1988 the International Earth Rotation Service (IERS) based in Paris, France, assumed the task of observing and determining earth rotation parameters. The principle techniques used for observation are laser ranging to satellites and to the moon and Very Long Baseline Interferometry (VLBI). The reference frame was initially based upon the combination of VLBI and SLR measurements. Since 1993, global GPS measurements have been implemented into the reference frame. This has been conducted by combining global VLBI, SLR, and GPS solutions from several research institutes to determine the coordinates of various stations and the associated station velocities. Doppler Ranging Integrated on Satellite, known as

DORIS, also contributed to the ITRF. The ITRF has been realised on an annual basis since 1988.

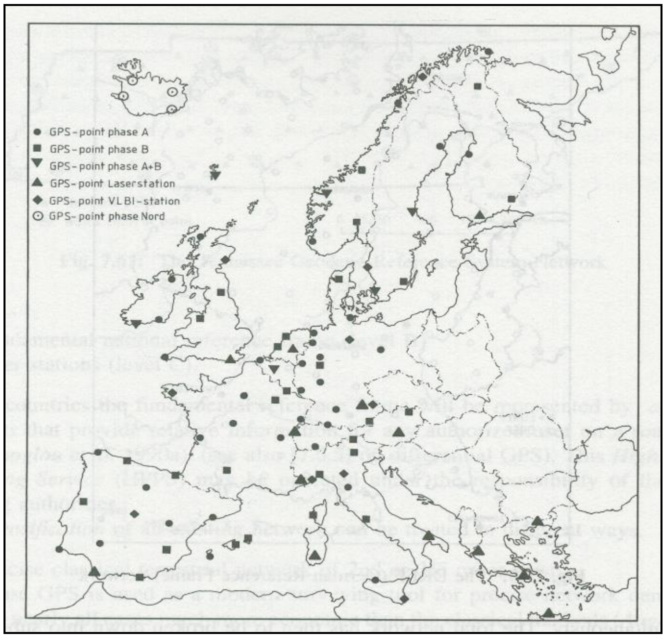
The ITRF is an alternative realisation of WGS84 that currently includes more than 500 stations at 290 sites around the world. It was created by a civil GPS community independent from the United States military, who operate the broadcast terrestrial reference frame. Each version of ITRF is given a code year to identify it. It consists of a list of coordinates (X, Y, and Z in metres) and velocities (ΔX, ΔY, and ΔZ in metres per year) of each station in the terrestrial reference frame. These values also maintain an estimated level of error. The coordinates relate to the time at a specific epoch. In order to obtain the coordinates of a station at any other time, the station velocity is applied appropriately to account for the effects of tectonic plate motion.

The datum realised by the ITRF is called the International Terrestrial Reference System (ITRS). Initially there was a difference between ITRF and ITRS, but are so similar that both can now be assumed as identical for most purposes. ITRS has its origin at the centre of mass of the whole Earth, including the oceans and the atmosphere. Its unit of length is the metre. The orientation of its axes is consistent with that of the BOH System at 1984.0 within ± 3 milliseconds. Its time evolution in orientation is such that it has no residual rotation relative to the Earth's crust. The ITRS is realised by estimates of the coordinates and velocities of a set of observing stations, the ITRF. The ITRF is important for a number of reasons. Firstly, the International GPS service provides geodetic services based upon ITRF on the Internet free of charge. Secondly, a user can use ITRF stations equipped with permanent GPS receivers as reference points of known coordinates to precisely coordinate his GPS stations using data downloaded from the Internet. This procedure is known as fiducial GPS analysis and is the conceptual background to the creation of the UK's Active GPS Network. Finally, a user can obtain precise satellite positions in ITRF that are not subject to the deliberate degradation of selective availability.

3.7.1 European Terrestrial Reference Frame

The European Reference Frame (EUREF) network was created with ITRF sites as fiducial points. The campaign was performed in May 1989 at 90 sites in 17 western European countries, with 25 sites collocated with either VLBI or SLR stations. The observations were conducted using 60 dual-frequency receivers, with 300km to 500km between network stations. Six stations are located in the United Kingdom, one being an SLR station and one being a VLBI site. It was the first campaign for the determination of transformation parameters between the national geodetic networks of all countries on a sub-continent. The stations coordinates had to be determined with the highest achievable accuracy (approximately ± 1 cm), which was realised using the fiducial point concept, one week of observations, dual-frequency receivers, precise orbits, and advanced software (Seeber, 1993). This technique constrained the GPS positions to VLBI locations at three stations in order to determine the precise orbits and define a terrestrial GPS reference frame aligned with prior VLBI results. Figure 12 shows the locations of the VLBI stations within the European Reference Frame Network, and includes GPS stations in the United Kingdom.

Figure 12: European Reference Frame Network (Seeber, 327)



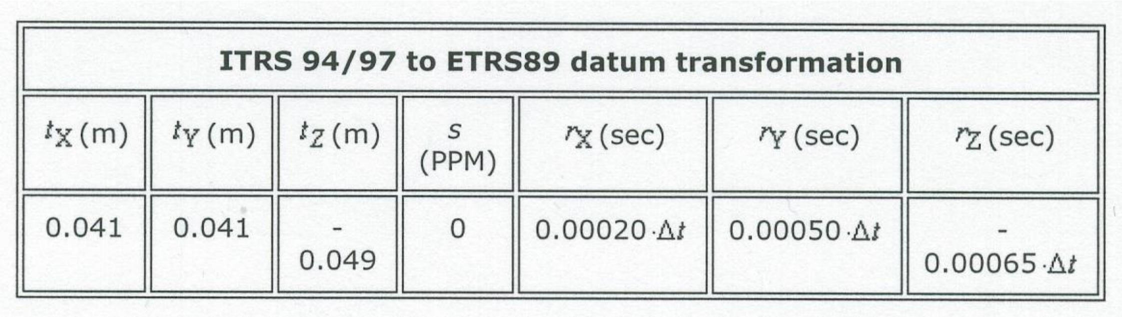
ETRS89 is the European geodetic datum, introduced to unify national reference systems for surveying, mapping, GIS and navigation in Europe. Its purpose is also to define the precise reference system to monitor tectonic and geodynamic motions and to integrate vertical datums in Europe. ETRS89 is a geocentric reference system fixed to the stable part of the European plate and identical to ITRS89 at the epoch 1989.0. Its geographical coordinates are based on the GRS80 ellipsoid. It is defined to 1cm accuracy and consistent with the global International Terrestrial Reference System (ITRS). Coordinates and velocities given in any ITRS year can be transformed into ETRS89 and vice versa. ETRS coordinates are based on the most recent realisation and referred to as the ITRF for a specified year. ETRS is accessible through the primary realisations of the EUREF permanent GPS stations network and the validated EUREF campaigns.

ETRF89 and ETRS89 are important to the realisation of the UK Active GPS Network because of the datum and terrestrial reference frame used for Ordnance Survey GPS positioning. The National GPS Network is a modern three-dimensional terrestrial reference frame that uses the ETRS89 as its datum and is a densification of the ETRF89 terrestrial reference frame. This coordinate system is the basis of modern Ordnance Survey control survey. The national network provides a single terrestrial reference frame that unifies the Ordnance Datum Newlyn (ODN) (traditional vertical coordinate system) and OSGB36 using a transformation software package. Note that tectonic plate effects are not a concern within British mapping, making it simpler to convert ETRS89 and ETRF89 coordinates to other types of coordinates if it is required. Using transformation techniques, precise positions can be determined by GPS in ETRS89 using the National GPS Network and then converted to national grid and ODN coordinates. Since the ETRS89 datum is realised by many European precise GPS reference points, the National GPS Network is essentially a terrestrial reference frame enabling easier access to this datum in Great Britain.

Coordinates are based upon the most recent realisation and represented at the time of computation as ITRF or ETRF using conversion formula through ETRS89. All National GPS Network points are coordinated in three dimensions by GPS in ETRS89. The ITRF or ERTF coordinates are computed in a high accuracy, physical reference frame, where the coordinates are fixed in time. Note that ITRF and ETRF coordinates must correspond to a reference year in order to maintain consistency. The values can be used and linked to future realisations. For the UK National GPS Network, a user can obtain ETRS89 coordinates for unknown points, which are suitable for use with the Ordnance Survey transformations to the mapping coordinate systems OSGB36 and ODN. Additionally, ETRS89 can be converted to the ITRS datum if necessary.

A six-parameter transformation between ETRS89 and the various versions of ITRS is listed in the figure below. Note that this transformation is not suitable for ITRFs prior to ITRF94 because these calculations are not in use for the active network.

Figure 13: Datum transformation: ITRS94 and ITRS97 to ETRS89 (Source: Ordnance Survey)



ITRS 94/97 to ETRS89 datum transformation

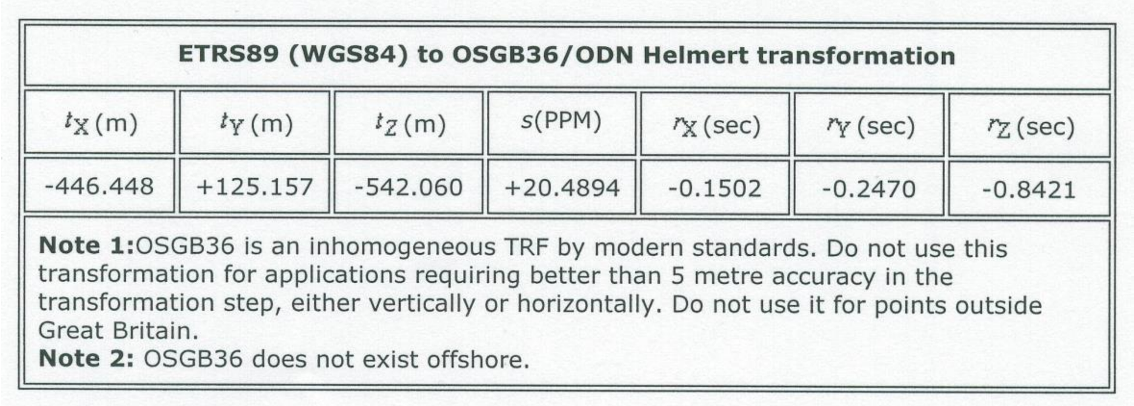
t_X (m)	t_Y (m)	t_Z (m)	s (PPM)	r_X (sec)	r_Y (sec)	r_Z (sec)
0.041	0.041	-0.049	0	$0.00020 \cdot \Delta t$	$0.00050 \cdot \Delta t$	$-0.00065 \cdot \Delta t$

The rotation parameters are time dependent and must be multiplied by the time difference in years between the epoch at which ITRS is being used and the fixed epoch ETRS89, represented in the figure above by Δt. This is necessary because ETRS89 is slowly diverging from ITRS due to the motion of the Eurasian tectonic plate. The tectonic plate is constrained by gravity and move about on the surface of the Earth. The finite motion of the plate can be described by rotation about an axis passing through the centre of the Earth. The relative motion of any pair of plates can be described by such a rotation, with the motions represented by angular velocity vectors (England, 1989).

The transformation can be used to determine the coordinates within a fiducial network using IGS permanent GPS stations as fixed control points and the free IGS Internet information such as Earth orientation parameters and satellite ephemeredes. The coordinates adopted for the fixed IGS stations should be ITRS coordinates in the same realisation of ITRS as used to determine the IGS precise ephemeredes, which is currently ITRF97. For a GPS survey, the ITRF97 coordinates of the IGS reference stations at the epoch are obtained by multiplying the ITRF97 station velocity by the time difference between the ITRF97 reference epoch and the GPS survey epoch, and adding this position update to the ITRF97 reference epoch station. The coordinates of the unknown stations can now be realised in ITRS at the epoch of the survey. To convert the coordinates to the ETRS89 datum, the transformation in Figure 13 can be used with Equation 8, which is listed later in this report.

The UK National GPS Network uses a Helmert transformation to convert ETRS89 and ITRS coordinates to OSGB36 and ODN heights. However, there is an error of up to five meters both horizontally and vertically, which is practical for navigation purposes but not valid for surveying applications. Again, the transformation listed below can be used in conjunction with Equation 8 of this report to convert the coordinates to the ETRS89 datum.

Figure 14: Datum Transformation: ETRS89 to OSGB36 and ODN (Source: Ordnance Survey)



ETRS89 (WGS84) to OSGB36/ODN Helmert transformation

t_X (m)	t_Y (m)	t_Z (m)	s(PPM)	r_X (sec)	r_Y (sec)	r_Z (sec)
-446.448	+125.157	-542.060	+20.4894	-0.1502	-0.2470	-0.8421

Note 1: OSGB36 is an inhomogeneous TRF by modern standards. Do not use this transformation for applications requiring better than 5 metre accuracy in the transformation step, either vertically or horizontally. Do not use it for points outside Great Britain.
Note 2: OSGB36 does not exist offshore.

