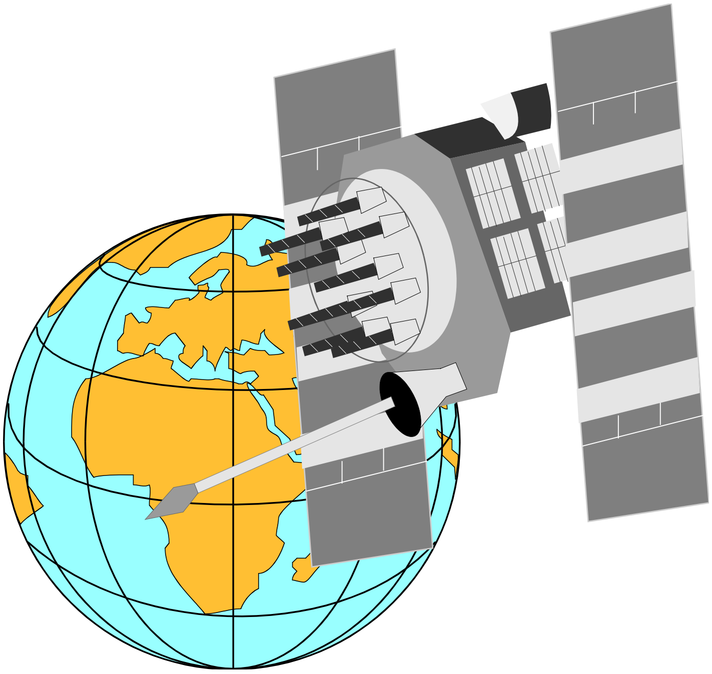
An Overview of the Global Positioning System (GPS)



Ken Campbell

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Environmental Sciences Department
Natural Resources Institute
Chatham Maritime
ME4 4TB
U.K.

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An Overview of the Global Positioning System (GPS)

Ken Campbell, Natural Resources Institute, Chatham Maritime, ME4 4TB, U.K.

1. INTRODUCTION

Global Positioning Systems (GPS) are space-based radio positioning systems that provide 24 hour, three-dimensional position, velocity and time information to suitably equipped users anywhere on or near the surface of the Earth. The NAVSTAR system, operated by the US Department of Defence, is the first GPS system widely available to civilian users. The Russian GPS system, GLONASS, is similar in operation and may eventually prove complimentary to the NAVSTAR system. Global Navigation Satellite Systems (GNSS) are extended GPS systems, providing users with sufficient accuracy to be useable for critical navigation applications.

The Global Positioning System (usually referred to as GPS) is a three-dimensional navigational positioning system. Using multiple satellites and hyperbolic geometry, it determines the position of a receiver in three dimensions – effectively it gives longitude, latitude, and altitude. If you have suitable receivers, these can calculate the (approximate) position and elevation of the receiving antenna, at any time of day, anywhere in the world, on land, at sea, or in the air.

Applications for GPS are numerous. Marine vessels, military and civilian, are important users. GPS is used for coastal, channel, and harbour navigation, as well as for navigation over the oceans. GPS is also applied to aircraft navigation, but is increasingly being used for land based navigation and position fixing. By recording information from GPS receivers, positional information can also be transferred to other sources of electronic information, for example databases, GIS and mapping systems.

1.1 GPS and Earlier Electronic Navigation Systems

Before GPS, a number of other systems, including LORAN-A, LORAN-C, Omega VLF, and Decca used basically similar navigation techniques. These systems functioned using the time differences between received radio signals to calculate positions. However, GPS represents a significant improvement over previous systems, both in terms of cost and accuracy.

Earlier navigation systems were, in many cases, costly and difficult to use. For example, A LORAN-C had a number of problems that effectively limited its wider utilisation. It was very expensive to maintain, and expensive to power, using over 1,000,000 W for each station. These stations needed to be placed far away from settlements, due to potentially dangerous radiation. Significantly, LORAN-C was not considered accurate enough for the US military. The system's 100-kHz signals were difficult to receive, needed large antennas and were subject to radio interference. Other systems had similar problems limiting their widespread use. In the early 1970's collaborative efforts by the US Military and US Coastguard resulted in the development of a system of navigation that would be safe, accurate, and relatively inexpensive to use in the field. The Global Positioning System was the result.

GPS is now an operational system with global utilisation. A complete satellite constellation, as well as spares, has been launched, and there is an ongoing programme for launching replacements well into the next century. It is currently possible to use relatively inexpensive, small hand-held instruments roughly the size of a portable phone, that receive GPS signals and provide quick and accurate measurements. The quality of equipment is excellent and GPS units are reliable and simple to use. Other than costs of purchasing the receiver, there is currently no charge for signal reception.

2. GPS POSITIONING

There are three main components of the GPS system. To deliver accurate measurements of position, all of these components must be accurate, precise, and functioning normally. If one component is slightly off, measurements can become corrupted.

The various parts of the GPS system are:

The Space Segment	The Control Segment	The User Segment
• Satellites	• Control / Upload stations • Monitor stations • Master control station	• User receivers

2.1 Space Segment

The Space Segment of the system consists of the GPS satellites broadcasting radio signals from space. The GPS operational constellation consists of 24 satellites, including 21 navigational SVs and 3 active spares orbiting the earth. These orbits therefore repeat the same ground track, as the earth circles beneath them, once each day. The orbit is such that the satellites repeat the same track and configuration over any point approximately every 24 hours (about 4 minutes earlier each day). There are six orbital planes with nominally four SVs in each, equally spaced 60° apart. This configuration provides the user with between five and eight SVs that are normally visible from any point on the earth.

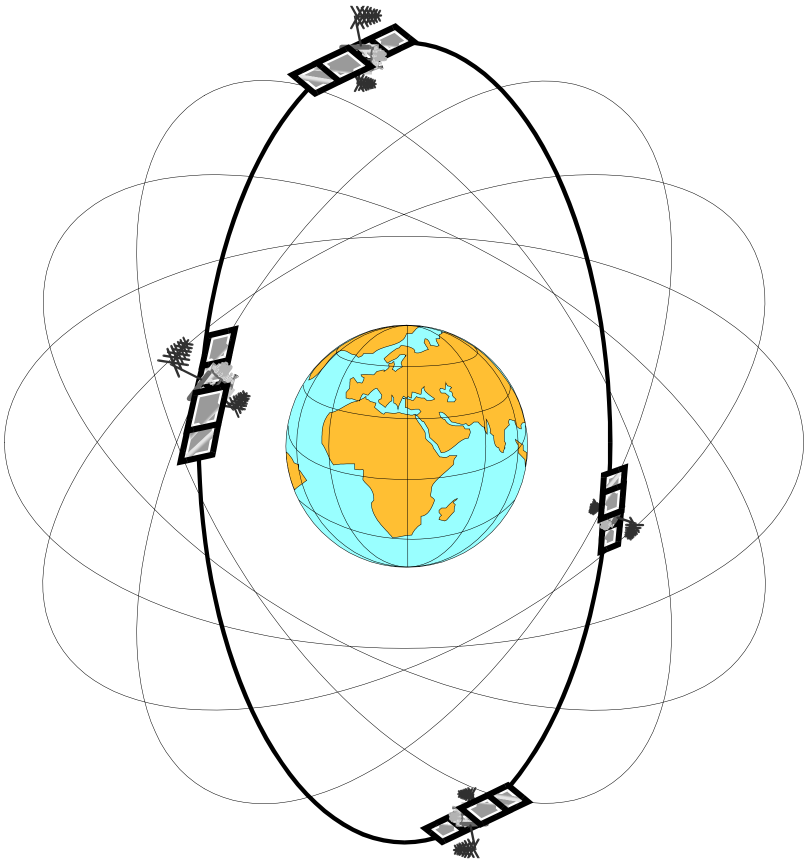


Figure 1

GPS constellation, indicating the 6 orbital planes with 4 satellites shown in one orbit.

Table 1 GPS Constellation History and Status (Status as of 08 Jan 97)

NAVSTAR	SVN/PRN	LAUNCH	SLOT	OPERATIONAL	NAV LOST	REASON FOR FAILURE	MONTHS OPERATIONAL
I-1	1 / 4	22FEB78	**	29MAR78	25JAN80	CLOCK	21.9
I-2	2 / 7	13MAY78	**	14JUL78	30JUL80	CLOCK	25.5
I-3	3 / 6	06OCT78	**	09NOV78	19APR92	CLOCK	161.3
I-4	4 / 8	11DEC78	**	08JAN79	27OCT86	CLOCK	93.6
I-5	5 / 5	09FEB80	**	27FEB80	28NOV83	WHEEL	45
I-6	6 / 9	26APR80	**	16MAY80	10DEC90	WHEEL	126.8
I-7	7 /	18DEC81	**			BOOSTER	0
I-8	8 / 11	14JUL83	**	10AUG83	04MAY93	EPS DEGR.	116.8
I-9	9 / 13	13JUN84	**	19JUL84	28FEB94	CLOCK	115.2
I-10	10 / 12	08SEP84	**	03OCT84	18NOV95	CLOCK	133.5
I-11	11 / 3	09OCT85	**	30OCT85	27FEB94	TT&C	99.9

TOTAL BLOCK I SATELLITE YEARS ON ORBIT = 79.40 YEARS
AVERAGE OPERATING LIFE TO DATE = 7.22 YEARS
(INCLUDING BOOSTER FAILURE)

NAVSTAR	SVN/PRN	LAUNCH	SLOT	OPERATIONAL	NAV LOST	REASON FOR FAILURE	MONTHS OPERATIONAL
II-1	14 / 14	14FEB89	E1	14APR89	OPERATING		92.8
II-2	13 / 2	10JUN89	B3	12JUL89	OPERATING		89.9
II-3	16 / 16	17AUG89	E5	13SEP89	OPERATING		87.8
II-4	19 / 19	21OCT89	A4	14NOV89	OPERATING		85.8
II-5	17 / 17	11DEC89	D3	11JAN90	OPERATING		83.9
II-6	18 / 18	24JAN90	F3	14FEB90	OPERATING		82.8
II-7	20 / 20	25MAR90	B5	19APR90	10MAY96		72.7
II-8	21 / 21	02AUG90	E2	31AUG90	OPERATING		76.3
II-9	15 / 15	01OCT90	D2	20OCT90	OPERATING		74.6
IIA-10	23 / 23	26NOV90	E4	10DEC90	OPERATING		72.9
IIA-11	24 / 24	03JUL91	D1	30AUG91	OPERATING		64.3
IIA-12	25 / 25	23FEB92	A2	24MAR92	OPERATING		57.5
IIA-13	28 / 28	10APR92	C5	25APR92	OPERATING		56.4
IIA-14	26 / 26	07JUL92	F2	23JUL92	OPERATING		53.5
IIA-15	27 / 27	09SEP92	A3	30SEP92	OPERATING		51.3
IIA-16	32 / 1	22NOV92	F1	11DEC92	OPERATING		48.9
IIA-17	29 / 29	18DEC92	F4	05JAN93	OPERATING		48.1
IIA-18	22 / 22	03FEB93	B1	04APR93	OPERATING		45.1
IIA-19	31 / 31	30MAR93	C3	13APR93	OPERATING		44.8
IIA-20	37 / 7	13MAY93	C4	12JUN93	OPERATING		42.9
IIA-21	39 / 9	26JUN93	A1	21JUL93	OPERATING		41.6
IIA-22	35 / 5	30AUG93	B4	20SEP93	OPERATING		39.6
IIA-23	34 / 4	26OCT93	D4	01DEC93	OPERATING		37.2
IIA-24	36 / 6	10MAR94	C1	28MAR94	OPERATING		33.3
IIA-25	33 / 3	28MAR96	C2	09APR96	OPERATING		9.0
IIA-26	40 / 10	16JUL96	E3	15AUG96	OPERATING		4.8
IIA-27	30 / 30	12SEP96	B2	01OCT96	OPERATING		3.2

TOTAL BLOCK II/IIA SATELLITE YEARS ON ORBIT = 125.08 YEARS
AVERAGE OPERATING LIFE TO DATE = 4.63 YEARS

2.2 Control Segment

The Control Segment consists of a system of tracking stations located around the world.

A Master Control station is located at Falcon Air Force Base, Colorado, USA. These monitoring stations measure signals from the SVs which are incorporated into orbital models for each satellite. The models represent precise orbital data, or ephemeris, as well as clock corrections for each satellite. This Master Control station uploads ephemeris and clock data to each satellite. The SVs then send subsets of the orbital ephemeris data to the GPS receivers comprising the user segment.

2.3 User Segment

The GPS User Segment consists of the GPS receivers and the user community. GPS receivers convert SV signals into position, velocity, and time estimates. Four satellites are required to compute the four dimensions of X, Y, Z (position) and Time. GPS receivers are used for navigation, positioning and time dissemination. Navigation in three dimensions is the primary function of GPS. Navigation receivers are made for aircraft, ships, ground vehicles, and for hand carrying by individuals.

2.4 Precise Positioning System (PPS)

Authorised users with cryptographic equipment and keys and specially equipped receivers use the Precise Positioning System. Only US and Allied military, certain US Government agencies, and selected civilian users that are specifically approved by the US Government, can use the PPS.

PPS Predictable Accuracy

22 meter Horizontal accuracy

27.7 meter vertical accuracy

100 nanosecond time accuracy

2.5 Standard Positioning System (SPS)

Civil users world-wide use the SPS without charge or restrictions. Most receivers are capable of receiving and using the SPS signal. The SPS accuracy is intentionally degraded by the DOD by the use of Selective Availability.

SPS Predictable Accuracy

100 meter horizontal accuracy

156 meter vertical accuracy

340 nanoseconds time accuracy

These GPS accuracy figures are from the 1994 Federal Radionavigation Plan. The figures are 95% accuracies, and express the value of two standard deviations of radial error from the actual antenna position to an ensemble of position estimates made under specified satellite elevation angle (five degrees) and PDOP (less than six) conditions.

For horizontal accuracy figures 95% is the equivalent of 2 drms (two-distance root-mean-squared), or twice the radial error standard deviation. For vertical and time errors 95% is the value of two-standard deviations of vertical error or time error.

