Chapter 7: Specifications and Field Surveys [5 hrs]

Contents:

Further Reading: Wellenhof and Licht, Chapter 7.2 Pre-survey Planning, 2001 # 146

5.1 Survey planning and Dilution of Precision (DOP)

7.1.1 Survey Planning

- Small surveys generally do not require project planning (Ghilani # 372)
- Positioning with a single receiver (absolute point positioning) – only little consideration – ensure a clear view of the sky, no multipath effects and no nearby radio/microwave transmitters that may interfere with GNSS signals (Schoffield # 348)
- Instantaneous solution is good to about 10 – 20 m with such observation (Schoffield # 348)
- If the solution is averaged over 1/2 – 2 hours then the solution may be as good as 5 m in plan and 10 m in height (Schoffield # 348)
- Relative positioning - additional factors to be taken into considerations (Schoffield # 348):
    - shorter the baseline – the more precise would be the result (effects of ionosphere and troposphere are the same at both ends of the baseline)
    - better to observe with short baselines with multiple reference stations rather than from one central station
    - example – better to measure two baselines of 5 km than to measure a single 10 km baseline
- For large projects and for higher-accuracy surveys - project planning is a critical component in obtaining successful results (Ghilani # 372)
- There are many factors that need to be considered when planning survey work (Schoffield # 348)
- Various aspects of project planning with emphasis on control surveys are (Ghilani # 372):
    - Preliminary Considerations
    - Selection of Appropriate Survey Method
    - Field Reconnaissance
    - Development of Observation Scheme
    - Availability of Reference Stations

Preliminary Considerations

- All new high-accuracy survey projects - employ relative positioning techniques - must be tied to nearby existing control points (Ghilani # 372)
- One of the first things that must be done - obtain information on the availability of existing control stations near the project area (Ghilani # 372)

- ❖ These control stations should be plotted in their correct locations on an existing map or aerial photos of the area (Ghilani # 372)
- ❖ Another important factor - the selection of the new station locations – must be chosen to meet overall project objectives (Ghilani # 372)
- ❖ In addition, terrain, vegetation, and other factors must be considered in their selection (Ghilani # 372)
- ❖ They should be reasonably accessible by either the land vehicles or aircraft if possible (Ghilani # 372)
- ❖ The stations can be somewhat away from vehicle access points since hardware components are relatively small and portable (Ghilani # 372)
- ❖ Once the preliminary selection of station locations are done, they should be plotted on the map or aerial photo of the area (Ghilani # 372)
- ❖ Canopy restrictions (obstructions to clear overhead view) that may possibly block satellite signals – adversely affect satellite geometry (Ghilani # 372)
- ❖ It is therefore necessary to assure for clear overhead view free of obstructions (Ghilani # 372)
- ❖ It is recommended to have clear visibility in all directions from a mask angle (altitude angle) of 10° – 20° from the horizon (Ghilani # 372)

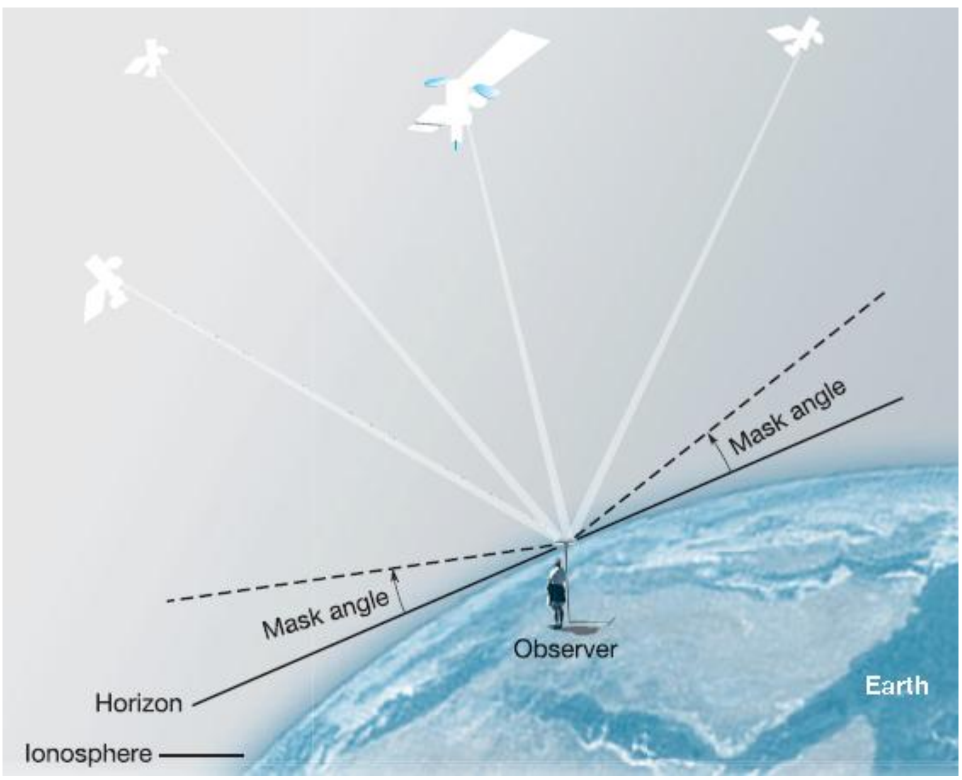

Figure 9: Relative positions of satellites, ionosphere, and receiver (Ghilani # 351)