The only difference between the EUREF and ITRF is a velocity term. In ITRF, stations move in a global reference frame. In EUREF, stations move relative to the stable portion of the Eurasian tectonic plate. With respect to ITRF, Europe moves at a speed of approximately 2cm per year. The transformation from ITRF to EUREF implies most sites in EUREF will have velocities near to zero. The ITRF is determined using global distributions of space geodetic sites, whereas EUREF is realised by a much denser regional network, to include all ITRF in Europe.

3.7.2. UK National GPS Network

The UK Active GPS Network, conceptually implemented in early 1989, was developed primarily to make surveys more efficient. The Ordnance Survey began using GPS in early 1987 to establish minor control points. Initially, all GPS measurements had to be adjusted to fit the existing network control in OSGB36. However, given the problems of accessibility of GPS equipment, computational problems and maintenance costs of the existing passive network, Ordnance Survey reviewed its requirements for a horizontal control network. The review concluded that a GPS network of stations should be established over those areas of Great Britain covered by 1:1250 large scale mapping (Christie and Wilson, 1993).

The UK National GPS Active Network was developed using specific criteria. Each station in the network was located at an interval of 20-25 km around urban centres and 40-50 km in rural areas. This density allowed for four controlling stations to be positioned around each urban centre to obtain a fairly even coverage nationally. This ensured that four control stations would enable sufficient redundancy to be introduced into the computation to solve for transformation parameters from satellite to a mapping datum. The intention was to create a national infrastructure rather than one that worked primarily in urban areas. To complete national coverage, active stations were to be deployed such that no point in Great Britain, including all offshore islands, is more than 100km from an active station. Major urban areas were to be within 50km of an active station.

The GPS network stations were selected based upon the ability to easily occupy the station. All stations were to be accessible 24 hours a day and preferably without having to submit for prior approval from an outside agency. All stations were to be accessible by two wheel drive vehicles in all weather conditions. Finally, all stations were to have no masks for GPS observations and no likelihood of masks developing.

The GPS site criteria were also based upon the nature of the receiver. The typical arrangement at a site included a tripod, antenna, and a 30m antenna cable (to keep the receiver indoors). All receivers, locked in a 0.5 x 8.0 x 0.8m cabinet, were to log data continuously for use with any field GPS survey. The Ordnance Survey field team searched for stations that could be ground or roof based that were vandal proof. The GPS station required good visibility above the horizon with a stable and fixed platform. The criteria also required a building that did not move, in that “high rise flats flex in strong winds” (Cox, 1998). The field team listed potential areas as the roof of an office building, sewage works, military bases, and airfields. Office buildings were a top priority if they could offer easy access, security, and had a lease agreement of at least five years. Airfields were the lowest priority because of possible disturbance from radar, antennas, and ground movement near the runways.

The active network was developed as the primary layer of reference stations. The network is active because each station is equipped with continuously observing permanent GPS receivers. The proliferation of GPS for precise positioning led to the development of the network using precisely known coordinates for each station. These coordinate values had to be determined to the highest order of accuracy possible. The stations were chosen based upon the ability of the receiver to collect and process the best data possible.

4. LITERATURE REVIEW

Extensive background research was conducted to verify the methodology in determining the southward shift of St. Catherine's Point Lighthouse. A significant amount of research has been conducted using GPS for both static and kinematic purposes. All publications to include books, journals, articles and manuals were checked and compared to ensure the consistency, validity, and accuracy of the information. Moreover, every effort was made to use current source material for the research. In the event of conflicting information between various sources, all technical questions were referred to Ordnance Survey. Dr. Paul Cruddace, Geodetic Advisor at Ordnance Survey, assisted with technical issues concerning the GPS active network and pointed to credible sources of data used by Ordnance Survey.

There is not an extensive amount of published information concerning the United Kingdom's National GPS Network. The best source of information about the network can be found on the Ordnance Survey's National GPS Network Internet site at http://www.gps.gov.uk. The site is dividing into four service areas, which are the information page, the active GPS network RINEX data server, the passive GPS station database, and the online coordinate converter page. The site provides an overview of the entire network and the locations of the GPS stations. The site provides all of the necessary information used to determine positional accuracy. This includes the Cartesian coordinates and latitude, longitude, and height of the GPS stations (ETRS Coordinates, Epoch 1989.0), the type of receiver established at each station, and the antenna data associated with each receiver. The site provides both updated and archived GPS information from all of the permanent reference stations within the active network.

Many of the books dealing with the topic of GPS are similar in design and content. Most books discuss the basic background and advent of GPS as a system. The books also have a detailed explanation of peripheral topics associated with GPS, such as the types of GPS signals, sources of error, various techniques to process data, and observable components of phase equations.

The most useful book applicable to this thesis was Gunter Seeber's Satellite Geodesy. This book had an excellent explanation of GPS time as the fourth component for computing accurate coordinates of a station. The text explained the International GPS Geodynamics Service (IGS), which provides precise earth rotation parameters, precise orbits, and precise reference data used for fiducial GPS. The information in this text for determining an epoch was critical to the experimental procedure undertaken, in that coordinate shifts at specific epochs were compared for all stations within the active network. Seeber explained the significance of the ITRF with respect to a national active network, and that a set of coordinates in the active network represents the satellite datum in the U.K. at a particular epoch. The book validated that a national fundamental network, with interstation distances of 50 to 100 kilometres, should maintain an accuracy goal of 1 centimetre over 100 kilometres. The theoretical explanation of signal propagation with respect to the path between the satellites and the ground stations was used ensure that the GPS station at St. Catherine's Point was receiving signals with interference. Chapter 7.2 was used to determine the possible affects upon the receiver at St. Catherine's Point and to understand the mathematical formulae the receiver uses to process data. Chapter 7.3 discussed GPS observables and data processing and provided an explanation of equations used in GPS computations.

The paper “The Ordnance Survey of Great Britain’s Contribution to the ETRF89” provided was used to determine the origins of the UK National Network. The SciNet92 project resulted in a homogeneous and coherent network that covered the whole of Great Britain. This project was a precursor to the UK National GPS Network The project provided the realisation of coordinates in ETRF89, which is used for the UK Active GPS Network. The paper outlined that the final coordinates were to be referenced in ETRF89, epoch 1989.0, and provided as Cartesian coordinates in frame ETRF89 and as Geodetic coordinates in frame ETRF89 and ellipsoid GRS80. The paper also provided the theoretical link between ITRF, ETRF, and the UK National Network.

The paper “A New Geodetic Datum for Great Britain – The Ordnance Survey Scientific GPS Network” by R.R. Christie and J.I. Wilson introduced the criteria needed to develop and construct a national GPS network in Great Britain. It validated that St. Catherine’s Point met the GPS-specific criteria to be used as a station in the active network. According to the report, the criteria for an ideal site for GPS occupation includes 24-hour access, accessible to two-wheel drive vehicles in all weather conditions, and have no masks for GPS observations with little likelihood of masks developing. The report also supported the use of fiducial GPS as the best available technique for use in the national network.

Another useful book was Alfred Leick’s <u>GPS Satellite Surveying</u>, (Second Edition). This was the best reference in terms of developing an overall understanding of GPS theory used to develop the UK National GPS Network. The chapter discussing the geometry of epoch solutions provided sufficient background information into understanding how to derive mathematical solutions for the comparison of epochs. This was the technique used in the analysis of the potential movement of St. Catherine's Lighthouse. The important features of the epoch solution are the equality of the standard deviation for both ambiguities and the high correlation between all parameters impacting the equation. Additionally, the geometry is the same for every epoch solution so long as the stochastic model remains unchanged. This technique was used to determine the movement of the lighthouse and that there was no extreme horizontal deformation in the network that may be contributing to the overall network solution at St. Catherine's Point.

Chapter 9, titled Propagation Media, Multipath, and Phase Centre, was used to gain an understanding of atmospheric effects on GPS signals, given that St. Catherine's Point is located adjacent to the ocean. The chapter explained the significance of multipath, ionospheric and tropospheric conditions, and how GPS antennas do not receive signals equally well from all directions. Chapter 14 provided an explanation of how GPS has increased the progress of improving the accuracy of reference frames, in that the software to process GPS data must ultimately produce coordinates in ETRF89. At a high level of accuracy, GPS vectors relate to the ITRF because the precise ephemeris is computed from observations taken at stations whose location is given in the ITRF. As theory has predicted and GPS experimentation confirms, the accuracy of GPS vectors only weakly depends on the distance between stations. The text validated that GPS is well suited to provide rigidity to geodetic networks of national extent and to prevent the build-up of systematic errors.

GPS For Everyone by L. Casey Larijani was a useful text for a basic understanding of type of GPS receiver and antenna used at the GPS station on St. Catherine's Point. It discussed the technical and scientific applications of GPS, such as natural-resource management for monitoring the withdraw of land surfaces. This information was useful in terms of the National GPS Network station on St. Catherine's Lighthouse. The lighthouse experienced slight movement southwards towards the ocean after a significant period of rainfall saturated the soil upon which the lighthouse was constructed. This book gave a few examples of how GPS can be used to monitor movements of features due to environmental factors, similar to how GPS was used to initially explore the potential movement of St. Catherine's Lighthouse.

A book produced by the Soil Survey of England and Wales entitled Soils and Their Use in South East England proved to be beneficial for understanding the soil conditions on the Isle of Wight. The book also gave detailed information on the soil components upon which the GPS station at St. Catherine's Point rests. Information on soils and the effect rainfall has upon their properties has been used in the analysis section of the thesis.

The book The Environment of the British Isles by A.S. Goudie and D. Brunsden provided an extensive amount of information on soil erosion, landslides, and rainfall on the Isle of Wight. Thematic maps from the book were used to describe the effects of the climate on particular areas within the United Kingdom and at St. Catherine's Point. The important information gained from this text was the average annual rainfall totals, the regions of relief, limestone landscapes with effects of landslides, and coastal erosion data, all used in the analysis of the potential movement of St. Catherine's Lighthouse. The changing summer rainfall patterns in the United Kingdom have indicated that the rainfall totals on the Isle of Wight from 1980-1991 are 30% lower than those over the period from 1951-1980, indicating overall that less rainfall has fell upon the soil at St. Catherine's Point in the past few decades.

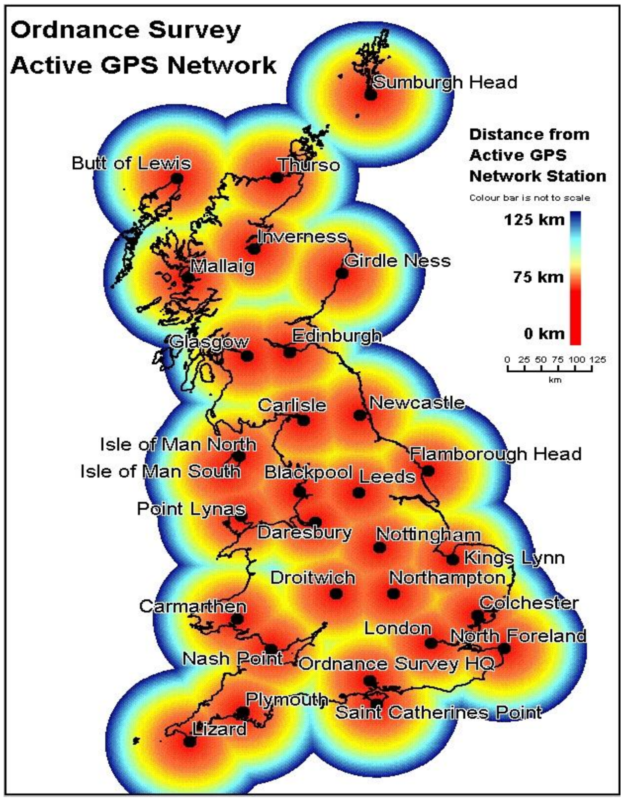
The article “Precipitation, Groundwater, and Ground Deformation” by the Disaster Prevention Research Institute provided a link to the deformation studies based upon significant amounts of localised rainfall leading to the displacement of soil. Ground tilts and strains caused by rainfall were studied at Yura, Japan. The investigation found that there were seasonal and secular changes in the tilt response to rainfall. The provisional analysis concluded that a seasonal change in the discharge of groundwater occurred, and this was the mechanism of deformation of the ground. The comparison was measured from the strains and tilts at different ground depths. The study also proposed that geodetic and astrometric measurements with very high precision were needed to record the strain and tilt movements. St. Catherine’s Point Lighthouse is a similar study, in that GPS was used to determine the magnitude of movement of the lighthouse, and horizontal deformation of the lighthouse was compared at various epochs based upon cumulative rainfall totals.