Receiver manufacturers may use other accuracy measures. Root-mean-square (RMS) error is the value of one standard deviation (68%) of the error in one, two or three dimensions. Circular Error

Probable (CEP) is the value of the radius of a circle, centred at the actual position that contains 50% of the position estimates. Spherical Error Probable (SEP) is the spherical equivalent of CEP, that is the radius of a sphere, centred at the actual position, that contains 50% of the three dimension position estimates. As opposed to 2 drms, drms, or RMS figures, CEP and SEP are not affected by large operator errors making them an overly optimistic accuracy measure.

Some receiver specification sheets list horizontal accuracy in RMS or CEP and without Selective Availability, making those receivers appear more accurate than those specified by more responsible vendors using more conservative error measures.

2.6 GPS Satellite Signals

The GPS satellites transmit two microwave carrier signals. The L1 frequency (1575.42 MHz) carries the navigation message and the SPS code signals. The L2 frequency (1227.60 MHz) is used to measure the ionospheric delay by PPS equipped receivers. These carrier signals are modulated by three codes:

- Coarse Acquisition Code
- Precise Code
- and the Navigation Message

The C/A Code (Coarse Acquisition) modulates the L1 carrier phase. The C/A code is a repeating 1 Mhz Pseudo Random Noise (PRN) Code. This noise-like code modulates the L1 carrier signal, "spreading" the spectrum over a 1 MHz bandwidth. The C/A code repeats every 1023 bits (one millisecond). There is a different C/A code PRN for each SV. GPS satellites are often identified by their PRN number, the unique identifier for each pseudo-random-noise code. The C/A code that modulates the L1 carrier forms the basis for the civilian SPS.

The Navigation Message also modulates the L1-C/A code signal. The Navigation Message is a 50 Hz signal consisting of data bits that describe the GPS satellite orbits, clock corrections, and other system parameters.

The P-Code (Precise) modulates both the L1 and L2 carrier phases. The P-Code is a very long (seven days) 10 MHz PRN code. In the Anti-Spoofing (AS) mode of operation, the P-Code is encrypted into the Y-Code. The encrypted Y-Code requires a classified Anti-Spoofing Module for each receiver channel and is for use only by authorised users with cryptographic keys. The P (Y)-Code is the basis for the PPS. Use of the two frequencies enables errors caused by atmospheric delays of the radio signals to be corrected because different frequencies are effected by atmospheric distortions to different extents.

2.6.1 GPS Navigation Message

The GPS Navigation Message consists of time-tagged data bits marking the time of transmission of each subframe at the time they are transmitted by each SV. A data bit frame consists of 1,500 bits divided into five 300-bit subframes. A data frame is transmitted every thirty seconds. Three six-second subframes contain orbital and clock data. SV Clock corrections are sent in subframe one and precise SV orbital data sets (ephemeris data parameters) for the transmitting SV are sent in subframes two and three. Subframes four and five are used to transmit different pages of system data. An entire set of twenty-five frames (125 subframes) makes up the complete Navigation Message that is sent over a 12.5 minute period.

Data frames (1500 bits) are sent every thirty seconds. Each frame consists of five subframes. Data bit subframes (300 bits transmitted over six seconds) contain parity bits that allow for data checking and limited error correction.

Clock data parameters describe the SV clock and its relationship to GPS time.

Ephemeris data parameters describe SV orbits for short sections of the satellite orbits. Normally, a receiver gathers new ephemeris data each hour, but can use old data for up to four hours without much error. The ephemeris parameters are used with an algorithm that computes the SV position for any time within the period of the orbit described by the ephemeris parameter set.

Almanacs are approximate orbital data parameters for all SVs. These describe SV orbits over extended periods of time (can be useful for months in some cases) and a set for all SVs is sent by each SV over a period of 12.5 minutes. The time taken to acquire signals from satellites on turning a GPS receiver on can be significantly aided by the availability of current almanacs. The time taken to receive a satellite signal and download an almanac can be longer than half an hour, especially if the GPS receiver was last used a long distance away, for example in another hemisphere. The approximate orbital data is used to preset the receiver with the approximate position and carrier Doppler frequency (the frequency shift caused by the rate of change in range to the moving SV) of each SV in the constellation.

Each complete SV data set includes an ionospheric model that is used by the receiver to approximate the atmospheric delay at any location and time. This model is transmitted to the satellites by the Master Control Station.

Each SV sends the amount to which GPS Time is offset from Universal Coordinated Time. This correction can be used by the receiver to set UTC to within 100 ns.

2.7 Pseudo-Range Navigation

The position of the receiver is where the "pseudo-ranges" from a set of SVs intersect. Position is determined from multiple pseudo-range measurements at a single moment in time. These pseudo range measurements are used together with SV position estimates based on the precise orbital elements (the ephemeris data) tat are sent by each SV. This orbital data allows the receiver to compute the SV positions in three dimensions at the instant that they sent their respective signals.

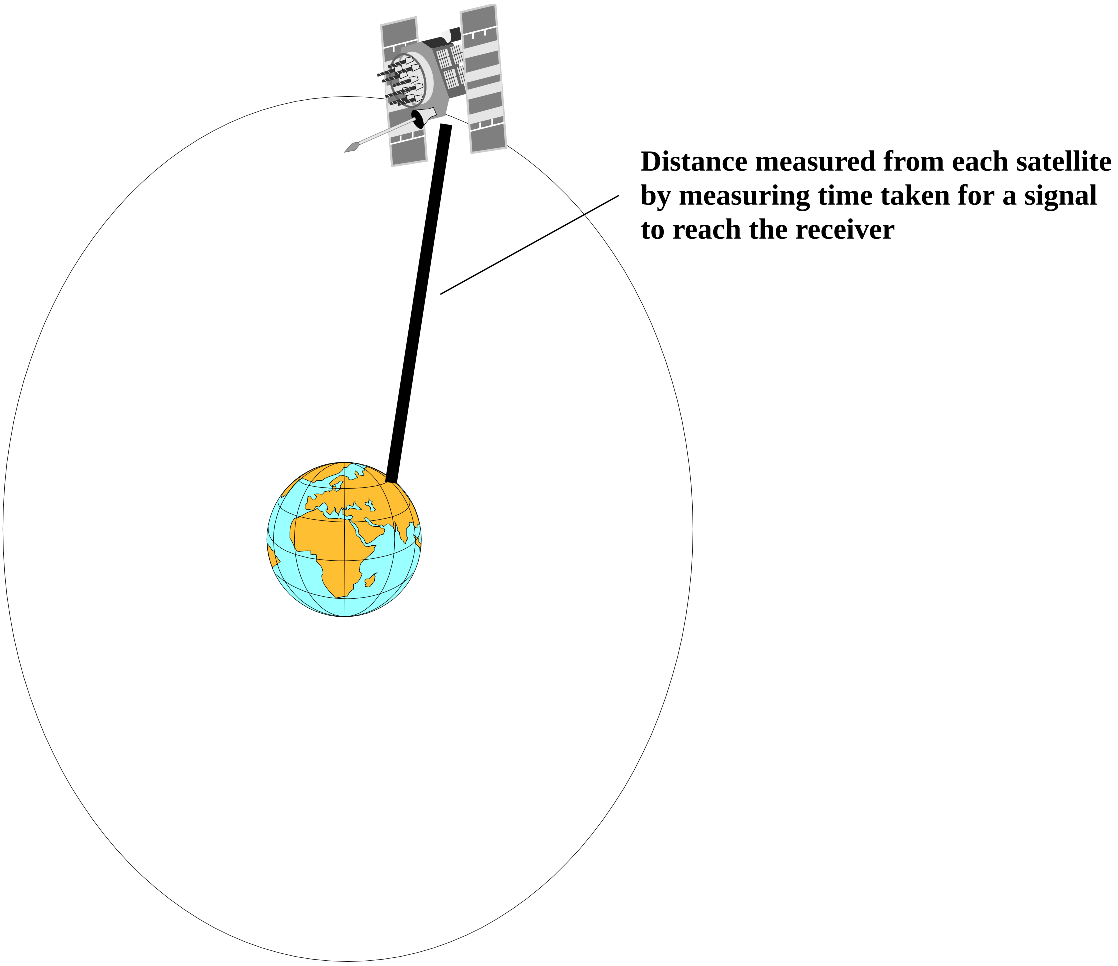
The distance from a single satellite to the receiver is calculated as the time taken for a specific sequence of radio signals to travel the intervening distance. To do this the receiver needs to know when the signal left the satellite. To establish this, the same pseudo-random code is generated by the satellite and the receiver at the same time - synchronised according to the time signals initially transmitted by the satellite. The receiver examines the incoming code and compares this with the time the same code sequence was generated by the receiver. The time difference represents a fairly precise measure of the distance between satellite and receiver at the precise moment when the signal was transmitted. Multiplied by the speed of light this time difference gives the distance from satellite to receiver. Accurate timing is therefore crucial to the operation of the system.

$$(T_{TRAVEL} \times 3 \times 10^{10} \text{cm/sec} = \text{Distance})$$

For normal navigation, four satellites can be used to determine three position dimensions as well as time. Position dimensions are computed by the receiver in Earth-Centred, Earth-Fixed X, Y, Z (ECEF XYZ) co-ordinates. Time, as transmitted by the SV, is used to correct the offset in the receiver clock, allowing the use of an inexpensive clock in each receiver. The use of inexpensive receiver clocks is one of the factors that has significantly reduced the costs of the GPS system compared with previous radio navigation systems - all of the costly components are located in the satellites. SV Position in three dimensions is computed from SV pseudo-ranges together with clock correction and ephemeris data. Receiver position is computed from the SV positions, the measured pseudo-ranges, and a receiver position estimate (usually the last computed receiver position).

Three satellites could be used determine three position dimensions with a perfect receiver clock. In practice this is impractical and three SVs can be used to compute a two-dimensional, horizontal fix given an assumed height. This is possible at sea or in altimeter equipped aircraft. Tracking five or more satellites can provide position, time and a level of redundancy that provides additional locational confidence. More SVs can provide extra position fix certainty, enabling optimally located satellites to be used in the calculations, and can under certain circumstances allow the detection of out-of-tolerance signals.

Figure 2



With a distance measured from a single satellite, the only places that the receiver can possibly be are anywhere on the surface of a sphere, with a radius equal to that distance. By using distances from two satellites, the location of a receiver can be narrowed down to the points where two spheres intersect.

Figure 3 **The intersection of two spheres is an ellipse.**

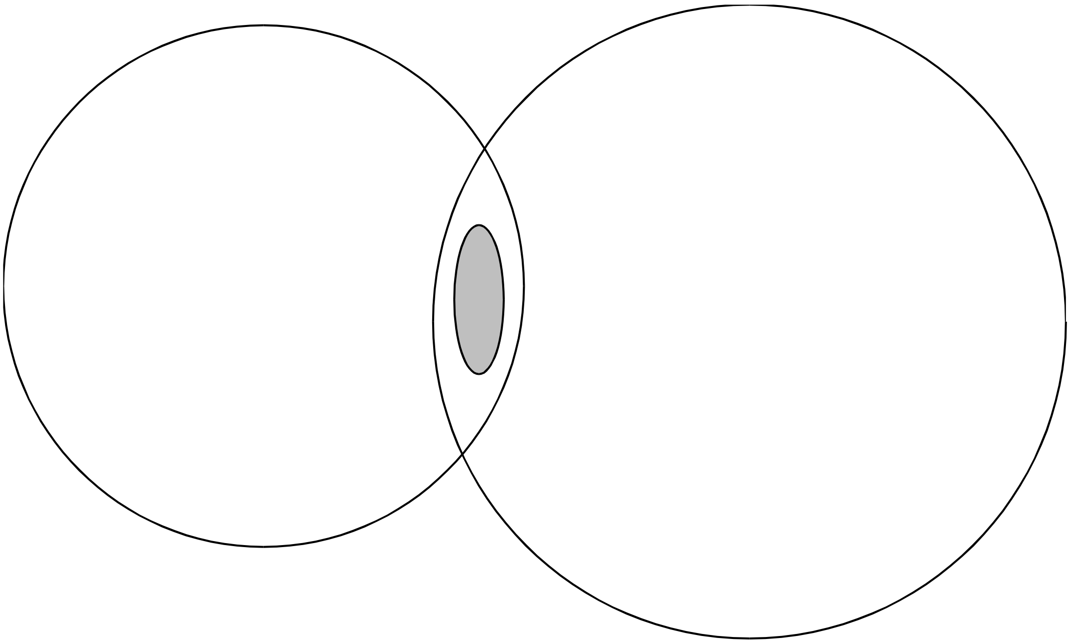
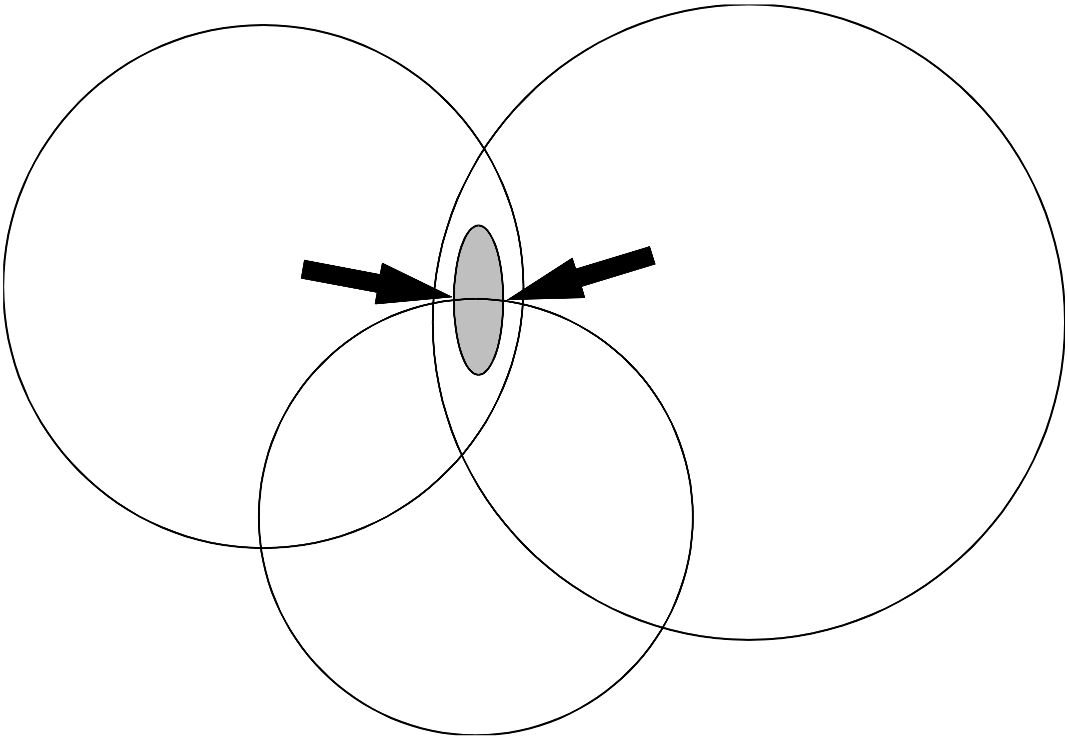


Figure 4 **By introducing the distance from a third satellite, the location of a receiver can be narrowed down to two points on that ellipse.**



A fourth distance measurement would go through one of these points. In theory, this may not be necessary because one of the two possible points may be so far from the surface of the Earth as to be unreasonable. However, in practice. partly due to inaccuracies in receiver clocks, movements of satellites and to the distortion of satellite transmissions by their passage through the atmosphere, measurements from a fourth satellite are usually required.