- ❖ Furthermore, potential sources that can cause interference and multipath errors should also be identified (Ghilani # 372)
- ❖ Selection of observation windows – determining satellites visible from the selected ground station or project area during the proposed observation period (Ghilani # 372)
- ❖ Almanac data for the times within the planned observation period aid in predetermining azimuth and elevation angles to each visible satellite (Ghilani # 372)

- Space weather should also be checked for possible solar storms during the periods of occupation - Days when the solar storm activity is rated from strong to extreme should be avoided (Ghilani # 372)
- A satellite availability plot, as shown in the figure, can be applied to aid in selecting suitable observation windows (Ghilani # 373)
- The shaded portion in this diagram shows the number of satellites (of 3 selected constellations) visible from the selected station whose position is 28°15'15.4451" N latitude and 83°58'36.3472" E longitude (https://www.gnssplanning.com/#/settings)
- At least 17 satellites from 3 constellations are available during the proposed session
- The plot is applicable for September 19, 2022 between the hours of 8:00 and 14:00 Local time. A mask angle of 15° has been used

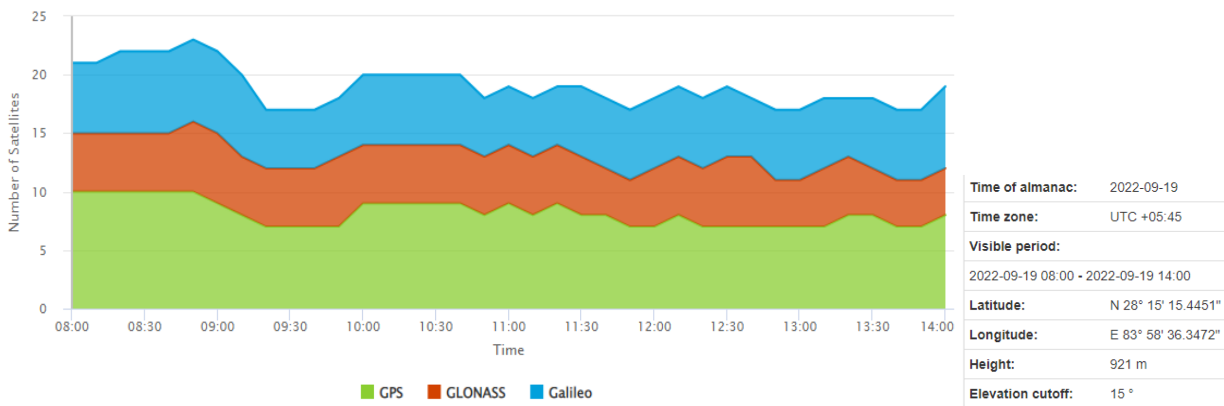

Figure 10: Predicted satellite availability at the selected station for 19 September 2022

- Similar plot depicts PDoP, HDoP, and VDoP for the same time period and as it depicts, there is no unacceptable window for the GNSS survey, however at around 9:30 am and 11:15 am, there is slightly weaker satellite geometry and DoP values are slightly larger