Overall, there is enough written material available to begin an investigation into determining how much St. Catherine’s Point Lighthouse has moved and why using GPS observable information provided by Ordnance Survey. There is also sufficient information available on the soil aspects of St. Catherine’s Point. There is little information concerning how to mitigate the effects of the environment with respect to a network of active GPS receivers. The literature used for this thesis provided a solid background for understanding GPS theory and how the accuracy of a base station can be affected within a network.

5. METHODOLOGY

The experimentation to determine the extent to which St. Catherine's Point Lighthouse shifted was conducted with computers and equipment available to all military surveyors at the Royal School of Military Survey in Hermitage, England. The data set was provided by Ordnance Survey, Southampton, England. The procedure consisted of four stages: Preparation, Site Study, Processing, and Analysis. The initial stage began with a visit to Ordnance Survey's Headquarters in Southampton. The Geodetic Department, Ordnance Survey, explained the situation regarding St. Catherine's Point Lighthouse. A GPS receiver is located on the lighthouse, and is part of the United Kingdom's Active GPS Network. A map of the entire network is provided below and in Annex A.

Figure 15: U.K. Active GPS Network

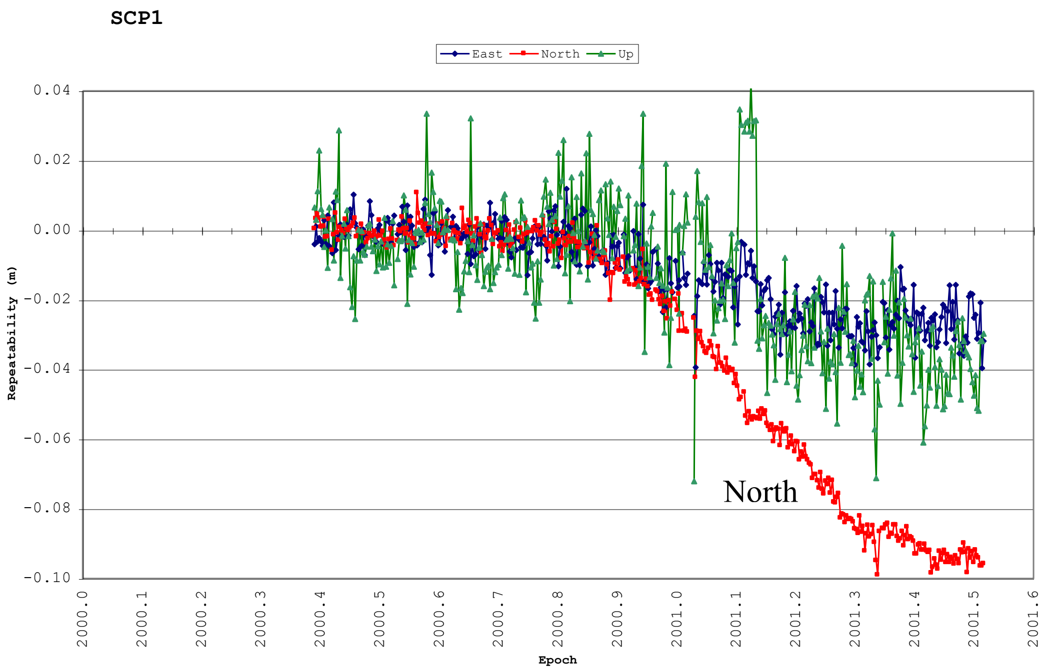


5.1. Preparation

St. Catherine's Point is located at the southernmost tip of the Isle of Wight. It was constructed in 1838 to provide safe passage for the shipping lanes of southern England. It resides at the periphery of the UK National GPS active network, where it continues to provide service to maritime activities. Since November 2000, the coordinates at St.Catherine's Point have produced large error residuals in the Northings value. It was thought to be a routine problem with the entire network adjustment, and was not problematic. However, the Northings value continued to show a gradual shift to the south. After a review of the entire network, it was determined that the receiver at St. Catherine's Point was experiencing a problem, and the site was deactivated from the GPS network. The Ordnance Survey asked that the site be examined to determine if there was an environmental problem with the site itself, and if the lighthouse had actual shifted south from its original coordinate position.

The Ordnance Survey provided all of the active network data from January 2000 until 30 June 2001 for review and inspection. This data set consisted of all of the stations and the coordinate shift information for every epoch between the aforementioned dates for every station in the active network. Each of the stations in the network is monitored for coordinate values shifts daily to ensure that the best possible accuracy is provided to the GPS customers using the active network. The station at St. Catherine's Point, SCP1, was determined to be the only station that experienced a large shift in coordinates. Another station, Ordnance Survey's London Office (LOND), was experiencing large error residuals but not to the extent of the station at St. Catherine's Point. Before the station could be returned to use in the active network, the source of the problem with the coordinate shift had to be determined and corrected. Below is a diagram provided by Ordnance Survey that outlines the repeatability at SCP1. A diagram is also listed in Annex B.

Figure 16: St. Catherine's Point Repeatability



The descending line shown in the diagram above with represents the Northings value of the station. The graph shows the deviation from the mean in centimetres for each continuous epoch. Note that the other values have also experienced a slight shift in a negative direction (west for the easting and a drop in height for the up component).

A review of the methods used to determine the coordinates was conducted. The system is based upon the International Terrestrial Reference Frame, which has its origin at the centre of mass of the earth. The basic procedure for the ITRF computation consists in the reduction of the individual sets of station coordinates at a common epoch using their respective velocity models, and to conduct least-squares estimation at the reference epoch.

This yields ITRF station coordinates as well as seven transformation parameters for each individual set of station coordinates with respect to the ITRF. The standard model used in the combination procedure is based upon Euclidean similarity with seven parameters, which is the general form of transformation between two terrestrial reference systems. The general form of the equation is listed below.

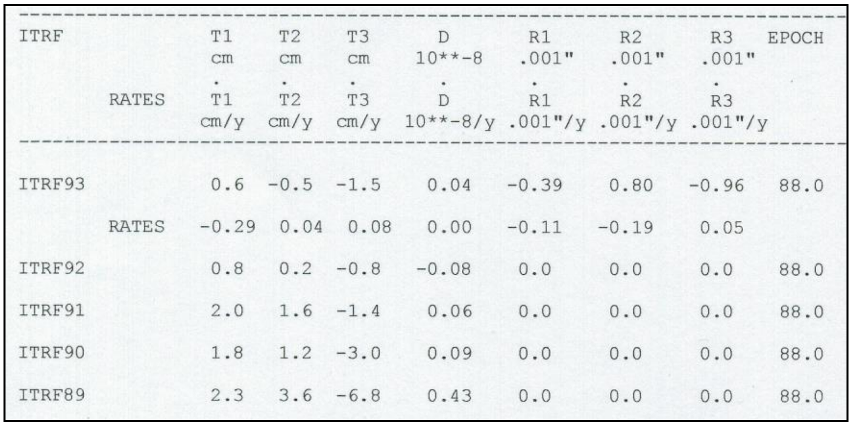
Equation 7: International Terrestrial Reference Frame Model

$$\begin{pmatrix} X_B \\ Y_B \\ Z_B \end{pmatrix} = \begin{pmatrix} X_A \\ Y_A \\ Z_A \end{pmatrix} + \begin{pmatrix} T1_{A,B} \\ T2_{A,B} \\ T3_{A,B} \end{pmatrix} + \begin{pmatrix} D_{A,B} & -R3_{A,B} & R2_{A,B} \\ R3_{A,B} & D_{A,B} & -R1_{A,B} \\ -R2_{A,B} & R1_{A,B} & D_{A,B} \end{pmatrix}$$

The values X_A, Y_A, and Z_A are the coordinates in the ITRF and the X_B, Y_B, and Z_B are the coordinates of the individual solution, $_{A,B}$. The values $T1_{A,B}$, $T2_{A,B}$, $T3_{A,B}$, $D_{A,B}$, $R1_{A,B}$, $R2_{A,B}$, and $R3_{A,B}$ are respectively the three translations, the scale factor and the three rotations between the ITRF and the individual solution $_{A,B}$. It should be noted that local ties between collocated stations are used with proper variances and that ITRF velocities are currently estimated either by combinations or by differentiating combined coordinates at two different epochs.

To define a terrestrial reference frame, the four datum components of orientation, origin, scale and time evolution should be clearly defined. This is accomplished by fixing or constraining at least seven transformation parameters and seven rates. To quantify the four ITRF datum components, all seven transformation parameters are needed along with their rate between successive ITRF solutions. An example of the transformation parameters and the rates are listed in the figure below.

Table 5: ITRF Rates by Epoch (Boucher and Altamimi, 1996)



ITRF		T1	T2	T3	D	R1	R2	R3	EPOCH
		cm	cm	cm	10**-8	.001"	.001"	.001"	
		.	.	.	.	.	.	.	
	RATES	T1	T2	T3	D	R1	R2	R3	
		cm/y	cm/y	cm/y	10**-8/y	.001"/y	.001"/y	.001"/y	
ITRF93		0.6	-0.5	-1.5	0.04	-0.39	0.80	-0.96	88.0
	RATES	-0.29	0.04	0.08	0.00	-0.11	-0.19	0.05	
ITRF92		0.8	0.2	-0.8	-0.08	0.0	0.0	0.0	88.0
ITRF91		2.0	1.6	-1.4	0.06	0.0	0.0	0.0	88.0
ITRF90		1.8	1.2	-3.0	0.09	0.0	0.0	0.0	88.0
ITRF89		2.3	3.6	-6.8	0.43	0.0	0.0	0.0	88.0

The resulting station coordinates of GPS at a given epoch are consistent with ITRF if IGS precise ephemeredes are used. However, this is only valid in a free network or if a minimal constraints analysis technique is used (Boucher and Altamimi, 1996).

To process GPS data, the ETRS89 system is commonly used in order to take full benefit of the most recent fiducials or GPS ephemeredes as provided by IGS. To realise the coordinates, a set of stations is needed along with the positions at specific epoch and the velocities. The general model is similar to the aforementioned model, and the transformation parameters can be linearly dependent of time. The model is listed in the equations below.

Equation 8: ETRS89 Transformation

$$\begin{pmatrix} X_B \\ Y_B \\ Z_B \end{pmatrix} = \begin{pmatrix} X_A \\ Y_A \\ Z_A \end{pmatrix} + \begin{pmatrix} T1_{A,B} \\ T2_{A,B} \\ T3_{A,B} \end{pmatrix} + \begin{pmatrix} D_{A,B} & -R3_{A,B} & R2_{A,B} \\ R3_{A,B} & D_{A,B} & -R1_{A,B} \\ -R2_{A,B} & R1_{A,B} & D_{A,B} \end{pmatrix} \begin{pmatrix} X_A \\ Y_A \\ Z_A \end{pmatrix}$$

To established coordinates in ETRF, a selection of points corresponding to sites belonging to ITRF and located in Europe must be selected, along with the correct coordinates and velocities. The process consists of three steps. First, compute 89.0 in ITRS. Second, compute ETRS at 89.0. Finally, compute the velocity in ETRS. A computer program was created to convert information taken from the active network and is found in Annex E of this report.

5.2 Data

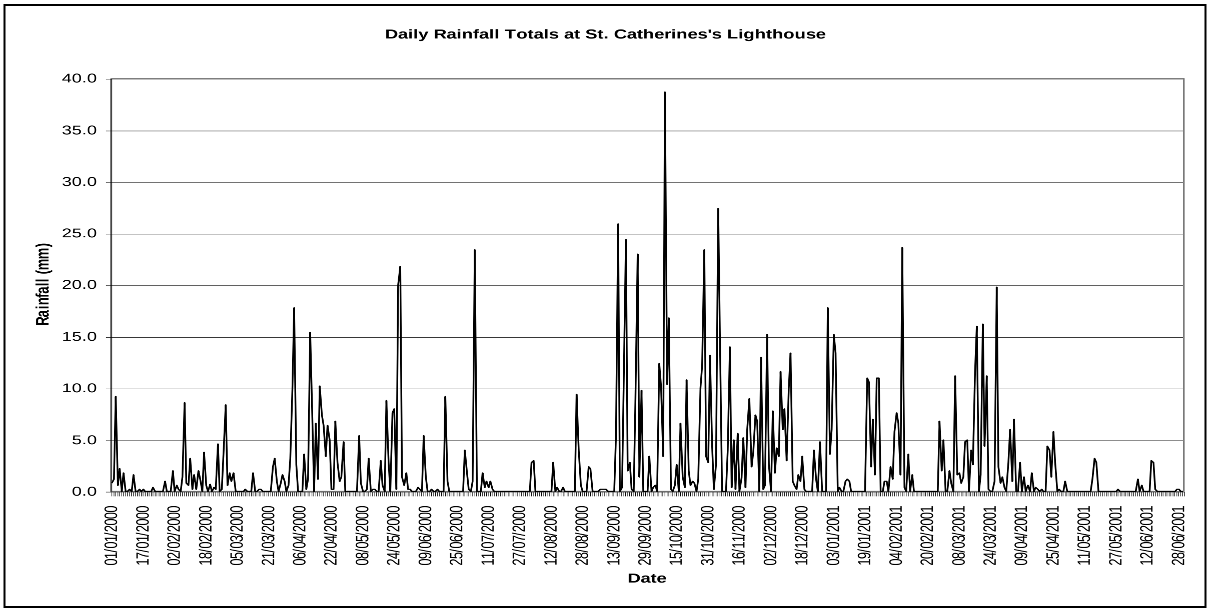
The next step was to investigate the UK Active GPS Network data set to determine the quality of the information. The quality of the data is a function of the number of stations analysed, their distribution around the globe (or region), and the quality of the software used to collect and process the data (Rothacher and Mervart, 1996). It is also dependent upon the length of the data span available. The Ordnance Survey analyses data from 30 stations in Great Britain using Bernese software. A comparison was made with data processed by Bernese software from the Center for Orbit Determination in Europe (CODE). CODE analyses the data from 80 IGS network stations daily. With three years of data analysed by CODE, the accuracy was in the order of approximately 1mm/year in horizontal shift for each station. For two and a half years of data analysed by OS, the accuracy was in the order of approximately 3mm/year in horizontal shift of each station.