Position in XYZ is converted within the receiver to geodetic latitude, longitude and height above the ellipsoid. Latitude and longitude are usually provided in the geodetic datum on which GPS is based (WGS-84). Receivers can often be set to convert to other user-required datums. Position offsets of hundreds of meters can result from using the wrong datum.

Velocity is computed from change in position over time, the SV Doppler frequencies, or both.

Time is computed in SV Time, GPS Time, and UTC. SV Time is the time maintained by each satellite. Each SV contains four atomic clocks (two caesium and two rubidium). SV clocks are monitored by ground control stations and occasionally reset to maintain time to within one-millisecond of GPS time. Clock correction data bits reflect the offset of each SV from GPS time. SV Time is set in the receiver from the GPS signals. Data bit subframes occur every six seconds and contain bits that resolve the Time of Week to within six seconds. The 50 Hz data bit stream is aligned with the C/A code transitions so that the arrival time of a data bit edge (on a 20 millisecond interval) resolves the pseudo-range to the nearest millisecond. Approximate range to the SV resolves the twenty millisecond ambiguity, and the C/A code measurement represents time to fractional milliseconds. Multiple SVs and a navigation solution (or a known position for a timing receiver) permit SV Time to be set to an accuracy limited by the position error and the pseudo-range error for each SV. SV Time is converted to GPS Time in the receiver.

GPS Time is a "paper clock" ensemble of the Master Control Clock and the SV clocks. GPS Time is measured in weeks and seconds from 24:00:00, January 5, 1980 and is maintained close to UTC by the Master Ground Station. Time in Universal Coordinated Time (UTC) is computed from GPS Time using the UTC correction parameters sent as part of the navigation data bits.

2.8 Sources of Error in GPS position fixes

GPS errors are the result of a combination of noise, bias and mistakes/human error.

1. Noise errors are the combined effect of PRN code noise and noise within the receiver.
2. Bias errors result from Selective Availability and from other factors
    a) Selective Availability (see 2.8.1)
    b) SV clock errors uncorrected by the Control Segment can result in errors.
    c) Ephemeris data errors
    d) Tropospheric delays: The troposphere is the lower part of the atmosphere (ground level to between 8 and 13 km) that experiences the changes in temperature, pressure, and humidity associated with weather changes. Complex models of tropospheric delay require estimates or measurements of these parameters.
    e) Unmodeled ionosphere delays. The ionosphere is the layer of the atmosphere from 50 to 500 km that consists of ionized air, and is particularly effected by the solar wind. When these particles hit the upper atmosphere they result in delays and distortions to the radio signals broadcast by the GPS satellites. The transmitted model can only remove about half of the delay leaving approximately ten metres of unmodeled residual error (for signals from each satellite).
    f) Multipath: Multipath errors are caused by reflected signals from surfaces near the receiver that can either interfere with, or be mistaken for, the signal that follows the straight line path from the satellite. Multipath errors are difficult to detect and often hard to avoid.

3. Mistakes or human error can sometimes result in errors of hundreds of kilometres. Control segment mistakes due to computer or human error can cause errors from one meter to hundreds of kilometres. Fortunately these are rare.

User mistakes, which are more common than the majority of users realise, including incorrect geodetic datum selection, can cause errors from about one metre to hundreds of meters.

Noise and bias errors combine, resulting in typical ranging errors of around fifteen meters for each satellite that is used in the position solution. These combine to produce the overall error of the calculated position fix. Added to this are errors associated with GDOP, or Geometric Dilution of Precision, discussed below.

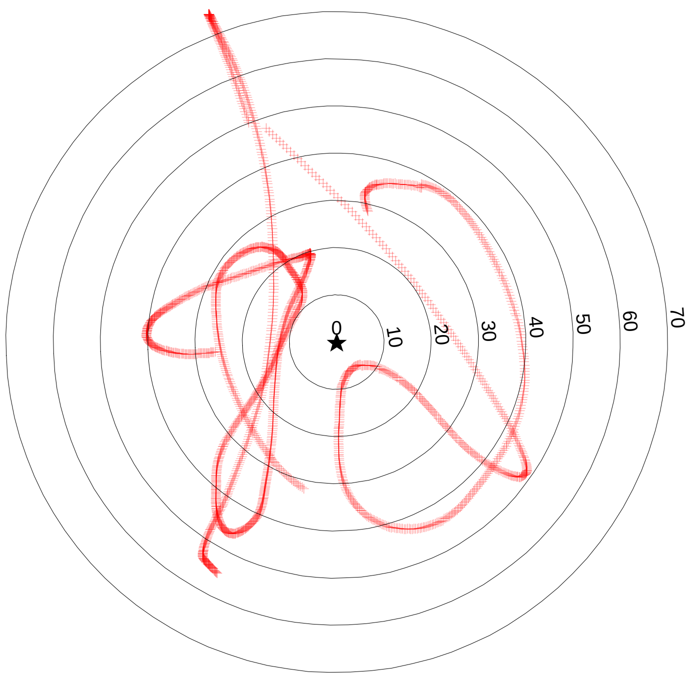
2.8.1 Selective Availability

Selective Availability (SA) is the deliberate degradation of the Standard Positioning System (SPS) signals through the introduction of a time varying bias. SA is controlled by the US Department of Defence with the aim of limiting accuracy for non-U. S. military and authorised government users. The potential accuracy of the C/A code of around 30 meters is reduced to 100 meters (two standard deviations).

The SA bias on each satellite signal is different, and so the resulting position solution is a function of the combined SA bias from each SV used in the navigation solution. Because SA is a constantly changing bias with low frequency terms in excess of a few hours, position solutions or individual SV pseudo-ranges cannot be effectively averaged over periods shorter than a few hours. Differential corrections must be updated at a rate less than the correlation time of SA (and other bias errors).

The effect of Selective Availability is shown by Figure 1. The diagram illustrates position fixes obtained every second over two one-hour recording periods on one day . The star in the centre represents the true position, fixed by DGPS. Concentric circles represent distance from the true location in metres.

Figure 5 **The effect of Selective Availability** (see text for description)



2.8.2 Geometric Dilution of Precision (GDOP)

In addition to the sources of error described above, the precision of locational fixes is also determined by the geometric positioning of the SVs used in relation to the GPS receiver. GPS ranging errors are magnified by the range vector differences between the receiver and the SVs. The volume of the shape described by the unit-vectors from the receiver to the SVs used in a position fix is inversely proportional to GDOP.

Poor GDOP — a large value representing a small unit vector-volume, results when angles from receiver to the set of SVs used are similar.

Good GDOP — a small value representing a large unit-vector-volume, results when angles from receiver to SVs are different.

GDOP is computed from the geometric relationships between the receiver position and the positions of the satellites the receiver is using for navigation. GDOP terms are usually computed using parameters from the navigation solution process.

In general, ranging errors from the SV signals are multiplied by the appropriate GDOP term to estimate the resulting position or time error. Various GDOP terms can be computed from the navigation covariance matrix. ECEF XYZ DOP terms can be rotated into a North-East Down (NED) system to produce local horizontal and vertical DOP terms.

GDOP Components

- PDOP = Position Dilution of Precision (3-D), sometimes the Spherical DOP.
- HDOP = Horizontal Dilution of Precision (Latitude, Longitude).
- VDOP = Vertical Dilution of Precision (Height).
- TDOP = Time Dilution of Precision (Time).

While each of these GDOP terms can be individually computed, they are formed from covariances and so are not independent of each other. A high TDOP (time dilution of precision), for example, will cause receiver clock errors which will eventually result in increased position errors.

2.8.3 A Practical Demonstration of Error: How good is a single position fix?

Accuracies of hand-held GPS receivers were investigated by D'Eon (1995). It was found that single-fix locations were accurate to under 100 metres more than 80% of the time. In other words, they were out by more than 100 metres 20% of the time. A realisation of the scale and probability of this error is important, especially since the great majority of position fixes obtained using hand-held GPS receivers are single-fix locations. D'Eon also found that the accuracy of locations were improved by using position averaging methods. This is where a receiver collects a number of fixes and averages them over time. However, allowing the receiver to continuously collect fixes for 15 to 30 minutes and then averaging these fixes yielded a median position error of 17 metres. In practice, many users will be unwilling to take the time to collect fixes over a half-hour period and the results of any averaging that does take place are likely to be less accurate than is generally taken for granted.

In a test carried out in the UK, a Trimble 12-channel roving GPS reciver recorded fixes at one second intervals during a walk along a series of paths (see Figure 6). These readings were downloaded to a computer and then corrected using Differential GPS techniques (see Section 2.9) to produce more accurate results (Figure 7).

Figure 6 Uncorrected fixes

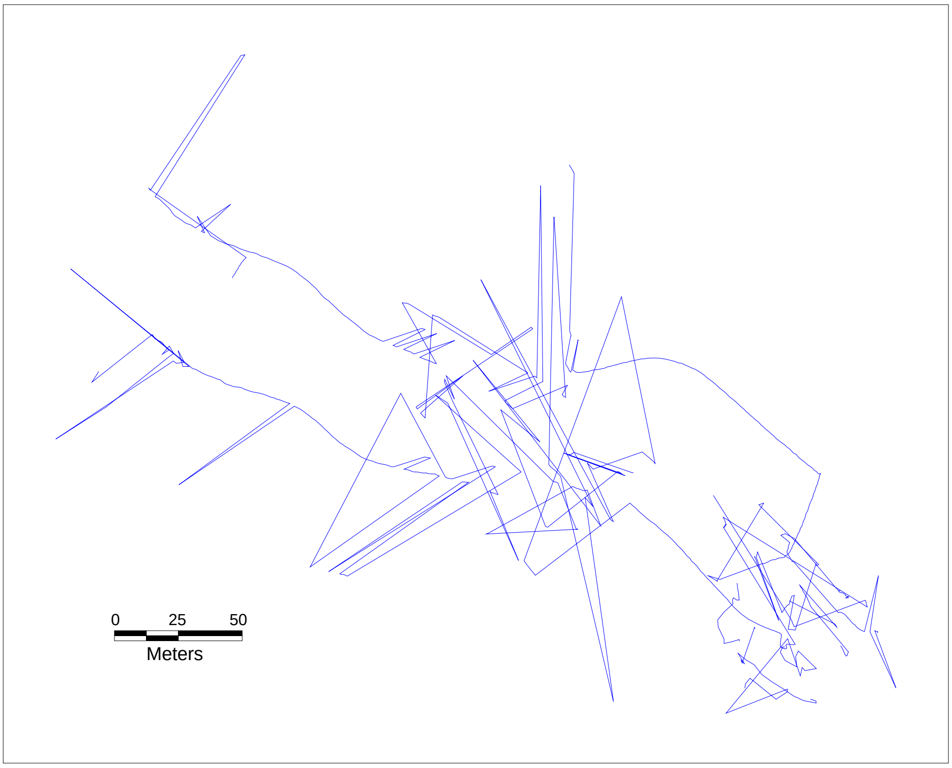
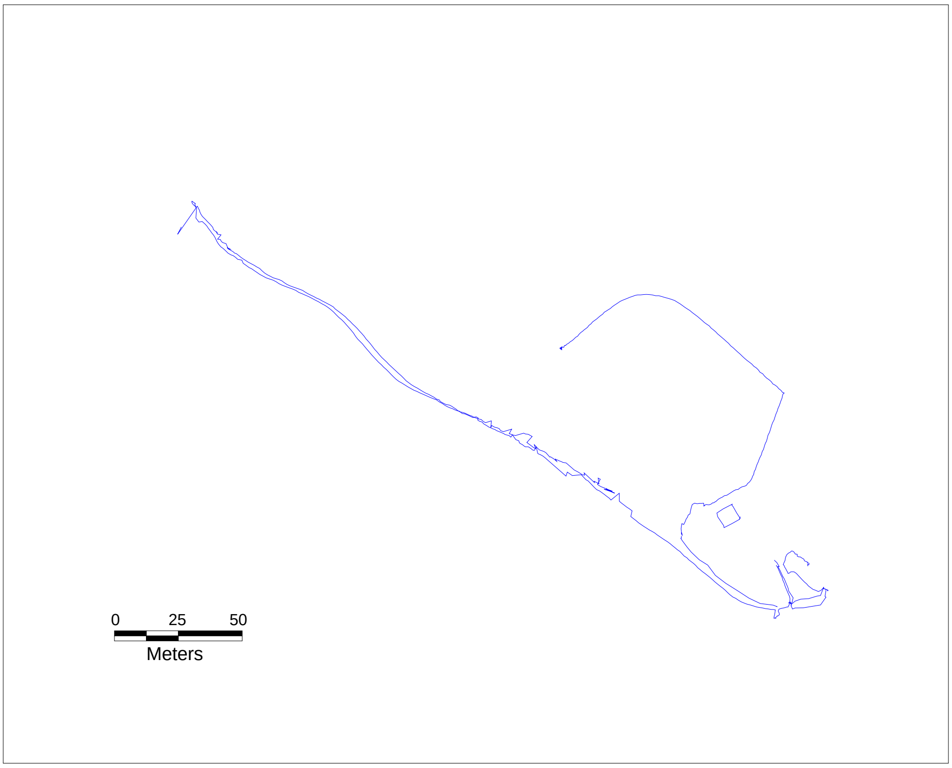


Figure 7 Fixes corrected using Differential GPS techniques.