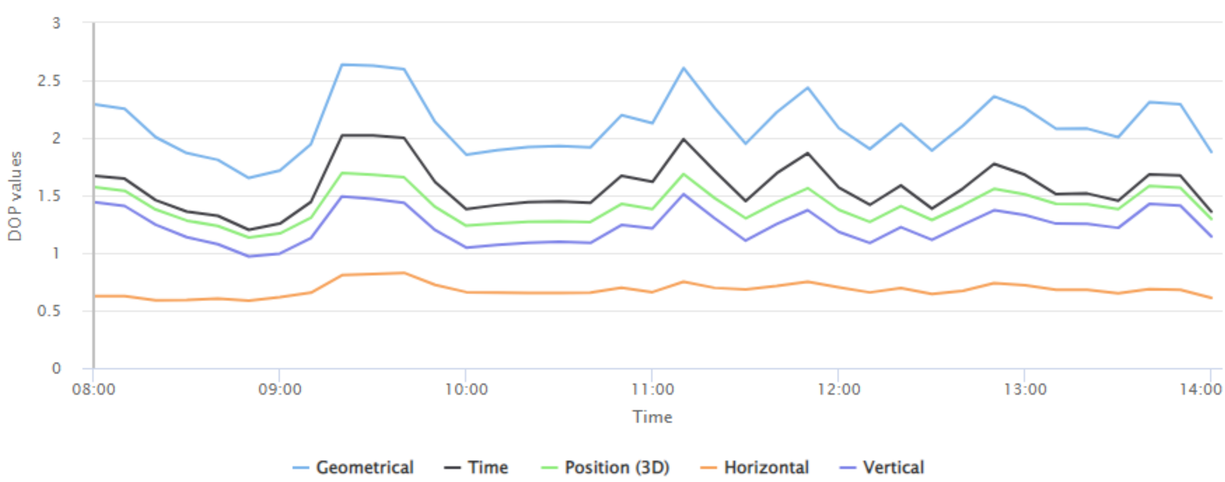

Figure 11: Predicted DoP values for the satellites at the selected station for 19 September 2022

- Sky plot (Figure 12) – satellite visibility at any station – easily and quickly investigated (Ghilani # 374)

- Sky plot – provides a graphic representation of azimuths and elevations to visible satellites from a given location (Ghilani # 374)
- Sky plots – consist of a series of concentric circles graduated from 0° to 360° to represent satellite azimuths – each circle progressing towards the center represent an increment in the elevation angle (Ghilani # 374)
- The center corresponds to zenith (Ghilani # 374)
- Sky plots are valuable in survey planning because they enable surveyors to quickly visualize the number of satellites available during a planned observation period, together with their geometric distribution in the sky. (Ghilani # 374)

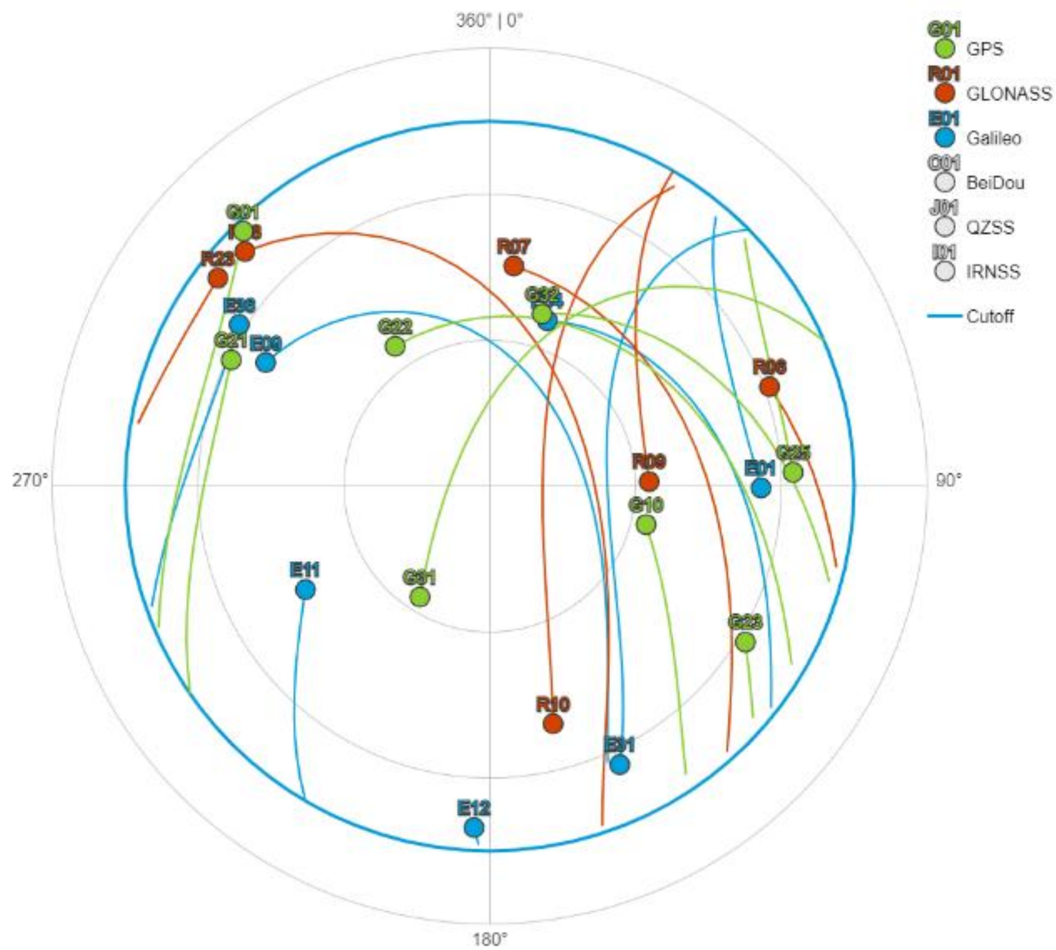

Figure 12: Sky plots for station the selected station for 19 September 2022

Selecting the Appropriate Survey Method

- As discussed in the previous chapter, several different methods are available with which to accomplish a GNSS survey (Ghilani # 376)
- High accuracy surveys – involving long baselines – static survey method with GNSS receivers is the best solution (Ghilani # 376)
- Surveys limited to small areas – a single frequency receiver using rapid static, pseudo-kinematic or kinematic survey methods – sufficient (Ghilani # 376)