The second step was to determine if any normal GPS errors were impacting the solution at St. Catherine’s Point. All of the possible errors were considered for the experimentation. The data was examined for receiver, atmospheric, ephemeris, and multipath errors. Since geodetic receiver error is almost negligible when sessions are conducted in a static mode, as with the Trimble 4000 SSI at St. Catherine’s Point, receiver error was ruled out as a problem impacting the station’s coordinate values. In terms of atmospheric errors, Bernese software uses a Saastomoinen tropospheric model to account for errors. After investigation, no indication of tropospheric errors was identified in the data set for St. Catherine's Point. No ionospheric errors were present because the Bernese software eliminated such errors through the ionosphere-free linear combination of L1 and L2 carrier waves. Very precise ephemeris data from the IGS ensured errors caused by earth tide and polar motion effects did not impact the solution, and the Bernese software removed systematic errors, thereby reducing the uncertainty of satellite orbits. Multipath errors were not present at St. Catherine's Point. There are no reflective surfaces near the receiver and antenna (which uses a choke ring) and no repeating patterns associated with multipath present in the data set.

The south of England experienced a record level of rainfall in the autumn and winter of 2000. The possible shift of the lighthouse at St. Catherine's Point was attributed to the rainfall. After investigating the hypothesis, it was determined that it was possible that the significant amount of rainfall could have possibly attributed to the movement of the lighthouse. The Meteorological (MET) Office of Great Britain maintains a rainfall collection site at St. Catherine's Point. The MET was contacted via email and asked to provide the rainfall data for St. Catherine's Point from 1 May 2000 to 30 June 2001, to cover the period of the record precipitation and to match the GPS data provided by Ordnance Survey. The data was reviewed to ensure its validity, and that the rainfall at St. Catherine's Point was in fact significant. The rainfall data can be found in Annex C of this report.

The GPS data and the rainfall data were compared to find any possible correlation between the shift in St. Catherine's Point Lighthouse and a heavy period of rainfall. The graph below shows the rainfall totals from 1 May 2001 to 30 June 2001.

Figure 17: Rainfall Data, St. Catherine's Point



The next figure shows the shift in the Northings component of the station coordinates.

Figure 18: SCP1 Northings Shift

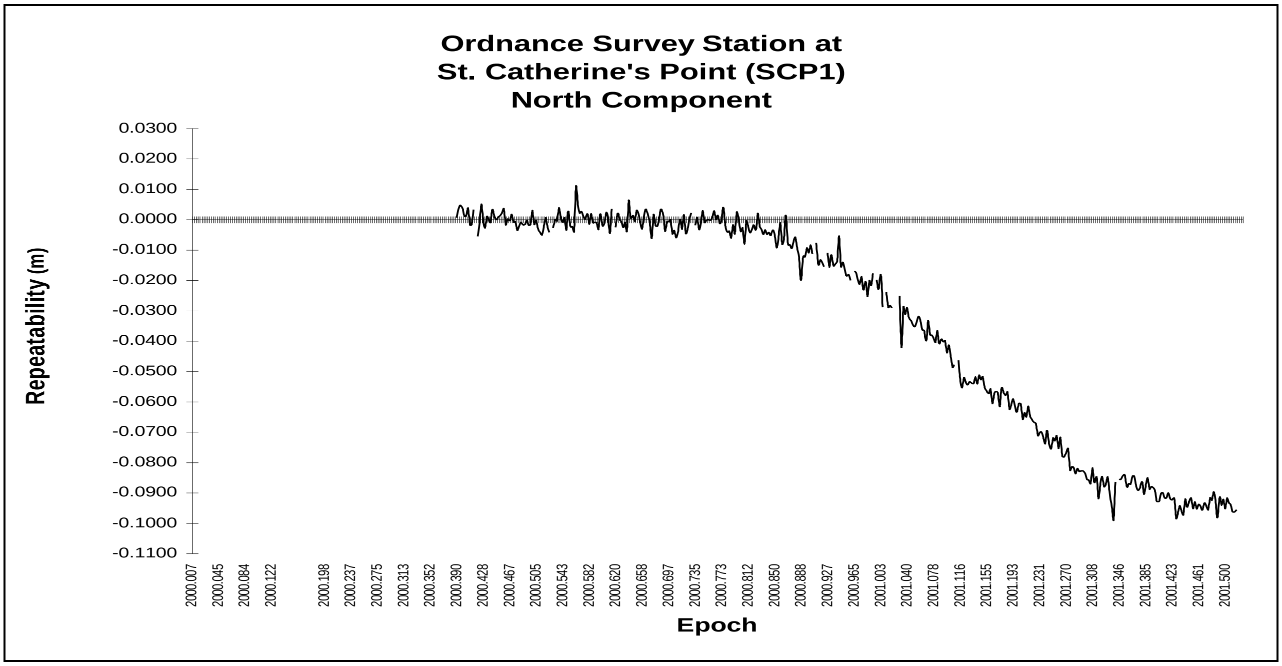
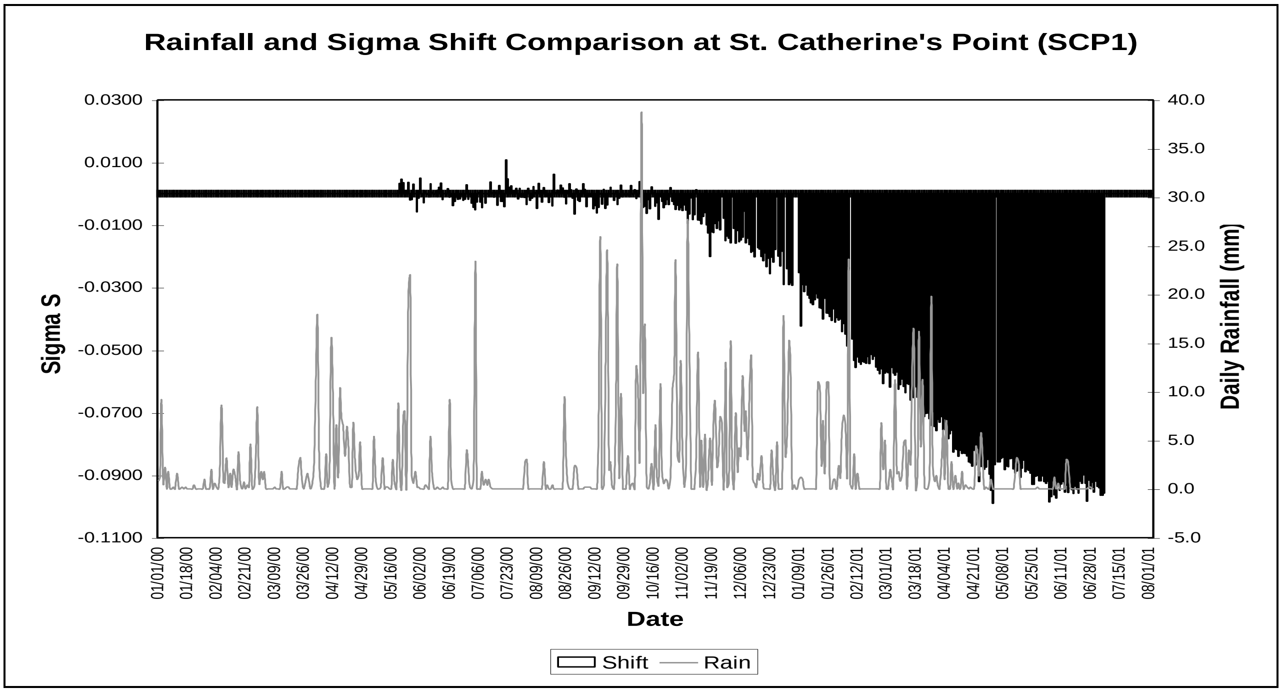


Figure 19: Rainfall and Southern Shift of St. Catherine's Point



The figure above shows the rainfall data and the station data superimposed in an effort to detect any correlation or trends. It was determined that a correlation did exist, in that the southern shift began to occur within two days of the peak rainfall day in 2000, and after a prolonged period of precipitation.

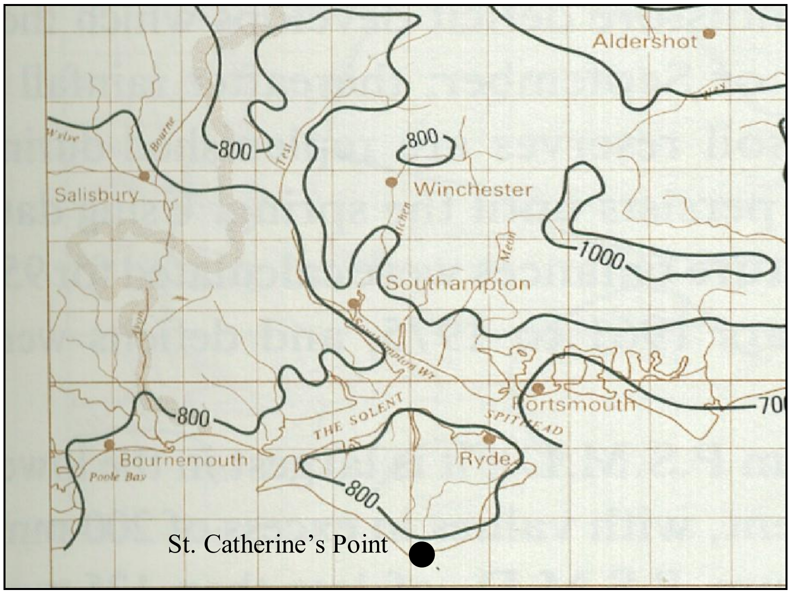
5.3. Soil

The soil composition was an important aspect of the correlation between the rainfall and the shift. The Isle of Wight experiences a significant amount of rainfall, and it was important to the experimentation to determine the composition of the soil and the effects a significant amount of rainfall could have on it. St. Catherine’s Point rests at the east-west divide of a central Chalk ridge. Geologically, it is located within Lower Greensand strata. This area has experienced rotational slippage of Upper Greensand sandstone over Gault which has left vertical cliffs and irregular landslipped footslopes.

The geomorphology of the area indicates it is near a cliff that is more than 15 metres high, and between two sites of past and present cliff failure. St Catherine's coastline has a boulder-dominated beach to the west and a gravel-dominated beach to the east. The soil at St. Catherine's Point is complex to classify, but is predominately of the Bignor Series. It consists of a dark greyish brown, stoneless sandy silt loam from the surface to 20cm below the surface. From 20cm to 70cm, the soil is brownish with a weak angular blocky structure (Jarvis et al, 1984). From 70cm to approximately 100cm, a fine brownish sandstone layer rests upon calcified chalk. The Bignor series soil usually passes downwards through solid rock through a zone of weathered, tabular sandstone. An additional one-metre mound of topsoil surrounds the lighthouse itself. The mound appears to have been constructed for aesthetic purposes and not structural reinforcement.

The Isle of Wight experiences approximately 800mm of rainfall annually, with minor variations of ±10 percent. The figure below shows the annual rainfall totals in the south of England.