2.9 Differential GPS (DGPS) Techniques

2.9.1 What is DGPS ?

The idea behind all differential positioning is to correct bias errors at one location with measured bias errors at a precisely known position. Data collected at the known site is used to determine what errors are contained in the satellite data. This information is then applied to the data collected from the roving units. Possible sources of error include Selective Availability, receiver clock inaccuracies, and atmospheric delays (see section 2.8 for more detail). A reference receiver, or base station, computes corrections for each satellite signal. Because individual pseudo-ranges must be corrected prior to the formation of a position fix, DGPS implementations require software in the reference receiver that can track all SVs that are in view and subsequently carry out individual pseudo-range corrections for each SV. These corrections are passed to the remote, or rover, receiver which must be capable of applying these individual pseudo-range corrections to each individual SV that is used for each position fix.

2.9.2 DGPS in Practice

Essentially, DGPS entails correcting a position fix from a remote receiver against a fix obtained by a receiver at a known location (the reference receiver). However, applying a simple position correction from an X/Y co-ordinate obtained from the reference receiver to one received by the remote receiver (as implemented by some GPS units, especially cheaper models) has a very limited effect at anything like useful distances from known locations. This is because both receivers would have to be using *exactly* the same set of SVs and also have identical GDOP terms (which is not possible at different locations) in order to be identically affected by bias errors.

To remove Selective Availability (and other bias errors), differential corrections should be computed at the reference station and applied at the remote receiver at an update rate that is less than the correlation time of SA. Suggested DGPS update rates are usually less than twenty seconds. Since satellite errors are continuously changing, the more frequently base station data are recorded the better. In practice the rate of collection at the base station will be determined by, and should not be less than, the rates used by mobile GPS units. Mobile GPS units updating fixes at five second intervals will require base station data also collected at five second intervals, or better still, at one second intervals to ensure maximum accuracy.

DGPS removes common-mode errors, those errors common to both the reference and remote receivers (not multipath or receiver noise). Errors are more often common when receivers are close together (less than 100 km). Differential position accuracies of 1-10 meters are possible with DGPS based on C/A code SPS signals.

2.9.3 Sources of Reference Station GPS Data

Differential corrections may be used in real-time or later, with post-processing techniques. Real-time corrections can be transmitted by radio link. For example, the US Coastguard maintains a network of differential monitors (base stations) and transmits DGPS corrections over radio-beacons covering much of the US coastline. DGPS corrections are often transmitted in a standard format (RTCM). This format is specified by the Radio Technical Commission Marine or RTCM. Instead of being transmitted for real-time use, corrections can be recorded on a data logger for post processing. Most GPS units currently available that support DGPS post processing are able to store SV data from quite large numbers of position fixes. Many public and private agencies record DGPS corrections for distribution by electronic means. Alternatively, users can invest in DGPS base stations. This latter option is most likely to be the only option in many countries, but may also be cheaper and more convenient than purchasing from a commercial provider.

2.9.4 Postprocessed DGPS

In postprocessed DGPS, the base station records the errors for each satellite directly into a computer file (usually together with the estimated positions as well). The rover also records the positions and the data received from each SV separately and after returning from the field this information is downloaded over a serial communications link to a computer file. Base station data that were collected at the same time as the roving data, ideally recorded at the same second, are compared and only those satellites actually “seen” and used by the rover at that time are used in the calculations.

GPS uses timing signals from at least three satellites to establish a position. Each of these signals will be associated with its own particular errors. Due to the great distances involved —over 20,000 km between satellites and receivers — and the relatively tiny distance from base station to roving receiver (usually less than 100 km), the signals that reach both will have been subjected to virtually the same atmospheric conditions and will essentially have identical errors.

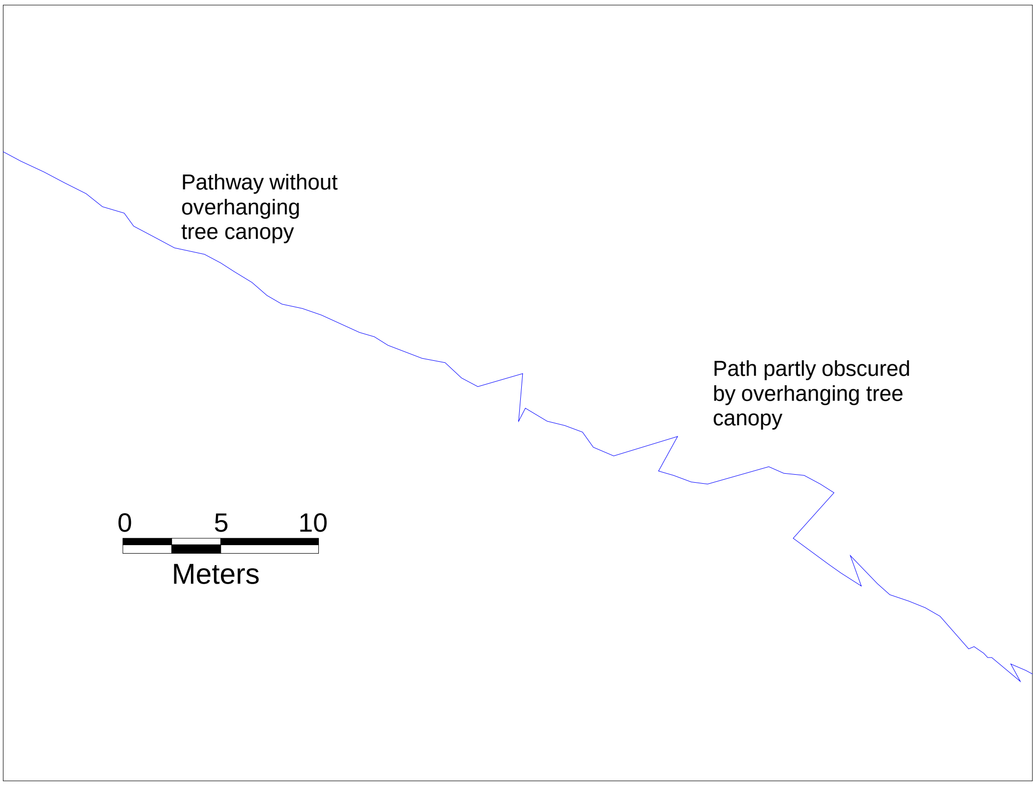
Instead of using timing signals to calculate a position, the DGPS software uses the precisely known reference position to calculate the errors in the timing for each satellite. These errors are then applied to the roving unit’s data. The distances travelled from the satellites to the roving receiver are then recalculated and a new, corrected, position is fixed.

2.9.5 How Accurate is DGPS?

Whilst DGPS techniques can result in highly accurate positioning, in practice and under sometimes sub-optimal field conditions, the expected metre or sub-metre-level accuracy may not be obtained. Perhaps one of the most difficult positioning problems occurs in woodland or forest, where the leaf canopy may obstruct or obscure satellite signals. Deckert and Bolstad (1996) tested GPS receivers under forest canopies. Differentially corrected positional accuracies from conifer woodland sites averaged 18.4 ft (5.6 metres). Positioning in broadleaf woodland sites was slightly more accurate, with an average of 14.5 ft (4.4 metres).

In addition to signals becoming obscured by objects such as trees and buildings, steep terrain can also have a significant effect on the potential accuracy of differentially corrected GPS fixes. In a valley bottom, for instance, satellites with low elevations may be obscured by the velley sides. This can result in less than the optimum number of visible satellites, or in a group of satellites with poor PDOP being used in the calculations.

Figure 8 An illustrstion of the effect on Differentially corrected GPS position fixes with and without overhanging tree canopy partly obscuring the view of the sky. .



2.9.6 Receivers

The equipment chosen will effect the accuracy of the GPS calculated positions. Receivers are divided into two categories depending on how the incoming signals from satellites are processed:

- Carrier Phase receivers use the radio signal itself to calculate positions. A constant lock on the satellites is essential for accurate positioning. These receivers are more expensive, currently largely limited to accurate surveying applications, and are not considered by this document.

- C/A code receivers use data contained in the satellite signals to calculates positions. These receivers do not need to maintain a constant lock on satellites in order to calculate positions and are therefore ideal for navigation and data collection applications.

C/A code receivers range in accuracy from sub-meter to 5 metres or more after differential correction. A minimum number of four satellites are required in order to calculate a three dimensional position. A single channel GPS receiver must use that channel to sequence through each visible satellite one at a time. Moreover, this channel must also be used to receive other important satellite data messages. Multi-channel receivers use several channels to track multiple satellites simultaneously and are both more efficient and more accurate. A minimum of four channels are required for accurate GPS work.

For use as a base station, a GPS receiver must be able to track all satellites that might be visible at any one moment in time. Currently the number of channels used by some of the more advanced base stations is 12. Nine-channel versions also occur but case must be taken to include elevation masks so that no more than 9 satellites can possibly be visible.

Roving GPS units need to be able to track as many satellites as possible. The actual number of satellites that it is possible to track simultaneously is the result of compromise between costs, size, intended application and other design criteria. An important factor is the design and physical position of the antenna - units with built-in antenna generally having poorer reception capabilities than those with large external antenna mounted in a prominent position.

Mapping grade receivers have between six and twelve channels. Those receivers that have eight or more channels are normally able to track all visible satellites continuously and as a result provide high quality information. For six-channel models, the receiver will track up to six satellites continuously, but if more than six are visible will track five and use the sixth channel to sequence through the remainder.

Many hand-held GPS units have either a single multiplexing channel or three channels. Using only a single channel, a GPS receiver is able to produce reasonable results when not moving, but ranging errors are introduced due to the time differences between information received from each different satellite. Improved results are obtained with three-channel receivers.

For any serious work, especially where mapping applications and GIS are concerned, it is essential that the GPS receiver have a capability to store calculated positions and associated information, as well as a facility to download these data to a PC. Normally this is accomplished by a serial link to the computer's RS-232 port. Relatively new developments in GPS include receivers mounted in PCMCIA cards that slot into notebook PCs. These utilise the computer's screen, keyboard and memory directly. This also means that GPS locations can, with suitable software, be displayed in real-time within GIS systems, or imported directly into spreadsheets and databases as X/Y co-ordinates together with any associated information.

2.10 Future Development of the civilian GPS system

Whilst DGPS techniques offer a high degree of accuracy for civilian users these facilities are not available to the majority of terrestrial GPS users. However, future developments of the GPS system may offer an increased accuracy over and above that currently available with the Standard Positioning System (SPS). There are plans by the US Military to turn off Selective Availability but a date for this has not been fixed. This will reduce positioning errors by removing the deliberately introduced components of the positioning error but still leaves atmospheric delays and distortions as major sources of error effecting the received radio signals. Errors caused by atmospheric disturbance will be at their peak in 2001, as the sun enters the most active phase of its sunspot cycle.

Since different frequencies are delayed by atmospheric disturbance by different extents the problem can be tackled through the use of a second frequency. If signals are broadcast on widely separated frequencies, measurements of the difference in delays between the two signals can be used to correct for this distortion. For mobile receivers, e.g. those on aircraft, the effectiveness of this correction reduces with the speed of the receiver. The US Military already has access to a second channel, but this is encrypted and unavailable for civilian use. However, there are plans to make another frequency available for civilian use by the year 2001, in the next generation of GPS satellites. Although this additional frequency is still to be decided, its use will improve the accuracy of position fixes made by suitably equipped civilian GPS receivers. This will not remove all sources of error and DGPS techniques may still be required in order to obtain sub-metre accuracy.

3. PROJECTIONS, CO-ORDINATE SYSTEMS AND DATUMS

Some knowledge of projections, co-ordinate systems and datums is required before attempting GPS field work. When comparing data from different sources, each must be referenced to the same datum and co-ordinate system. Importantly, significant errors can be introduced if different datums are mixed. This elementary procedure is often overlooked by many GPS users but is critical for accurate GPS recording and especially for differential GPS.

A projection is a method of reducing the distortion of curved earth features on a flat paper map or computer screen. A co-ordinate system is a collection of parameters that describe co-ordinates. One of the parameters is projection.

3.1 Datums

Geodetic datums define the reference systems that describe the size and shape of the earth's surface for a portion of the earth or sometimes for the whole globe. A datum therefore represents a model of the globe. The Earth's size and shape can broadly be described as an ellipse. However, such mathematical models do not provide an exact representation, but only a best fit. Over limited areas, and depending on the accuracy required, it has been found that ellipsoidal models do fit with reasonable accuracy. The size and shape of the best-fit ellipsoid differs from place to place and, as a result, many ellipsoids have been created for use in different parts of the world (Table 1).

Different countries use different datums as the basis for national co-ordinate systems. Annex 1 provides a partial list of Geographic Datums with an indication of the areas where they are typically used. The large number of datums currently in use, and the rapid technological advances that have enabled GPS readings with sub-metre level accuracy means that care is required in datum selection, and in the conversion between co-ordinates recorded using different datums. Referencing co-ordinates to the wrong datum can result in position errors of hundreds of metres (see Figure 9).