- Wide variation in requirements and restrictions of surveys – selection of appropriate survey method (Figure 13) depends on (Ghilani # 376):
    - Desired level of accuracy in the final coordinates
    - Intended use of the survey
    - Type of equipment available for the survey
    - Size of the survey
    - Canopy and other local conditions for the survey, and
    - Available software for reducing the data
- Surveying community – use methods depicted on the left side of the Figure 13
- GNSS receivers – increased number of satellites and improved satellite geometry – reduce time required at each station in a static survey (Ghilani # 376)
- For mapping or inventory surveys – centimeter to sub-meter accuracy is sufficient – code-based receivers or an RTK survey – most economical (Ghilani # 377)
- In areas with several overhead obstructions – use of one of static survey procedures – recommended to bring control into the region (Ghilani # 377)
- In small areas where clear overhead views to the satellites are available - kinematic mapping (Ghilani # 377)
- With the modernized GNSS constellations in place – restrictions in use of GNSS surveys due to canopy restrictions will be greatly reduced (Ghilani # 377)

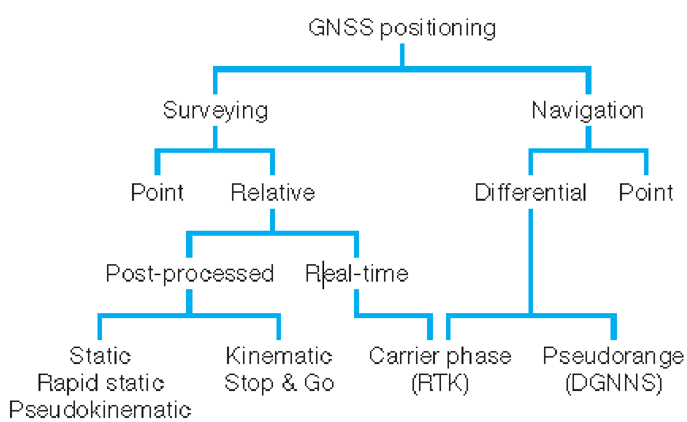

Figure 13: GNSS Positioning Methods (Ghilani # 376)

- High-accuracy control surveys – static method is preferred (Ghilani # 377)
- Often combinations of static methods – provide the most economical results for large projects (Ghilani # 377)
- For example: static survey for sparse network of accurate control into a project area followed by a rapid static survey to densify the control and finally kinematic survey could be used to establish control along specific alignments (Ghilani # 377)
- In smaller areas with favourable viewing conditions – suitable methods would be rapid static or kinematic survey – simplify the survey (Ghilani # 377)
- Available equipment, software, and experience also dictate the selection of survey method (Ghilani # 377)

- NGS provides the Online Positioning User Service (OPUS) - https://geodesy.noaa.gov/OPUS/ (Ghilani # 377)
- Using this service with post processed kinematic survey – does not need base station positioned over a point of known coordinates – rather use of CORS can be made as base station (Ghilani # 377)
- To achieve maximum accuracy with this service – base station must collect data for a minimum of 2 hours (Ghilani # 377)
- Using dual-frequency or GNSS receivers – NGS provides static OPUS survice – determine the position of a receiver with as little as 15 min data (Ghilani # 377)
- Initialization of rover – obtained on-the-fly ambiguity resolutions (Ghilani # 377)
- After initialization – rover can proceed with the survey (Ghilani # 377)
- Before post-processing – data from the roving receiver (the RINEX observation file) from the base station submitted to the NGS – post processing over the Internet (Ghilani # 377)
- In a matter of minutes – OPUS returns the coordinates of the base station using the data from the nearby CORS station (Ghilani # 377)
- This procedure removes the need for an initial know base station (Ghilani # 377)
- https://webapp.csrs-scrs.nrcan-rncan.gc.ca/geod/tools-outils/ppp.php