Figure 20: Annual Rainfall in southern England (Adapted from Jarvis et al., Page 23)

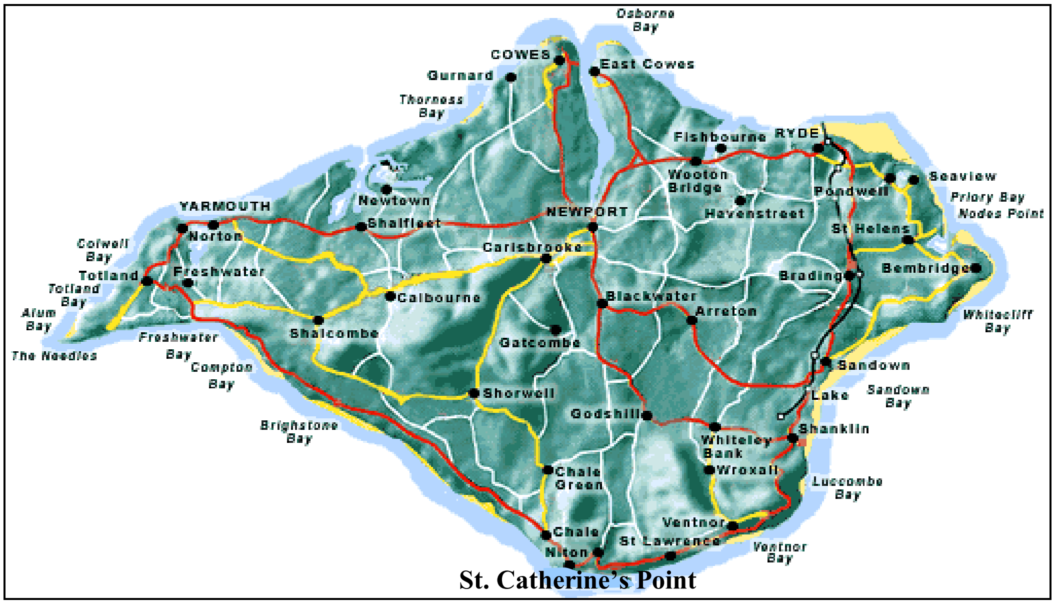


Seasonal distribution varies similarly, with a marked winter maximum in the south but a more even distribution in the north and east of England (Jarvis et al, 1984). The Isle of Wight experienced an exceptional amount of winter rainfall in 1994 and 2000, and landslide activity increased on the southern coast in Blackgang and Ventnor, respectively. With Bignor Series soil, periodic winter waterlogging is caused when the slowly permeable tabular sandstone fissures fill with alluvial clay. In most cases, excess winter rainfall is absorbed but run-off will occur after heavy rainfall, thereby increasing the likelihood of soil slippage.

5.4 Site Study

To ensure the validity of the hypothesis that St. Catherine's Point Lighthouse had shifted due to the significant rainfall, a visit was arranged to the Isle of Wight on 12 September 2001. St. Catherine's Point is located on the southernmost tip of the Isle of Wight. The purpose of the visit was to gain an understanding of the environmental factors that impact the station, to include the atmospheric conditions and landscape.

Figure 21: Isle of Wight



The aim of the visit was to inspect the GPS receiver/antenna at the station and to gain a better understanding of the topography and soil composition of the area. The GPS receiver located at SCP1 is a Trimble 4000 SSI with a TRM 33429.00 antenna with a GP Dome and ground plane. The antenna offsets are listed in the table below.

Table 6: Antenna Phase Centre Offsets, SCP1

	East	North	Up
L1	0.0012	-0.0002	0.0740
L2	0.0009	0.0006	0.0703

Figure 22: GPS Antenna, SCP1

The soil was found to match the description as previously mentioned. The foundation of the lighthouse was constructed on a layer of solid calcified chalk. The base of the lighthouse is encompassed by a thin layer of topsoil and Bignor Series soil. A mound surrounds the lighthouse, and it was evident that the mound had experienced soil shear within the past few months. The picture below shows the soil composition and the soil shear at the base of the mound.

Figure 23: St. Catherine's Lighthouse Soil Composition

5.5. Processing

The next phase was to conduct an assessment of the potential horizontal deformation of the station, and compare the station with other stations in the network by epochs. The COMPARE program developed by Professor Terry Moore at the University of Nottingham was thought to provide the necessary software needed to conduct this analysis. COMPARE is a program used to compare and analyse horizontal and vertical coordinates from two epoch sets of deformation survey data. It computes the movements and assesses their statistical significance by comparing them to the corresponding standard errors (Moore, 1995).

After discussing this option F. Norman Teferle, a graduate student at the University of Nottingham, and Dr. Paul Cruddace at Ordnance Survey, it was found that COMPARE could not be used in its present form for GPS observations, mainly because the analysis of systematic differences between horizontal data sets is performed in terms of scale difference, orientation difference, and origin shift based upon terrestrial observations. To statistically determine whether a point in a GPS network has moved, a network of stations at an epoch_1 and at an epoch_2 are required. The variance-covariance information is also required from both epochs. With this information, both epochs can be compared and movements in a station or some stations can be detected and statistically described (Teferle, 2001). After requesting the variance-covariance information from Ordnance Survey, it was found that Ordnance Survey does not store the variance-covariance information for the active network stations in its data sets (Cruddace, 2001). Therefore, an alternate means was developed to statistically describe the movement of St. Catherine's Point. The methodology uses Ordnance Survey data for coordinate shifts (in three dimensions) at each station in the network and the theoretical principles used to create the COMPARE software program.

To conduct analysis, a spreadsheet was developed using the principles of COMPARE, and adapted to meet the requirements of GPS observations. Two epochs would be compared, with one epoch being set at the base epoch. For each epoch a set of adjusted coordinates would be determined for each station in the network in the east, north, and up components. The coordinates shifts and RMSE (in millimetres) would be found for the east, north, and up components of each station. If the horizontal deformation was greater than three times the standard error, then there exists a 99.7% probability of movement. Additionally, if the horizontal deformation was greater than two times the standard error, then there exists a 95.4% probability of movement. For each epoch comparison, the coordinate shift and standard error were found for each station in the network with respect to the east, north, and up components. This information was then used for the basis of all statistical analysis and eventually matched to monthly rainfall totals for trend analysis. A final statistical check was carried out on the north component only for each station in the network for Epoch 2000.335 and Epoch 2001.497 to ensure that the network itself was not experiencing deformation in the north component. The statistical output can be found in Annex M of this report.

An initial epoch was determined for the network analysis, which was epoch 2000.335 (1 May 2000). All epochs in the network were initially referenced to 1 May 2000, which was a period of no rainfall and in which no major deviations from the coordinate mean at SCP1 occurred. A set of epochs was selected for analysis based upon coordinate shifts and periods of heavy rain and periods of no rainfall. Epochs were matched with the calendar days using the GPS calendars located in Annex G and Annex H of this report. All of the stations within the network were used in the analysis. The ITRF and ETRS Cartesian coordinate information for each station was provided in a CD-ROM by Ordnance Survey, as well as all station coordinates in three dimensions in the ETRS89 terrestrial reference frame. However, the Ordnance Survey website only provides coordinate information in latitude, longitude, and height. The current active network station coordinates had to be converted to eastings, northings, and up for further analysis, because the coordinate shifts were in that format. The software program Survey Computation Suite was used to convert the coordinates from latitude, longitude, and height to eastings, northings, and up, because it uses the same transformation algorithm used for the active network (Price, 1996).

The comparison of epochs was essential to determine whether the shifts at St. Catherine’s Point were due to network deformation or whether the lighthouse shifted due to another factor. It was necessary to compare the stations in the network at times of normal precipitation, no precipitation, and during period of heavy rainfall to determine if rainfall has an overarching effect on the entire network. It was also to determine if the rainfall has a “triggering effect” on the soil once the soil reached a point of saturation.

Various epochs to be compared were determined based upon a number of factors. The base epoch, 2000.335, was chosen because this was a period when the residuals in the network were small and there was little rainfall occurring during this period. Epoch 2000.779 was chosen because it was the day on which the greatest amount of rainfall occurred at St. Catherine’s Point. Epochs 2001.089 and 2001.122 were chosen because this was a period when during the first two weeks of February where the lighthouse experienced almost 1 centimetre of movement to the south. Epoch 20001.251 was chosen because the cumulative rainfall total decreased significantly, and the overall movement of the lighthouse appears to have subsided. The epoch, which correlated to the first day of each month, were also chosen in an effort to match monthly rainfall totals with the movement of the lighthouse. All coordinates adjustments for every epoch used in the analysis were developed for each station in the active network and are listed in Annex I, Pages 1 through 8. Then, all station coordinates in the active network were grouped according to epoch. These epoch compilations are listed in Annex I, Page 9 through 14.

The next stage was to compare every epoch used in the analysis with the base epoch, 2000.335, 1 May 2000. This was done to compare station coordinates against the initially accepted coordinates, and to determine if any significant coordinate shifts occurred at a specific station. All station coordinates were analysed for shifts in eastings, northings, and up. It was found in the comparison of Epoch 2001.497 with the base epoch of 2000.335 that a 92-millimetre shift occurred in the north component for station SCP1. All other network stations experienced movements in the north component of less than 7 millimetres for the same epoch comparison. It was determined in a comparison of Epoch 2000.839 (1 November 2000) with the Epoch 2000.335 (1 May 2000) that a 5-millimetre shift occurred in the north component at station SCP1, and 14 stations experienced a shift of 1 millimetre of less. The remaining epoch comparisons can be found in Annex K of this report.

Statistical testing was conducted to ensure the validity of the epoch comparisons. A least squares analysis was applied to the shifts (in three dimensions) for each station in the network for a specific epoch comparison. In comparing the coordinate shifts between Epoch 2000.335 and Epoch 2001.497, a mean shift for the east component was 1 millimetre. For the north component the mean shift was 4 millimetres and 17 millimetres for the up component. In comparing the coordinate shifts between Epoch 2000.335 and Epoch 2000.839, the mean shift for the east, north, and up components were 1 millimetre, 1 millimetre, and 4 millimetres, respectively. The remaining statistical comparisons can be found in Annex L of this report.

The trend analysis was developed using the cumulative monthly rainfall totals and the cumulative shifts in St. Catherine's Point Lighthouse for a given period. The figure is listed on Page 1 of Annex J. The trend lines were adjusted into two-parameter, second order polynomial equations, which were statistically developed from the cumulative rainfall and shift data. This figure is displayed on Page 2 of Annex J.

6. RESULTS

Ordnance Survey provided the initial results from the overall network coordinates, which are root mean square errors for every station within the network. The information derived from each station is the mean, the standard deviation of the mean (at 95% confidence), and the calculated root mean square error. SCP1 is the only station in the network to experience centimetric RMS errors in the horizontal components, whilst all other stations are producing millimetric results. The results are listed below.