Geodetic datums and the co-ordinate systems based on them were developed to describe geographic positions for surveying, mapping and navigation. Through history, the model of the Earth was refined from flat-earth models to spherical models of sufficient accuracy to allow global exploration, mapping and navigation. True geodetic datums were employed after the late 1700s when measurements indicated that the Earth was not spherical, but ellipsoidal in overall shape. Modern geodetic datums range from flat-earth models used by surveyors to complex models used over larger areas. Each datum is based on a spheroid (ellipsoid) which is an idealised curved surface on which x, y, and z reference points and a centre of the earth are defined.

The ellipsoid chosen for GPS was the GRS-80 ellipsoid. The datum incorporating this ellipsoid, and the one used by GPS, is called the World Geodetic System 1984 (WGS-84). This is the currently accepted best fit for the overall shape of the earth.

Flat-earth models are still used for surveying, when distances are small enough so that the earth's curvature is not significant. This is usually less than 10 km. Spherical earth models represent the shape of the earth as a sphere with a specified radius. Spherical models fail to model the actual shape of the earth, for example a slight flattening at the poles results in a difference of about 20 km between a sphere of average radius and the measured polar radius of the earth.

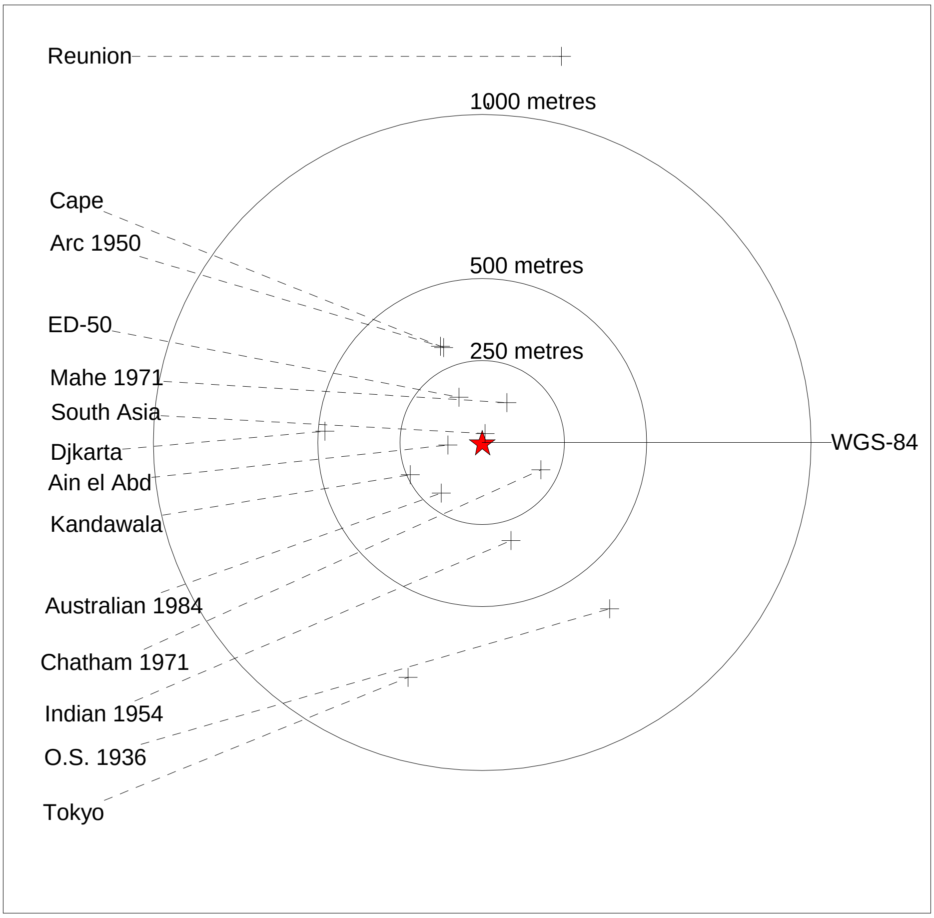
Table 1 A partial list of defined Ellipsoids and Ellipsoidal Constants

Ellipsoid Name	Semi-Major Axis (m)	Flattening Reciprocal
Airy 1830	6377563.396	299.324964600
Modified Airy	6377340.189	299.324964600
Australian National	6378160.000	298.250000000
Bessel 1841	6377397.155	299.152812800
Clarke 1880	6378249.145	293.465000000
Everest - 1969	6377295.664	300.801700000
Fischer 1968	6378150.000	298.300000000
GRS 1980	6378137.000	298.257222101
International 1924	6378388.000	297.000000000
South American 1969	6378160.000	298.250000000
WGS 1972	6378135.000	298.260000000
WGS 1984	6378137.000	298.257223563

A more complete list is presented in the Annex 1.

Ellipsoidal models are required for accurate range and bearing calculations, and these are used by most topographic maps and by GPS. Ellipsoidal models define an ellipsoid with an equatorial radius and a polar radius (sometimes defined as the flattening at the poles instead of the radius - see Table 1). The best of these models represent the shape of the earth over the smoothed, averaged sea-surface to within about one-hundred metres.

Figure 9 Position shifts resulting from Datum differences (81°E 7°N, WGS-84)



3.2 Co-ordinate Systems

Co-ordinate systems specify how a particular place on the Earth's surface is identified. While the terms "projection" and "co-ordinate system" are often used interchangeably, they do not have the same meaning. A projection is an equation or set of equations containing a set of parameters - the exact number and nature of the parameters depends on the projection. A co-ordinate system is an agreed system for locating points and the same co-ordinate system may be applied to different projections. Latitude/Longitude (Geodetic), Universal Transverse Mercator, and the Landsat World-wide Reference System are all examples of co-ordinate systems. Examples of co-ordinate systems include:

Geodetic

A Geodetic Co-ordinate System is a three-dimensional co-ordinate system defined by an ellipsoid, the equatorial plane of the ellipsoidal and a plane defined along the polar axis (a meridional plane). Co-ordinates in a Geodetic Co-ordinate System are given by a geodetic latitude (the angle between the normal to the ellipsoid at a location and the equatorial plane), a geodetic longitude (the angle between the meridional reference plane and a meridional plane containing the normal to the ellipsoid at a location) and a geodetic height (the perpendicular distance of a location from the ellipsoid).

A geodetic datum is the only required defining parameter for a Geodetic Co-ordinate System in most software packages. A geodetic datum defines constants that relate a Geodetic Co-ordinate System to the physical earth, the dimensions of the reference ellipsoid, the location of the origin of the system, and the orientation of the system. A geodetic co-ordinate is specified by latitude and longitude, and may also contain ellipsoidal height values.

UTM

The Universal Transverse Mercator (UTM) Co-ordinate System is an international plane co-ordinate system developed by the US Army. It extends around the globe from 84 degrees north to 80 degrees south. The World is divided into 60 segments of 6° each in the northern hemisphere and 60 corresponding segments in the southern hemisphere. Each segment, or zone, is identified by a zone number. Each zone extends 3 degrees eastward and 3 degrees westward from its central meridian. Zones are numbered west to east from the 180-degree meridian. For transformations from UTM to Lat./Long, a Geodetic Datum must be defined, such as ED50 for Europe, WGS-84 etc.

The geodetic datum and the UTM zone are required parameters for the UTM Co-ordinate System supported in most software packages. A UTM co-ordinate is specified by northing and easting values. The metre is the standard unit in the UTM Co-ordinate System.

The US Military Grid Reference System (MGRS) is designed for use with UTM grids. The world is divided into large geographic areas, each of which is given a unique identification, called the Grid Zone Designations. These areas are covered by a pattern of 100,000-meter squares. Each square is identified by two letters called the 100,000-meter square identification. This identification is unique with the area covered by the Grid Zone Designation.

A reference keyed to a gridded map of any scale is made by giving the 100,000-meter square identification together with the numerical location. Numerical references within the 100,000-meter square are given to the desired accuracy in terms of easting and northing UTM grid co-ordinates for that point.

Landsat World-wide Reference System

The Landsat 4 World-wide Reference System (WRS) is a co-ordinate system that consists of a global network of 233 paths and 119 rows. The path and row intersections correspond to geographic locations over which Landsat satellite images are generally centred. These locations are identified by three-digit path and row numbers and, when combined, identify a nominal scene centre. The WRS path and row identifiers are typically specified when ordering Landsat imagery for a particular area of interest.

3.3 Projections

No flat map can match the globe in preserving distances, areas, angles, shapes and directions. A projection is an attempt to portray the surface of the earth, or a small portion of it, on a flat surface. Projections, therefore, are mathematical techniques for converting spherical co-ordinates into two-dimensional ones. Since one is trying to "squash" the surface of an ellipsoid onto a flat plane, distortions are inevitable and any map is a compromise. Distortions include those of conformality, distance, direction, scale and area. Projections usually minimise distortions in some of these factors at the expense of others

Conformality	When the scale of a map at any point on the map is the same in any direction, the projection is said to be conformal. Meridians (lines of longitude) and parallels (lines of latitude) intersect at right angles. Shape is preserved locally on conformal maps.
Direction	A map preserves direction when azimuths (angles from a point on a line to another point) are portrayed correctly in all directions.
Scale	Scale is the relationship between distance portrayed on a map and the same distance on the earth's surface.
Area	When a map portrays area over the entire map so that all mapped areas have the same proportional relationship to the actual areas on the Earth's surface that these objects represent, the map is said to be an equal-area map.

Map projections fall into four general classes:

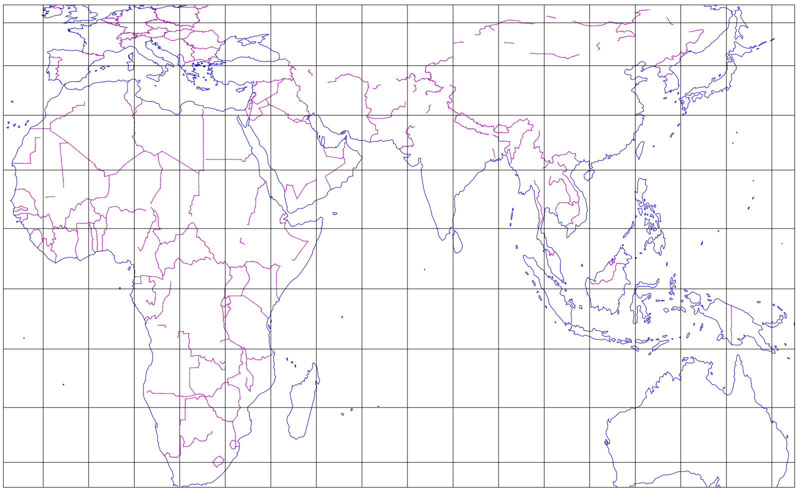
Cylindrical	These projections result when a spherical surface is projected onto a cylinder
Conic	The projection of a spherical surface onto a cone
Azimuthal	These result from the projection of a spherical surface onto a plane
Miscellaneous	projections include unprojected ones such as rectangular latitude and longitude grids, and other examples that do not fall into the cylindrical, conic or azimuthal categories.

A small number of the possible range of projections are illustrated below. A more complete listing is provided in Annex 1. Maps were prepared using MapInfo's *MapInfo* GIS software.

3.3.1.1 Cylindrical

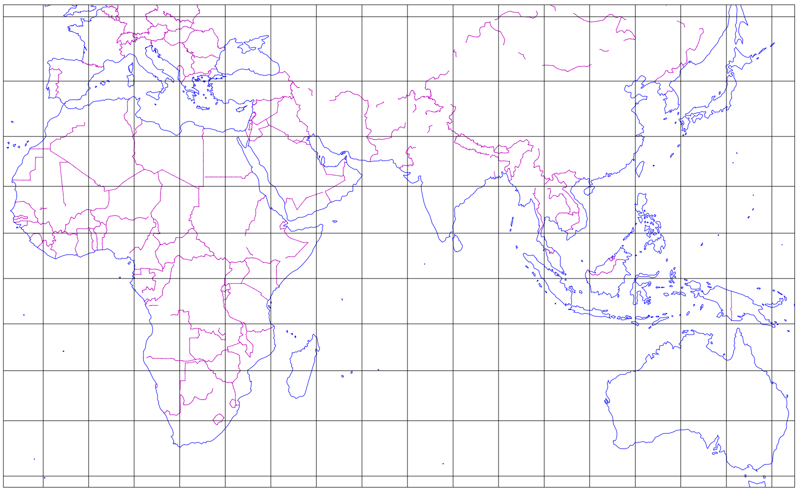
Cylindrical equal-area projections have straight meridians and parallels, the meridians are equally spaced, the parallels are unequally spaced. There are normal, transverse and oblique cylindrical equal-area projections. Scale is true along the central line (the equator for normal, the central meridian for transverse and a selected line for oblique) and along two lines equidistant from the central line. Shape and scale distortions increase near points 90 degrees from the central line.

Behrmann Cylindrical Equal-Area A projection using 30:00 North as the parallel of no distortion.



3.3.1.2 Mercator

The Mercator projection has straight meridians and parallels that intersect at right angles. Scale is true at the equator, or at two standard parallels equidistant from the equator. This projection is often used for marine navigation since all straight lines on the map are lines of constant azimuth.



Transverse Mercator

Transverse Mercator projections are the result of projecting a sphere onto a cylinder tangent to a central meridian. Transverse Mercator maps are often used to portray areas with larger north-south than east-west dimensions. Distortions of scale, distance, direction and area increase away from the central meridian. Many national grid systems are based on the Transverse Mercator projection.

UTM

The Universal Transverse Mercator (UTM) projection is used to define horizontal positions world-wide by dividing the Earth's surface into 6-degree segments or zones. Each zone is mapped by the Transverse Mercator projection with a central meridian in the centre of the zone. UTM zone numbers designate 6 degree longitudinal strips extending from 80°S to 84°N. In addition, zone characters designate 8 degree zones extending north and south from the equator. Eastings are measures from the central meridian, with a 500 km false easting to ensure positive co-ordinates. Northings are measured from the equator, with a 10,000 km false northing for positions south of the equator.

Southern India and Sri Lanka: UTM Zone 44 (N), WGS-84

Robinson Projection

The Robinson projection, unlike a majority of others, is based on tables of co-ordinates rather than on equations or mathematical formulae. This projections distorts shape, area, scale and distance in an attempt to balance the errors in all projections properties.