Field Reconnaissance

- Once control stations and new stations are located on paper – a reconnaissance trip to the field has to be undertaken to check (Ghilani # 377):
  - overhead obstructions that rise above 10° to 15° from the horizon
  - reflecting surfaces that can cause multipathing
  - nearby electrical installations that can interfere with the satellite's signal
  - other potential problems
- If found unsatisfactory – adjustments shall be made to the positions of the previously selected station locations (Ghilani # 377)
- In case of existing control stations – ties can be made to nearby permanent objects – photos of rubbings of the monument caps should be created (Ghilani # 377)
- These will provide aid to the survey crews in locating the stations during the survey – reduce the time spent at each station – minimize station mis-identifications (Ghilani # 377)
- There are many online and offline digital platforms to make preliminary decision about the suitability of a site for occupation by a GNSS receiver (Ghilani # 377)
- However, a site visit is the only method to confirm its suitability (Ghilani # 377)
- Once selection of new stations are confirmed – permanent monuments are set – positions of these stations are also documented with ties (Ghilani # 378)
- At the same time – accurate horizon plot of any surrounding obstructions can be prepared, and road directions and approximate driving times between stations are recorded (Ghilani # 378)
- Monuments in general – metal caps (often brass) with the name of the point and other information about the station (Ghilani # 378)
- This information stamped onto the cap – rubbed onto a piece of paper by directly laying it over the cap – rubbing across the surface with the side of a pencil lead (Ghilani # 378)
- Imprint of the cap is obtained – helps to eliminate mistakes in station identification (Ghilani # 378)

Developing an Observation Scheme

- Existing control points, new stations and the observations made – comprise a network (Ghilani # 378)
- Based on the nature of the project and extent of the survey – network can vary from only a few stations to very large and complicated configurations (Ghilani # 378)
- Figure 14 illustrates a small network consisting of only two existing control points and four new stations. (Ghilani # 378)

Approx. Distances

Line	Length (km)
AB	17 (between 2 control points)
AC	13
AE	7
AF	7
BC	11
BD	11
BF	11
FC	11
FE	7
FD	9
ED	9
CD	18

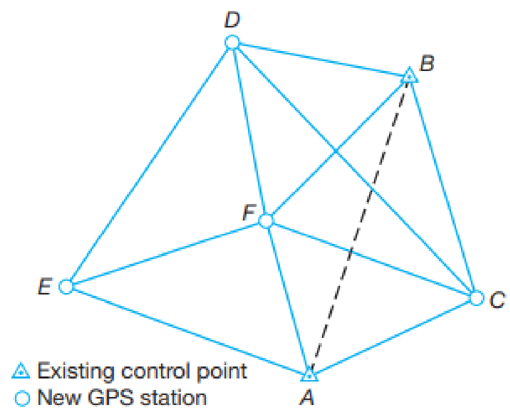

Figure 14: A GNSS network (Ghilani # 378)

- Stations established and network formed – an observation scheme developed for performing survey (Ghilani # 378)
- The scheme – planned sequence of observing sessions and accomplishes the objectives of the survey in the most efficient manner (Ghilani # 378)
- As a minimum – ensure that – every station in the network is connected to at least another station by a nontrivial (independent) baseline (Ghilani # 378)
- The scheme should also include some redundant observations (i.e., baseline observations between existing control stations, multiple occupations of stations, and repeat observations of certain baselines) – used for checking purposes and improving the precision and reliability of the work (Ghilani # 378)
- Desired accuracy – principal factor governing the number and type of redundant observations (Ghilani # 378)
- Federal Geodetic Control Subcommittee (FGCS) – a set of standards and specifications for GPS relative positioning (Ghilani # 378)
- Large, high-accuracy projects – these standards and specifications or other similar ones – govern the survey works and must be carefully followed (Ghilani # 378)
- Relative positioning – for any observing session – the number of nontrivial baselines measured is (Ghilani # 379):

$$b = n - 1$$

where b is the number of nontrivial baselines, and
n is the number of receivers being employed in the session

- When two receivers are used in a session, then only one baseline is observed and it is nontrivial (Ghilani # 379)
- With more than two receivers, both nontrivial and trivial (dependent) baselines will result (Ghilani # 379)
- Total number of baselines is (Ghilani # 379):

$$T = n(n - 1) /2$$

where T is the total number of baselines possible and
n is as previously defined.

- The number of trivial baselines is (Ghilani # 379):

$$t = (n - 1)(n - 2) / 2$$

where t is the total number of trivial baselines.

- If four receivers are used in a session, six baselines will result: three nontrivial and three trivial (Ghilani # 379)
- At least one baseline should be observed between existing controls for higher accuracy for every receiver-pair used on a project to check the performance of equipment and the reliability of the control (Ghilani # 380)
- Some baselines should be observed more than once – ideally at or near the beginning and end of the project observations (Ghilani # 379)
- For control surveys – baselines should form closed geometric figures – perform closure check (Ghilani # 379)