Figure 24: RMSE of the Station within the UK National Active GPS Network

		BLAC			BRIS			BUT1			CARL			CARM	
	East	North	Up	East	North	Up	East	North	Up	East	North	Up	East	North	Up
Mean:-	-0.0006	0.0009	-0.0015	-0.0011	-0.0002	-0.0044	-0.0002	-0.0012	-0.0122	-0.0014	-0.0006	-0.0050	-0.0008	-0.0003	-0.0066
95% STDev:-	0.0063	0.0045	0.0187	0.0055	0.0045	0.0151	0.0085	0.0072	0.0241	0.0078	0.0058	0.0186	0.0069	0.0047	0.0189
RMSE:-	0.0033	0.0025	0.0098	0.0030	0.0023	0.0089	0.0044	0.0039	0.0173	0.0042	0.0030	0.0107	0.0036	0.0024	0.0117
		COLC			DARE			DROI			EDIN			FLA1	
	East	North	Up	East	North	Up	East	North	Up	East	North	Up	East	North	Up
Mean:-	0.0020	0.0001	-0.0028	-0.0008	-0.0008	-0.0041	-0.0004	-0.0004	-0.0056	-0.0011	-0.0009	-0.0043	-0.0017	-0.0014	-0.0066
95% STDev:-	0.0055	0.0036	0.0156	0.0073	0.0053	0.0175	0.0067	0.0044	0.0171	0.0074	0.0064	0.0178	0.0080	0.0060	0.0189
RMSE:-	0.0035	0.0019	0.0085	0.0038	0.0028	0.0098	0.0034	0.0023	0.0104	0.0040	0.0034	0.0100	0.0044	0.0034	0.0117
		GIR1			GLAS			INVE			IOMN			IOMS	
	East	North	Up	East	North	Up	East	North	Up	East	North	Up	East	North	Up
Mean:-	-0.0012	-0.0004	-0.0081	-0.0012	-0.0004	-0.0047	-0.0008	0.0001	-0.0034	0.0034	-0.0014	-0.0004	0.0036	-0.0012	-0.0018
95% STDev:-	0.0085	0.0063	0.0211	0.0073	0.0057	0.0179	0.0080	0.0064	0.0172	0.0081	0.0056	0.0195	0.0073	0.0057	0.0222
RMSE:-	0.0045	0.0032	0.0135	0.0039	0.0030	0.0103	0.0042	0.0033	0.0094	0.0054	0.0032	0.0100	0.0052	0.0032	0.0115
		KING			LEED			LIZ1			LOND			LYN1	
	East	North	Up	East	North	Up	East	North	Up	East	North	Up	East	North	Up
Mean:-	-0.0008	0.0002	-0.0019	-0.0007	-0.0003	-0.0054	-0.0014	-0.0004	-0.0075	0.0034	-0.0007	-0.0086	-0.0012	-0.0005	-0.0084
95% STDev:-	0.0059	0.0035	0.0148	0.0067	0.0053	0.0167	0.0073	0.0047	0.0201	0.0161	0.0065	0.0236	0.0082	0.0056	0.0190
RMSE:-	0.0031	0.0018	0.0078	0.0035	0.0028	0.0101	0.0040	0.0025	0.0127	0.0089	0.0034	0.0149	0.0044	0.0029	0.0129
		MALL			NAS1			NEWC			NFO1			NORT	
	East	North	Up	East	North	Up	East	North	Up	East	North	Up	East	North	Up
Mean:-	0.0002	0.0000	-0.0056	-0.0016	0.0004	-0.0080	-0.0006	0.0001	-0.0028	-0.0001	0.0008	-0.0012	-0.0007	-0.0005	-0.0059
95% STDev:-	0.0088	0.0066	0.0195	0.0100	0.0057	0.0202	0.0074	0.0052	0.0171	0.0065	0.0048	0.0156	0.0068	0.0045	0.0162
RMSE:-	0.0045	0.0034	0.0114	0.0053	0.0029	0.0130	0.0038	0.0026	0.0092	0.0033	0.0026	0.0081	0.0036	0.0023	0.0101
		NOTT			OSHQ			PLYM			SCP1			SUM1	
	East	North	Up	East	North	Up	East	North	Up	East	North	Up	East	North	Up
Mean:-	-0.0005	-0.0002	-0.0055	0.0008	-0.0002	-0.0037	-0.0012	-0.0003	-0.0055	-0.0122	-0.0344	-0.0132	-0.0007	-0.0018	-0.0101
95% STDev:-	0.0065	0.0045	0.0146	0.0107	0.0044	0.0177	0.0077	0.0046	0.0196	0.0240	0.0719	0.0398	0.0084	0.0063	0.0259
RMSE:-	0.0034	0.0023	0.0093	0.0055	0.0022	0.0098	0.0041	0.0023	0.0114	0.0173	0.0504	0.0242	0.0043	0.0037	0.0167
		THUR													
	East	North	Up												
Mean:-	-0.0012	-0.0006	-0.0027												
95% STDev:-	0.0089	0.0066	0.0192												
RMSE:-	0.0047	0.0034	0.0102												

The figure below shows the active network coordinates which are shown on the Ordnance Survey website. The coordinates listed in latitude, longitude, and height was converted to eastings, northings, and up because all coordinate shift information was provided in eastings, northings, and up.

Figure 25: Adjusted Coordinates (Active Network)

Station		Latitude				Longitude			Height	Eastings	Northings	Height
BLAC	53	46	44.79692	N	3	2	25.63766	W	64.94000	331445.8600	431946.2010	64.9400
BRIS	51	25	39.17076	N	2	32	38.67427	W	104.01800	362178.0860	170032.9680	104.0180
BUT1	58	30	56.17302	N	6	15	39.29240	W	115.02600	151899.4600	966440.0460	115.0260
BUT2	58	30	56.04956	N	6	15	39.27189	W	115.02200	151899.5490	966436.2120	115.0220
CARL	54	53	43.52425	N	2	56	17.79869	W	93.54100	339830.4920	556044.6370	93.5410
CARM	51	51	32.07228	N	4	18	30.68915	W	81.35200	241046.2050	220381.8720	81.3520
COLC	51	53	39.71895	N	0	53	50.07579	W	75.27300	475874.5080	222380.5680	75.2730
DARE	53	20	41.29010	N	2	38	25.77554	W	88.41100	357363.8460	383321.7490	88.4110
DROI	52	15	19.05773	N	2	9	16.51013	W	101.52600	389449.0700	261957.6380	101.5260
EDIN	55	55	29.21754	N	3	17	41.25187	W	119.03200	319100.2700	670942.3870	119.0320
FLA1	54	7	0.66519	N	0	4	39.83277	W	86.77800	525631.2040	470725.3900	86.7780
FLA2	54	7	0.78770	N	0	4	40.00944	W	86.78000	525627.8940	470729.0880	86.7800
GIR1	57	8	20.49069	N	2	2	54.81713	W	108.61000	397061.3590	805327.6870	108.6100
GIR2	57	8	20.36917	N	2	2	54.80511	W	108.62100	397061.5580	805323.9290	108.6210
GLAS	55	51	14.39830	N	4	17	47.36456	W	71.61700	256261.5930	664692.6020	71.6170
INVE	57	29	10.50001	N	4	13	9.35036	W	66.17800	266974.5780	846149.4410	66.1780
IOMN	54	19	45.10347	N	4	23	18.56824	W	94.50300	244702.7120	495272.1850	94.5030
IOMS	54	5	11.98745	N	4	38	4.27806	W	84.36600	227702.7320	468868.2650	84.3660
KING	52	45	4.92074	N	0	24	5.52771	W	66.43100	507874.6610	318318.9120	66.4310
LEED	53	48	0.77471	N	1	39	49.65003	W	215.60900	422141.5150	433844.2990	215.6090
LIZ1	49	57	36.22097	N	5	12	10.96596	W	124.26900	170299.4610	11643.1670	124.2690
LIZ2	49	57	36.24525	N	5	12	11.06876	W	124.25800	170297.4460	11644.0040	124.2580
LOND	51	29	21.71632	N	0	7	11.73203	W	66.05700	530513.7180	178442.7580	66.0570
LYN1	53	24	58.62656	N	4	17	21.05049	W	100.77600	247880.3040	393522.9330	100.7760
LYN2	53	24	58.71330	N	4	17	21.04053	W	100.85400	247880.5740	393525.6070	100.8540
MALL	57	0	21.84107	N	5	49	42.12093	W	68.49400	167565.6700	797044.4040	68.4940
NAS1	51	24	2.81593	N	3	33	4.62055	W	112.37100	292100.7830	168057.9140	112.3710
NAS2	51	24	2.87540	N	3	33	4.62121	W	112.37800	292100.8090	168059.7510	112.3780
NEWC	54	58	44.84186	N	1	36	59.67664	W	125.87800	424537.3150	565021.8610	125.8780
NFO1	51	22	28.09293	N	1	26	40.37030	W	99.43900	438657.4760	164136.6840	99.4390
NFO2	51	22	28.04570	N	1	26	40.31596	W	99.43700	438658.5370	164135.2330	99.4370
NORT	52	15	5.79423	N	0	54	44.96245	W	131.59400	474230.6420	262093.6830	131.5940
NOTT	52	57	43.88794	N	1	11	50.91562	W	93.82500	453899.0100	340872.1150	93.8250
OSHQ	50	55	52.60575	N	1	27	1.85162	W	100.40500	438610.2940	114852.5010	100.4050
PLYM	50	26	19.88971	N	4	6	31.12430	W	215.25100	250280.3200	62081.7870	215.2510
SCP1	50	34	32.29194	N	1	17	52.16197	W	94.68800	449714.5760	75400.3540	94.6880
SCP2	50	34	32.34975	N	1	17	52.14204	W	94.71000	449714.9510	75402.1430	94.7100
SUM1	59	51	14.75691	N	1	16	29.52880	W	149.89000	440619.5750	1107822.4730	149.8900
SUM2	59	51	14.63392	N	1	16	29.48401	W	149.88600	440620.3140	1107818.6770	149.8860
THUR	58	34	52.33661	N	3	43	34.71675	W	98.63400	299634.5300	967161.2870	98.6340

Spreadsheets were used to place the results of the epoch comparisons into a format that could be easily interpreted. All information was summarised into a spreadsheet format to allow for statistical testing and the comparison of various epoch combinations to identify trends. The principle is that if the degree of uncertainty is greater than the corrected coordinate shift, then the shift is not significant. In the case of SCP1, the coordinate shift in the north component is greater than the degree of uncertainty, indicating a possibly shift in the station. This is particularly evident in epoch comparisons during periods of heavy rainfall.

The record level of rainfall during the winter season contributed an additional 200 millimetres of rainfall to St. Catherine's Point from 1 May 2000 to 30 June 2001 (Annex C). The highest daily total of rainfall occurred on 9 October 2000. Within one week of this high intensity rainfall, movement in the north component of SCP1 began to occur.

The results of the adjusted coordinates for each station in the active network for all epochs computed are located in Annex I, Pages 1 to 8. The comparison of all network stations for Epoch 2000.335, 1 May 2000, is located in Annex I, Page 9. The comparison of all network stations for Epoch 2000.839, 1 November 2000, is located in Annex I, Page 10. The comparison of all network stations for Epoch 2001.089, 1 February 2001, is located in Annex I, Page 11. The comparison for all network stations for Epoch 2001.122, 13 February 2001, is located in Annex I, Page 12. The comparison for all network stations for Epoch 2001.251, 1 April 2001, is located in Annex I, Page 13. The comparison for all network stations for Epoch 2001.497, 30 June 2001, is located in Annex I, Page 14.

A comparison between the data sets of two epochs for the adjusted coordinates for all stations is located in Annex K. The statistics for all data sets of epoch compared is located in Annex L. The total summary of statistics for the entire network from 1 May 2000 and 30 June 2001 are located in Annex M. The future trend analysis is located in Annex J of this report.

7. ANALYSIS

The analysis of the overall network indicates that the residuals fall within the accepted range of 3σ at a 99% confidence level.[2] The entire network is able to achieve millimetric precision the entire data period analysed. In general, the eastings and northings for each station tend to be twice as precise as the up component. The only station to experience a significant coordinate shift is SCP1, and this is solely in the north component. It is also the only station in the network to produce a RMS error above the 1 centimetre level for both eastings and northings.

St. Catherine's Point experienced 940.8 millimetres of rainfall from 1 January 2000 to 31 December 2000. From 1 May 2000 to 1 April 2001 the area received 1067.7 millimetres of rainfall, which is over 200 millimetres more rainfall than experienced in a normal year. This indicates that St. Catherine's Point was affected by a significant amount of rainfall, which attributed to the shift in the lighthouse with respect to the soil shear at its base. Given previously saturated soil, the intensely heavy rainfall within a short time period appears to have triggered the movement of the lighthouse, which will be analysed later in this report.

The lighthouse began to shift southwards immediately after the largest daily rainfall total of the year, which was approximately 38 millimetres, which occurred the middle of October 2000. Similarly, the greater the daily rainfall total for amounts over 10 millimetres, the steeper the rate of change of the shift of the lighthouse, which is displayed in Annex D, Page 3. The north component was experiencing millimetric deviations from

---

[2] Note that Ordnance Survey calculates results at a 99% confidence level but guarantees results at a 95% confidence level for its customers. The RSM error information is available at both confidence levels upon request from Ordnance Survey.

the mean coordinate value in both the positive and negative directions until late November 2000. Conversely, when little or no rainfall occurred, the rate of change of the lighthouse's shift was practically nonexistent. Again, this can be observed in the figure located on Page 3 of Annex D.

In comparing various epochs it is evident that SCP1 has moved due to soil shear and not because of deformations in the network. When Epoch 2000.335 is compared with Epoch 2001.497, the change between the adjusted coordinate values for SCP1 is approximately 2 centimetres in east, 9 centimetres in north, and 4 centimetres in up (Annex K, Page 1). The data was statistically evaluated using a least squares adjustment for all three components of the station coordinates. The standard deviations were millimetric in nature for all three components, with no outliers being found in the process. The results are listed on Page 1 of Annex L. When comparing both epochs (2000.335 and 2000.497) for Station OSHQ, there is no coordinate change at all. This indicates that the data for the network is good and that the network itself is not experiencing deformation. The average coordinate change for any one station in the network is 3 millimetres in east, 3.5 millimetres in north, and 1 centimetre in up. Refer to Annex K, Pages 1-3 for the comparison of the adjusted station coordinates, which are listed by the epochs chosen based upon various periods of rainfall. These epochs were chosen in order to determine the strength of the active network's data and demonstrate that horizontal deformation was not impacting the coordinate results at SCP1.

In comparing Epoch 2000.335 with Epoch 2001.497, the standard error was 1 millimetre in east, 3 millimetres in north, and almost 2 millimetres in up. When Epoch 2000.335 is compared with Epoch 2001.251, the standard error is 1 millimetre in east, 2 millimetres in north, and almost 2 millimetres in up. This shows that the network has a strong geometry and does not suffer from horizontal or vertical deformation. Yet, SCP1 has an average standard error of 1 centimetre in east, 8 centimetres in north, and 4.5 centimetres in up for the same epoch comparisons. The standard deviation for this epoch comparison is 0.005 the north component, 0.012 in the east component, and 0.010 for the up component. The statistical information is listed in Page 1 of Annex L.