Unprojected Maps

These include those that are formed by considering longitude and latitude as a simple rectangular co-ordinate system. Scale, distance, area and shape are all distorted with the amount of distortion increasing the greater the distance away from the equator.

4. GLOSSARY

Accuracy:	The data from satellites that is available for civilian use can produce accuracies within 25 meters. However, the US Department of Defense reserve this accuracy for the military, and has introduced Selective Availability (SA) to add a random error which reduces the accuracy of the average GPS receiver. This error varies, but usually does not exceed 100 meters.
Acquisition Time:	This is the amount of time it takes for your GPS receiver to determine its location when you turn it on. If you are near your last fix, it takes 2-5 minutes. If the GPS unit has no idea where it is at, it may take up to 15 minutes to search for all satellites and pinpoint your location.
Almanac	A file that contains orbit information on all satellites, clock corrections, and atmospheric delay parameters. It is transmitted by a GPS satellite to a GPS receiver, where it facilitates rapid SV acquisition. It can be downloaded from a GPS receiver to GPS processing software on a PC where it can be used to predict the best time to collect GPS data.
Altitude	Vertical height above the ellipsoid or geoid. It is always stored as height above ellipsoid in the GPS receiver but can be displayed as height above ellipsoid, or as height above mean sea level.
Bandwidth	The range of frequencies in a signal
Bearing:	If you pick a landmark or waypoint, and you want to know which direction it is from where you are now, you need to know its bearing. This is a direction in degrees, in a clockwise direction from north. It is the direction you need to head in order to reach the selected point.
C/A Code	The standard (Coarse Acquisition) GPS code. A sequence of 1023 pseudo-random binary, biphase modulations on the GPS carrier at a chip rate of 1.023 MHz. Also known as the “civilian code”.
Carrier	A signal that can be varied from a known reference by modulation
Carrier frequency	The frequency of the unmodulated fundamental output of a radio transmitter
Carrier Phase GPS	GPS measurements based on the L1 or L2 carrier signal
Carrier-aided-tracking	A signal processing strategy that uses the GPS carrier signal to achieve an exact lock on the pseudo random code.
Channel	A channel of a GPS receiver consists of the circuitry necessary to receive the signal from a single GPS satellite
Clock bias	The difference between the clock’s indicated time and true universal time
Code Phase GPS	GPS measurements based on the C/A Code

Control Segment	A world-wide network of GPS monitor and control stations that ensure the accuracy of satellite positions and their clocks
Co-ordinate:	Set of numbers that describes your location on (or above) the earth. These may be either latitude (N or S) and longitude (E or W), or in the Universal Transverse Mercator system, or UTM co-ordinates, which measures distance in meters from the equator (N or S) and a prime meridian (E or W).
Co-ordinate System	Any three-dimensional reference frame that locates objects in space.
Cycle slip	A discontinuity in the measured carrier beat phase resulting from a temporary loss-of-lock in the carrier tracking loop of a GPS receiver.
Data message	A message included in the GPS signal which reports the satellite's location, clock corrections and health. Also included is rough information on the other satellites in the constellation.
Datum	See Geographic Datum
Differential positioning	Accurate measurement of the relative positions of two receivers tracking the same GPS signals. The process of correcting GPS positions at an unknown location with data collected simultaneously at a known location. Applies to receivers that use C/A code positioning techniques.
Dilution of Precision	The multiplicative factor that modifies ranging error. it is caused solely by the geometry between the user and his set of satellites. Also known as GDOP.
Dithering	The introduction of digital noise. This is the process that the US Department of Defence uses to add inaccuracy to GPS signals in order to induce Selective Availability
Dopler shift	The apparent change in the frequency of a signal caused by the relative motion of the transmitter and receiver.
Dopler aiding	A signal processing strategy that uses a measured dopler shift to help the receiver smoothly track the GPS signal. This allows more precise velocity and position measurement.
Elevation:	GPS units can provide elevation information (altitude, usually above sea level) if a minimum number of satellites are visible (at least four).
Ellipsoid	The 3-D mathematical figure formed by rotating an ellipse around its minor axis. Earth's minor axis is the polar axis. The major axis is the equatorial. An ellipse is completely defined by specifying the lengths of both axes, or by specifying the length of the major axis and the flattening.
Ellipsoid Height	The distance, measured along the normal, between a point and the surface of the ellipsoid. Not the same as elevation above a physical, vertical datum. GPS receivers output position fix-height relative to WGS-84.

Ephemeris	The predictions of current satellite position that are transmitted to the user as part of the data message. A set of numerical parameters that can be used to determine a satellite's position as a function of time. Available as a broadcast ephemeris or as a postprocessed precise ephemeris.
Fast-switching channel	A single channel which rapidly samples a number of satellite ranges. "Fast" means that the switching time is sufficiently fast (2 to 5 milliseconds) to recover the data message.
Frequency band	A particular range of frequencies.
Frequency spectrum	The distribution of signal amplitudes as a function of frequency
GDOP	Geometric Dilution of Precision - see Dilution of Precision
Geographic Datum	A mathematical model designed as a best fit to the geoid. Defined by the relationship between an ellipsoid and a point on the Earth's surface established as the origin of the datum. Geodetic datums are defined by the size and shape of an ellipsoid and the location of the centre of the ellipsoid with respect to the centre of the Earth. The datum is established by tying a reference ellipsoid to a particular point on the Earth.
Geoid	The average position of mean sea level. Unlike the ellipsoid, it undulates and is sensitive to gravity forces. The particular equipotential surface that best fits mean sea level, and which can be imagined to extend through the continents. This surface is perpendicular to the force of gravity.
Geoid Height	The distance of the geoid above or below the reference ellipsoid.
Handover word	The word in the GPS message that contains synchronisation information for the transfer of tracking from the C/A to P code
Heading:	This is the direction that the GPS receiver is moving over the earth's surface, not necessarily the direction the unit is pointing. This is best viewed while moving, because the value stops if you do. Heading is a value in degrees in a clockwise direction, between 0 and 359 and it corresponds to compass values.
Ionosphere	The band of charged particles 80 to 120 miles above the earth's surface
Ionospheric refraction	The change in the propagation speed on a signal as it passes through the ionosphere.
L-band	The group of radio frequencies extending from 390 MHz to 1550 MHz. GPS carrier frequencies (1227.6 MHz and 1575.42) MHz are in the L-band

Landmark or Waypoint:	This is a position that is stored into the GPS unit memory. It may be from a position fix that you have taken, or you may input the co-ordinates of other locations that may be intermediate or final destinations. The GPS unit will either give the position a name, such as LMK02 or LOC 01, or you may provide a name that you will easily recognise.
Multi-channel receiver	A GPS receiver that can simultaneously track more than one satellite signal
Multipath error	Errors caused by the interference of a signal that has reached the receiver antenna by two or more different paths. Usually caused by one path being reflected.
Multiplexing channel	A channel of a GPS receiver that can be sequenced through a number of satellite signals. Sequenced at a rate synchronous with the satellite message bit-rate. One complete sequence is completed in a multiple of 20 milliseconds, depending on the number of available satellites.
NAVSTAR	The name given to GPS satellites. NAVSTAR is an acronym formed from NAVigation Satellite Timing And Ranging.
P-code	The Precise code. A very long sequence of pseudo-random binary biphase modulations on the GPS carrier at a chip rate of 10.23 MHz which repeats about every 267 days. Each one week segment of this code is unique to one GPS satellite and is reset every week.
PDOP	Position Dilution of Precision A unitless figure that expresses the relationship between the error in user position and the error in satellite position. It indicates when the satellite geometry can provide the most accurate results. The best data collection time can be selected based on reports and graphs showing PDOP. Geometrically, PDOP is proportional to 1 divided by the volume of the pyramid formed by lines running from the receiver to four satellites observed. It is the result of a calcuation that takes into account each satellites location relative to other satellites in the constellation. Good values are small, less than 3. Values greater than 7 are poor. Thus, small PDOP is associated with widely separated satellites. A low PDOP indicates higher probability of accuracy.
Position Fix:	When your receiver obtains information from GPS satellites to determine what co-ordinates you are at, it provides you with a position fix. Each receiver has a minimum number of satellites it must be able to "see" to give a good position fix. Most GPS units allow you the option of marking and storing your current position as a landmark or waypoint.
Precise Positioning Service (PPS)	The most accurate dynamic positioning possible with standard GPS, base don the dual frequency P-code and no SA.

Projection	A mathematical expression of the curved surface of the ellipsoid on a rectangular co-ordinate grid.
Pseodo random code	A signal with random-noise like properties. It is a very complicated but repeated pattern of 1's and 0's.
Pseudolite	A ground based differential GPS receiver which transmits a signal like that of an actual GPS satellite, and can be used for ranging.
Pseudorange	A distance measurement based on the correlation of a satellite transmitted code and the local receiver's reference code, that has not been corrected for errors in synchronisation between the transmitter's clock and the receiver's clock.
Route:	A route contains a starting and an ending position, as well as intermediate locations along the way. Each segment between positions is called a leg. Routes can be made up of one leg, or a series of legs. If you are going on a hike, you might input a route composed of planned rest stops or camp sites, and your destination. Some units allow you to backtrack, or reverse your route.
Satellite constellation	The arrangement in space of a set of satellites.
Satellite Tracking:	Most GPS receivers have the capability to track up to 8-12 satellites. Usually 3-4 satellites are needed to compute LAT/LONG (2-D) with at least one more satellite needed to compute altitude (3-D). For a given location, a GPS unit knows which are the satellites that should be nearby at a given time.
Signal Interference:	Your GPS unit needs to be able to see at least 3-5 satellites to give you a position fix. If you are travelling in a canyon or the streets of the urban jungle or in heavy tree cover, you may have difficulty maintaining adequate satellite contact. You may lose your satellite lock, or only be able to compute a 2-D position. Also, if you are inside a building, you will not be able to update your position.
Slow switching channel	A sequencing GPS receiver channel that switches too slowly to allow the continuous recovery of the data message.
Space segment	The part of the whole GPS system that is in space, i.e. the satellites.
Spread spectrum	A system in which the transmitted signal is spread over a frequency band much wider than the minimum bandwidth needed to transmit the information being sent. This is done by modulating with a pseudo-random code.
Standard Positioning Service (SPS)	The normal civilian positioning accuracy obtained by using the single frequency C/A code.
Static positioning	Location determined when the receiver's antenna is presumed to be stationary in the earth. This allows the use of various averaging techniques that improve accuracy by factors of over 1000.

User interface	The way in which a receiver conveys information to the person using it. The controls and displays.
User segment	The part of the whole GPS system that includes the receivers of GPS signals.

5. BIBLIOGRAPHY AND FURTHER READING

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Internet Sources:

http://www.utexas.edu/depts/grg/gcraft/notes/coodsys.html	An overview of coordinate systems.
http://www.utexas.edu/depts/grg/gcraft/notes/mapproj/mapproj.html	Map projection overview.
http://www.utexas.edu/depts/grg/gcraft/notes/datum/datum.html	Geodetic datum overview.

Journal Articles (including Abstracts):

Title	Global positioning system (GPS) accuracies in eastern US deciduous and conifer forests.
Author	Deckert-CJ; Bolstad-PV
Source	Southern-Journal-of-Applied-Forestry. 1996, 20: 2, 81-84; 7 ref.
Year	1996
Abstract	This study determined horizontal positional errors when using C/A (pseudo-random) code Global Positioning System (GPS) receivers under forest canopies and in varied terrain. Positional errors were evaluated for a total of 18 sites: 3 sites for each of 6 combinations of canopy (conifer or broadleaf) and terrain (ridge, slope and valley). Ten replicates were collected at each site for each of 60, 200 and 500 position fixes. Differentially corrected positional accuracies from conifer sites averaged 18.4 ft, which was significantly greater that the 14.5 ft observed for broadleaf sites. For differentially corrected data, positional errors generally increased from ridge top to valley positions. Errors decreased when the number of position fixes was increased.

Title Sensitivity of computed terrain attributes to the number and pattern of GPS-derived elevation data.
Author Spangrud-DJ; Wilson-JP; Nielsen-GA; Jacobsen-JS; Tyler-DA; Robert-PC (ed.); Rust-RH (ed.); Larson-WE (Editors)
Source Site-specific management for agricultural systems: Proceedings of Second International Conference, Minneapolis, MN, USA, March 27-30, 1994. 1995, 285-301; 29 ref.
Year 1995
Abstract Soil specific crop management requires precise knowledge of soil properties and soil-landscape processes. Detailed soil maps at scales of 1:6000 or 1:8000 and spatially variable soil data are needed to guide soil specific crop management in most landscapes. Elevation data were collected at 6,284 locations in 1991 with an Ashtech Sensor GPS receiver mounted on a pickup truck and an Ashtech P-12 GPS receiver operating in kinematic mode. These data were converted to a 10 m grid for subsequent analysis and display. Some of the results are shown graphically as elevation contours. Spatial analyses of the differences in elevation, gradient, specific catchment area, and steady-state wetness index were used to summarize the performance of the different samples. The statistical comparisons show that the number and pattern of the GPS input data will influence the digital elevation models and terrain attributes computed. In particular, it was found that: the magnitude and clustering of the spatial distribution of these errors diminishes as sample size increases, the magnitude and clustering of the errors diminishes as the spread of the input data increases, and that seemingly small differences in elevation may result in large differences in the primary and secondary topographic attributes.