Availability of Reference Stations

- In order to achieve highest order of accuracy in positioning – availability of high-quality reference control stations is necessary (Ghilani # 383)
- In recent years, the National Geodetic Survey (NGS) - created a national system of **Continuously Operating Reference Stations**, also called the National CORS Network with cooperation from other public and private agencies (Ghilani # 383) (http://www.ngs.noaa.gov/CORS/)
- CORS - have their positions known to high accuracy and they are occupied by a receiver that continuously collects satellite data (Ghilani # 383)
- CORS - can be used as base station to support roving receivers operating in the vicinity of the CORS station (Ghilani # 383)
- CORS data files are easily downloaded using the user-friendly CORS options on the NGS website (Ghilani # 384)
- Provides interactive form requesting the (1) starting date, (2) time, (3) duration of the survey, (4) site selection, and (5) the collection interval among other things (Ghilani # 384)
- Data request is interpreted by the server and appropriate data is sent via the Internet within minutes (Ghilani # 384)
- Data may not be collected at a particular CORS site for a short period of time – caused by several factors (Ghilani # 384)

- Those factors include local power outages, storm damage, and software and hardware failures (Ghilani # 384)
- If a CORS station is planned for use on a particular survey – important it check the availability of the station prior to the beginning of a survey – ensure if it is functioning properly and if necessary data will be available following the survey (Ghilani # 384)

7.1.2 Satellite Geometry and Dilution of Precision (DoP)

- Distribution of the satellites above an observer's horizon has a direct bearing on the quality of the position derived from them (Van Sickle # 89)
- Geometry of the visible satellites - an important factor in achieving high quality results especially for point positioning and kinematic surveying (Figure 15) (Wellenhof # 262)
- Visibility - characterized by the unobstructed line of sight between receiver and satellite (Wellenhof # 262)
- Geometry changes with time due to the relative motion of the user and satellites (Wellenhof # 262)
- Measure of the instantaneous geometry is the dilution of precision (DoP) factor (Wellenhof # 262)
- Dilution of Precision (DoP) - the concept where the problem of geometry is analysed and a numerical parameter is derived to describe the quality of the geometric relationship between the user's equipment and the chosen satellites (Schoffield # 344)

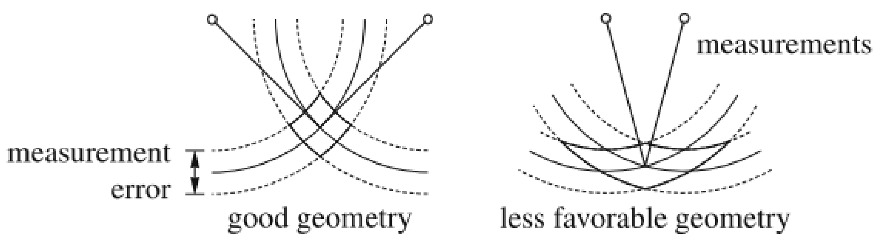

Figure 15: Position error as a function of geometry and measurement error (Wellenhof # 241)

- DoP - the geometric strength of the figure described by the positions of the satellites with respect to one another and the GNSS receivers (Van Sickle # 89)
- A low DoP factor is good; a high DoP factor is bad - In other words, when the satellites are in the optimal configuration for a reliable GPS position, the DoP is low; and vice versa (Figure 16). (Van Sickle # 89)

An important additional error source in satellite surveying deals with the geometry of the visible satellite constellation at the time of observation. This is similar to the situation in traditional surveys, where the geometry of the network of observed ground stations affects the accuracies of computed positions. Figure 13.11 illustrates both weak and strong satellite geometry. As shown in Figure 13.11(a), small angles between incoming satellite signals at the receiver station produce weak geometry and generally result in larger errors in computed positions. Conversely, strong geometry, as shown in Figure 13.11(b), occurs when the angles between incoming satellite signals are large, and this usually provides an improved solution. Whether conducting a satellite survey or a traditional one, by employing least-squares adjustment in the solution, the effect of the geometry upon the expected accuracy of the results is determined. (Ghilani # 353)

Table 1: Important Categories of Dilution of Precision (Ghilani # 355)

DoP Category	Stand. Dev. Terms	Equation	Acceptable Value (Less than) *
PDoP	σ in geocentric coordinates X, Y, Z	$\sqrt{\sigma_X^2 + \sigma_Y^2 + \sigma_Z^2}$	6
HDoP	σ in local x, y coordinates	$\sqrt{\sigma_X^2 + \sigma_Y^2}$	3
VDoP	σ in height, h	σ_h	5
*These recommended values are general guides for average types of GPS surveys, but individual project requirements may require other specific values.			