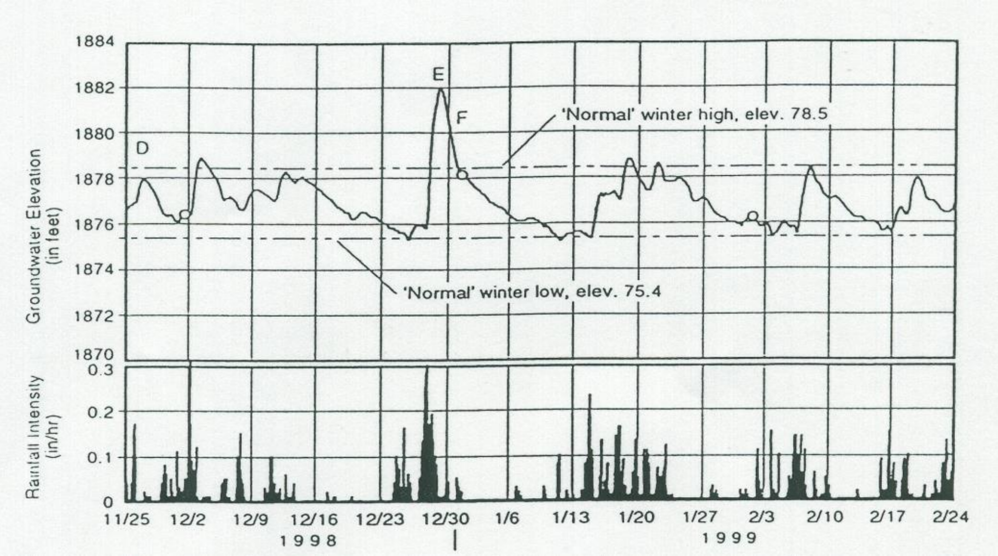
The standard errors in the north, east, and height vector components are consistent with results from other GPS networks. A 5-day GPS campaign conducted in January 1987, which monitored 19 stations around the San Andreas Fault in California, evaluated the accuracy and viability of the fiducial GPS procedure. The north vector repeatabilities produced a root mean square error of 2.6mm + 0.0017 ppm. The east vector repeatibilities produced a root mean square error of 5.9mm – 0.0037 ppm. The height, or up, vector repeatabilities produced a root mean square error of 9.1mm + 0.0647 ppm. Overall baseline length repeatabilities produced a root mean square error of 4.3mm – 0.0008 ppm. The repeatabilities (rms) of the results averaged about 3mm, 6mm, and 4mm for north, east, and length, respectively, with hardly any component proportional to the length of the line in parts per million (Ashkenazi and Ffoulkes-Jones, 1990).

The root mean square error data provided by Ordnance Survey was analysed to ensure that the network was obtaining credible GPS data. This data has been collected for almost three years without a change to the original adjusted coordinate values at each station. The figure listed in Annex F shows the RMSE for each station in terms of eastings, northings, and up. The RMSE for all stations is approximately 4 millimetres in the east component, 3 millimetres in the north component, and 10 millimetres in the up component. The horizontal values for the UK network are consistent with the study conducted in California. The exceptions are stations SCP1 and LOND. SCP1 experienced a RMSE of 17 millimetres in the east component, 50 millimetres in the north component, and 24 millimetres in the up component. Also, it is the only station where the north component had a higher RMSE than the up component.

It was determined that no structural damage such as twisting or bending had occurred with the GPS antenna. This was confirmed after a visual inspection of the antenna in September 2000 and checking maintenance inspection records at Ordnance Survey. Additionally, there is no indication of the antenna moving or bending in the post processed data from the station. The figure in Annex B for station SCP1 indicates that a significant shift in the north component occurred during periods of heavy rainfall, and that little or no movement occurred during dry periods. The east and north components have also slightly shifted to the degree of 1 centimetre in a pattern consistent with the up component. Had the antenna been damaged due to twisting or bending, the pattern would most likely have shown an abrupt change in the coordinates in all three components, and no further movement would have occurred after the antenna was twisted.

The lighthouse at St. Catherine’s Point is located on the Isle of Wight and typically experiences its heaviest rainfall during the winter months between October and March. The Bignor soil has a weak but somewhat stable structure that becomes more elastic as the soil moisture content rises. It is evident that the 38mm of rainfall on October triggered the southern movement of the lighthouse, which was surrounded by previously saturated soil. Moreover, the additional 200 millimetres of rainfall during the period examined kept the soil saturated for a longer time frame and allowed for additional shifts in the lighthouse. A groundwater response analysis was conducted in the United States in the state of Oregon, which experiences rainfall totals and landslide activity similar to that on the southern coast of the Isle of Wight. Much like St. Catherine's Point, western Oregon groundwater levels fall steadily during the drier summer months. As winter rainfall begins, groundwater rises and reaches a seasonal high in mid-winter. During the winter, periodic heavy storms provide high intensity rainfall that can temporarily raise groundwater to short-term highs (Cornforth and Mikkelsen, 2000). These "spikes" are frequently triggering events for movements on marginally stable slopes such as landslide terrain. The figure below shows the groundwater level and rainfall intensity of the western Oregon site.

Figure 26: Groundwater Elevation and Rainfall Intensity (Cornforth and Mikkelsen, 2000)



During periods of heavy rainfall, the groundwater elevation rose rapidly, where as in periods of no rainfall, the elevation dipped to its normal winter low. It was concluded that precipitation in the early fall did not contribute to a rise in groundwater levels, possibly to due the water filling the voids and cracks in the dry soil above the groundwater. It was also suggested in a marginally stable terrain in a wet climate that active movements of the terrain can be triggered by high intensity rainfall (Cornforth and Mikkelsen, 2000).

St Catherine's Point began to experience a shift in the north component in the winter months, and this shift is attributed to ground saturation from heavy rainfall. When the rain begins and exceeds a certain threshold the ground saturates and continues until the amount of precipitation reaches some critical value. A ground deformation study was conducted at Yura Station in southwestern Japan to determine the effects of rainfall on ground deformation using strainmeters and tiltmeters. It was concluded that the tilt response was a seasonal phenomenon. In cold seasons larger tilts are generated by the same amount of rainfall than in warmer seasons. This is considered to be caused by a thermal effect on gaps between sand grains or fissures in shallow parts of the ground (Tanaka et all, 1989).

The trend analysis indicated that 40 millimetres of rainfall in a four-day period would contribute to a potential shift in the station, namely the lighthouse moving southwards after an intensely heavy rainfall. The ground deformation due to rainfall could be generated by sources or some mechanism at shallow parts of the ground, since deformation is observed when the groundwater reaches a few metres under the ground. In terms of the seepage of groundwater, it has been determined that the response of the groundwater to precipitation is faster in the cold seasons and larger for heavy rainfall (Tanaka et al, 1989). St. Catherine's Point, with marginally stable soil and previously saturated soil, experienced heavy winter rainfall (Annex C). The high intensity rainfall in October raised the groundwater level and triggered the southern movement of the Bignor Series soil. It is possible that the lighthouse was tilted to the south as the saturated soil shifted. However, it is highly unlikely that the base of the lighthouse experienced movement, as the statistical analysis of the coordinate shifts has indicated.

8. CONCLUSIONS

The adjusted coordinates for St. Catherine's Point station are as follows:

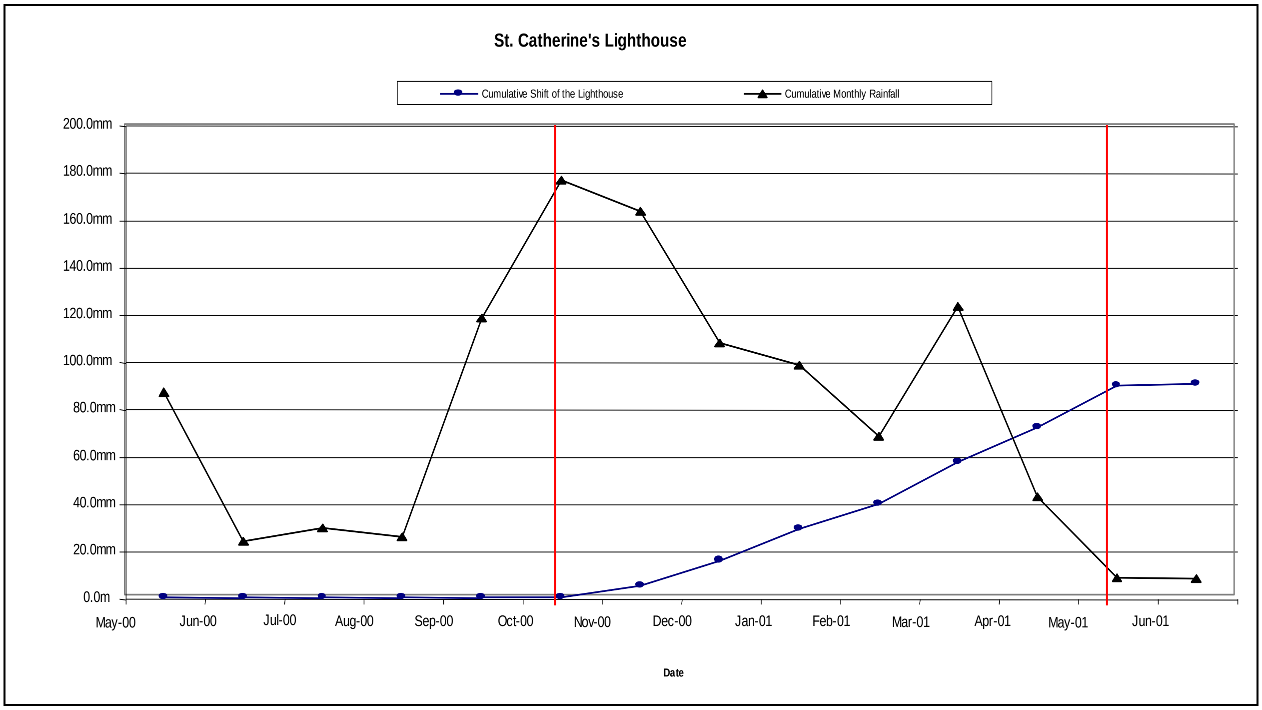
East: 449714.5766 North: 75400.2617 Up: 94.6443 (at Epoch 2001.497)

The station has experienced over 9 centimetres of shift southwards since October 2000. The station appears to have stopped moving, and will not move until another significant period of rainfall occurs. This equates to approximately 40mm of rainfall in a four-day period. The table below shows the monthly rainfall totals in relation to the cumulative coordinate shift south for SCP1. It is visible in the table below that excessive rainfall in previously saturated soil is directly proportional to the rate of change of movement of the lighthouse in the north component. In a period of little rainfall activity such as May and June of 2001, the shift was less than 1 millimetre for the north component. In months of heavy rainfall such as December and January, the shift was approximately 13.5 millimetres.

Table 7: Cumulative Shifts and Rainfall Data, SCP1

Date	Shift (mm)	Rainfall (mm)
1-May-00	0.0	86.8
1-Jun-00	0.0	24.0
1-Jul-00	0.0	29.4
1-Aug-00	0.0	25.8
1-Sep-00	0.0	118.1
1-Oct-00	0.2	176.3
1-Nov-00	5.0	163.3
1-Dec-00	15.7	107.6
1-Jan-01	29.1	98.4
1-Feb-01	39.6	68.2
1-Mar-01	57.4	123.0
1-Apr-01	72.1	42.8
1-May-01	89.7	8.4
1-Jun-01	90.3	8.2

Figure 27: Cumulative Monthly Rainfall and Shifts, SCP1

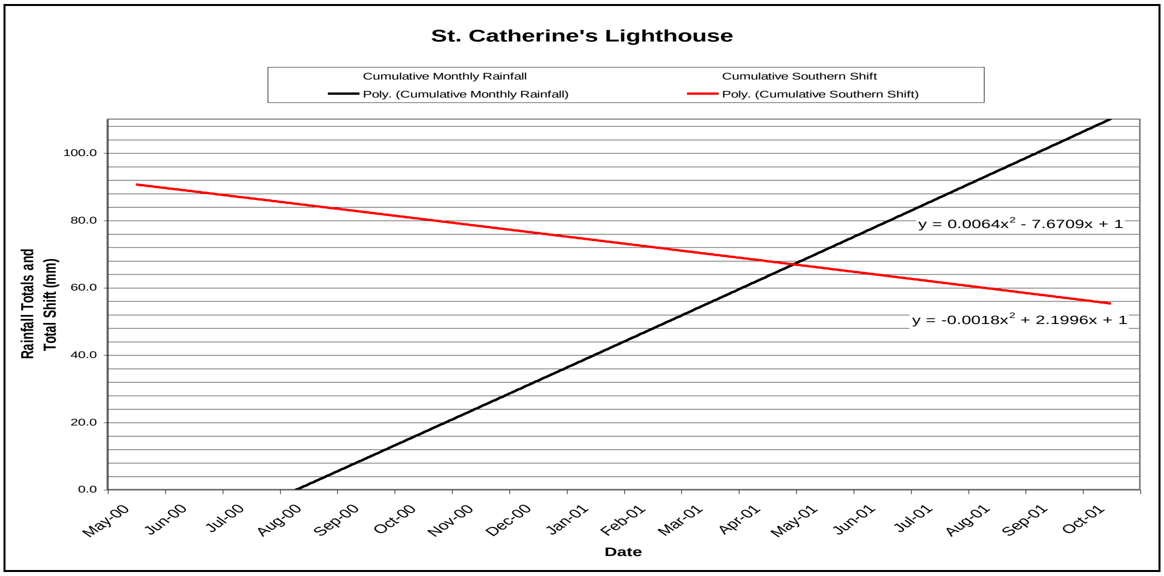


The figure above demonstrates this phenomenon. Note the linear southward shift in the coordinate value of SCP1, which began after the highest period of rainfall for the year 2000. It also suggests that St. Catherine’s Point Lighthouse has stopped moving as of May 2001, which is a dry period for the area. It also suggests that the lighthouse will not move until another period of sustained rainfall occurs at the station, presumably in the winter season. Note the cumulative rainfall totals above 100mm occurred during mid-winter.