Title Forest canopy, terrain, and distance effects on Global Positioning System point accuracy.
Author Deckert-C; Bolstad-PV
Source PE-and-RS,-Photogrammetric-Engineering-and-Remote-Sensing. 1996, 62: 3, 317-321; 15 ref.
Year 1996
Abstract Tests were conducted to determine the realizable accuracies of the Global Positioning System under eastern North American forest conditions. The effects of terrain, forest canopy, number of consecutive position fixes, and position dilution of precision (PDOP) on accuracy were evaluated. Position accuracies were determined for a total of 27 sites: three replicate sites selected for all combinations of three canopy (deciduous, conifer, open) and three terrain (ridge, slope, valley) types. Ten visits (replicates) were made to each site over 8 months; at each visit separate observations of 60, 100, 200, 300, and 500 position fixes were logged. The mean differentially corrected positional accuracy for all sites was 4.35 m, with 95% of the mean positions estimated within 10.2 m of the true value. The least accurate differential position data were observed at conifer sites. Positional accuracy was higher for deciduous sites and highest at open sites. Mean positional accuracy increased from valley to ridge locations. Mean accuracy increased with increasing number of position fixes collected per point. The average time required by the GPS receiver to lock onto four satellites and begin collecting positions varied from one to two minutes, and collection times increased from open, through deciduous, to conifer sites. There was an observed, but statistically non-significant, trend between accuracy and the field receiver's distance from the base station. Nine replicates of 300 position fixes were averaged for six sites, which ranged from 43 to 247 km from a base station. Mean accuracy ranged from 1.48 to 2.43 m.

Title Using differential GPS for forest traverse surveys.
Author Liu-CJ; Brantigan-R
Source Canadian-Journal-of-Forest-Research. 1995, 25: 11, 1795-1805; 21 ref.
Year 1995
Abstract This report documents the accuracy and efficiency of differential GPS (DGPS) when it is applied in forest environments. The report contains research results obtained from using DGPS for forest-stand boundary surveys conducted in hardwood forests in the Cumberland Plateau region [Kentucky]. The result of a cost-effectiveness analysis that contrasts the satellite-based DGPS positioning and the conventional land-based compass-and-chain surveys is also reported. The study found that: (1) both forest canopy and undulating terrain in mountainous regions would exert a definite effect on DGPS traverse surveys, but neither would reduce stand area determination accuracy; (2) in general, static DGPS was more accurate but less productive than the kinematic DGPS when accuracy and cost were

weighted equally; (3) inaccurate two-dimensional position determinations degraded positioning accuracy in both the kinematic and static positioning mode; and (4) kinematic DGPS traverse was a cost-effective survey technique capable of achieving closer forest stand area approximation than the compass-and-chain traverse.

Title Three forestry applications of the global positioning system (GPS) in New Zealand.
Author Lawrence-M; Firth-J; Brownlie-R
Source New-Zealand-Forestry. 1995, 40: 2, 21-22; 5 ref.
Year 1995
Abstract Descriptions are presented of experience using a medium-accuracy GPS receiver in New Zealand for (i) locating sample plots in a 30-yr-old stand of Pinus radiata, (ii) navigating for an aerial survey of 194 forest compartments, and (iii) delineating forest roads. The system worked well, provided the satellite's signals were not attenuated by overhead vegetation or the topography, in which case the accuracy decreased and, in some cases, no data was collected at all.

Title Accuracy of GPS for updating forest maps: the Marlborough Sounds experience.
Author Firth-J; Brownlie-R
Source Report -New-Zealand-Logging-Industry-Research-Organisation. 1994, 19: 13, 6 pp.; 7 ref.
Year 1994
Abstract A study was carried out in the Marlborough Sounds, New Zealand, to assess the value of a medium accuracy Global Positioning System (GPS) for updating forest stand maps. A number of forest tracks and point objects were mapped using the system, and their coordinates compared with those obtained from conventional aerial photography and a stereoplotter. It was found that the GPS could provide XY coordinates to within 5 m of those obtained from the stereoplotter. However, it was also found that the system ha d limitations where steep hillsides and tree crowns interrupted the signal from the satellites.

Title Recent information sources on global positioning system (GPS) technology.
Author Guarino-L
Source Plant-Genetic-Resources-Newsletter. 1995, No. 102, 39; 1 ref.
Year 1995
Abstract GPS receivers are used by plant collectors to record accurate passport data on latitude and longitude in the field. This paper cites 3 publications (Ackroyd, N. and Lorimer, R. (1994) Global navigation - a GPS user's guide. 2nd Ed.; Chodota, M. W. L. (1994) Should you acquire a global positioning system receiver now? The current GPS status. Earth Resources Mapping in Africa 1, 1-2,4,7; Dierendonck, A. J. van (1995) Understanding GPS receiver terminology: a tutorial. GPS World 6 (1) 34...44) which are a source of information for plant genetic resources workers wanting to purchase a GPS receiver.

Title Accuracy and signal reception of a hand-held Global Positioning System (GPS) receiver.
Author D'-Eon-SP
Source Forestry-Chronicle. 1995, 71: 2, 192-196; 8 ref.
Year 1995
Abstract Accurate and precise reporting of forest survey locations is required to integrate forest survey data with geographical information systems. The accuracies of five Global Positioning System (GPS) survey methods using a hand-held receiver were tested in a mixed forest of trembling aspen [Populus tremuloides] and spruce [Picea sp.]. Accuracy improved by eliminating positions obtained under poor satellite configurations and by using position averaging methods. Single fix positions, taking as little as two minutes to obtain, yielded better than 100-m accuracy more than 80% of the time. Allowing the receiver to continuously collect fixes for 15 to 30 minutes and then averaging the fixes yielded a median position error of 17m. Sixty one stands representing a diversity of cover types, canopy heights, and crown closure in the Petawawa Research Forest were tested during June and July of 1992 for canopy interference with GPS signals. A GPS position was obtained under the canopy in 74% of the stands. Launches of additional GPS satellites since the summer of 1992 have further improved the probability of obtaining accurate geographical positions under forest canopies.

Title Performance of a GPS animal location system under boreal forest canopy.
Author Rempel-RS; Rodgers-AR; Abraham-KF
Source Journal-of-Wildlife-Management. 1995, 59: 3, 543-551; 16 ref.
Year 1995
Abstract An automated animal location system, based on Global Positioning System (GPS) technology, is being used for wildlife research. The GPS is a divergent technology, and positional accuracies vary between millimetres and tens of metres, depending on the system used and operating conditions. Before GPS-based tracking data can be used for habitat analyses, the influence of habitat on GPS-collar performance must be evaluated under various canopy conditions, including the optimal condition of no canopy. Performance of nondifferentially corrected GPS collars was evaluated in a spacing trial in an experimental forest with mature, evenly spaced trees at Thunder Bay, and on wild free-ranging moose (Alces alces) in NW Ontario, to determine the influence of canopy on positional accuracy and observation rate. In the spacing trial, canopy characteristics of tree species, spacing, height, basal diameter, and canopy closure had no influence on positional accuracy ($P>0.05$), but had an influence on GPS observation rate ($P<0.001$). Location error was greater if positions were based on 2-dimensional rather than 3-dimensional mode of operation ($P<0.001$), with location errors of 65.5 and 45.5 m, respectively. Location error in 3-dimensional mode did not differ from the expected error of 40 m ($P=0.43$). As tree density increased, observation rate decreased and the probability of the GPS receiver operating in 2-dimensional mode increased ($P<0.001$), resulting in increased location error. Observation rate for the free-ranging moose did not differ for the average observation rate in the spacing trial. With future development of differentially corrected GPS collars, location errors of <10 m are expected.

Title Use of global positioning system (GPS) for forest plot location.
Author Evans-DL; Carraway-RW; Simmons-GT
Source Southern-Journal-of-Applied-Forestry. 1992, 16: 2, 67-70; 7 ref.
Year 1992

Title Global positioning systems.
Author Greer-JD; Brice-CE; Lance-K; Kruczynski-LR; Jasumback-A; Sumpter-C; Graham-LA
Source Journal-of-Forestry. 1993, 91: 8, 10-32; ref.
Year 1993
Abstract Six features are included on the theme for this issue: an overview of global positioning systems (GPS) and remote sensing (Greer, 10-14, 26 ref.); a glossary of GPS terms (Brice, 15-16, 5 ref.); a user's guide to choice of GPS units (Lance, 17-19); an account of GPS experience in the US Forest Service (Kruczynski; Jasumback, 20-24, 1 ref.); an account of property surveys with GPS in the Rocky Mountain region (Sumpter, 26-27); and a discussion of airborne video, tagged with GPS time, for near-real-time vegetation mapping in Arizona (Graham, 28-32, 15 ref.).

Title GPS for mapping and tracking.
Author Fuelling-TG; Chappel-RJ; Moore-DG; Pease-JC; Egan-BT
Source Proceedings of the 14th conference 1992 of the Australian Society of Sugar Cane Technologists held at Mackay, Queensland, 28 April to 1st May 1992. 1992, 116-122; 5 ref.
Year 1992
Abstract The benefits of global positioning system (GPS) for monitoring sugarcane productivity and crop management are discussed.

Title GPS, GIS and geomorphological field work.
Author Cornelius-SC; Sear-DA; Carver-SJ; Heywood-DI
Source Earth-Surface-Processes-and-Landforms. 1994, 19: 9, 777-787; 31 ref.
Year 1994
Abstract The Global Positioning System (GPS) is described and its role as a technique for use in geomorphological fieldwork discussed. The utility of GPS in geomorphology is enhanced when used in combination with geographical information system (GIS) technology in the field. GPS is reviewed highlighting its structure, available methods and their relative accuracies, potential problems associated with the technology and its relationship with GIS. Examples are presented of the succesful

use of GPS and GIS to study hydrology and snow patch regime from recent the GeoAltai expedition to southern Siberia.

Title Field experience with differential GPS.
Author Shropshire-G; Peterson-C; Fisher-K
Source Paper -American-Society-of-Agricultural-Engineers. 1993, No. 93-1073, 13 pp.; 7 ref.
Year 1993
Abstract Experiences with the Global Positioning System (GPS) in differential mode for use in an agricultural application are reported, specifically, spatially variable farming in dryland wheat. The GPS was used in post-processed differential mode for determining the spatial location as data was acquired on wheat yield and soil properties. Later, real-time differential GPS was used to determine the location of a liquid fertilizer application machine so that previously specified fertilizer rates could be selected and applied.

Title Use of global positioning navigational systems in mosquito control.
Author Birse-I
Source Journal-of-the-American-Mosquito-Control-Association. 1993, 9: 4, 454-455.
Year 1993
Abstract The use of a global positioning navigational system (G.P.S.) as a navigational tool to identify "no spray" and specialized treatment sites during annual aerial spraying operations of Edmonton's mosquito abatement programme in Alberta, Canada, where Aedes vexans is the principal pest species and granular formulations of Dursban [chlorpyrifos] and Bacillus thuringiensis subsp. israelensis are applied via helicopters, is discussed.

Title Precision navigation with GPS.
Author Larsen-WE; Nielsen-GA; Tyler-DA
Source Computers-and-Electronics-in-Agriculture. 1994, 11: 1, 85-95; 10 ref.
Year 1994
Abstract The global positioning system (GPS), when used in a high-precision differential mode, can be used to navigate a tractor and implement along a pre-determined path with 1-2 cm level relative precision. The actual machine position is determined using high-precision differential GPS and this position is then compared to the desired position. The difference is an error signal that can be used to operate steering controls and bring the implement back to the desired path. The desired path of the implement through the field is determined prior to entry to the field to minimize point turns where skips or overlaps cannot be avoided. The geometry of the path is defined by a turning radius and turning centre for each point along the path. The implement geometry then determines a path for the tractor hitch point, and a turning radius, turning centre and steering angle are then determined for the tractor.

Title The use of GIS, GPS and satellite remote sensing to map woody vegetation in Kazgail area, Sudan.
Author El-Deen-FAM
Source ITC-Journal. 1991, No. 1, 3-10; 10 ref.
Year 1991
Abstract A pilot project is described for the mapping and inventory by the Forests National Corporation (SFNC) of Sudan of the Acacia senegal lands (known as the 'Gum Belt') in central Sudan in 1989-90. New base maps (1:250 000 and 1:100 000) were prepared based on Landsat TM 1985 data and a sample field survey of 53 plots (20X100 m) using the Global Positioning System (GPS) to locate the plots in the Kazgail rural district, Kordofan Province (350 km SW of Khartoum). All trees with a diameter at root collar (DRC) ò5 cm were identified and measured for diameter at breast height, total height along bole and crown diameter for estimates of timber volume. A smaller plot (1X10 m) was nested within the sample plot where only trees <5 cm DRC were recorded to assess regeneration rates. A stand table was produced showing that more than 70% of the trees are ó15 cm DRC. Of these, more than half (66.7%) are Acacia mellifera, which is also the dominant tree, representing 58% of total standing timber volume. Acacia senegal, producer of gum arabic and also fuelwood and charcoal, is the second most important tree species, representing 10.6% of standing timber volume.

Title Comparing global vegetation maps with the Kappa statistic.

Author Monserud-RA; Leemans-R

Source Ecological-Modelling. 1992, 62: 4, 275-293; 43 ref.

Year 1992

Abstract The Kappa statistic is presented as an objective tool for comparing global vegetation maps. Such maps can result from either compilations of observed spatial patterns or from simulations from models that are global in scope. The method is illustrated by comparing global maps resulting from applying a modified Holdridge Life Zone Classification to current climate and several climate change scenarios (CO2 doubling). These scenarios were based on the results of several different general circulation models (GCMs). The direction of change in simulated vegetation patterns between different GCMs was found to be quite similar for all future projections. Although there were differences in magnitude and extent, all simulations indicate potential for enormous ecological change. The Kappa statistic gave a straightforward measure of agreement between the different global vegetation maps, clearly indicated differences and similarities between those maps for individual vegetation zones and was useful for rank ordering of agreement, both across a series of maps and across the various vegetation zones within a map.

Title Global Positioning System as a tool for ecosystem studies at the landscape level: an application in the Spanish Mediterranean.

Author Zavala-I; Zavala-MA

Source Landscape-and-Urban-Planning. 1993, 24: 1-4, 95-104; 9 ref.

Year 1993

Abstract Global Positioning System (GPS) is a satellite-based method which allows the coordinates for points to be determined with high accuracy and improved speed and efficiency. GPS was applied to the problem of determining the infected areas of Arceuthobium oxycedri (an Iberian dwarf mistletoe found on Juniperus oxycedrus) within Parque Regional del Alto Manzanares (Madrid, Spain), a protected ecological area. The results illustrate the interaction of dwarf mistletoe spreading and perturbation agents such as wildfires and human influence.