As noted above, by employing least squares in the solution, the effect of satellite geometry can be determined. In fact, before conducting a satellite survey, the number and positions of visible satellites at a particular time and location can be evaluated in a preliminary least-squares solution to determine their estimated effect upon the resulting accuracy of the solution. This analysis produces so-called Dilution Of Precision (DOP) factors. The DOP factors are computed through error propagation (see Section 3.17). They are simply numbers, which when multiplied by the errors of Table 13.2, give the sizes of errors that could be expected based upon the geometry of the observed constellation of satellites. For example, if the DOP factor is 2, then multiplying the sizes of errors listed in Table 13.2 by 2 would yield the estimated errors in the ranges for that time and location. Obviously, the lower the value for a DOP factor, the better the expected precision in computed positions of ground stations. If the preliminary least squares analysis gives a higher DOP number than can be tolerated, the observations should be delayed until a more favorable satellite constellation is available (Ghilani # 354)

The DOP factors that are of most concern to surveyors are PDOP (dilution of precision in position), HDOP (dilution of precision in horizontal position), and VDOP (dilution of precision in height). For the best possible constellation of satellites, the average value for HDOP is under 2 and under 5 for PDOP. Other DOP factors such as GDOP (dilution of precision in geometry) and TDOP (dilution of precision in time) can also be evaluated, but are generally of less significance in surveying. Table 13.3 lists some important categories of DOP, explains their meanings in terms of standard deviations and equations, and gives maximum values that are generally considered acceptable for most surveys. (Ghilani # 354)

Multiplying the DOP factor by the UERE yields the positional error in code ranging using Equations (13.13). For example, the HDOP is typically about 1.5. Recall from Equation (3.8) that the 95% probable error is obtained using a multiplier of about 1.96. Using the error values from Table 13.2 and a HDOP of 1.5 the current 95% probable error in horizontal positioning is (1.96 x 1.5 x 7.5) ± 22.5 m .When the newer coded signals are available and used by receivers, the 95% horizontal positioning error will be approximately ± 8.5 m. (Ghilani # 355)

Bad Dilution of Precision

- ❖ Four or more satellites must be above the observer's mask angle for the simultaneous solution of the clock offset and 3 dimensions of the receiver's position (Van Sickle # 90)
- ❖ However, if **all the satellites are crowded together** in one part of the sky - the **DoP would be high -** the position would be likely to have an unacceptable uncertainty (Van Sickle # 90)

- A **high DoP** is a like a warning **-** the **actual errors** in a GNSS position are liable to be **larger than expected** (Van Sickle # 90)
- An approximation of the effect is (Van Sickle # 90):

$$\sigma = DoP\sigma_o$$

where σ = Uncertainty of the position
DoP = Dilution of Precision
σ_o = Uncertainty of the measurements (User equivalent range error – UERE)

- Since GNSS position is derived from 3D solution – **several DoP factors** – useful for the evaluation of uncertainties in the GNSS position components (Van Sickle # 90)
- **HDoP and VDoP** – horizontal and vertical dilution of precisions respectively – uncertainty of a positioning solution has been isolated into its horizontal and vertical components (Van Sickle # 90)
- Both HDoP and VDoP combined – the uncertainty of 3D positions is called position dilution of precision **(PDoP)** (Van Sickle # 90)
- Time dilution of precision **(TDoP)** – uncertainty of clock (Van Sickle # 90)
- Geometric dilution of precision **(GDoP)** – combination of all of above (Van Sickle # 90)
- Relative dilution of precision **(RDoP)** – includes number of receivers, number of satellites they can handle, length of the observing session as well as the geometry of the satellites'configuration (Van Sickle # 90)
- User equivalent range error **(UERE) -** total error budget affecting a pseudorange **-** square root of the sum of the squares of the individual biases (Van Sickle # 90)

Good Dilution of Precision

- **Size of the DOP factor -** inversely proportional to the **volume of the tetrahedron** (Figure 16) described by the satellite's positions and the position of the receiver (Van Sickle # 91)
- The **larger the volume** of the body defined by the lines from the receiver to the satellites, the better the satellite geometry and the **lower the DoP** (Van Sickle # 91)
- An **ideal arrangement** of four satellites **- one directly above the receiver**, the **others 120° from one another** in azimuth near the horizon (Van Sickle # 91)
- With that distribution **- DoP** would be **nearly 1**, **the lowest possible value** (Van Sickle # 91)
- In practice, the lowest DOPs are **generally around 2** (Van Sickle # 91)
- GNSS receivers can be set a PDoP mask to guarantee that data will not be logged if the PDoP goes above the set value (Van Sickle # 91)
- A **typical PDOP mask is 6** (Van Sickle # 91)
- As PDoP increases – positional accuracy probably deteriorate and as PDoP decreases – the accuracy probably improves (Van Sickle # 91)
- When DoP factor exceeds a maximum limit in a particular location – indicates unacceptable level of uncertainty exists over a period of time – this time period as an outage (Van Sickle # 91)
- This expression of uncertainty is useful – interpretation of measured baselines and planning a GNSS survey (Van Sickle # 91)