The figure in Annex B shows that SCP1 has shifted most significantly during periods of heavy rainfall, and that the pattern is consistent in all three dimensions. It is unlikely that the foundation of the lighthouse has moved, but it is concluded that the lighthouse has tilted to the south. The Bignor soil at the base of the lighthouse became saturated due to rainfall, and additional rainfall in October and November triggered soil slippage around the lighthouse. The weight of the surface soil shifted the lighthouse to the south as the saturated soil moved down the slope towards the ocean. The lighthouse appears to have experienced a leaning effect to the south, with the foundation remaining in its original position. Had the base of the lighthouse actually moved, the east and up components would have shown significant coordinate shifts similar to that of the north component. The height of the lighthouse has dropped approximately 4 centimetres over the period between 1 May 2000 and 30 June 2001, but has moved less than 1 millimetre since 1 March 2000. This indicates the lighthouse did not shift during periods of little rainfall activity, but experienced southward shifts during periods of heavy winter rainfall.

The figure below outlines the trend in rainfall and the potential shift in the lighthouse. A two-parameter, second-degree polynomial model was used to develop the trend. The period forecasts 6 months into the future. It suggests that rainfall will be at approximately 75 millimetres greater than in an average year. This equates to a 2-centimetre shift southward in the lighthouse. The trend equations are listed on the figure.

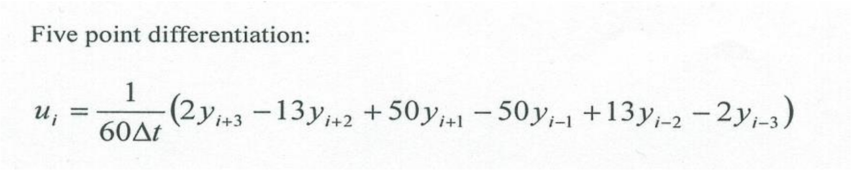
Figure 28: Rainfall and Shift Trends at St. Catherine's Point



9. RECOMMENDATIONS FOR FURTHER WORK

Further work needs to be carried out on the trend analysis of movement patterns at St. Catherine's Point, with an emphasis on the southward shift of the lighthouse. This location is located below a steep cliff and adjacent to the ocean. It is recommended that a higher order trend analysis model be used to take into account both factors. A time series analysis can be undertaken if the variance-covariance information for all network stations is made available from Ordnance Survey. Additionally, five-point differentiation in Equation 9 can determine a trend by using a predicted starting point.

Equation 9: Five Point Differentiation for Trend Analysis (Teferle, 2001)



Five point differentiation:

$$u_i = \frac{1}{60\Delta t}\left(2y_{i+3} - 13y_{i+2} + 50y_{i+1} - 50y_{i-1} + 13y_{i-2} - 2y_{i-3}\right)$$

The term u_i is the estimate for Day *i* (the current day). The term Δt is the step size of one entire day, and *y* represents the coordinate values at *i* + (# of days) or *i* – (# of days). If u changes significantly, then a time series trend is occurring (Teferle, 2001).

Further research should be carried out into the application of real-time OTF GPS for the monitoring of the lighthouse. This research should be aimed at using the coordinate shifts as a basis to determine whether the lighthouse is moving due to increased rainfall or through some other factor such as landslides. The GPS receiver located on the top of the lighthouse allows for monitoring through the adjustment of the active network, but it is a "de facto" system and not specifically designed to monitor movement of the lighthouse, but as a station in the network itself. Additionally, the movement cannot actually be determined until the coordinate information is processed from precise ephemeris data. The Pacoima Dam, located in the Gabriel Mountains north of Los Angeles, California, was equipped with GPS receivers to test the feasibility of applying continuous GPS to structural monitoring. Quantitative methods were assessed (at 3σ level) to allow for the identification of a number of outlying data points that could have been interpreted as GPS station motion. It was determined after the examination of the derived baseline time series that Pacoima Dam was experiencing an annual cycle of upstream-downstream (east-west) displacement at the centre of the dam arch of approximately 15-18 millimetres (Behr et al, 1998). The Pacoima Dam experiment successfully demonstrated the applicability of continuous GPS to the field of structural monitoring, and achieved a daily horizontal resolution of 4-6 millimetres.

It is also recommended that more soil analysis be carried out on the soil composition and geology at the base of the lighthouse. The trend between times of heavy precipitation and the movement of the lighthouse indicate that soil shear is occurring, and the movement could potentially be mitigated through some form of reinforcement to the base of the lighthouse. In the Pacoima Dam experiment, an impulse response function was derived and applied between input temperature and output displacement that enabled a resolution of 2-4 millimetres over periods of a few days (Behr et al, 1998). The residual deformation record could then be used to model the structure's response to changes in reservoir level and to identify anomalous displacements at the dam. A similar function could be derived and applied between input rainfall and output displacement at St. Catherine's Point Lighthouse, and the residual information could be used to model the lighthouse's response to soil saturation and to identify horizontal displacements of the lighthouse.

REFERENCES

Altamimi, Z., Sillard, P. and Boucher, C. "A New Release of the International Terrestrial Reference Frame for Earth Science Application" submitted to *J. Geophys. Res.*, 2001.

Ashkenazi, V., Beamson, G., Bingley, R.M., Dodson, A.H. Dodson, and Baker, T.F. "The Determination of Tide Gauge Heights Using GPS" Proudman Oceanographic Laboratory, Internal Document No. 75, August 1994.

Ashkenazi, V. and Ffoulkes-Jones, G. "Millimetres Over Hundreds of Kilometres" *GPS World*, November / December 1990.

Behr, Jeffrey, Kenneth Hudnut and Nancy King "Monitoring Structural Deformation at Pacoima Dam, California Using Continuous GPS" Proceedings of the 11th International Meeting of the Satellite Division of the Institute of Navigation, Nashville, Tennessee, 15-18 September 1998.

Boucher, Claude and Altamimi, Zuheir "The ITRF and its relationship to GPS" *GPS World*, Vol. 7, No. 9, September 1996.

Christie, R.R. and Wilson, J.I. "A New Geodetic Datum for Great Britain- The Ordnance Survey Scientific GPS Network" 17th UKGA Conference, Oxford, 14-16 April 1993.

Cornforth,D.H. and Mikkelson, P.E. "Continuous Monitoring of Groundwater Response to Winter Rainfall" *Landslides in Research, Theory, and Practice Vol. 1*. Proceedings of the 8th International Symposium on Landslides, Cardiff, Wales, 26-30 June 2000

Cruddace, Paul, Geodetic Advisor, Ordnance Survey. Email correspondence from 7 September to 21 September 2001.

Denys, Paul and Cross, Paul "The Ordnance Survey of Great Britain's Contribution to the ETRF89" Report Number 93/0602 - Version 3.0, August 1993.

Dodson, A.H., "The Effects of Atmospheric Refraction on GPS Measurements" Royal School of Military Survey Lecture Notes, 25 June 2001.

England, Philip "The Use of GPS in Studying the Deformation of the Earth" Department of Earth Sciences, Oxford University, 16 March 1989.

Farrell, Jay A. and Barth, Matthew The Global Positioning System and Inertial Navigation McGraw-Hill, New York, 1999.

Jahn, Cord-Hinrich, Gunter Seeber, Gillian Fouger, Axel Björnsson "A GPS Survey in The North-East Volcanic Zone of Iceland 1987 – First Results" Sixth International Seminar of the Global Positioning System, Institute of Engineering Surveying and Space Geodesy, University of Nottingham, 22-24 April 1993.

Jarvis, M.G., Allen, R.H., Fordham, S.J., Hazelden, J., Moffat, A.J., and Sturdy, R.G. Soils and their Use in South East England Harpenden, Kent, 1984.

Klobuchar, J. A. "Ionospheric Effects on GPS" Global Positioning System: Theory and Application Volume I. American Institute of Aeronautics and Astronautics, Inc. Washington, D.C., 1996.

Langley, Richard B. "The GPS Error Budget" *GPS World*, March 1997.

Larijani, L. Casey GPS for Everyone American Interface Corporation Publishing Division, New York, 1998.

Leick, Alfred GPS Satellite Surveying Second Edition, John Wiley & Sons, Inc., 1995

Meteorological Office of Great Britain "Rainfall Totals from St. Catherine's Point" 1 May 2000 to 30 June 2001.

Moore, T. "COMPARE" Version 2.01, Institute of Engineering Surveying and Space Geodesy, University of Nottingham, January 1995.

Moore, T. "High Precision GPS Positioning" Sixth International Seminar of the Global Positioning System, Institute of Engineering Surveying and Space Geodesy, University of Nottingham, 22-24 April 1993.

Murray, M., Baxter, R, Karavas, B, and Burgmann, R. "Permanent GPS Network: Bay Regional Deformation Array" Berkeley Seismological Laboratory, 1997.

Ordnance Survey "National GPS Network Information" Internet Site www.gps.gov.uk

Price, E.J. "Survey Computation Suite" Geodesy Department, Royal School of Military Survey.

Rothacher, Markus and Leos Mervart "Bernese GPS Software Version 4.0" Astronomical Institute, University of Berne, September 1996.

Royal School of Military Survey (RSMS), GPS Phase and Range Equations Lecture, 26 June 2001.

Seeber, Gunter Satellite Geodesy Walter de Gruyter & Company, Berlin, 1993.

Seeber, Gunter and Lai Xian " A GPS Survey in the Yunnan Earthquake Experimental Field – Objectives and First Results" Global and Regional Geodynamics Symposium No. 101, Edinburgh, Scotland, 3-5 August 1989.

Tanaka, T., E. Shimojima, K. Mitamura, Y. Hoso, and Y. Ishihara, "Precipitation, Groundwater, and Ground Deformation" Global and Regional Geodynamics Symposium No. 101, Edinburgh, Scotland, 3-5 August 1989.

Teferle, Felix N., Institute of Engineering Surveying and Space Geodesy, University of Nottingham. Email correspondence 17 September to 21 September 2001.

Trimble Navigation Limited GPSurvey Software 2.2 Training Manual Sunnyvale, California, 1996.

Wells, D.E, Beck N., Delikaraoglou, A., Kleusberg, E., Lachapelle, G., Langley, R., Nakiboglu, M., Schwarz, K., Vanicek, P., Guide to GPS Positioning, Canadian GPS Associates, Fredericton, N.B., Canada, 1986.

BIBLIOGRAPHY

Brewin, Bob "NOAA Measuring Washington Monument Using GPS" *Federal Computer Week,* 18 Aug 1999.

Dragert, H. and Schmidt, M. "The Use of Continuous GPS Tracking for Deformation Studies in Southwestern B.C." Proceedings of the International Technical Meeting of the Institute of Navigation (ION-GPS-94), Salt Lake City, Utah, 1994

Goudie, A.S. and Brunsden, D. The Environment of the British Isles Clarendon Press, Oxford, 1994.

Maye, Phil "Control Networks and Deformation Monitoring- Practical Exercise" Institute of Engineering Surveying and Space Geodesy, University of Nottingham, 15 February 1999.

Wong, Kai-yuen, Man, King-leung, and Chan, Wai-yee "Real Time Kinematic Spans the Gap" *GPS World* Vol. 12, No. 7, July 2001.