Title Use of the global positioning system in soil survey.

Author Long-DS; DeGloria-SD; Galbraith-JM

Source Journal-of-Soil-and-Water-Conservation. 1991, 46: 4, 293-297; 13 ref.

Year 1991

Abstract Use of the global positioning system (GPS), a satellite-based radio navigation system, was tested to determine its potential application in soil survey. Accuracy of positioning was determined by comparing readings of indicated distance and azimuth with their corresponding true values at sampling stations located relative to a common waypoint. GPS-derived positions were within the 30.5 m standard of accuracy that is prescribed for detailed soil surveys in delineating soil boundaries. Positioning was best beyond 100 m of a waypoint, where distance and azimuth readings generally differed by < 8 m and 1ø from true. Within 100 m of a waypoint, azimuth readings were erroneous, and distance and azimuth readings were variable. The GPS methods appear to be sufficiently accurate for positioning and navigating in the field digitizing of soil boundaries. Soil surveyors reported greater efficiencies in the field than with conventional methods.

Title Performance of a backpack GPS in a tropical rain forest.

Author Wilkie-DS

Source PE-and-RS,-Photogrammetric-Engineering-and-Remote-Sensing. 1989, 55: 12, 1747-1749; 8 ref.

Year 1989

Abstract A battery powered, solar recharged GPS (Global Positioning System) receiver mounted on a backpack was assembled and tested for 6 months within the Ituri rain forest of NE Zaire in order to assess the practicality of NAVSTAR (satellite) GPS location determination within an isolated forest region. The backpack GPS performed well under demanding conditions (including average humidity of 70-90% and frequent torrential rain) and was able to obtain 3-dimensional positions within 20 min in inaccessible areas often moderately enclosed by vegetation (canopy closure <20%).

ANNEX 1.

Table 2 A list of datums, areas where they are typically used and their reference ellipsoids.

Datum	**Area**	**Ellipsoid**
Deutsches Hauptdreicksnetz (DHDN)	Germany	Bessel
Adindan	Ethiopia, Mali, Senegal, Sudan	Clarke 1880
Afgooye	Somalia	Krassovsky
Ain el Abd 1970	Bahrain Island	International
Anna 1 Astro 1965	Cocos Islands	Australian National
Arc 1950	Botswana, Lesotho, Malawi, Swaziland, Zaire, Zambia, Zimbabwe	Clarke 1880
Arc 1960	Kenya, Tanzania	Clarke 1880
Ascension Island 1958	Ascension Island	International
Astro Beacon "E"	Iwo Jima Island	International
Astro B4 Sorol Atoll	Tern Island	International
Astro DOS 71/4	St. Helena Island	International
Astronomic Station 1952	Marcus Island	International
Australian Geodetic 1966 (AGD 66)	Australia and Tasmania Island	Australian National
Australian Geodetic 1984 (AGD 84)	Australia and Tasmania Island	Australian National
Belgium	Belgium	International
Bellevue (IGN)	Efate and Erromango Islands	International
Bermuda 1957	Bermuda Islands	Clarke 1866
Bogota Observatory	Colombia	International
Campo Inchauspe	Argentina	International
Canton Astro 1966	Phoenix Islands	International
Cape	South Africa	Clarke 1880
Cape Canaveral	Florida and Bahama Islands	Clarke 1866
Carthage	Tunisia	Clarke 1880
Chatham 1971	Chatham Island (New Zealand)	International
Chua Astro	Paraguay	International
Corrego Alegre	Brazil	International
Djakarta (Batavia)	Sumatra Island (Indonesia)	Bessel 1841
DOS 1968	Gizo Island (New Georgia Islands)	International
Easter Island 1967	Easter Island	International
European 1950 (ED 50)	Austria, Belgium, Denmark, Finland, France, Germany, Gibraltar, Greece, Italy, Luxembourg, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland	International
European 1979 (ED 79)	Austria, Finland, Netherlands, Norway, Spain, Sweden, Switzerland	International
European 1987 (ED 87)	Europe	International
Gandajika Base	Republic of Maldives	International
Geodetic Datum 1949	New Zealand	International

Geodetic Reference System 1967 (GRS 67)	Worldwide	GRS 67
Geodetic Reference System 1980 (GRS 80)	Worldwide	GRS 80
Guam 1963	Guam Island	Clarke 1866
GUX 1 Astro	Guadalcanal Island	International
Hito XVIII 1963	South Chile (near 53°S)	International
Hjorsey 1955	Iceland	International
Hong Kong 1963	Hong Kong	International
Hu–Tzu–Shan	Taiwan	International
Indian	Thailand and Vietnam	Everest
Indian	Bangladesh, India, Nepal	Everest
Ireland 1965	Ireland	Modified Airy
ISTS 073 Astro 1969	Diego Garcia	International
Johnston Island 1961	Johnston Island	International
Kandawala	Sri Lanka	Everest
Kerguelen Island	Kerguelen Island	International
Kertau 1948	West Malaysia and Singapore	Modified Everest
L.C. 5 Astro	Cayman Brac Island	Clarke 1866
Liberia 1964	Liberia	Clarke 1880
Lisboa (DLx)	Portugal	International
Luzon	Philippines (excluding Mindanao Island)	Clarke 1866
Luzon	Mindanao Island	Clarke 1866
Mahe 1971	Mahe Island	Clarke 1880
Marco Astro	Salvage Islands	International
Massawa	Eritrea (Ethiopia)	Bessel 1841
Melrica 1973 (D73)	Portugal	International
Merchich	Morocco	Clarke 1880
Midway Astro 1961	Midway Island	International
Minna	Nigeria	Clarke 1880
Nahrwan	Masirah Island (Oman)	Clarke 1880
Nahrwan	United Arab Emirates	Clarke 1880
Nahrwan	Saudi Arabia	Clarke 1880
Naparima, BWI	Trinidad and Tobago	International
Netherlands	Netherlands	Bessel
North American 1927 (NAD 27)	Continental US	Clarke 1866
North American 1927 (NAD 27)	Alaska	Clarke 1866
North American 1927 (NAD 27)	Bahamas (excluding San Salvador Island)	Clarke 1866
North American 1927 (NAD 27)	San Salvador Island	Clarke 1866
North American 1927 (NAD 27)	Canada (including Newfoundland Island)	Clarke 1866
North American 1927 (NAD 27)	Canal Zone	Clarke 1866

North American 1927 (NAD 27)	Caribbean (Turks and Caicos Islands)	Clarke 1866
North American 1927 (NAD 27)	Central America (Belize, Costa Rica, El Salvador, Guatemala, Honduras, Nicaragua)	Clarke 1866
North American 1927 (NAD 27)	Cuba	Clarke 1866
North American 1927 (NAD 27)	Greenland (Hayes Peninsula)	Clarke 1866
North American 1927 (NAD 27)	Mexico	Clarke 1866
North American 1927 (NAD 27)	Michigan (used only for State Plane Coordinate System 1927)	Modified Clarke 1866
North American 1983 (NAD 83)	Alaska, Canada, Central America, Continental US, Mexico	GRS 80
Nouvelle Triangulation Francaise (NTF)	France	Modified Clarke 1880
NWGL 10	Worldwide	WGS 72
Observatorio 1966	Corvo and Flores Islands (Azores)	International
Old Egyptian	Egypt	Helmert 1906
Old Hawaiian	Hawaii	Clarke 1866
Oman	Oman	Clarke 1880
Ordnance Survey of Great Britain 1936	England, Isle of Man, Scotland, Shetland Islands, Wales	Airy
Pico de las Nieves	Canary Islands	International
Pitcairn Astro 1967	Pitcairn Island	International
Provisional South Chilean 1963	South Chile (near 53°S)	International
Provisional South American 1956	Bolivia, Chile, Colombia, Ecuador, Guyana, Peru, Venezuela	International
Puerto Rico	Puerto Rico and Virgin Islands	Clarke 1866
Qatar National	Qatar	International
Qornoq	South Greenland	International
Reunion	Mascarene Island	International
Rikets Triangulering 1990 (RT 90)	Sweden	Bessel
Rome 1940	Sardinia Island	International
Santo (DOS)	Espirito Santo Island	International
São Braz	São Miguel, Santa Maria Islands (Azores)	International
Sapper Hill 1943	East Falkland Island	International
Schwarzeck	Namibia	Modified Bessel 1841
South American 1969	Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Guyana, Paraguay, Peru, Venezuela, Trinidad, and Tobago	South American 1969
South Asia	Singapore	Modified Fischer 1960
Southeast Base	Porto Santo and Madeira Islands	International
Southwest Base	Faial, Graciosa, Pico, Sao Jorge, Terceira Islands (Azores)	International

Timbalai 1948	Brunei and East Malaysia (Sarawak and Sabah)	Everest
Tokyo	Japan, Korea, Okinawa	Bessel 1841
Tristan Astro 1968	Tristan da Cunha	International
Viti Levu 1916	Viti Levu Island (Fiji Islands)	Clarke 1880
Wake–Eniwetok 1960	Marshall Islands	Hough
World Geodetic System 1960 (WGS 60)	Worldwide	WGS 60
World Geodetic System 1966 (WGS 66)	Worldwide	WGS 66
World Geodetic System 1972 (WGS 72)	Worldwide	WGS 72
World Geodetic System 1984 (WGS 84)	Worldwide	WGS 84
Yacare	Uruguay	International
Zanderij	Surinam	International
Nouvelle Triangulation Francaise (NTF) Greenwich Prime Meridian	France	Modified Clarke 1880
Potsdam	Germany	Bessel
Pulkovo 1942	Germany	Krassovsky
Rauenberg	Germany	Bessel

Source: MapInfo

Table 3 A list of defined Ellipsoids and Ellipsoidal Constants

Ellipsoid Name	Semi-Major Axis (m)	Flattening Reciprocal
Airy 1830	6377563.396	299.324964600
Modified Airy	6377340.189	299.324964600
Australian National	6378160.000	298.250000000
Bessel 1841	6377397.155	299.152812800
Bessel 1841 - Namibia	6377483.865	299.152812800
Clarke 1866	6378206.400	294.978698200
Clarke 1880	6378249.145	293.465000000
Everest - Brunei	6377298.556	300.801700000
Everest - 1830	6377276.345	300.801700000
Everest - 1956	6377301.243	300.801700000
Everest - 1948	6377304.063	300.801700000
Everest - 1969	6377295.664	300.801700000
Fischer 1960	6378166.000	298.300000000
Modified Fischer 1966	6378155.000	298.300000000
Fischer 1968	6378150.000	298.300000000
GRS 1967	6378160.000	298.247167427
GRS 1980	6378137.000	298.257222101
Helmert 1906	6378200.000	298.300000000
Hough	6378270.000	297.000000000
International 1924	6378388.000	297.000000000
Krassovsky	6378245.000	298.300000000
South American 1969	6378160.000	298.250000000
WGS 1960	6378165.000	298.300000000
WGS 1966	6378145.000	298.250000000
WGS 1972	6378135.000	298.260000000
WGS 1984	6378137.000	298.257223563

Source: Geographic Calculator, Golden Software.

Table 4 A List of projections, together with brief descriptions of some.

Albers Equal–Area Conic		
Azimuthal Equidistant		
Cylindrical Equal–Area		
Eckert IV	pseudo-cylindrical	Used for world maps. Pseudo-cylindrical and equal area. Central meridian is straight. The 180th meridians are semi-circles. Other meridians are elliptical. Scale is true along the parallel at 40:30 N & 40:30 S.
Eckert VI	pseudo-cylindrical	Used for world maps. Pseudo-cylindrical and equal area. Central meridian and all parallels are at right angles. All other meridians are sinusoidal curves. Shape distortions increase towards the poles. Scale is correct at the standard parallels of 49:16 N & S.
Equidistant Conic (Simple Conic)		
Gall	cylindrical	Galls stereographic cylindrical projection results from projecting the earth's surface from the equator onto a secant cylinder intersected by the globe at 45 degrees north and 45 degrees south. This projection moderately distorts distance, shape, direction and area.
Oblique Mercator		Oblique Mercator projections are used to portray regions along great circles. Distances are true along a great circle defined by the tangent line formed by the sphere and the oblique cylinder. Elsewhere, distance, shape and areas are distorted. Use for areas that are along long thin zones at a diagonal with respect to north-south.
Lambert Azimuthal Equal–Area		
Lambert Conformal Conic		
Longitude/Latitude		
Mercator	cylindrical	The Mercator projection has straight meridians and parallels that intersect at right angles. Scale is true at the equator, or at two standard parallels equidistant from the equator. This projection is often used for marine navigation since all straight lines on the map are lines of constant azimuth.
Miller Cylindrical	cylindrical	A projection with straight meridians and parallels that intersect at right angles, but straight lines are not of constant azimuth. Shapes are distorted. Directions are true only along the equator. The projection avoids the scale exaggerations of the Mercator projection.
New Zealand Map Grid		

Mollweide	pseudo-cylindrical	Used for world maps. Pseudo-cylindrical and equal area. The central meridian is straight. The 90th meridians are circular arcs. Parallels are straight but unequally spaced. Scale is true only along the standard parallels of 40:44 N and 40:44 S.
Robinson		The Robinson projection, unlike a majority of others, is based on tables of co-ordinates rather than on equations or mathematical formulae. This projections distorts shape, area, scale and distance in an attempt to balance the errors in all projections properties. Compare the figure below with that of the UTM projection above.
Peters	cylindrical	A cylindrical equal-area projection that de-emphasizes area exaggerations in high latitudes by shifting the standard parallels to 45 or 47 degrees.
Sinusoidal		
Stereographic		
Transverse Mercator, (also known as Gauss–Kruger)	cylindrical	Transverse Mercator projections are the result of projecting a sphere onto a cylinder tangent to a central meridian. Transverse Mercator maps are often used to portray areas with larger north-south than east-west dimensions. Distortions of scale, distance, direction and area increase away from the central meridian. Many national grid systems are based on the Transverse Mercator projection. A number of different TM projections are defined that are modified for application in particular areas.

Source: MapInfo & http://www.utexas.edu/depts/grg/gcraft/notes/mapproj/mapproj.html