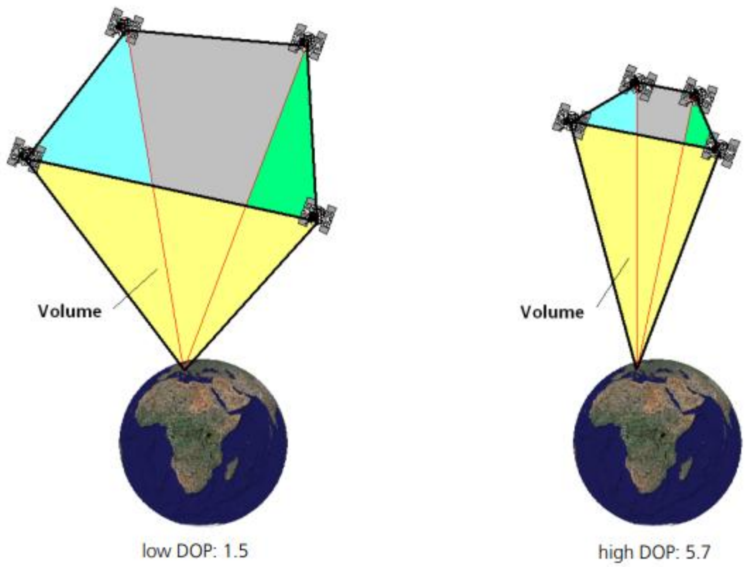

Figure 16: The larger the enclosed volume, the smaller the DOP value (u-blox 2009 # 93)

Depending upon the user's application, there are several interrelated DOP statistics; Geometrical, Position, Horizontal, Vertical and Time Dilutions of Precision. In each case the DOP statistics are the amplification factor, which, when multiplied by the pseudo-range measurement error, give the error of the computed position or time, etc. These statistics are only a function of the effect of satellite and user geometry. The reader is probably a surveyor and therefore most interested in three-dimensional position and hence the PDOP of the satellites. A sailor navigating on the relatively flat sea would be more interested in HDOP, since they will already have sufficient information about their height. If a particular user were using the GPS for time transfer, their interest would only be in TDOP, since they will not need to know where they are (Schoffield # 344)

We will consider the surveyor's PDOP, but similar arguments can apply for any of the DOPs. PDOP is a dimensionless number which will vary from about 1.6 in the best possible geometrical configurations with four satellites, to much larger numbers when satellites are badly positioned for a particular user. For example, if the user was able to measure pseudo-range from a user set to a satellite to 5 metres and at a particular instant the satellite and user geometry was such that the PDOP was 2.2, then the user error of position would be $2.2 \times 5 = 11$ m. (Schoffield # 344)

PDOP and all the other DOPs are (Schoffield # 346):

- Independent of the coordinate system employed, both in terms of scale (unit of distance) and orientation.
- A means of user selection of the best satellites from those that are visible.
- The amplification factor of pseudo-range measurement error into the user error due to the effect of satellite geometry

5.2 Survey Specifications

7.1.3 Specifications for Static Survey

The Federal Geodetic Control Subcommittee (FGCS) has published the document entitled "Geometric Geodetic Accuracy Standards and Specifications for Using GPS Relative Positioning Techniques."5 The document specifies seven different orders of accuracy for relative positioning and provides guidelines on instruments and field and office procedures to follow to achieve them. Table 14.4 lists these orders of accuracy. (Ghilani # 387)

The FGCS document also makes recommendations concerning categories of surveys for which the different orders of accuracy are appropriate. Some of these recommendations include order AA for global and regional geodynamics and deformation measurements; order A for "primary" networks of the National Spatial Reference System (NSRS), and regional and local geodynamics; order B for "secondary" NSRS networks and high-precision engineering surveys; and the various classes of order C for mapping control surveys, property surveys, and engineering surveys. The allowable error ratios given in these standards imply the extremely high accuracies that are now possible with relative positioning techniques. (Ghilani # 388)

Table 2: GPS RELATIVE POSITIONING ORDERS OF ACCURACY (Ghilani # 388)

TABLE 14.4 GPS RELATIVE POSITIONING ORDERS OF ACCURACY

Order	Allowable Error Ratio	Parts Per Million (ppm)
AA	1:100,000,000	0.01
A	1:10,000,000	0.1
B	1:1,000,000	1.0
C-1	1:100,000	10
C-2-I	1:50,000	20
C-2-II	1:20,000	50
C-3	1:10,000	100

The National Geodetic Survey has created geodetic height accuracy standards that can be used for vertical surveys. These standards are based on the changes in geodetic heights between control stations. Following a correctly weighted, minimally constrained, least-squares baseline adjustment (see Section 14.5.5), the geodetic height order and class can be determined. This standard is based on the standard deviation (s) of the geodetic height difference (in millimeters) between two points obtained from the adjustment, and the distance (d) between the two control points (in kilometers). The ellipsoid height difference accuracy (b) is computed as (Ghilani # 388):

$$b = \frac{s}{\sqrt{d}} \qquad (14.2)$$

5.3 Quality Assurance